

Present-day tectonics in and around the Adria plate inferred from GPS measurements

Yuksel Altner*

Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany

Željko Bačić

State Geodetic Administration, Zagreb, Croatia

Tomislav Bašić

University of Zagreb, Croatia

Alberto Coticchia

Military Geographical Institute, Firenze, Italy

Mathia Medved

State Geodetic Administration, Ljubljana, Slovenia

Medžida Mulić

University of Sarajevo, Bosnia and Herzegovina

Bilbil Nurçe

University of Tirana, Albania

ABSTRACT

Movement of the Adria microplate is one of the main elements for understanding crustal deformations in the central Mediterranean and central Europe. To study present-day tectonics in Adria and the nature of its boundary relative to those of the Africa and Eurasia plates, three GPS (Global Positioning System) campaigns involving 41 stations were carried out within CRODYN (the Croatian and Slovene Geodynamic Network). Movement of stations derived in the International Terrestrial Reference Frame 1996 (ITRF96) with respect to the permanent ITRF/IGS (International GPS Service) station GRAZ in Austria, located north of the network, and values of the principal strain rates determined on the basis of analytical surface deformation theory suggest that Adria is divided into three different deformation zones (northern, central, and southern).

The domain of northeastern Italy moves 5 mm/yr in an east-northeast direction. The stations in southwestern Slovenia move 3–7 mm/yr in a north-northwest direction, whereas those in southern and northeastern Istria move 4–5 mm/yr in a more easterly direction. The greatest movement (8–10 mm/yr) occurs in central Adria between the Gargano zone and the central Dinarides; there, the movement is northeast-oriented. A fragmentation of Adria into subblocks linking the Gargano zone to the central Dinarides cannot be clearly demonstrated. The southeastern part of Adria, along the coastline of Albania, moves 5–7 mm/yr in an almost east-west direction, and

*E-mail: yuksel.altner@bkg.bund.de.

eastern Albania moves 6 mm/yr in an east-southeast direction. The permanent ITRF/IGS stations POTS and WTZR in Germany, BOR1 in Poland, and PENC in Hungary demonstrate no significant movement. The movement of the stations discussed here differs very clearly from the known north-west motion of the Africa plate and suggests that Adria is an independent microplate.

Keywords: Adria microplate, analytical surface deformation theory, GPS, Mediterranean

INTRODUCTION

The tectonic evolution of the central Mediterranean and central Europe was significantly influenced by the motion of Adria, a microplate or block of continental lithosphere covering eastern Italy and the Po Plain, and the Adriatic Sea west of the Dinarides, which behaved as a tectonic indenter during convergence between the Africa and the Eurasia plates (Channell and Horváth, 1976; Aliaj, 2005). The time distribution of crustal deformations in the central Mediterranean indicates that up to the late Miocene, Adria moved as a part of the Africa plate (Babucci et al., 2004). According to Mantovani et al. (2005), in the late Miocene, the Anatolian-Aegean-Balkan system, due to its westward movement, pushed the southern part of Adria and caused it to decouple from the Africa plate. After this tectonic change, Adria underwent a clockwise rotation with respect to the Eurasia plate and induced a strong compressional regime in the central Mediterranean. During the late Pliocene and the early Pleistocene, Adria collided with the southern part of the Apennines and its movement changed to a slow counterclockwise rotation with respect to the Eurasia plate.

At present, movement of Adria is an important factor for crustal deformations and earthquake occurrences in the regions bounded by it. Studying the current movement of Adria can give us some understanding of its connection to the Africa and Eurasia plates and can explain the geodynamics in the African-Eurasian collisional zone, as well as tectonic processes in the central Mediterranean (Fig. 1).

If we consider the Earth as a body consisting of points, geodynamic processes cause geometrical changes of the positions of these points. These geometrical changes of the point positions are in general very small, but can be mapped by displacement vectors or strain fields. Global models for plate motions (NUVEL-1, NUVEL-1A) combine ocean floor spreading rates, transform fault azimuths, and earthquake slip vectors to describe average relative plate motions by means of a rotation vector (Euler vector) for a time period of the past few million years (DeMets et al., 1990, 1994). The investigation of present-day tectonic activities by means of global plate motion models in a small area with complex movements cannot supply satisfactory results. To detect and quantify small plate motions, a high degree of measurement precision is necessary. Accurate estimation of small movements of points over plate boundaries and faults has been made possible by the development of space-based

techniques including very long baseline interferometry (VLBI), satellite laser ranging (SLR), and use of the GPS. Use of the GPS is the technique most frequently used for determination of crustal movement due to its economic advantages and mobility. With a carefully conducted analysis of GPS data on the horizontal movement of specific points, a precision of ± 2 mm/yr can be achieved. Generally, the accuracy estimated for elevation changes is 2 to 4 times poorer than the accuracy for horizontal displacement of the points.

TECTONICS IN ADRIA AND ITS SURROUNDINGS

Geological and seismological studies indicate that the tectonic features of Adria have been dominated by the collision of the Africa plate with the Eurasia plate. Earthquake epicenters in the Adriatic region recorded by the Advanced National Seismic System (ANSS) hosted by the Northern California Earthquake Data Center show that seismic activity is concentrated mostly in the on-shore areas (Fig. 2). In the off-shore area, the domain between the Gargano zone and the central Dinarides appears to be a significant active tectonic region. Most of the strong earthquakes in the study area occur in the Apennine Mountains in Italy, in the central Dinarides in northeastern Italy and Slovenia, and along the western coast of the Federal Republic of Yugoslavia (Serbia and Montenegro) and Albania.

Based on geological, seismological, and geodetic studies, many hypotheses have been developed about the past and current tectonic features of Adria and its surroundings. Argand (1924) suggested that Adria moved into Europe as a promontory of the African continent, and the collision formed the Alpine mountain chain. With respect to the focal mechanism solutions, Anderson and Jackson (1987) described Adria as a relatively rigid block that rotates counterclockwise relative to Eurasia about a pole located in northwestern Italy. Jackson and McKenzie (1988) suggested that Adria is not a promontory of the Africa plate now, but may have been in the past. Using a block model, Battaglia et al. (2004) lent support to the idea that the Adriatic block is part of neither the Eurasia plate nor the Africa plate, giving the Apulia escarpment as a possible location of the southern Adriatic-African boundary. Westaway (1990) assumed that Adria is an independent rigid block and that a southwest-northeast-oriented decoupled zone existed between the Africa plate and Adria, linking the area from the northern Gargano zone to the central Dinarides, whereas Favali et al. (1993) identified

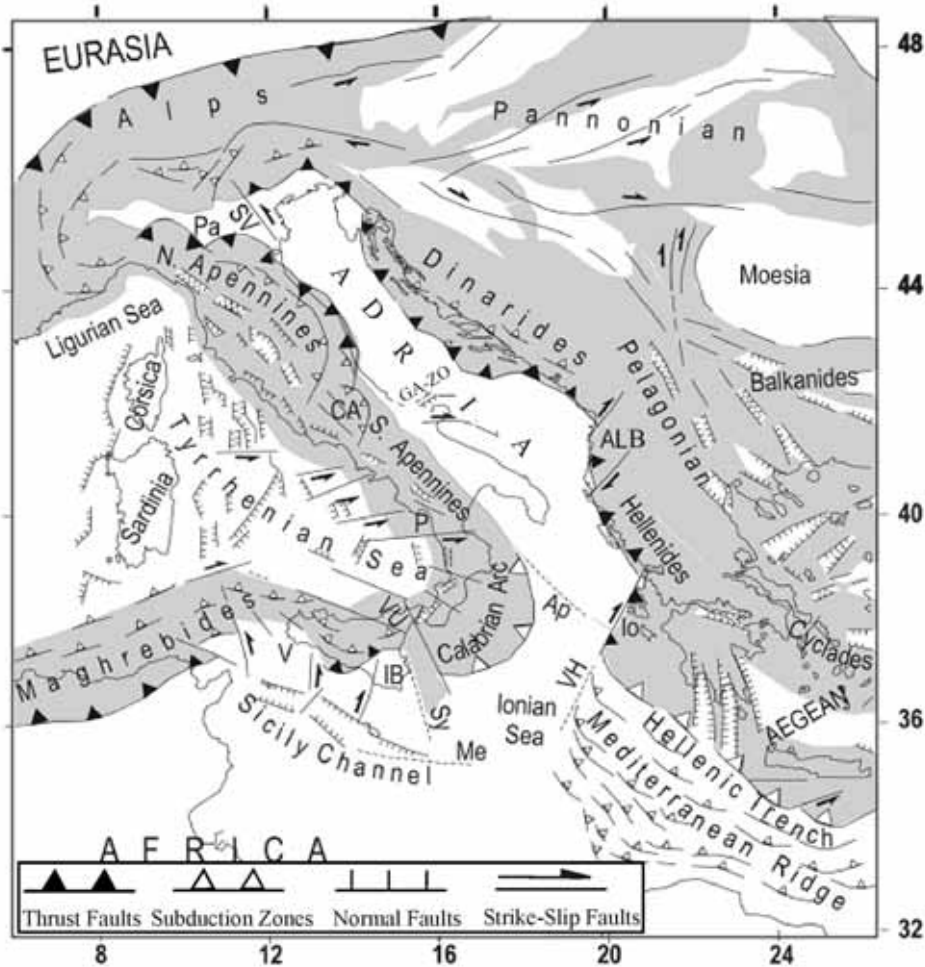


Figure 1. Tectonic features in the central Mediterranean. The gray areas indicate the orogenic belts. ALB—Albania; Ap—Apulian escarpment; CA—central Apennines; GAZO—Gargano zone; IB—Iblean block; Io—Ionian islands; Me—Medina fault; P—Palinuro fault; Pa—Padanian region; SV—Schio-Vicenza fault system; Sy—Syracuse escarpment; VH—Victor Hensen fault system; V—Ventura block; VU—Vulcano fault (after Mantovani et al., 2005).

the fact that seismicity crosses the central Adriatic from the Gargano zone to the central Dinarides as evidence for a tectonic boundary separating Adria into north and south blocks. Based on GPS site velocities and seismicity, Oldow et al. (2002) subdivided Adria into northwestern and southeastern tectonic blocks separated by a boundary extending around the southern Tyrrhenian Sea, across central Italy, and along the coast of the eastern Adriatic. Oldow et al. (2002) suggested that sites in northwestern Adria exhibit little or no motion relative to the Eurasia plate, whereas those in southeastern Adria are moving together with the Africa plate and exhibit a spatially heterogeneous velocity field, with northward velocities of ~ 10 mm/yr. Mantovani et al. (2005) suggested that the Gargano structural high and the adjacent off-shore area are an active tectonic zone including faults with limited seaward extension, but there is no clear evidence in support of central Adriatic decoupling zones. Weber et al. (2005) inverted GPS velocities from sites on the Istria Peninsula for an Adria-Eurasia Euler pole and obtained a slow counterclockwise rotation and a pole position very close to that of Anderson and Jackson (1987), supporting the rigid microplate model.

Kuk et al. (2000) and Markusić et al. (1998) proposed that Adria is divided into three seismic zones (northern, central, and southern), giving as a physical reason for the zonation the differential movement of the zones due to resistance of the Dinarides to the pressure force of the Africa plate and the existence of the active faults along the Adriatic margin.

PROCESSING GPS DATA

A GPS network (CRODYN, or the Croatian and Slovene Geodynamic Network) of twenty stations located in Croatia, Italy, and Slovenia was established in 1994 for the study of present-day tectonics in the Adriatic region. In 1996, the network was extended to include twenty-one new stations distributed across Albania, Bosnia and Herzegovina, Croatia, and Italy. The first GPS campaign was conducted from 7 to 10 June 1994 in three sessions, each with a length of 24 hours. Observations were repeated from 9 to 12 September 1996 and from 4 to 7 September 1998 using the same observation strategy, applying an elevation of 10° for observations and using identical sets of Trimble receivers as well as antennas (Čolić et al., 1996;

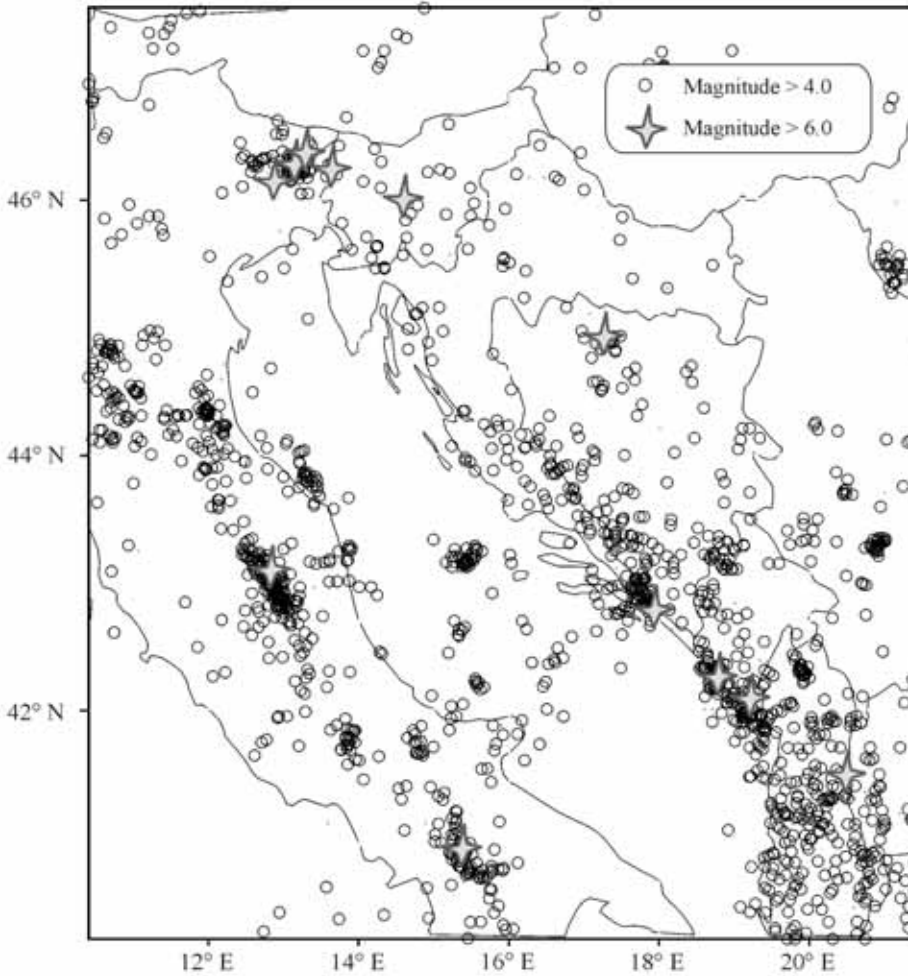


Figure 2. Recorded earthquake epicenters in the study area. These indicate that the seismic activity is concentrated mostly in the on-shore areas. Most of earthquakes in the off-shore area occur between the Gargano zone and the central Dinarides (<http://quake.geo.berkeley.edu/cnss/catalog-search.html>).

Mišković and Altner, 1997; Medak and Piribičević, 2005). GPS data were acquired through cooperation between the Bundesamt für Kartographie und Geodäsie in Frankfurt am Main (BKG), the Croatian State Geodetic Administration in Zagreb, the Slovene State Geodetic Administration in Ljubljana, the Military Geographical Institute in Firenze, the Military Geodetical Institute in Tirana, and the University of Sarajevo in Bosnia and Herzegovina.

Data processing was carried out at BKG using the GPS software developed at the University of Bern (Hugentobler et al., 2001). For data processing, the IGS final orbits and Earth rotation parameters of the relevant GPS campaigns, which referred to the different realizations of the ITRF (ITRF92 for the GPS campaign in 1994, ITRF94 for the GPS campaign in 1996, and ITRF96 for the GPS campaign in 1998), were converted into ITRF96 (McCarthy, 1996; Boucher et al., 1998). Transformation of satellite coordinates from ITRF92 into ITRF96 yielded no improvement in the accuracy of the orbits. The accuracy of the orbits defined in ITRF92 is less than the accuracies of those given in ITRF94 and ITRF96, among others, due to the lack of density of the permanent ITRF/IGS stations located in the study area and the dif-

ferent space technique used, i.e., SLR, for estimation of the coordinates of some permanent ITRF/IGS stations. For an accurate solution of station coordinates and velocities, data for thirteen permanent ITRF/IGS stations located in the areas surrounding the network (BOR1, BRUS, GRAZ, KOSG, MATE, MEDI, ONSA, PENC, POTS, UPAD, VENE, WTZR, ZIMM) were also determined during the processing of the local observations.

Estimated Velocities

Due to the possible undesirable effect of a local geodetic datum defined by coordinates of at least three stations located on the Eurasia plate on the coordinates and velocities of stations to be estimated (Altner, 2001), annual horizontal and vertical velocities of stations in ITRF96 (epoch 1996.56) were determined through a combination of reaching ionosphere-free daily solutions and fixing the coordinates and velocity of the permanent station GRAZ, the closest ITRF/IGS station located north of the network. The formal station velocity uncertainties have been scaled using a factor of 5 and are listed in Table 1 (Brockmann, 1996). After scaling, the horizontal velocities were significant at

TABLE 1. DERIVED STATION VELOCITIES AND THEIR UNCERTAINTIES IN THE CRODYN NETWORK

Station	Longitude, °	Latitude, °	Campaign ^a			East σ_E^b mm/yr	North σ_N^b mm/yr	DH σ_{DH}^b mm/yr
			1	2	3			
1 Rovinj	13.629	45.084	x	x	x	1.4 ± 0.5	3.4 ± 0.5	-5.9 ± 3.5
2 Bakar	14.586	45.255	x	x	x	-3.0 ± 0.5	6.2 ± 0.5	-2.1 ± 3.5
3 Zadar	15.230	44.119	x	x	x	2.6 ± 0.5	4.0 ± 0.5	-1.1 ± 3.5
4 Split	16.438	43.507		x	x	2.3 ± 0.5	1.1 ± 1.0	-3.6 ± 5.0
5 Dubrovnik	18.061	42.658	x	x	x	4.7 ± 0.5	4.7 ± 0.5	8.1 ± 3.5
6 Ucka	14.216	45.308	x	x	x	2.1 ± 0.5	4.0 ± 0.5	-3.6 ± 3.5
7 Veli Brh	14.676	45.007	x	x	x	5.2 ± 0.5	3.3 ± 0.5	-4.4 ± 3.5
8 Vis Hum	16.114	43.030	x	x	x	4.1 ± 0.5	8.4 ± 0.5	2.2 ± 3.5
9 Lastovo	16.861	42.752	x	x		4.7 ± 0.5	5.3 ± 1.0	-6.8 ± 5.0
10 Palagruza	16.255	42.393	x	x	x	4.3 ± 0.5	6.6 ± 0.5	1.3 ± 3.5
11 Zuta Lokva	15.062	44.969	x	x	x	5.8 ± 0.5	3.0 ± 0.5	-4.8 ± 3.5
12 Kapela	16.593	43.600	x	x	x	2.3 ± 0.5	4.0 ± 0.5	4.0 ± 3.5
13 Tjarica	16.876	43.608	x	x	x	5.7 ± 0.5	-0.1 ± 0.5	-2.7 ± 3.5
96 Makarska	17.010	43.295		x	x	11.0 ± 0.5	13.2 ± 1.0	4.7 ± 5.5
294 Svilaja	16.485	43.791		x	x	1.1 ± 0.5	4.9 ± 1.0	-5.0 ± 5.0
316 Sv. Andrija	17.953	42.645		x	x	3.7 ± 0.5	7.8 ± 1.0	-8.4 ± 5.5
525 Trebacnik	15.871	44.175		x	x	0.9 ± 1.0	1.9 ± 1.0	-7.5 ± 6.0
534 Karlobag	15.073	44.524		x	x	5.0 ± 0.5	3.2 ± 1.0	-0.8 ± 5.5
729 Pula	13.846	44.865	x	x	x	2.9 ± 0.5	3.2 ± 0.5	-2.8 ± 3.5
731 Zirje	15.644	43.655		x	x	4.6 ± 0.5	1.9 ± 1.0	2.5 ± 5.5
732 Hvar	16.598	43.144	x	x		4.7 ± 0.5	7.1 ± 1.0	0.7 ± 5.0
733 Sveti Ivan	17.457	42.874	x	x	x	4.9 ± 0.5	6.1 ± 0.5	-3.2 ± 3.5
1101 Ivsic Brdo	15.580	45.119		x	x	6.0 ± 0.5	2.7 ± 1.0	-4.9 ± 5.5
1724 Ilin Vrh	18.386	42.499		x	x	2.1 ± 0.5	5.5 ± 1.0	3.4 ± 5.5
51 Blegos	14.114	46.165	x	x	x	1.2 ± 0.5	2.9 ± 0.5	0.3 ± 3.0
52 Koper	13.724	45.548	x	x	x	-0.5 ± 0.5	5.2 ± 0.5	-5.0 ± 3.0
724 Malija	13.643	45.504	x	x	x	-0.6 ± 0.5	1.7 ± 0.5	-2.4 ± 3.0
53 Trieste	13.760	45.647	x		x	1.1 ± 0.5	6.8 ± 1.0	7.0 ± 4.0
101 Alpe Pelleg	10.489	44.198		x	x	5.0 ± 0.5	0.4 ± 1.0	3.4 ± 5.5
102 Monte Capod	13.767	43.198		x	x	6.2 ± 0.5	6.3 ± 1.0	-6.4 ± 6.0
103 Terracina	13.260	41.291		x	x	3.7 ± 0.5	-1.2 ± 1.0	0.1 ± 6.5
MATE 12734M008	16.704	40.649	x	x	x	3.0 ± 0.5	6.7 ± 0.5	0.3 ± 3.5
MEDI 12711M003	11.647	44.520		x	x	5.4 ± 0.5	1.2 ± 1.0	0.9 ± 4.5
UPAD 12750M002	11.878	45.407		x	x	4.3 ± 0.5	2.1 ± 1.0	13.6 ± 4.5
VE NE 12741M001	12.332	45.437		x	x	2.5 ± 0.5	0.7 ± 1.0	6.4 ± 4.5
235 Kudic Brdo	15.868	45.054		x	x	2.5 ± 1.0	3.6 ± 1.0	1.3 ± 6.5
280 Cvrnisnica	17.565	43.599		x	x	2.2 ± 1.0	8.3 ± 1.0	-13.8 ± 6.5
1447 Sarajevo	18.406	43.873		x	x	6.8 ± 0.5	7.1 ± 1.0	-1.8 ± 5.5
201 Shkodra	19.495	42.046		x	x	4.8 ± 1.0	2.0 ± 1.0	3.9 ± 5.5
203 Oaf Thane	20.603	41.068		x	x	4.9 ± 1.0	-3.2 ± 1.0	8.6 ± 5.5
204 Vlore	19.505	40.408		x	x	7.7 ± 1.0	1.2 ± 1.0	-0.7 ± 6.0
BOR1 12205M002	17.073	52.277		x	x	0.9 ± 0.5	2.6 ± 1.0	-7.2 ± 5.5
PENC 11296M002	19.282	47.790		x	x	1.5 ± 0.5	1.0 ± 0.5	-1.9 ± 4.0

Notes: ^aAn x indicates that stations were observed within the relevant GPS campaign.

^bThe *E*, *N*, and *DH* indexes of σ_E , σ_N , and σ_{DH} stand for easting, northing, and height differences, respectively.

the 0.95 confidence level for all stations with the exception of Malija (station no. 724), Split (station no. 4), Trebacnik (station no. 525), Terracina (station no. 103), and VENE.

The magnitudes of the horizontal velocities relative to GRAZ vary from 3 to 10 mm/yr, increasing from north to south (Fig. 3). The stations in southwestern Slovenia move from 3–7 mm/yr in a north-northwest direction, whereas those in southern and northeastern Istria move 4–5 mm/yr in a north-northeast

direction. The northeastern part of Italy moves 5 mm/yr in an east-northeast direction. The stations in southeastern Italy, southern and central Croatia, and Bosnia and Herzegovina move 5–7 mm/yr toward the northeast.

The greatest movement (8–10 mm/yr) occurs in central Adria between the Gargano zone and the central Dinarides. There, the stations move in a northeast direction. The earthquake occurrences recorded independently from the ANSS cat-

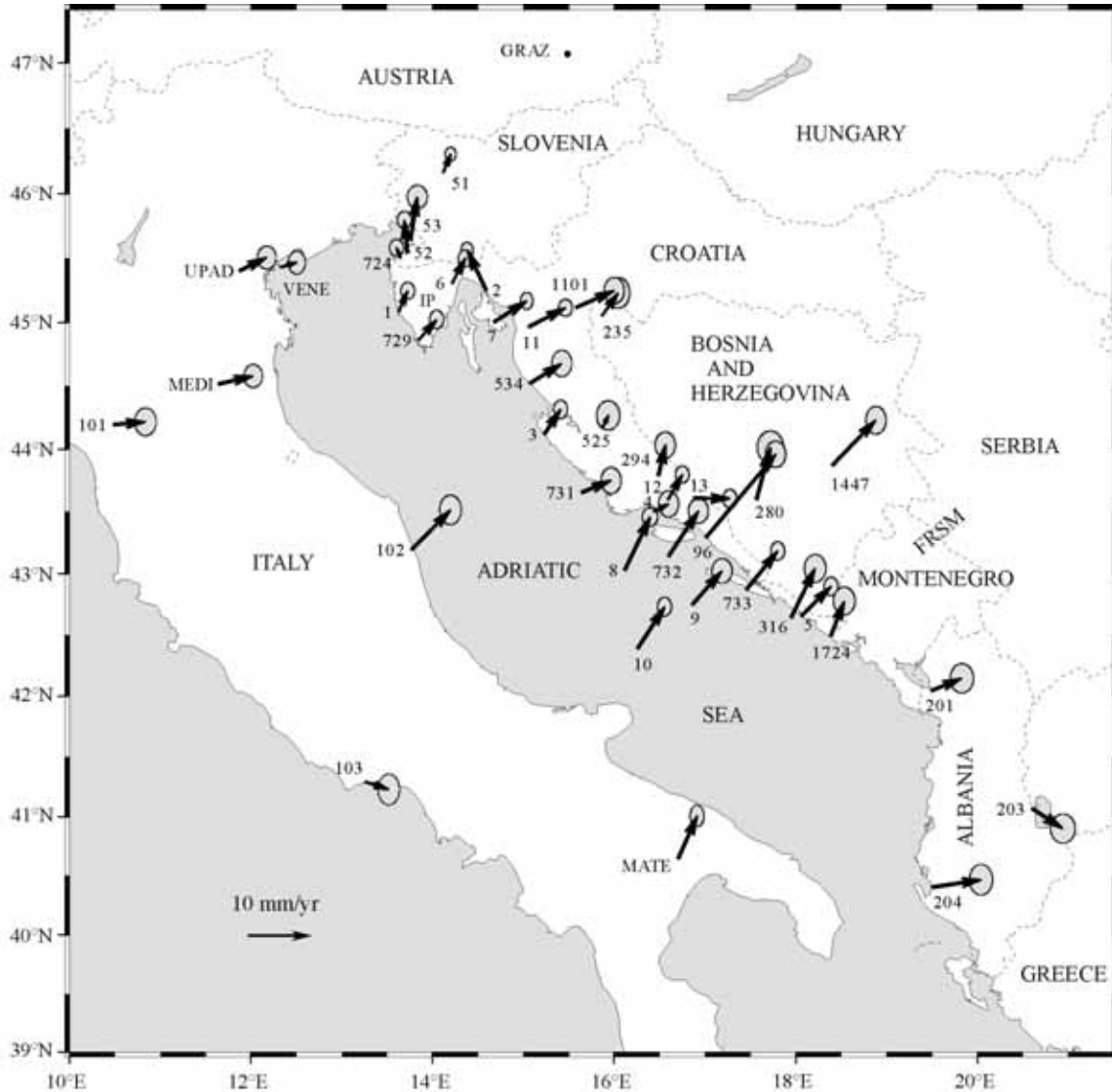


Figure 3. Horizontal velocities of ITRF/IGS stations and their confidence ellipses for a probability of 95% (confidence level $1 - \alpha = 0.95$) for a normal distribution of observations. For all the stations except Malija (724), Trebacnik (525), Terracina (103), Split (4), and VENE, the horizontal velocities are significant. FRSM—Federal Republic of Yugoslavia; IP—Istria Peninsula.

ologue suggest that this region is the most active zone in the study area. The station Makarska (station no. 96) is an exception (17 mm/yr). Stations along the coastline of Albania move 5–7 mm/yr, and the direction of movement is almost east-west; those in eastern Albania move 6 mm/yr in an east-southeast direction. The permanent ITRF/IGS stations POTS and WTZR in Germany, BOR1 in Poland, and PENC in Hungary exhibit no significant horizontal movement (Fig. 4). At the 0.95 confidence level, the vertical velocities for most of the stations are not significant, so we dispense with further discussion of the vertical movement of the stations.

For detection of station movements arising due to the local geological processes, an additional solution using only data from the last two GPS campaigns in 1996 and 1998 was created. The formal station velocity uncertainties for this second solution (1996–1998) are at the same level as the first solution (1994–1998). A comparison of horizontal velocities between these two solutions (1996–1998 and 1994–1998) indicates that the movement of the station Bakar (station no. 2) exhibits a different magnitude and direction for each solution (Fig. 5). We assume that movement for this station is local due to an unstable pillar.

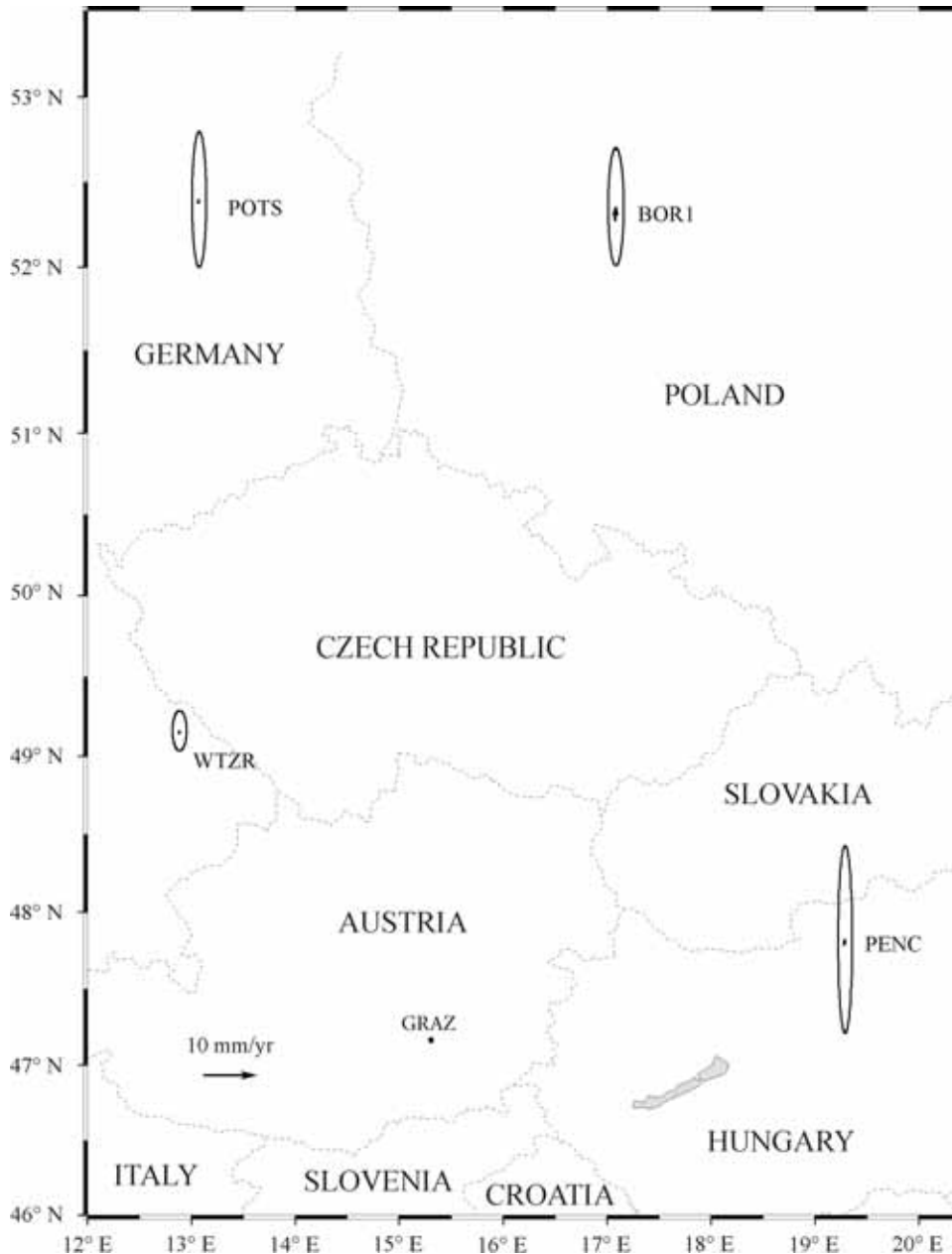


Figure 4. Horizontal velocities of the ITRF/IGS stations POTS and WTZR in Germany, PENC in Hungary, and BOR1 in Poland with their confidence ellipses for a probability of 95%. The horizontal movement of these stations is not significant.

Comparison of velocities with those from the earlier solution derived by processing data from the first GPS campaigns in 1994 and 1996 and published in Altiner et al. (1999), Altiner (1999, 2001), and Cigrovski-Detelić (2003) indicates that the magnitudes of the velocities of stations in the northeastern part of the study area are different in the two solutions. In reprocessing data from the three GPS campaigns during the current study, the elevation-dependent phase center variations of antennas were taken into account (Bilajbegović et al., 1999). This potential error source was unknown during the earlier processing of data from the 1994 and 1996 campaigns; the offsets for L1

and L2 were known, but variations of the phase center were not. Additional important differences with respect to the earlier data processing include an improved realization of the ITRF (here ITRF96, in the earlier solutions ITRF94) and a significantly longer time span between the initial and final data epochs in this study.

Deformation Method Applied

Seen from a physical point of view, the observation stations are always tied to surface points of bodies. The results derived

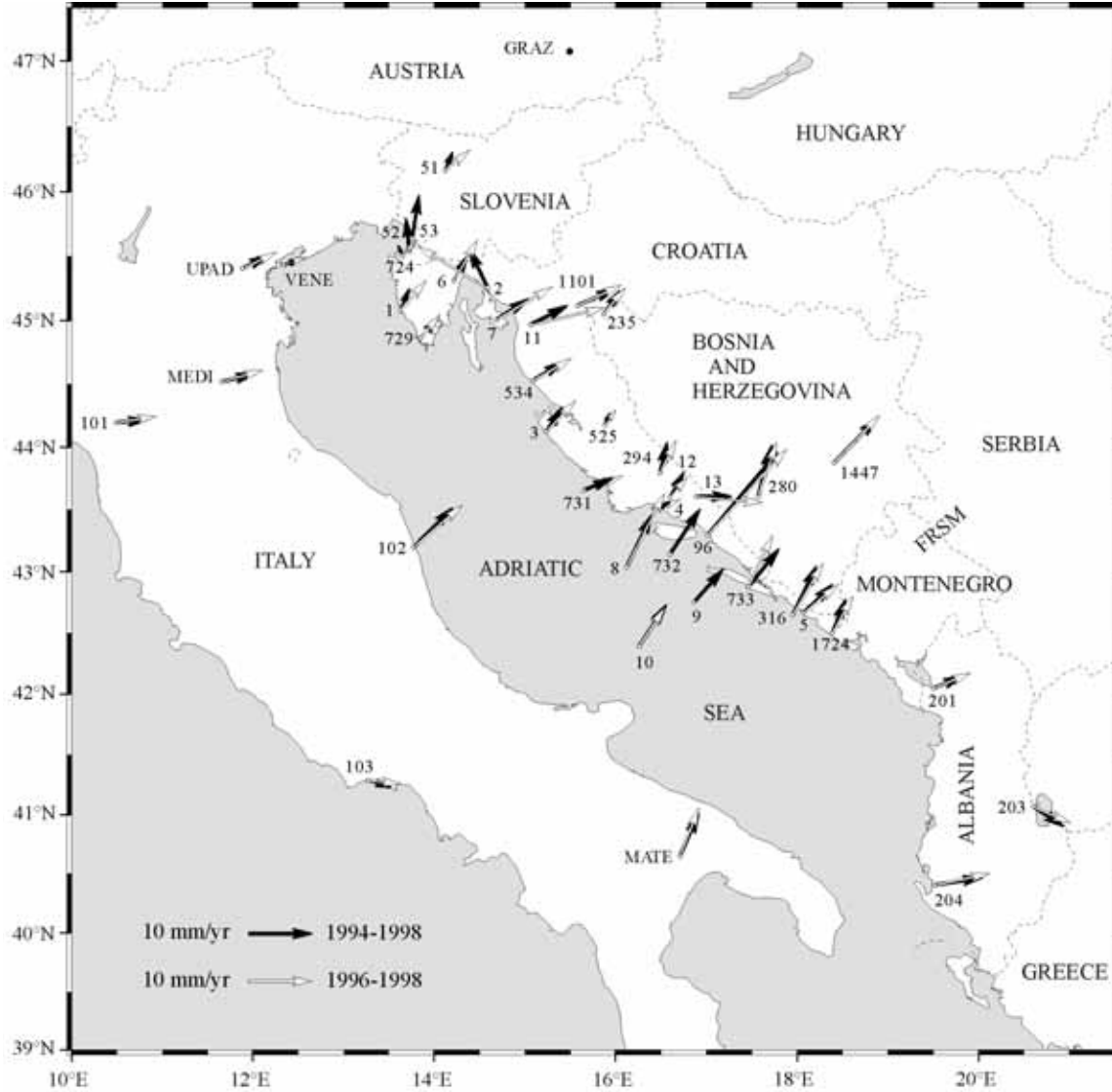


Figure 5. Comparison of horizontal velocities of GPS stations. The black arrows indicate the solution from three GPS campaigns (1994–1998), the white arrows the solution from the last two GPS campaigns (1996–1998). The uncertainties of velocities are at the same level for both solutions. Due to the local effects, the magnitude and direction of velocity of station Bakar (2) differ for both solutions, so local movement for this station has been assumed. FRSM—Federal Republic of Yugoslavia.

using observations for these stations also have to refer to the surface of these bodies (in our case: topography). This requires a representation of the Earth's surface as a generally curved surface that is embedded in three-dimensional Euclidian space (Heitz, 1998; Marjanović-Kavanagh, 2005).

For the description of deformation, we consider two points, P_1 and P_2 , in a Cartesian coordinate system, at an observation time t , and we define the range convention of the mathematical formulae for the indexes i and j as 1, 2, and 3 (Fig. 6). With time the points undergo displacements, and in observation time \bar{t} the two points are deformed with new locations \bar{P}_1 and \bar{P}_2 . $x_{i,2}$

and $x_{i,2}$ are the position vectors for points P_1 and P_2 , respectively, and $\bar{x}_{i,1}$ and $\bar{x}_{i,2}$ are position vectors for \bar{P}_1 and \bar{P}_2 , respectively. $z_{i,1}$ and $z_{i,2}$ stand for displacement vectors of points P_1 and P_2 , with

$$\bar{x}_i = x_i + z_i. \quad (1)$$

Differences between the position vectors and displacement vectors are given as follows:

$$\delta x_i = x_{i,2} - x_{i,1}, \quad (2)$$

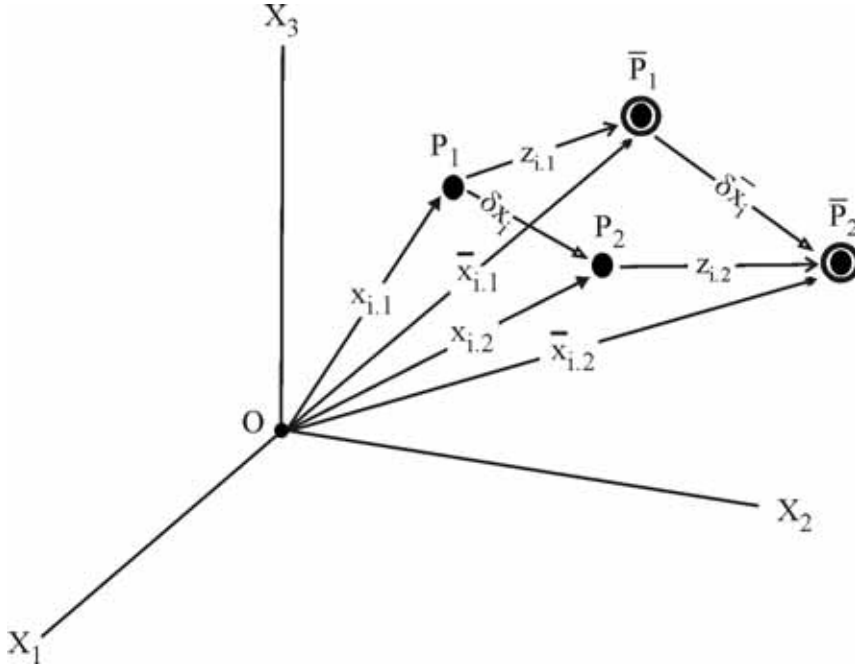


Figure 6. Development of deformation tensor in a Cartesian coordinate system. $x_{i,1}$ and $x_{i,2}$ are the position vectors for points \bar{P}_1 and \bar{P}_2 after deformation. $z_{i,1}$ and $z_{i,2}$ express the displacement vectors of points P_1 and P_2 . For a realistic result, deformation measures are to be determined on the basis of the differential geometric modeling procedures developed for a three-dimensional Euclidean space.

$$\delta \bar{x}_i = \bar{x}_{i,2} - \bar{x}_{i,1}, \quad (3)$$

and

$$\delta z_i = z_{i,2} - z_{i,1} = \partial_{\bar{x}_i} \delta x_j, \quad (4)$$

with

$$\partial_{\bar{x}_i} z_j = \partial a_j / \partial x_i = V_{ij} \quad (5)$$

V_{ij} is the displacement tensor. If we consider that

$$\delta \bar{x}_i = \delta x_i + \delta z_i, \quad (6)$$

owing to equations 5 and 6, the difference of the position vectors $\delta \bar{x}_i$ in time \bar{t} results in

$$\delta \bar{x}_i = (\delta_{ij} + V_{ij}) \delta x_j, \quad (7)$$

where δ_{ij} stands for the Kronecker delta, with

$$\delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

In equation 7, the tensor $(\delta_{ij} + V_{ij})$ expresses the deformation that occurred between times t and \bar{t} . Rigid body motions such as rotation and translation cause no deformation on a body. Because V_{ij} does not equal zero in the case of rigid body motion, it is not suitable for definition as a deformation measure (Duschek and Hochreiner, 1965).

Owing to equation 6 and according to the square of the linear line elements in times

$$\delta s^2 = \delta x_i \delta x_i \quad (8)$$

and \bar{t} ,

$$\delta \bar{s}^2 = \delta \bar{x}_i \delta \bar{x}_i, \quad (9)$$

we may obtain the differences between the squares of the linear line elements as a primary deformation measure:

$$\delta \bar{s}^2 - \delta s^2 = (\delta x_i + \delta z_i)(\delta x_i + \delta z_i) - \delta x_i \delta x_i. \quad (10)$$

Owing to equations 3.4–3.10, we obtain

$$\delta \bar{s}^2 - \delta s^2 = (2V_{ij} + V_{ki}V_{kj})\delta x_i \delta x_j, \quad (11)$$

and this (equation 11) finally leads to

$$\delta \bar{s}^2 - \delta s^2 = 2D_{ij}\delta x_i \delta x_j, \quad (12)$$

where D_{ij} is the symmetrical Cartesian deformation tensor, with

$$D_{ij} = D_{ji} = (V_{ij} + V_{ji} + V_{ki}V_{kj})/2. \quad (13)$$

In the case of rigid body motions, the Cartesian deformation tensor D_{ij} in equation 13 equals zero. For small displacements ($|z_i| \ll |x_i|$), disregarding the part of high degree ($V_{ki}V_{kj}$) in equation 13 leads to the linear Cartesian deformation tensor ϵ_{ij} :

$$D_{ij} = \varepsilon_{ij} = (V_{ij} + V_{ji})/2 = (\partial_i z_j + \partial_j z_i)/2. \quad (14)$$

In the Gaussian surface representation, with surface coordinate u^α (α and $\beta = 1, 2$ for coordinate axes, e.g., for latitude and longitude), which is usually used for the determination of the surface deformations, the linear surface deformation tensor is

$$\varepsilon_{\alpha\beta} = (x_{i,\alpha} z_{i,\beta} + x_{i,\beta} z_{i,\alpha})/2, \quad (15)$$

with

$$x_{i,\alpha} = \partial x_i / \partial u^\alpha \quad (16)$$

and

$$z_{i,\alpha} = \partial z_i / \partial v^\alpha. \quad (17)$$

Altmer (1996, 1999, 2001) dealt with the derivation of internal and external surface deformation measures using Cartesian and ellipsoidal coordinates in a detailed manner and applied this to observations for different VLBI and GPS networks (Haas et al., 2000; Hefty and Duraciova, 2003). Here we limit our explanations to a brief presentation of some advantages of analytical surface deformation theory (see also Voosoghi, 2000) for strain analysis based on Cartesian coordinate differences in a

mean horizontal plane. With the application of analytical surface deformation theory,

- the effects of rigid body motions such as shifting and rotation on station velocities are eliminated,
- ellipsoidal height variations in the study area are taken into account,
- three-dimensional deformations become detectable on the physical surface of the Earth,
- not only internal but also external surface deformations may be determined, and
- for a dynamic model, stress changes can be locally focused.

Results of Deformation Analysis

Internal deformation measures (largest and smallest principal strain rates) for the Adriatic region were evaluated by means of analytical surface deformation theory considering ellipsoidal coordinates for a regular areawide grid spanning 40.4° to 46.4° latitude and 12.8° to 20.4° longitude with a mesh spacing of 0.5° . Model velocities, illustrated in Figure 7, were interpolated using the spline method (Bronstein et al., 1995); the motions of stations Bakar and Makarska were not used for the reasons given earlier.

The results of the deformation analysis suggest the existence of three different deformation zones within the study area (Fig. 8).

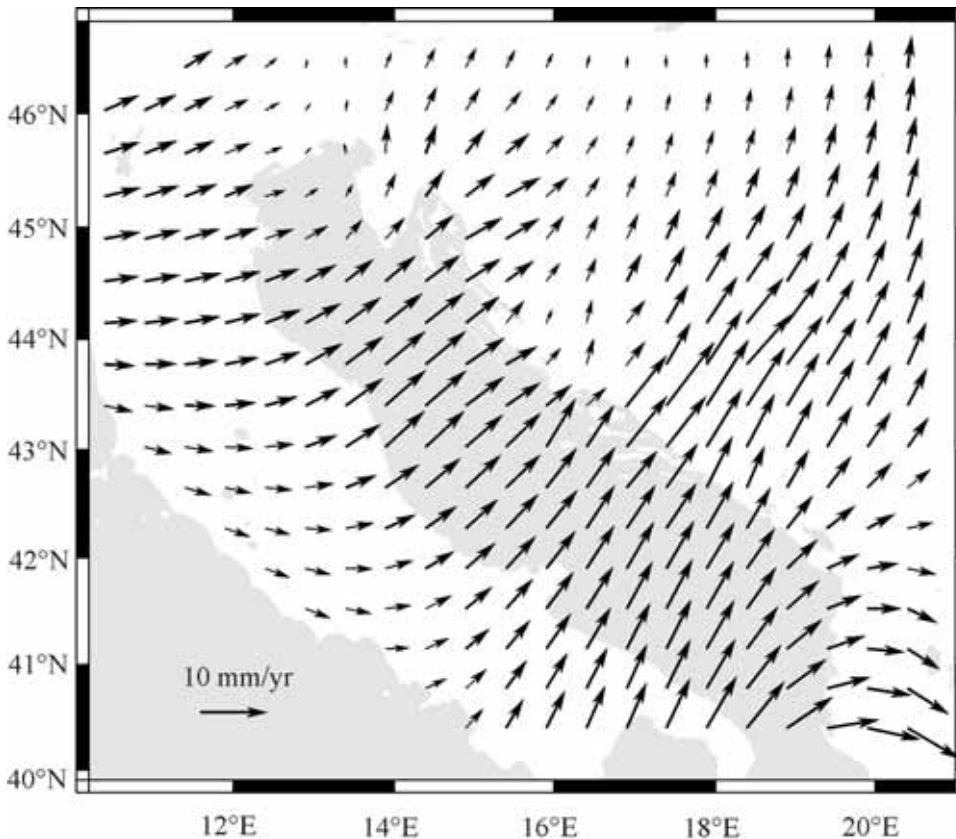


Figure 7. The arrows indicate the horizontal model velocities, which were interpolated from the horizontal velocities of GPS stations in the network using the spline method. According to the horizontal velocities in and around the Adriatic plate, the domain between the Gargano zone and the central Dinarides is the most active tectonic region. A fragmentation of Adria into subblocks cannot be clearly proved.

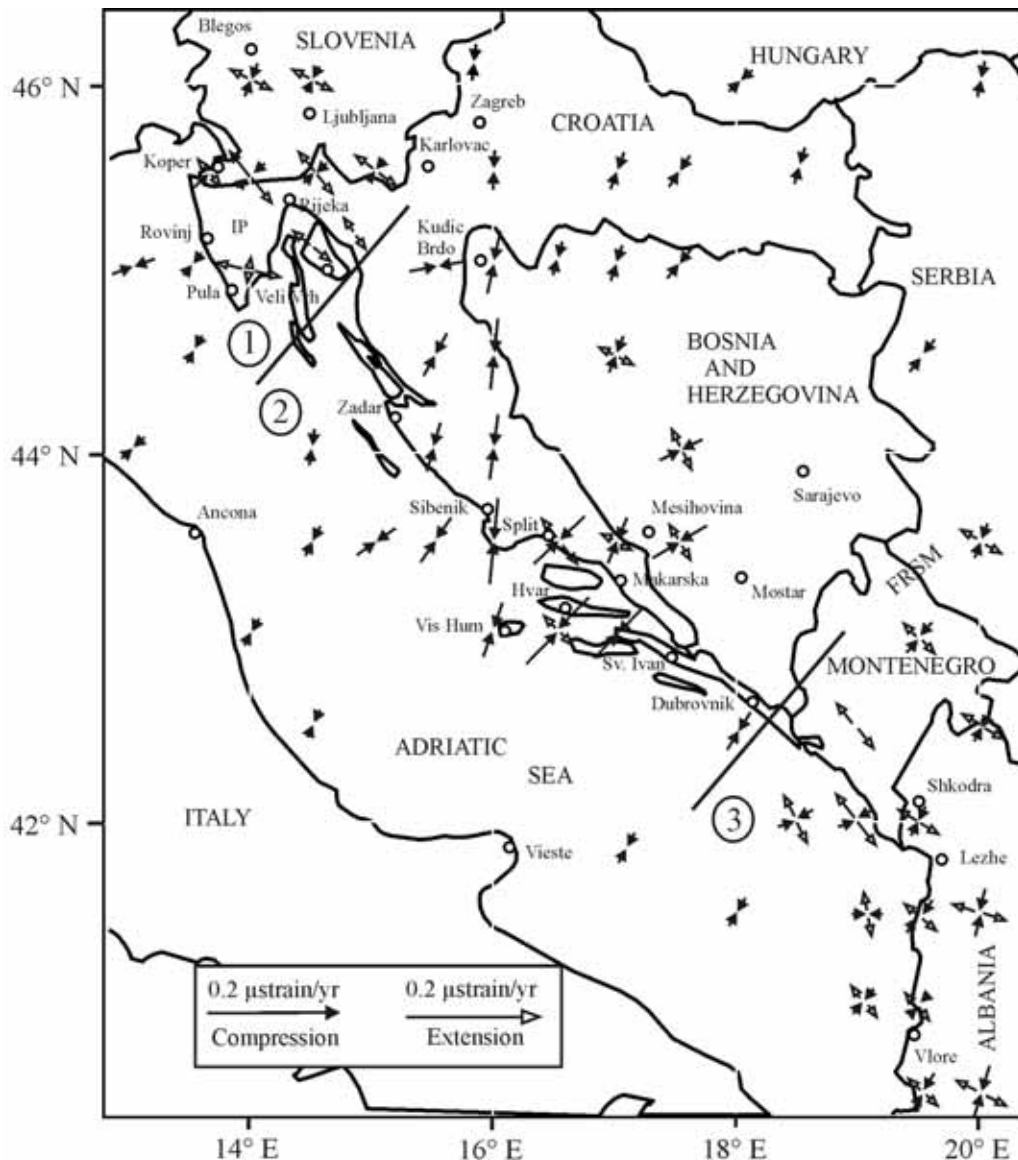


Figure 8. Principal strain rates. IP—Istria Peninsula; FRSM—Federal Republic of Yugoslavia. 1, 2, and 3 express the numbers of different deformation zones detected within the investigation area. The arrows directed outward indicate extensions, whereas those directed inward correspond to compression. Strong compressions takes place in the central Dinarides around Sveti Ivan, Hvar, Makarska, Split, and Sibenik. The northeastern part of the study area is compressed from the northeast and extends northwest-southeast. The southeastern part is subject to a northeast-southwest compression with a predominant north-south and northwest-southeast extension.

The Istria Peninsula in southern Slovenia is compressed in a northeast-southwest direction. Strong compression takes place in central Croatia between Split and Sibenik and extends to the north over Karlovac and Kudic Brdo. The domain around Sveti Ivan, Hvar, and northern Bosnia is also subject to compression. Along the coastlines of Albania and Federal Republic of Yugoslavia, northwest-southeast-oriented extension predominates. The results of deformation analysis discussed here are highly correlated with the outcomes of the geological studies in eastern Adria given in Kuk et al. (2000) and Markusić et al. (1998).

CONCLUSIONS

According to the space-geodetic data, the Africa plate moves northwestward relative to Eurasia with a velocity of

6 mm/yr (McClusky et al., 2000, 2003; Ayhan et al., 2002; Caporali et al., 2003; Kreemer et al., 2003; Hollenstein et al., 2005). Due to the fact that the horizontal movement of the stations within the CRODYN network is generally northeast-oriented and very clearly differs from the northwest-oriented motion of the Africa plate relative to Eurasia, we suggest that Adria exists as an independent microplate. Northeastern Adria moves very slowly and produces almost no surface deformation (Oldow et al., 2002). The movement of stations in southeastern Istria exhibits a north-northwest direction, whereas that of stations in southern and northeastern Istria is northeast-oriented. According to the magnitude of model velocities, the domain between the Gargano zone and the central Dinarides is the most active tectonic region (Westaway, 1990; Favali et al., 1993). Recorded earthquake epicenters in the off-shore area also support the idea

of tectonic activity throughout this region. In spite of this support, a fragmentation of Adria into subblocks with a boundary linking the areas from the Gargano zone to the central Dinarides cannot be clearly proved, because, as the model velocities show, the northern and southern parts of this active zone exhibit movement with similar magnitudes and directions.

The movement of stations located along the coast of Albania is almost east-west oriented. The difference between the motion of stations in Albania and the northeast-oriented movement of stations in southern Croatia is very conspicuous and raises the question of whether the domain that includes the stations in Albania is part of Adria or the coastline of Albania is located along a plate boundary subject to strong surface deformations. Stations POTS and WTZR in Germany, BOR1 in Poland, and PENC in Hungary demonstrate no significant deformation (Grnerczy et al., 2002). The direction of movement of stations as well as the results of principal strain rate estimates suggest that Adria is divided into northern, central, and southern deformation zones.

ACKNOWLEDGMENTS

We thank Maurizio Battaglia, Richard Harrison, and John Weber for helpful suggestions that improved this manuscript. We also thank Yildirim Dilek for friendly cooperation. We are especially grateful to Salvatore Bushati, Krešimir Čolić (1938–2000), Zdravko Galić, Branimir Gojčeta, Božena Lipej, Zlatko Medić, Dušan Mišković (1955–2000), Myslim Pasha, Ewald Reinhart, Hermann Seeger, and Aleš Seliškar for the support they have given to this project.

REFERENCES CITED

- Alij, S., 2006, The Albanian orogen: Convergence zone between Eurasia and the Adria microplate, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 133–150.
- Altner, Y., 1996, Geometrische Modellierung innerer und äußerer Deformationen der Erdoberfläche: München, Deutsche Geodätische Kommission C-462, Main, 83 p.
- Altner, Y., 1999, Analytical surface deformation theory for detection of the Earth's crust movements: Berlin, Springer, 110 p.
- Altner, Y., 2001, The contribution of GPS data to the detection of the Earth's crust deformations illustrated by GPS campaigns in the Adria region: *Geophysical Journal International*, v. 145, p. 550–559, doi: 10.1046/j.0956-540x.2001.01411.x.
- Altner, Y., Cigrovski-Detelić, B., Čolić, K., and Seeger, H., 1999, Present crustal deformations in the Adriatic Sea area on the basis of GPS-observations, *in* Čolić, K., et al., eds., *The second international symposium Geodynamics of the Alps-Adria Area by Means of Terrestrial and Satellite Methods*: Zagreb and Graz, p. 37–48.
- Anderson, H., and Jackson, J., 1987, Active tectonics of the Adriatic Region: *Royal Astronomical Society (UK) Geophysical Journal*, v. 91, p. 937–983.
- Argand, E., 1924, La Tectonique de l'Asie, *in* Proceedings, 13th International Geological Congress, Brussels, v. 7, p. 171–372.
- Ayhan, M.E., Demir, C., Lenk, O., Kilicoglu, A., Altiner, Y., Barka, A.A., Ergintav, S., and Özener, H., 2002, Interseismic strain accumulation in the Marmara Sea region: *Bulletin of the Seismological Society of America*, v. 92, p. 216–229, doi: 10.1785/0120000818.
- Babbucci, D., Tamburelli, C., Viti, M., Mantovani, E., Albarello, D., D'Onza, F., Cenni, N., and Mugnaioli, E., 2004, Relative motion of the Adriatic with respect to the confining plates: Seismological and geodetic constraints: *Geophysical Journal International*, v. 159, p. 765–775, doi: 10.1111/j.1365-246X.2004.02403.x.
- Battaglia, M., Murray, M.H., Serpelloni, E., and Burgmann, R., 2004, The Adriatic region: An independent microplate within the Africa-Eurasia collision zone: *Geophysical Research Letters*, v. 31, p. L09605, doi: 10.1029/2004GL019723.
- Bilajbegović, A., Groetchen, T., Vierus, M., and Weber, T., 1999, Untersuchungen der Hybriden GPS-GLONASS-Empfänger Ashtech GG 24 RTK für Praxiseinsätze: *Allgemeine Vermessungsnachrichten*, v. 8, p. 274–283.
- Boucher, C., Altamimi, Z., and Sillard, P., 1998, Results and analysis of the ITRF96: *IERS Technical Note 24*, Observatoire de Paris, 166 p.
- Brockmann, E., 1996, Combination of solutions for geodetic and geodynamic applications of the Global Positioning System: *Astronomical Institute of the University of Bern*, 211 p.
- Bronstein, I.N., Semendjajew, K.A., Musiol, G., and Mühlhlin, H., 1995, *Taschenbuch der Mathematik*: Frankfurt am Main, Harri Deutsch, 1020 p.
- Caporali, A., Martin, S., and Massironi, M., 2003, Average strain rate in the Italian crust inferred from a permanent GPS-network, II: Strain rate versus seismicity and structural geology: *Geophysical Journal International*, v. 155, p. 254–268, doi: 10.1046/j.1365-246X.2003.02035.x.
- Channell, J.E.T., and Horváth, P., 1976, The African-Adriatic promontory as a palaeogeographic premise for Alpine orogeny and plate movements in Carpatho-Balkan region: *Tectonophysics*, v. 35, p. 71–110, doi: 10.1016/0040-1951(76)90030-5.
- Cigrovski-Detelić, B., 2003, Geodetic contribution to the determination of recent tectonic activities at the area of Croatia: *Allgemeine Vermessungsnachrichten*, v. 8, p. 288–298.
- Čolić, K., Bašić, T., Seeger, H., Gojčeta, B., Altiner, Y., Rasić, L., Medić, Z., Piribičević, B., Medak, D., Marjanović, M., and Prelogović, E., 1996, Croatia in EUREF '94 and the Project CRODYN: *Geodetski List*, v. 50, p. 331–351 (in Croatian).
- DeMets, C., Gordon, R., Argus, D., and Stein, S., 1990, Current plate motions: *Geophysical Journal International*, v. 101, p. 425–478.
- DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions: *Geophysical Research Letters*, v. 21, p. 2191–2194, doi: 10.1029/94GL02118.
- Duschek, A., and Hochreiner, A., 1965, *Grundzüge der Tensorrechnung in analytischer Darstellung (III. Teil)*: Wien, Springer, 287 p.
- Favali, P., Funicciello, R., Mattiotti, G., Mele, G., and Salvini, F., 1993, An active margin across the Adriatic sea (central Mediterranean sea): *Tectonophysics*, v. 219, p. 109–117, doi: 10.1016/0040-1951(93)90290-Z.
- Grnerczy, G., Kenyeres, A., and Fejes, I., 2000, Present crustal movement and strain distribution in Central Europe inferred from GPS measurements: *Geophysical Research Letters*, v. 105, p. 835–846.
- Haas, R., Gueguen, E., Scherneck, H.-G., Nothnagel, A., and Campbell, H., 2000, Crustal motion results derived from observations in the European geodetic VLBI network: *Earth Planets Space*, v. 52, p. 759–764.
- Hefty, J., and Duraciova, R., 2003, Stochastic properties of deformation characteristic obtained from GPS site velocities: *Reports on Geodesy*, v. 64, p. 33–40.
- Heitz, S., 1998, *Coordinates in geodesy*: Berlin, Springer, 255 p.
- Hollenstein, C., Kahle, H.-G., and Geiger, A., 2005, Geodetic measurement and geodynamics plate tectonic framework and GPS-derived strain-rate field within the boundary zones of the Eurasian and African plates, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 35–50.
- Hugentobler, U., Schaer, S., and Fridez, P., 2001, *Bernese GPS software version 4.2*: *Astronomical Institute of the University of Bern*, 515 p.
- Jackson, J., and McKenzie, D., 1988, The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East: *Geophysical Journal*, v. 93, p. 45–73.

- Kreemer, C., Holt, W.E., and Haines, J., 2003, An integrated global model of present-day plate motions and plate boundary deformation: *Geophysical Journal International*, v. 154, p. 8–34, doi: 10.1046/j.1365-246X.2003.01917.x.
- Kuk, V., Prelogović, E., and Dragicević, I., 2000, Seismotectonically active zones in the Dinarides: *Geological Journal of Croatia*, v. 53, p. 295–303.
- Mantovani, E., Babbucci, D., Viti, M., Albarello, D., Mugnaioli, E., Cenni, N., and Casula, G., 2006, Post-late miocene kinematics of the Adria microplate: Inferences from geological, geophysical, and geodetic data, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 51–70.
- Marjanović-Kavanagh, R., 2006, Instrumentation for terrestrial measurements of geodynamics and the main sources of disturbance, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 193–206.
- Markusić, S., Herak, D., Ivančić, I., Sović, I., Herak, M., and Prelogović, E., 1998, Seismicity of Croatia in the period 1993–1996 and the Stone-Slano earthquake of 1996: *Geofizika*, v. 15, p. 83–101.
- McCarthy, D.D., 1996, IERS convention (1996): IERS Technical Note 21, Observatoire de Paris, 95 p.
- McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., and Veis, G., 2000, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: *Geophysical Research Letters*, v. 105, p. 5695–5719, doi: 10.1029/1999JB900351.
- McClusky, S., Reilinger, R., Mahmoud, S., Sari, D.B., and Tealeb, D., 2003, GPS constraints on Africa (Nubia) and Arabia plate motions: *Geophysical Journal International*, v. 155, p. 126–138, doi: 10.1046/j.1365-246X.2003.02023.x.
- Medak, D., and Piribičević, B., 2006, Processing of geodynamic GPS-networks in Croatia with GAMIT software, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 209–222.
- Mišković, D., and Altner, Y., 1997, National report of the Republic of Slovenia, *in* Gubler, E., et al., eds., *Report on the Symposium of the IAG Sub-commission for EUROPE*: München, Astronomisch-Geodätische Arbeiten (58), Verlag der Bayerischen Akademie der Wissenschaften, p. 202–208.
- Oldow, J.S., Ferranti, L., Lewis, D.S., Campbell, J.K., D'Argenio, B., Catalano, R., Rappone, G., Carmignani, L., Conti, P., and Aiken, C.L.V., 2002, Active fragmentation of Adria, the North African promontori, central Mediterranean orogen: *Geology*, v. 30, p. 779–782, doi: 10.1130/0091-7613(2002)030<0779:AFOATN>2.0.CO;2.
- Voosoghi, B., 2000, Intrinsic deformation analysis of the Earth's surface based on 3-dimensional displacement fields derived from space geodetic measurements: *Geodätisches Institut der Universität Stuttgart*, 110 p.
- Weber, J., Vrabc, M., Stopar, B., Pavlović-Preseren, P., and Dixon, T., 2006, The PIVO-2003 GPS experiment: A study of Istria peninsula and Adria microplate motion and neotectonics in the northeastern, Slovenian corner of the Alps, *in* Pinter, N., et al., eds., *The Adria microplate*: Dordrecht, Springer, p. 305–320.
- Westaway, R., 1990, Present-day kinematics of the plate boundary zone between Africa and Europe, from the Azores to the Aegean: *Earth and Planetary Science Letters*, v. 96, p. 393–406, doi: 10.1016/0012-821X(90)90015-P.