4.4.1. GEOLOGY, TECTONICS, GEODESY AND GEODYNAMICS OF CROATIA

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ABSTRACT: This paper summarizes recent research activities on merging the geodetic, geologic and neotectonic evidence of geodynamics in Croatia. The area of the City of Zagreb, which is the boundary zone of Eastern Alps, Dinnarides and Pannonian Basin is included as well. It is shown here that the evidence for fractures of Eastern Adriatic differs from the previous hypotheses. This conclusion is derived from the results of various geodetic measurements: satellite positioning (GPS), astro-geodetic measurements of deflections of the vertical. These results are combined with geologic measurements and results of seismic activity studies in order to give more detailed and more accurate picture of the current situation in the tectonically very active region of Dinnarides. Several GPS-campaigns performed in the City of Zagreb area are examined as well. Due to the proximity of Croatian capitol, special attention has been paid to the effects of possible hazard on construction code.

INTRODUCTION

Research on the regional structure fabric, structural classifications and deep geological structure of Dinnarides was summarised in numerous papers (Dewey et al., 1973; Martinis, 1975; Premru, 1976; Herak, 1986; Aljinović et al., 1987; Skoko et al., 1987; Horvath, 1984; Mantovani et al., 1992, 1995; Prelogović et al. 1997; Moors & Twiss, 1995; Decker & Peresson, 1996). Special care was taken to make use of data on the seismotectonic activity and stress regime (Finetti et al., 1979; Reber et al., 1987; Anderson & Jackson, 1987; Skoko & Prelogović, 1988; Slejko et al., 1989; Carulli et al., 1990; Grünthal & Stromeyer, 1992; Slejko, 1993; Prelogović & Lapajne, 1994; Lapajne et al., 1994; Prelogović et al., 1998; Mišković, 1999; Bada, 1999). Several papers from the NATO Workshop confirmed that the geology, tectonics and geodesy should closely cooperate in solving the hypotheses of movements in the area of Adriatic micro-plate and Dinnarides (Pinter et al. 2006).

GEOLOGIC STRUCTURES

The major role in geodynamics of Croatia belongs to the Adriatic Microplate and Dinnarides. Figure 1 shows the structural map of Dinnarides. Movements of the Adriatic micro-plate (1) are crucial in formation of the recent structure fabric. Pushed by the African plate it is being indented into the European continent thus causing deformation of the Earth's crust and gradual shaping of the Alpine-Dinarides orogenic belt.

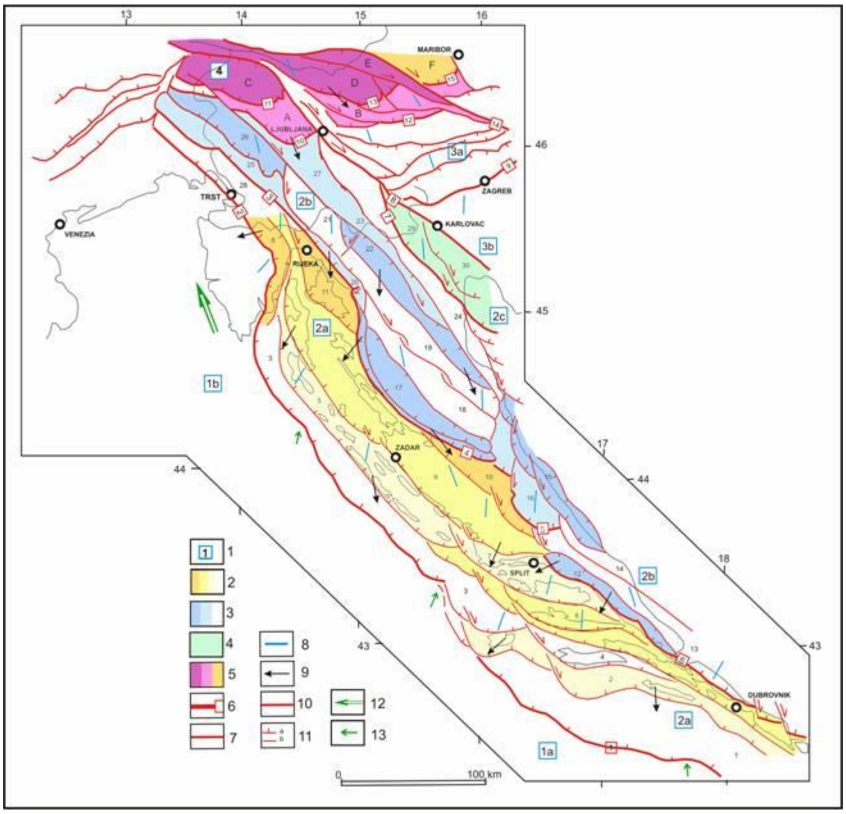

Figure 1. Structural map of the Dinnarides

Legend: 1 – principal structure units: Adriatic micro-plate (1a – Southern part, 1b – Northern part), Dinarides (2a – Adriaticum, 2b – Dinaricum, 2c – Supradinaricum), Pannonian basin (3a – Western marginal part, 3b – Southern marginal part), Alps (4 A,B,C,D – Southern Alps, 4F – Eastern Alps); structure units within: 2 – Adriaticum; 3 – Dinaricum; 4 – Supradinaricum; 5 – Alps; 6 – the most important faults of the structure fabric: Vis-Southern Adriatic fault (1), Trieste-Učka-Vis fault (2), Gorica-Rijeka-Vinodol valley fault (3), Mt. Velebit fault (4), Knin-Muć fault (5), Mt. Mosor-Mt. Biokovo-Dubrovnik fault (6), Črnomelj-Slunj-Cazin fault (7), Fella-Ljubljana-Karlovac fault (8), Žumberak Mts.-Mt. Medvednica fault (9), Kobarid-Gorenja Vas-Ljubljana fault (10), Julian Alps fault (11), Domžale-Zagorje-Laško (12) fault, Savinja Alps fault (13), Periadriatic-Drava fault (14), Pohorje Mts. fault (15); 7 – faults delimiting structure units; 8 – orientation of the maximal horizontal component of regional stress; 9 – directions of displacement of structure units at the surface; 10 – fault sections with prevailing strike-slip; 11 – reverse faults (a) and fault sections lacking positively defined character of displacement (b); 12 – direction of the regional movement of the Adriatic microplate; 13 – inferred direction of displacement of the parts of Adriatic micro-plate.

In the youngest active period, area of the Adriatic micro-plate is being significantly reduced so that the micro-plate is fragmented. That's why it is important that the recent tectonic activity can only be assessed having in mind that there are the two larger fragments of the Adriatic micro-plate – the southern part (1a) and the northern part (1b). Their existence is revealed by the different orientation of the maximal horizontal component of stress, by different displacement of structures and by seismic activity as well. Variations in direction of displacement of both parts of the micro-plate are observed and interpreted to be probably influenced by their retrograde rotation and be different rates at which this transport takes place.

The structure units of the Dinarides and Southern Alps are resisting to displacements of the parts of the Adriatic micro-plate. Within the structure fabric, this process is constrained by the size, spatial position and relations between the rock masses of different density, because these masses condition the formation of the stress field which in turn influences the deformations and displacement of structures. This is illustrated in Fig. 1 by the variable orientation within some regional structure units – in the Dinarides between 340-160^0 and 30-210^0, and in the Southern Alps between 320-140^0 and 340-160^0. The parts of the Adriatic micro-plate exhibit variable directions of displacement, i.e. their rotation. The Southern part of the micro-plate (1a) causes the strongest compression of the area between the island of Mljet and Dubrovnik. West of this region, displacements of the parts of structure units in SW direction were measured, while east of the region, the displacements were towards SE. Displacements of the Northern part of the Adriatic micro-plate (1b) condition the compression in the Alpine area and in the northern part of the Dinarides. Eastern region is characterised by the dextral tectonic transport of structure units. Directions of displacement of the parts of the Adriatic micro-plate are marked in Fig. 2, together with the main directions of displacement of the parts of Alps and Dinarides. Especially observed are the parts of the Dinarides whose deformations are conditioned with displacements and activity of the Southern and Northern part of the Adriatic micro-plate (1a,b). Furthermore, the common characteristics of displacement and deformation of the studied part of Alps and the northern part of the Dinarides are stressed out. This means that the influence of activity of the Northern part of the Adriatic micro-plate (1b) is observable till the area of Northern Dalmatia.

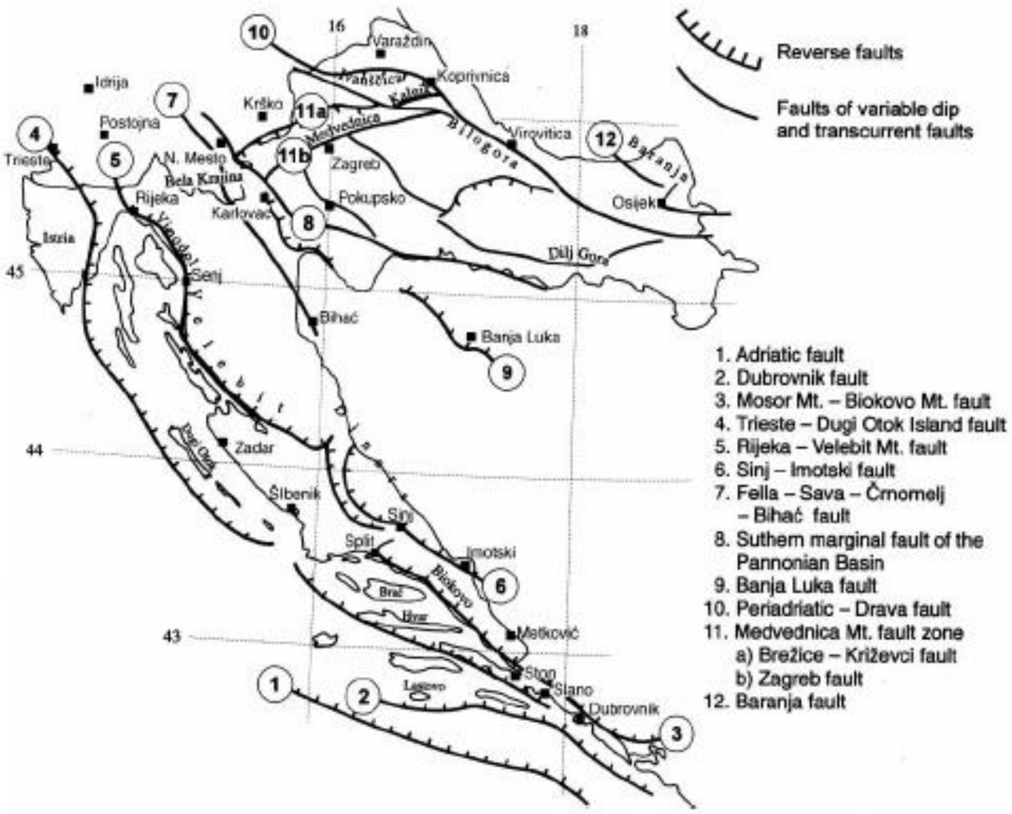

Figure 2: Map of major faults related to the tectonic activity

TECTONIC ACTIVITY

The subdivision of the geographical area into seismic source zones, or seismic zoning, is one of the crucial elements of the post- and pre-earthquake seismic surveying. The process of delineation of seismic source zones itself is often the most difficult and controversial, but also one of the most important parts of a seismic hazard study. By its nature it is a rather subjective process since no firm criteria can be established. In general, the zones are defined as not to intersect the most active parts of seismogenic faults, fault zones or the clouds of epicenters belonging to aftershocks of significant earthquakes. It is also required that major earthquakes within a single source zone share similar focal mechanisms, and that they occur at similar depths. Furthermore, the zone should be as homogeneous as possible regarding the frequency of earthquake occurrence (the magnitude-frequency relationship).

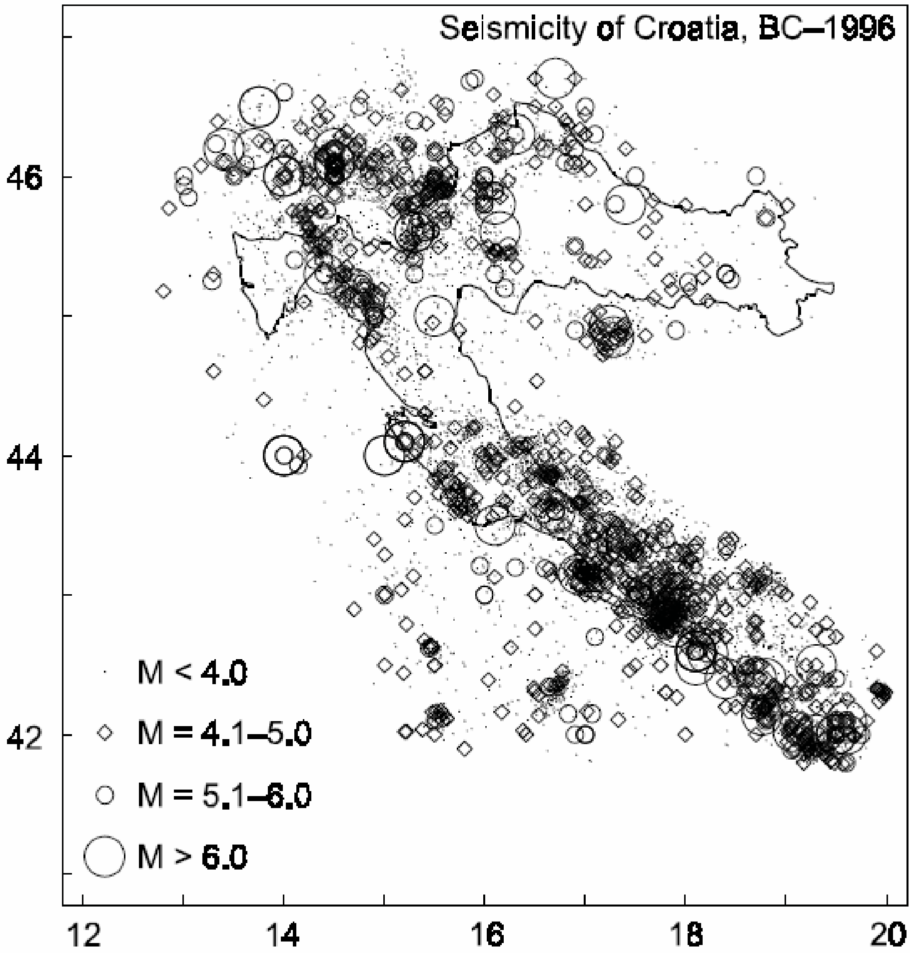

Figure 3. Epicenters of the earthquakes in Croatia and adjacent regions in the period BC–1996. Symbols increase with the magnitude

Finally, the geological, structural and tectonic properties should not significantly change within the zone. In practice, however, it is only seldomly possible to uniquely delineate seismic source zones strictly satisfying all of the above criteria, and the relative weights assigned to each of them will in effect determine the final result (Markusic and Herak, 1999).

During the 1997–2001 period seismic activity of Croatia was confined to the previously identified seismically active areas. All together 1925 earthquakes were located. Seismically the most active was the coastal part of Croatia, especially its southernmost part where the Ston–Slano epicentral area exhibited the continuation of the great earthquake sequence after the September 5, 1996 main shock. The strongest aftershock was recorded on April 26, 1997 at 07:30 (*ML* = 4.5, *Imax* = VI °MSK). The earthquake with the same magnitude *ML* = 4.5, recorded in the Zrmanja river valley, near Obrovac,on November 9, 2000 at 03:01 (*Imax* = VI °MSK). These two events were the strongest ones recorded in Croatia during the studied period.

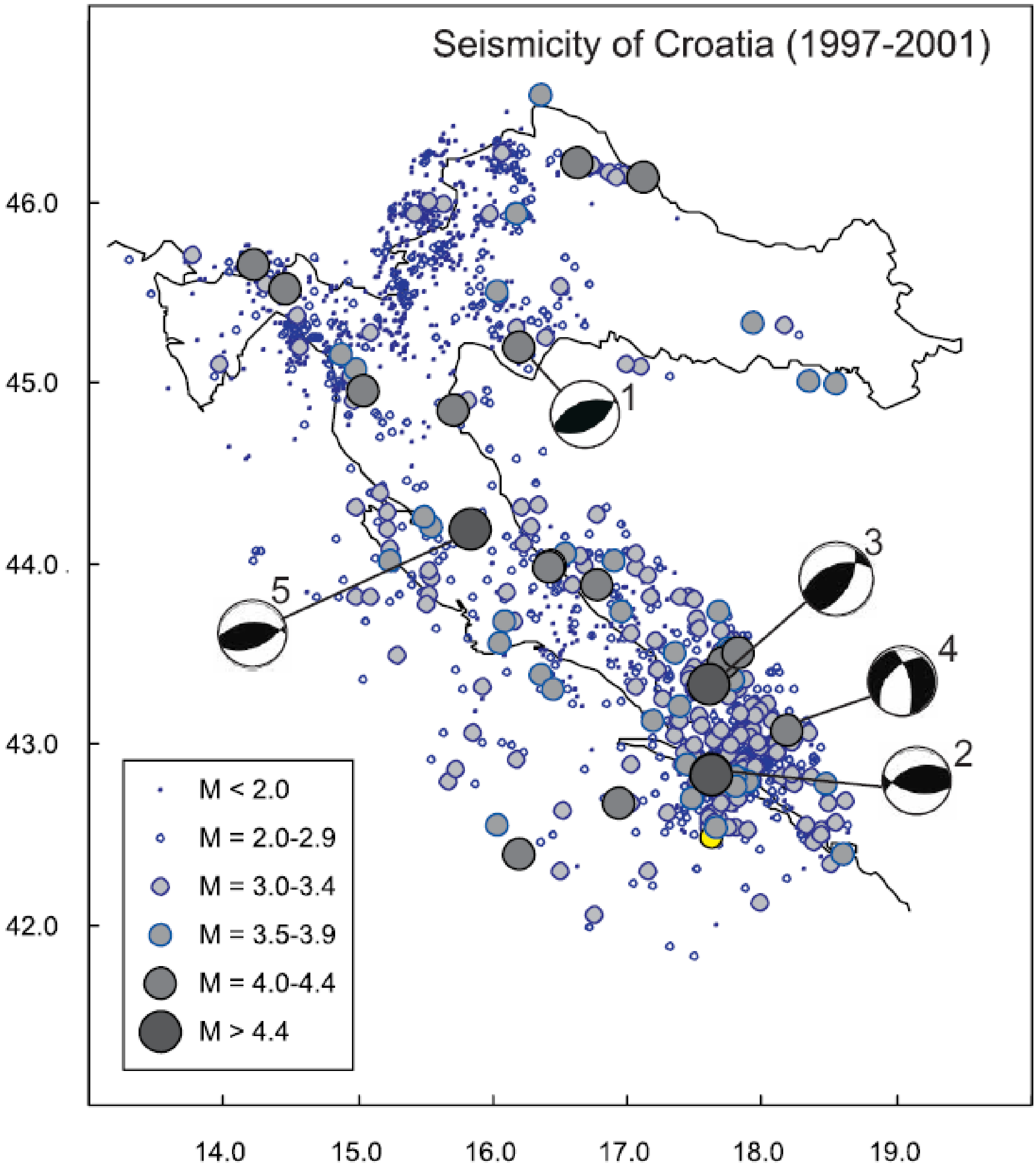

Figure 4. Map of epicenters in Croatia and the surrounding areas in the period 1997–2001. Fault-plane solutions for 5 earthquakes obtained in this study are shown (Ivancic et al. 2002)

GEODETIC GPS-MEASUREMENTS

Since 1960, the movement of the Earth's litospheric plates has been explained by the analysis of global ocean floor spreading rates, transform fault systems and earthquake slip vectors. According to this theory, the Earth's crust consists of 14 to 16 major litospheric plates, floating on the fluid astenosphere.

At the mid-oceanic ridge hot magmatic material emerges, spreading the ocean floor apart. By this spreading the plates are shifted on their boundaries and begin to move. The horizontal motions of the litospheric plates generally range from a few to more than 150 mm/yr.

The NUVEL-1 model describes motions of 14 major plates relative to the fixed Pacific Plate (DeMets et al., 1990). The NNR-NUVEL1 model (no net rotation) gives absolute angular velocities of the plates (Argus and Gordon, 1991). Tectonic development of the Adriatic Sea area was and still is a very interesting puzzle for scientists. Some of them believe that the Adriatic Microplate is a promontory of the African Plate (Mantovani et al., 1995), asserting that this promontory moves in the northwest direction with the velocity of cca. 5 mm/yr.

On the other hand, other scientists explain the earthquakes that are frequently occurring in this area as an internal deformation of the Adriatic microplate (Anderson and Jackson, 1987). The measurement of such small movements between points that are far away from each other has been made possible by the development of the space techniques like Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and recently with GPS. In order to enable precise ground control for GPS measurements, a multi-purpose international network has been established: International GPS-Service for Geodynamics (IGS). Beside the controlling of measurement accuracy for the whole system (orbit determination and correction), the role of such a network is substantial in the determination of the movement of the Earth's crust. Croatian geodesy joined to this world project in 2000 through establishing of two permanent GPS-stations (Dubrovnik and Osijek) within the EUREF Permanent subproject of IGS Network. Activity of these stations shall contribute to our knowledge of motions of the Adriatic Microplate as an important successor of the CRODYN project (Altiner, 1999; Altiner et al. 2001).

Since the late 1980s, the U.S. Global Positioning System (GPS) constellation of satellites has come to play a major role in regional and global studies of Earth. In the face of continued growth and diversification of GPS applications, the worldwide scientific community has made an effort to promote international standards for GPS data acquisition and analysis, and to deploy and operate a common, comprehensive global tracking system.

As a part of this effort, the IGS was formally recognized in 1993 by the International Association of Geodesy (IAG), and began routine operations on January 1, 1994, providing GPS orbits, tracking data, and other data products in support of geodetic and geophysical research (Beutler et al., 1994; 1996). There are 288 IGS-stations as of January 2002.

Within the IAG Commission X, EUREF is the sub-commission, which is responsible for the maintenance of the European Reference System ETRS89. Members of the group are mainly federal survey authorities, universities and research institutes interested in the realization of a unified horizontal and vertical reference frame. Since 1995, the epoch-wise EUREF GPS campaigns were replaced to a great extent by the installation of the EPN, the EUREF Permanent GPS Network (EPN), (Bruyninx et al., 1996). This was done in close collaboration with the IGS seeking for regional densifications. In 1996 the EPN was accepted as a regional Network Associate Analysis Center (RNAAC) of the IGS for Europe. The number of stations was 118. From these, 47% of them belong to the IGS network as well.

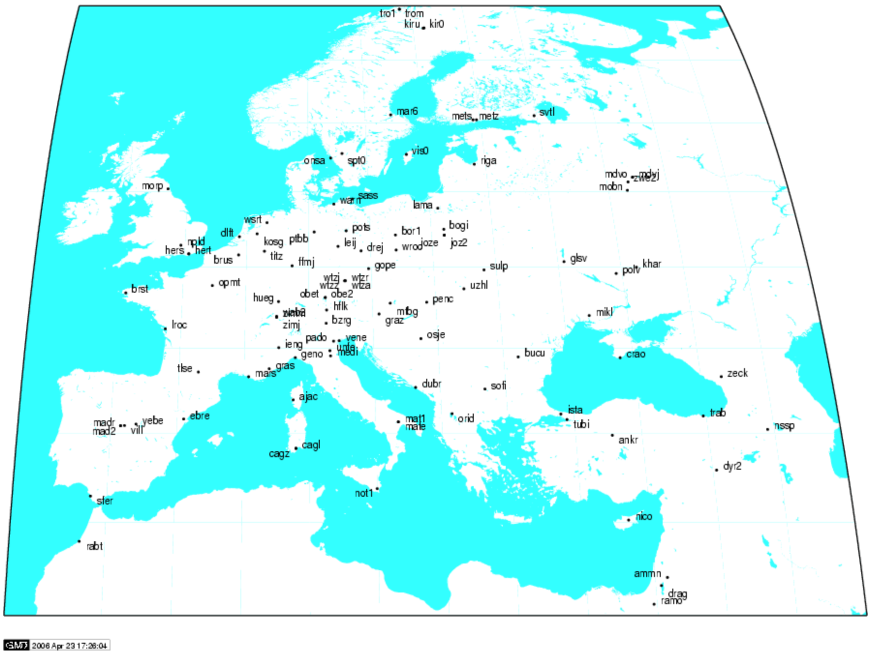

Figure 5. IGS stations in EUREF permanent tracking network

Figure 5 shows the IGS stations in EUREF permanent tracking network as in April 2006. To encourage the installation of EPN stations in less dense regions, the EUREF Technical working group has adopted a new guideline concerning the station location: a minimal distance of 300 km to already existing EPN stations is required, accepting the interest of each nation to have at least one EPN station. Exceptions to this rule are possible for stations submitting hourly data or contributing to EPN Special Projects. Thanks to this new guideline, 45% of the EPN stations are now submitting hourly data. The quality of daily data flow has been improved: at the EUREF Data Centre (BKG), the proportion of bad files (unreadable or wrong contents) fell from 1% to 0.05%. A part of this improvement was achieved by introduction of checking routines at the EPN Data Centres. The observations of the European Permanent Network are currently analysed by 13 Local Analysis Centers, which submit weekly solutions of their subnets to the EUREF Data Center at BKG.

In 1998, several reconnaissance campaigns were undertaken in order to determine which sites suit the needs of potential GPS Permanent sites. Figure 6 shows the vicinity of Croatian territory with locations of existing IGS permanent stations.

Figure 6. IGS stations in Adriatic Sea area

The shape of the Croatian territory dictated the choice: one point in the north-east and one point in the south-east. Finally, the experts from BKG agreed with Croatian colleagues to set up the stations in Osijek and Dubrovnik. According to the guidelines for European Permanent Network that were valid at that time (Gurtner, 1992), the area in north-east Croatia was not particularly suitable since it was not possible to set up the marker onto a bedrock foundation. Therefore, the building of the Geodetski zavod Osijek was chosen for stabilization of the marker. In Dubrovnik, the station was placed in an ancient fortress named Imperial, located at the Mount Srdj, the hill dominating the area. Special construction for antenna support was erected to achieve better angle for low-elevation satellites. Both stations are equipped with an Ashtech Z-12 GPS-receiver and an Ashtech Choke Ring antenna with Radome. Personal computers running the program GPS-Base are used for the control of receivers and data transfer. Observation interval has been set to 1 second, but these datasets are available only directly from the station within 14 days. The data that are hourly sent to the Data Center in BKG are rendered to 30 seconds intervals. Special GPS-campaigns were performed to determine the coordinates of the stations in the official Croatian reference frame CROREF96. It is important to stress that the Dubrovnik station was directly linked with the Dubrovnik tide gauge, yielding the important information of sea level rise in the long run.

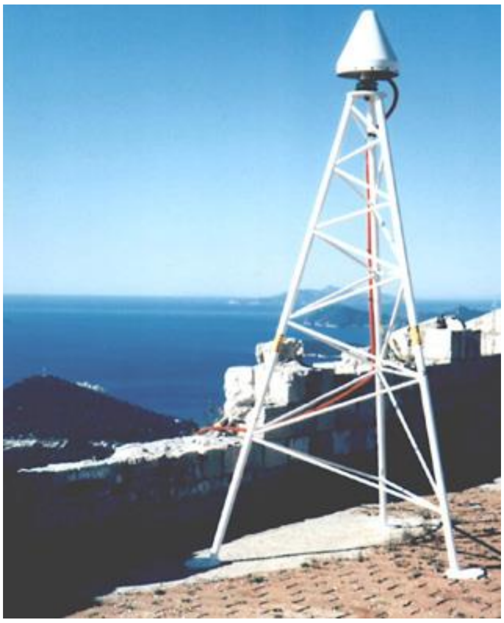

Figure 7. The monument at DUBR station

The stations are operating since October 2000. Although the obtained performance and stability of the stations is very good, it would be very useful to establish the ground control micro-network. High-precise terrestrial measurements should be used for long-term monitoring of monument stability, especially in Osijek.

Two another permanent stations, in Zagreb and Pula, are operating for even longer time, but these stations were not included into international projects so far. Because of their location and good stabilization, their inclusion in international projects has been recently considered. The station in Zagreb is operated by the City Cadastre and located on an independent part of the building of the City Computing Centre. This station had an important role in both geodynamical GPS-campaigns within the project Geodynamic GPS-Network of the City of Zagreb (Medak and Pribicevic 2001).

Through the realization of the project GPS-network for Zagreb, a well-founded network of points was established (Medak and Pribičević, 2001). All 43 points in the base network had special stabilization that fulfilled all criteria for geodynamic research. The first measurements were carried out in 1997. The purpose of the network was twofold: to be used for the state survey and to monitor tectonic movements. The first goal was fulfilled in 1998, as the homogenous field with more than 4000 GPS-points in Zagreb area was measured and adjusted. The second goal, geodynamic monitoring is a long-term project involving repeated observations every 3-4 years.

Figure 8 shows the damaging effects of tectonic activity in the area of Kasina, where the most seismic activity is recorded.

Figure 8. Examples of damages on houses in the epicentral area near Zagreb

During the choice of point locations scientists from other disciplines were included: geologists, geophysicists , seismologists and civil engineers. The stability of points was the most important issue during the preparatory phase of the project. All pillars are equipped with forced centering screws. Since the area is mainly gravel, special stabilization is constructed and checked with precise leveling after a couple of years to determine if the pillars are vertically stable with respect to nearby leveling points. Locations are chosen with respect to fault zones to optimally describe motions. Several other criteria were important: nearby leveling points, durability with respect to landslides, engineering works, vehicle accessibility and, clear sky view at 10-15° elevation and above, especially in S, SW and SE direction. Sources of strong radio-emission, and reflective surfaces were avoided. Altogether, 33 points were stabilized with special pillars, while the rest of the points had other marks for forced centering of GPS-antennas. The locations of all points are shown in Fig. 9.

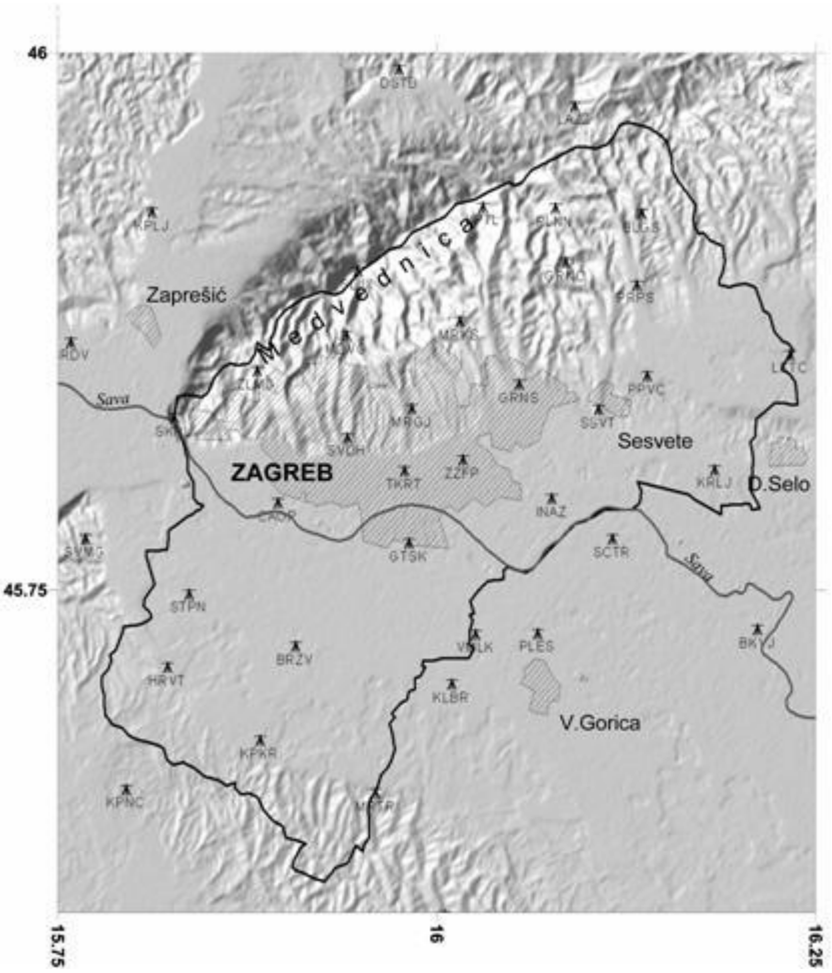

Figure 9. Distribution of points in the Zagreb Geodynamic Network

GEODYNAMICS OF CROATIA

Directions of displacement of the parts of the Adriatic micro-plate are marked in Fig. 10, together with the main directions of displacement of the parts of Alps and Dinarides. Especially observed are the parts of the Dinarides whose deformations are conditioned with displacements and activity of the Southern and Northern part of the Adriatic micro-plate (1a,b). Furthermore, the common characteristics of displacement and deformation of the studied part of Alps and the northern part of the Dinarides are stressed out. This means that the influence of activity of the Northern part of the Adriatic micro-plate (1b) is observable till the area of Northern Dalmatia.

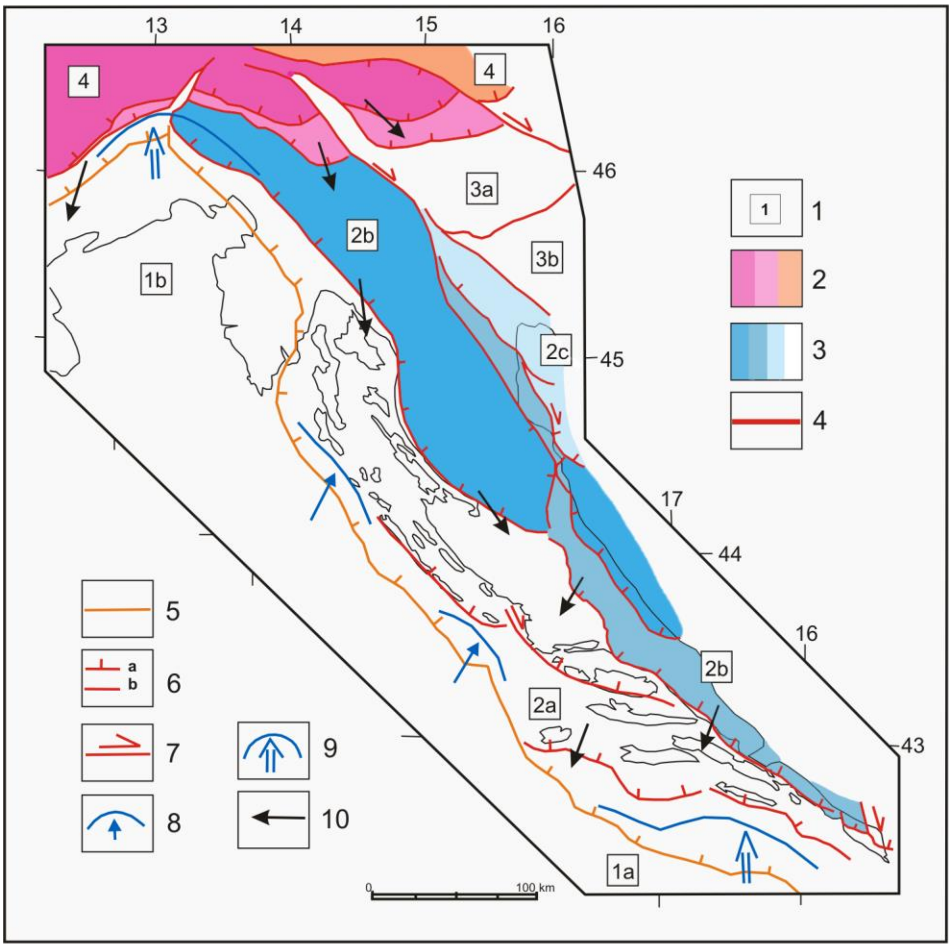

Figure 10. Displacements of the Adriatic micro-plate, Dinarides and Alps

Legend: 1 – principal structure units: Adriatic micro-plate (1a – Southern part, 1b – Northern part), Dinarides (2a – Adriaticum, 2b – Dinaricum, 2c – Supradinaricum), Pannonian basin (3a – Western marginal part, 3b – Southern marginal part), Alps (4); 2- the most important parts of the Dinarides; 3 – the most important parts of the Alps; 4 – contacts between the seismotectonically active structural units, marked at the surface by the fault zones; 5 – borders of the youngest compressional structures; 6 – reverse faults (a) and fault sections lacking positively defined character of displacement (b); 7 – fault sections with prevailing strike-slip; 8 – inferred direction of displacement of parts of the Adriatic micro-plate; 9 – direction of displacement of the Adriatic micro-plate in regions of the more pronounced subduction, and of reverse-overthrust displacements and compression; 10 – the most important directions of displacement of the structure units close to the surface.

The common character of deformation of the recent structural fabric in the Southern Alps and northern part of the Dinarides can be proved by analysis of the subsurface data. Following most important characteristics are observed:

- the minimal and maximal values of gravimetric anomalies depict locations of the rock masses of different density at shallower and deeper positions;
- the masses are most subsided under the Southern Alps and Northern part of the Dinarides; this also marks the area of the largest compression caused by tectonic movements of the Adriatic micro-plate;
- strike of the minimal axes illustrates the 3D position of the reverse relations between the structures;

- **regions of maxima between Trieste and Ljubljana, and in the Savinja Alps as well, mark folding of structures and reverse relations; maxima around Zagreb and Maribor are also caused by the folding and compression in these areas, but rather caused by the dextral tectonic transport and transpression;**
- **zones of increased gravimetric gradients depict the step-like subsidence of rock masses in depth, i.e. the most active fault sections, while their position and strike coincide with the prevailingly reverse displacement of structures;**
- **changes in strike of structures and faults in the northern part of the Dinarides result from the dextral tectonic transport of structures that are located to the right of the area of the largest compression.**

Aside from CEGRN GPS-campaigns, researchers from the Faculty of Geodesy, University of Zagreb are performing precise GPS-measurements on the Geodynamic Network of the City of Zagreb since 1997. First results has been presented in (Medak and Pribicevic 2001), and a comprehensive description of achievments can be found in (Medak and Pribicevic 2006).

Figure 11 shows the vector displacement field derived from campaigns in 1997, 2001 and 2004. In 2005 this network has been densified with the new points in the seismically most active area in eastern Medvednica. In 2006 new series of measurements of the whole network has been performed.

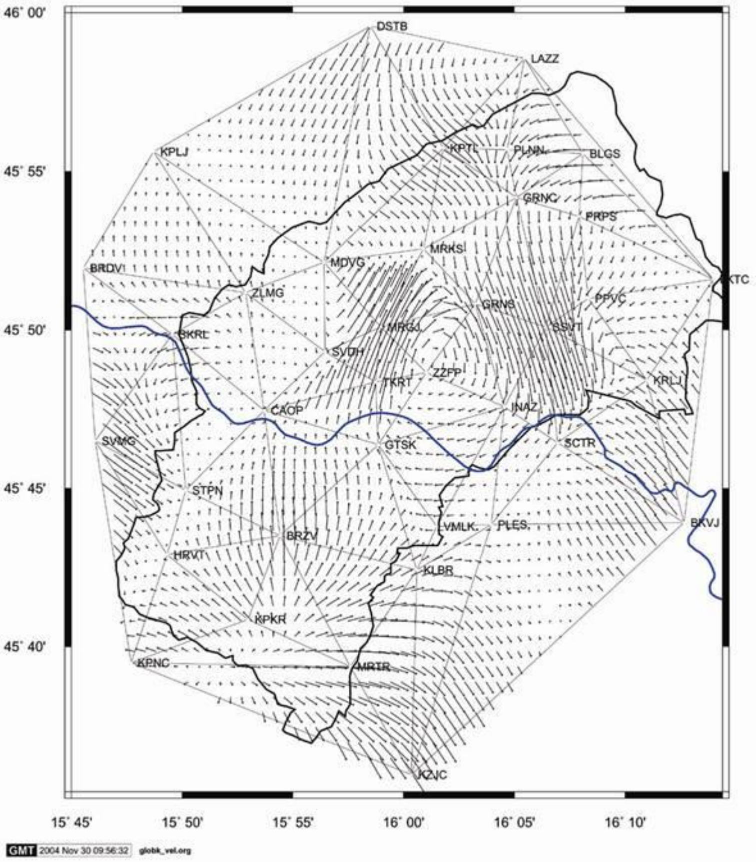

Figure 11. Displacement map in the area of Zagreb geodynamic network

CONCLUSION

The zone of Dinnarides delineated by the Alps in the north, the Adriatic in the south west, and with the Pannonian basin in the north-east is seismically and tectonically very active area, which deserves further interdisciplinary research. Geodesy is contributing a lot with precise GPS-measurements which yield very accurate displacements even on local or regional level. The CEGRN network observed several times in this region has proven the hypothesis that Dinnarides are an important research area. Several campaigns performed on the Geodynamic GPS-Network of the City of Zagreb confirm the hypothesis that the movement of Eastern Alps toward Dinnarides and Pannonian basin are causing significant tectonic activity in the Mount Medvednica area. Further meausurements and interdisciplinary and international cooperation is necessary in order to track these potential hazard movements.

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