

Article

Present Tectonic Dynamics of the Geological Structural Setting of the Eastern Part of the Adriatic Region Obtained from Geodetic and Geological Data

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Abstract: The Adriatic microplate has always attracted scientific attention, and various studies on the geodynamics of this area have been performed over the years. With the development of global navigation satellite system (GNSS) technology in the last 30 years, most significant research in this field has used it as the primary source of data on geodynamic movements. However, apart from a few global positioning system (GPS) campaigns conducted in the 1990s, the measurements had a low spatiotemporal density. Therefore, the eastern side of the Adria region or the territory of the Republic of Croatia was usually omitted from the results presented in the various published papers. A study of this literature concluded that the territory of Croatia represents a kind of scientific gap and that denser measurement data from GPS/GNSS stations could be used to supplement the geodynamic picture of the area in question. Thus, GPS/GNSS measurements from 83 stations (geodynamic, reference, and POS' GPS/GNSS) all over Croatia and neighboring countries for a period of almost 20 years (1994–2013) were collected and processed with Bernese software to obtain a unique database of relative velocities. From the geological perspective, the most important and latest insights on the recent geological structural setting, tectonic movements, most active faults, and relationships and movements of structures were taken into account. It was important to compare the geodetic and geological data, observe the present tectonic dynamics of the geological structural setting, and determine the causes of the obtained directions of movement. The research presented in this paper, based on a combination of geodetic and geological data, was conducted to broaden the current knowledge of the present tectonic dynamics of the geological structural setting of the eastern part of the Adriatic region.

Keywords: Adriatic microplate; comparison; geodynamics; GNSS; geological structural setting



Citation: Pavasović, M.; Đapo, A.; Marjanović, M.; Pribičević, B. Present Tectonic Dynamics of the Geological Structural Setting of the Eastern Part of the Adriatic Region Obtained from Geodetic and Geological Data. *Appl. Sci.* **2021**, *11*, 5735. <https://doi.org/10.3390/app11125735>

Academic Editor: Paraskevi Nomikou

Received: 13 April 2021

Accepted: 18 June 2021

Published: 21 June 2021

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1. Introduction

The Adriatic microplate has always attracted scientific attention, and various studies on the geodynamics of the area have been performed over the years. With the development of the global navigation satellite system (GNSS) technology in the last 30 years, most significant research in this field has used it as the primary source of data on geodynamic movements. However, apart from a couple of global positioning system (GPS) campaigns conducted in the 1990s (e.g., CRODYN), the measurements had a low spatiotemporal density. Therefore, the eastern side of the Adria region or the territory of the Republic of Croatia was usually omitted from the results presented in the various published papers (i.e., [1–3]). Based on a study of this literature, the conclusion was reached that the territory of Croatia represents a kind of scientific gap and that denser measurement data from GPS/GNSS stations could be used to supplement the geodynamic picture of the area in question (Figure 1). Thus, GPS/GNSS measurements from 83 stations (geodynamic,

reference, and POS' GPS/GNSS stations) distributed over the territory of Croatia and neighbouring countries for a period of almost 20 years (1994–2013) were collected. By processing this data in the ADDNEQ2 program module of the scientific software Bernese 5.0 [4] for the central epoch of 15 January 2004 (e 2004.04), a unique database of the relative velocities for all 83 stations was obtained. Special attention was also given to the collection and analysis of geological data. In gathering the necessary data, the latest and most important insights on the recent geological structural setting, tectonic movements, most active faults, and relationships and movements of the structures were considered [5–19]. Some details were also collected during the study of the seismotectonic activity [7,20–27]. Particularly prominent were recent studies that directly addressed geodynamic processes [2,3,28–39].

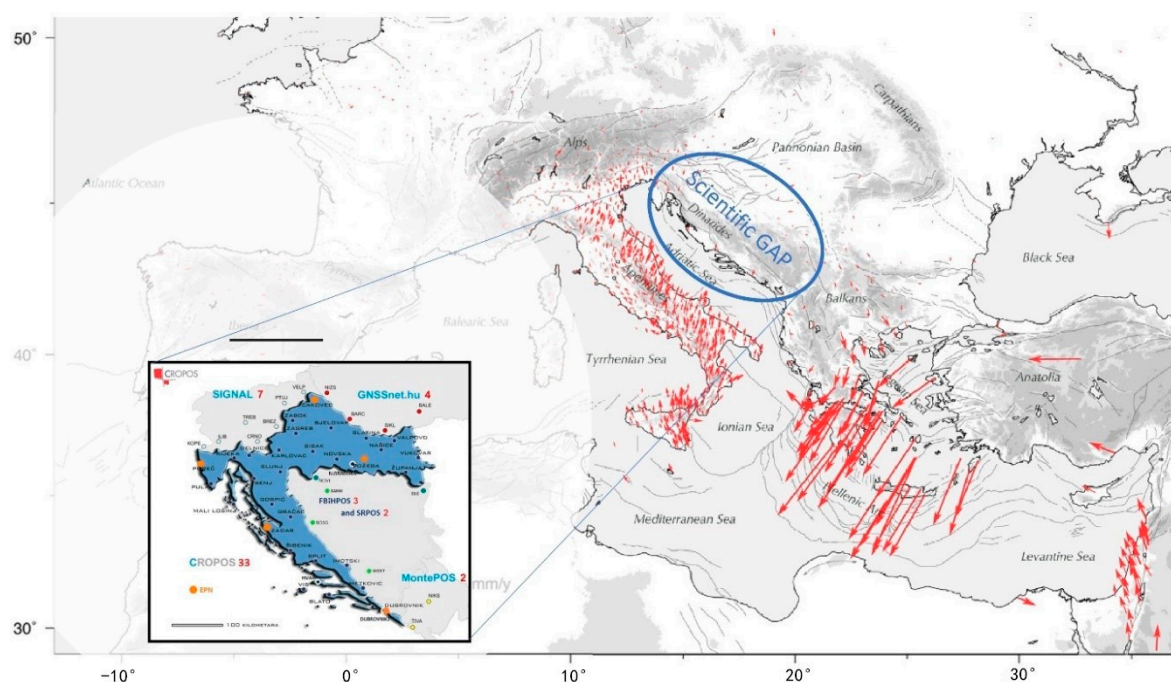


Figure 1. Low coverage of GNSS-derived velocities in the area of the Republic of Croatia represents a scientific gap (modified from [3]).

The research presented in this paper was based on a combination of the abovementioned geodetic and geological data and aimed to broaden the current knowledge of the present tectonic dynamics of the geological structural setting of the eastern part of the Adriatic region.

2. Geodetic Surveys and Data Processing

The use of the GPS measurement technique in the Republic of Croatia began in the late 1980s and early 1990s as part of several domestic and international scientific collaborative projects: CROATIA'91, TYRGEONET'91, TYRGEONET'92, AGREF'92, IGS'92, ZAGORJE'92, IGS'92, BRZA PRUGA'93, SLAVONIJA'93, ADRIATIC MICROPLATE'93, and TYRGEONET'95 [40].

The first reference GPS measurement campaign in the Republic of Croatia, EUREF-CROSLO-1994 (CROSLO'94), was organized in 1994 in collaboration with the Republic of Slovenia [41,42]. This campaign aimed to connect the national coordinate networks of both countries to EUREF and adopt the reference coordinate system ETRS89. Later, in 1995, Croatia and Slovenia established national reference GPS networks within the CROREF'95 and SLOVENIA'95 [42] GPS measurement campaigns. In 1996, during the second EUREF GPS measurement campaign, CROREF'96 [43] was performed in the territory of the Republic of Croatia, with simultaneous collaborative measurements in Slovenia and Bosnia and Herzegovina. The last reference GPS measurement campaign in Croatia, CROREF'05, was

performed in 2005 [44]. The campaign was again conducted in collaboration with Slovenia and Bosnia and Herzegovina.

Parallel to these national reference GPS measurement campaigns, in 1994, the Republic of Croatia (Croatian State Geodetic Administration) started the so-called Croatian Geodynamic project, CRODYN [45], in collaboration with the former IfaG (today BKG). The purpose of CRODYN was (and still is) to track and monitor the displacements of the Adriatic microplate (AMP) using the GPS campaign measurements performed in 1994 (CRODYN'94), 1996 (CRODYN'96), 1998 (CRODYN'98) [29], and finally in 2013 (CRODYN'13) [46,47].

The Republic of Croatia also participated in international geodynamic projects by extending the project networks to Croatian national (GPS) ones. Croatia participated in CERGOP (in 2002, followed by CERGOP-2; [48], which is in CERN ([49], with eight GPS measurement campaigns (1994, 1995, 1996, 1997, 1999, 2001, 2003, and 2005) [50]. In 1997, the BKG started the EUVN [1] (Ineichen et al., 1998) project to unify the different European height data from GPS/levelling stations. Croatia participated in EUVN with the GPS measurement campaign EUVN'97 [51]. In 2002 and 2003, the Republic of Slovenia was active in an AMP geodynamic study within the PIVO project [52] through GPS measurement campaigns in the territory of Slovenia, as well as Croatia. The last international geodynamic research project of AMP in which the Republic of Croatia took part was RETREAT [53], with measurement campaigns in 2003, 2004, and 2005. Details on the Croatian national networks and project results are available in [54].

The most crucial milestone in future geodynamic studies of AMP over the territory of Croatia in the 20th century was the establishment of a national network of continuously operating (GNSS) reference stations (CORS) called the Croatian positioning system (CROPOS) in December 2008 by the Croatian State Geodetic Administration within the PHARE-2005 project [55]. It included the exchange of CORS data with the positioning systems (POSs) of bordering countries, including Slovenia (SIGNAL), Hungary (GNSSnet.hu), and Montenegro (MontePOS).

The geodetic observation data and obtained results used in this paper were a part of the geodynamic studies in the territory of the Republic of Croatia received from [47,56–58]. The data from the 17 selected GPS measurement campaigns for 20 years (1994–2013) listed in Table 1, as well as the GNSS data from the CROPOS and POSs of bordering countries (2008–2013), were used to obtain the combined solution for the campaign data and POS data using the Bernese 5.0 GPS software [4]. The results were the relative velocities (horizontal component v_H) of 83 stations (Figure 2) concerning the GRAZ station as the velocity datum station.

Table 1. General information on GPS campaign data (17) used for Croatian territory.

Campaign	Date		Number of Sessions	Number of Stations
	from	to		
GEGRN'94	2 May 1994	6 May 1994	5	5
CROSLO'94	30 May 1994	3 June 1994	4	16
CRODYN'94	7 June 1994	10 June 1994	3	19
CEGRN'95	29 May 1995	2 June 1995	5	5
CROREF'95	25 September 1995	2 October 1995	7	15
CEGRN'96	10 June 1996	15 June 1996	6	6
CROREF'96	29 August 1996	7 September 1996	6	24
CRODYN'96	9 September 1996	12 September 1996	3	28
EUVN'97	22 May 1997	28 May 1997	7	12
CEGRN'97	5 June 1997	9 June 1997	5	7
CRODYN'98	4 September 1998	7 September 1998	3	29
CEGRN'99	14 June 1999	19 June 1999	6	7
CEGRN'01	18 June 2001	23 June 2001	6	9
CEGRN'03	16 June 2003	21 June 2003	6	7
CEGRN'05	20 June 2005	25 June 2005	6	8
CROREF'05	21 September 2005	23 September 2005	2	40
CRODYN'13	23 September 2013	28 September 2013	4	32

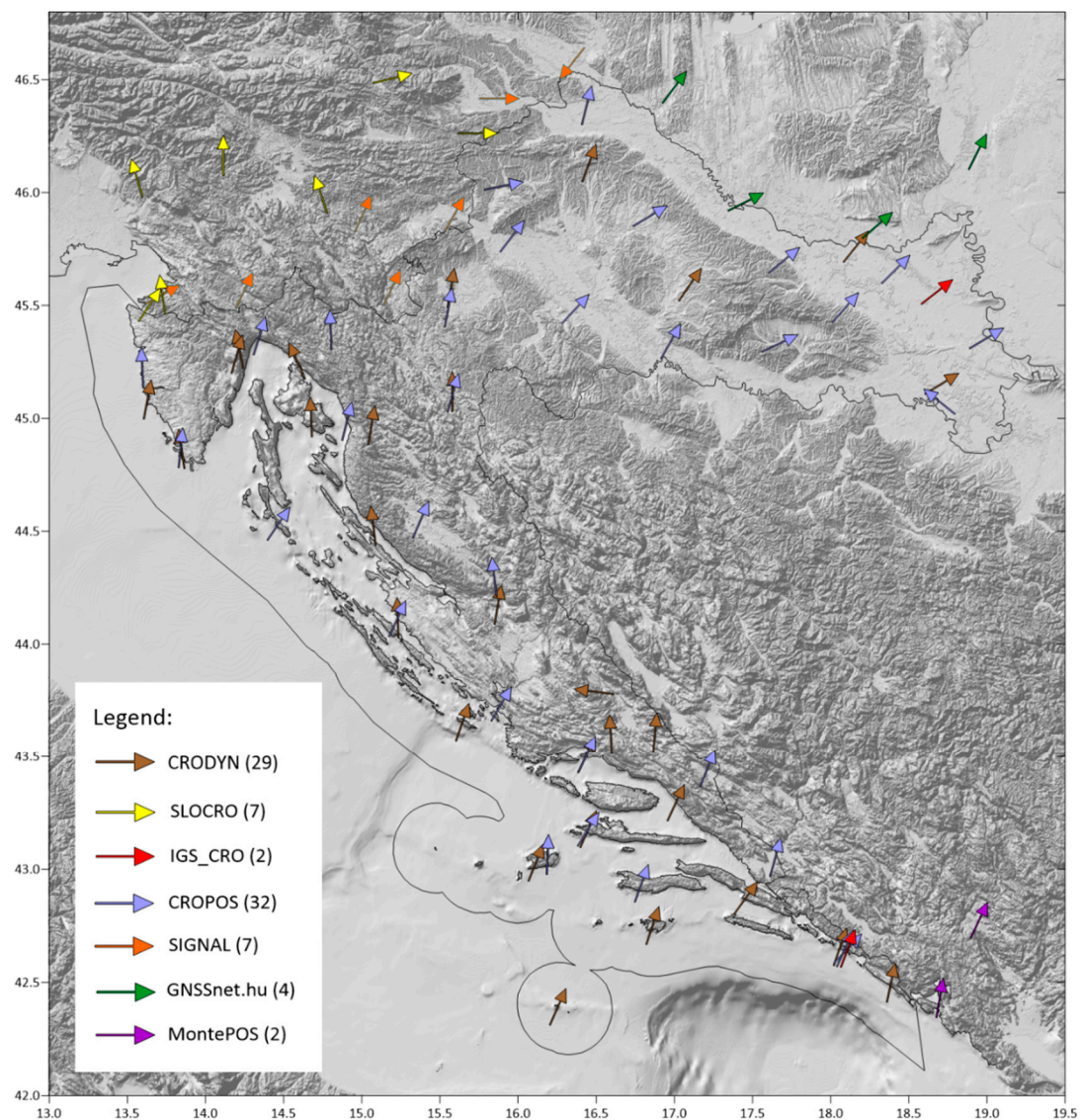


Figure 2. Relative velocity vectors (horizontal component v_H) of 83 stations for the territory of Croatia, Slovenia, Hungary, and Montenegro concerning station GRAZ (all velocity vectors have the same scale). CRODYN includes the Croatian stations that are most frequently observed in campaigns from Table 1.

3. Geological Data Interpretation

In the Republic of Croatia, new data were collected on the directions and amplitudes of movements at individual geodetic points. In Figure 2, the directions of the velocities determined at the geodetic stations are slightly different in some parts of the covered area.

Most importantly, the movements at particular stations point to the constantly present tectonic activity and the regional shifting of particular parts of the geological structural settings. In comparing the obtained geodetic and known geological data, the determination of the causes of recent tectonic activity is emphasized, especially the selection of the most active structures and spaces in which seismic activity can be expected.

First of all, it should be pointed out that the most common directions of movement, determined at individual geodetic points, are north-northeast (NNE) and northeast (NE), but also with the directions of the north (N) and north-northwest (NNW), are predominantly in the western part of the covered area. There are also changes observed in the narrower areas, most often from the NNE direction to N and NNW, such as around Zadar, Rijeka, and Ljubljana. The obtained data were compared with the characteristics of the regional and local geological structural setting and especially with the present seismotectonic activity.

In the process of collecting the necessary data, the most important knowledge, and particularly the latest developments concerning the recent structural setting, tectonic movements, faults, and movements of parts of the structures were taken into account [6,8,12,14–17,19]. Some details were also collected in previous studies of seismotectonic activity [13–16,25,26,59]. The most important data were obtained from recent work that directly considered the geodynamic processes in the observed area [2,28,30–32,35,36,38,39].

Geological structural relationships need to be highlighted first. Figure 3 shows marked regional geological structural units, the most important faults, and the movement directions of the surface parts of the structure according to the geological data.

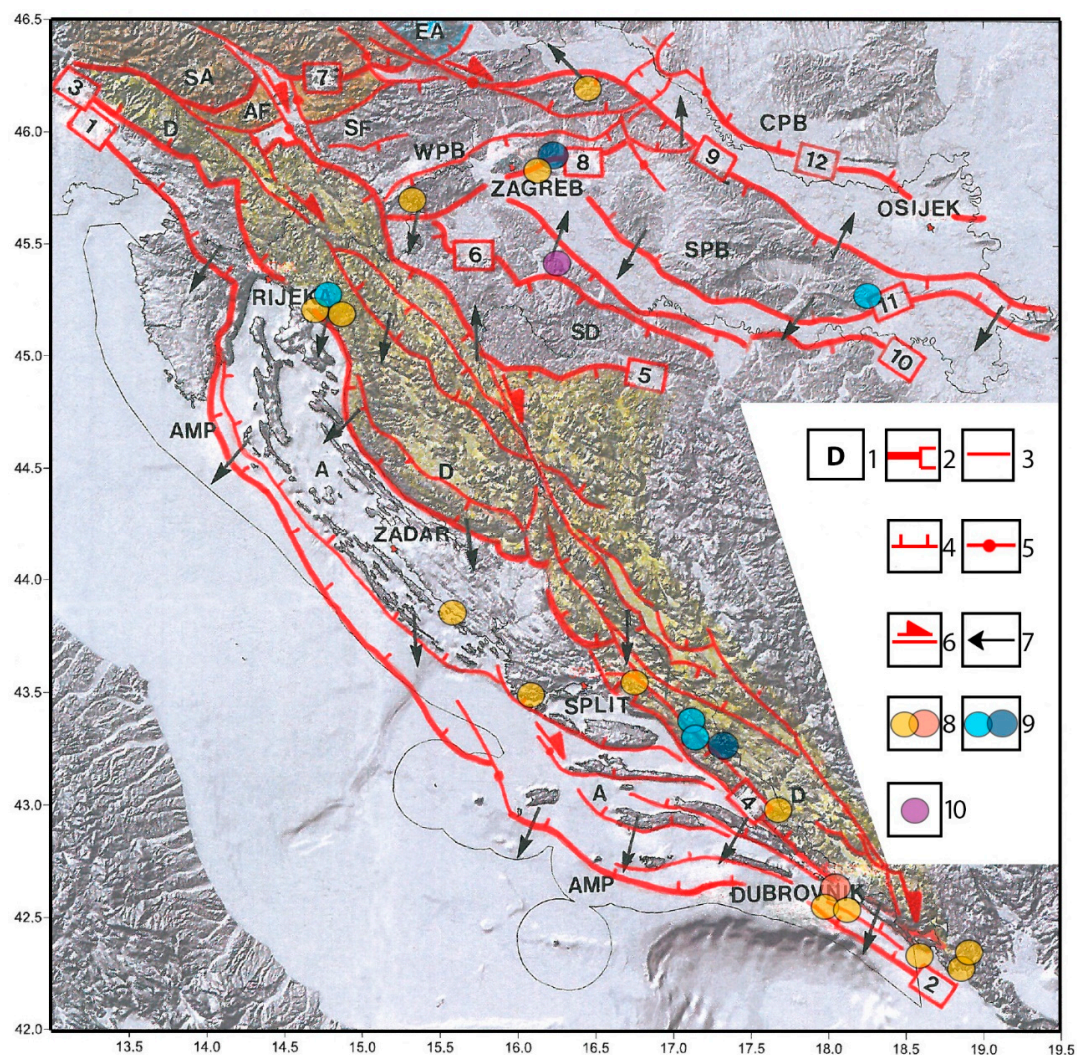


Figure 3. Recent geological structure setting and basic directions of movement of structural parts along the surface according to geological data. Legend: 1—Regional geological structural units: a—Adriatic microplate (AMP) and Adriatic unit (A); b—Southern Alps (SA), Prealps (AF), and Sava faults (SF); c—Dinarides: Dinaric and Supradinaric (SD); d—Pannonian Basin: Western (WPB), Southern (SPB), and Central part (CPB); 2—The most important faults bordering regional structural units: Trieste–Učka–Vis fault (1), Vis–South Adriatic fault (2), Postojna–Rijeka–Vinodol fault and extension, Velebit–Sinj fault (3), Mosor–Biokovo–Dubrovnik fault (4), Fela–Sava fault and continuation, Ljubljana–Karlovac–Slunj fault (5), southern boundary fault of the Pannonian Basin (6), fault of the Southern Alps (7), Zagreb fault (8), Periadriatic fault and continuation and Drava fault (9), Sava fault (10), Zagreb–Vinkovci fault (11), and Barcs–Baranja fault (12); 3—other important faults; 4—reverse faults; 5—faults of indeterminate character; 6—direction of horizontal movement along the fault; and 7—direction of movement of structure parts along the surface according to geological data; 8—earthquake epicentres, intensity IX and X, yr. 361–1900; 9—earthquake epicentres yr. 1901–1970, M 5.7–6.1 and M 6.2–6.6; 10—earthquake epicenter M 6.2, south of Zagreb in 2020.

The most crucial point that should be emphasized is the existence of reverse structures in the Dinarides (D, SD), Alps (SA, AF), and Adriatic (A) regional structural unit. Among these, the prevailing horizontal movements of particular parts of the Dinarides are emphasized, especially in the northern part and in the Alps. In the southern part of the Pannonian Basin (SPB, distinct pools and larger elevated structures in the WNW–ESE direction are dominant. In the zones of the most important faults, reversal shifts in parts of the structures of different vergences are noticed. In the western part of the Pannonian Basin (WPB), the structures are stretched in the NE–SW direction, as well as in the areas of the Sava fault (SF) and Prealps (AF). This indicates the connection between these parts of the structural setting and the recent emergence of common tectonic movements.

Direct indicators of the presence of tectonic activity are earthquakes. Their presence in all parts of the included geological structural setting shown in Figure 1 is emphasized. High-intensity earthquake locations stand out in particular. They also indicate the seismotectonically most active areas [20,23,26,60]. Earthquake concentrations around Zagreb, Rijeka, south of Zadar, in parts of the Pannonian Basin and especially a number of epicentres between Split and Dubrovnik, stand out. The locations of the strongest earthquakes are Dubrovnik-X° MCS scale (1667), Zagreb-magnitude 6.3 (1880) and east of Split-magnitude 6.2 (1923).

4. Results and Discussion: Recent Geological Structure Setting, Causes of Tectonic Activity, and Structure Movements

The velocities and amplitude of the tectonic movements determined by geodetic measurements in the observed period are shown in the chart of Figure 4. The most important observations are highlighted. First, amplitudes greater than 4 and 5 mm were determined at the stations located on the AMP (Figure 3 and Figure 7). These were on Palagruža Island and in part of Istria west of Rijeka. Most important were the amplitudes of movements greater than 4 mm in the area between Split and Dubrovnik and especially those higher than 5 and 7 mm on the south Adriatic islands and around Dubrovnik [47]. It is evident that the expressed movements of the Adriatic microplate (AMP) toward the NNE (Palagruža Island) increase the tectonic activity in the Adriatic (A) regional structural unit and, as a result of the movement toward the NNE, in the contact area with Dinarides, along the Dinaric unit (D).

A detailed understanding of the relations was obtained based on the data from four points in Dubrovnik (Figure 4b). The points are located in the broader zone of the most important fault, the Mosor–Biokovo–Dubrovnik fault (4), marking the contact area of the Adriatic (A) and Dinaric (D) units. At the DUBM (1 in Figure 4b) and DUBR (2) stations, the amplitudes were greater than 3 and 4 mm, and at the DUBI and DUB2 stations, they were greater than 5 and 7 mm respectively [47]. It is evident that the amplitude increases in the local reverse structure Srđ in the hanging wall of the main branch (4b) of the Mosor–Biokovo–Dubrovnik fault (4a). This is a sign of space compression and reverse structure elevation. The geological movements show vergence toward the SSW, opposite to the movement direction determined at the geodetic points. This is a consequence of the in-depth resistance of the Dinaric rock complex (D) to the initial direction of the Adriatic microplate movement (AMP).

In the greater part of the Dinarides, and then along the regional structural unit Adriatic (A) and in the western part of the Pannonian Basin (WPB) near Zagreb, the amplitudes of the tectonic movements are greater than 3 mm. However, some geodetic points are spaced relatively far apart. Larger amplitudes of movement could be expected in the hinterland of Rijeka, north of Zadar, and in the Žumberak–Medvednica structural unit (8 in Figure 11).

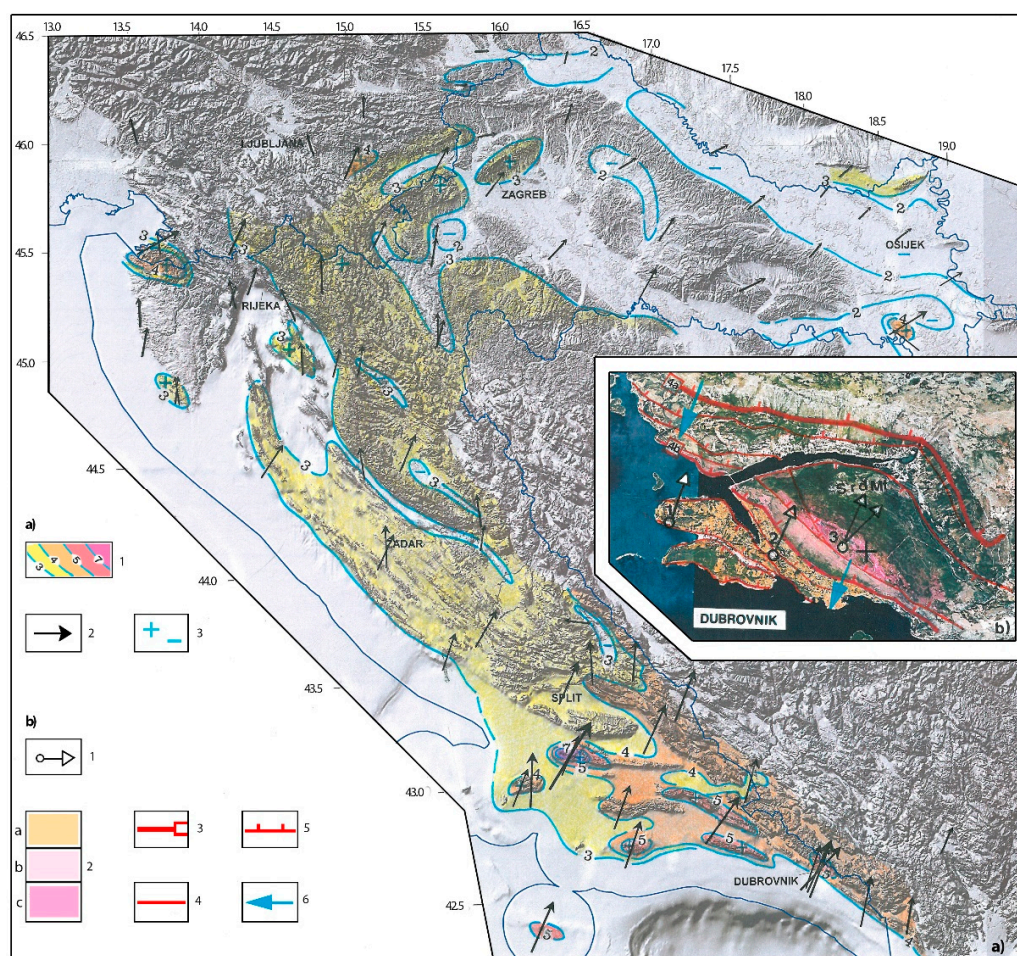


Figure 4. (a) Amplitudes and directions of annual velocities at geodetic stations (2008–2013). Legend (a): 1—velocity amplitudes; 2—movement directions at geodetic stations; 3—maximum and minimum movement amplitudes. (b) Amplitudes and directions of annual velocities around Dubrovnik. Legend (b): 1—direction of annual velocities at geodetic points in mm/yr; 2—amplitudes greater than 4 (a), 5 (b), and 7 (c) mm/yr at geodetic stations in Dubrovnik DUBM(1), DUBR(2), DUBI, and DUB2 (3); 3—major fault at Mosor–Biokovo–Dubrovnik (4a), bordering regional structural units and its main branch (4b); 4—faults extending along local reverse structures and branches of major faults; 5—reverse faults; 6—the movement directions of structural parts along the faults, according to geological measurements.

The established angles of the velocity directions at the geodetic points are particularly interesting (Figure 5). The most important are the almost horizontal directions of the movements, because they show the greatest movements of the particular parts of the regional structural units. This causes the compression of space and reversal movements of larger and local structures and emphasizes the tectonically and even seismotectonically most active sections of the faults. Of course, spatially negative movements show the lowering of parts of the structures. Most commonly, they appear in the footwalls of the tectonically most active sections of the faults. This is particularly evident along specific faults between Zadar and Dubrovnik and around Rijeka and in some places in the Pannonian Basin. Spatial positive movements represent elevated parts of the recent structural setting. In the area covered, the vertical movement angles are greater than 30° , and in some places even higher than 60° . It is probable that the latter movement angles are also present along larger geological structures where there are no geodetic points, e.g., along the area of the Adriatic (A) and Dinaric (D) and the western part of the Pannonian Basin (WPB) near

Zagreb. Sudden changes in the inclination angles are pointed out on tectonically very active sections of the faults around Dubrovnik, Split, Rijeka, Zagreb, and Osijek.

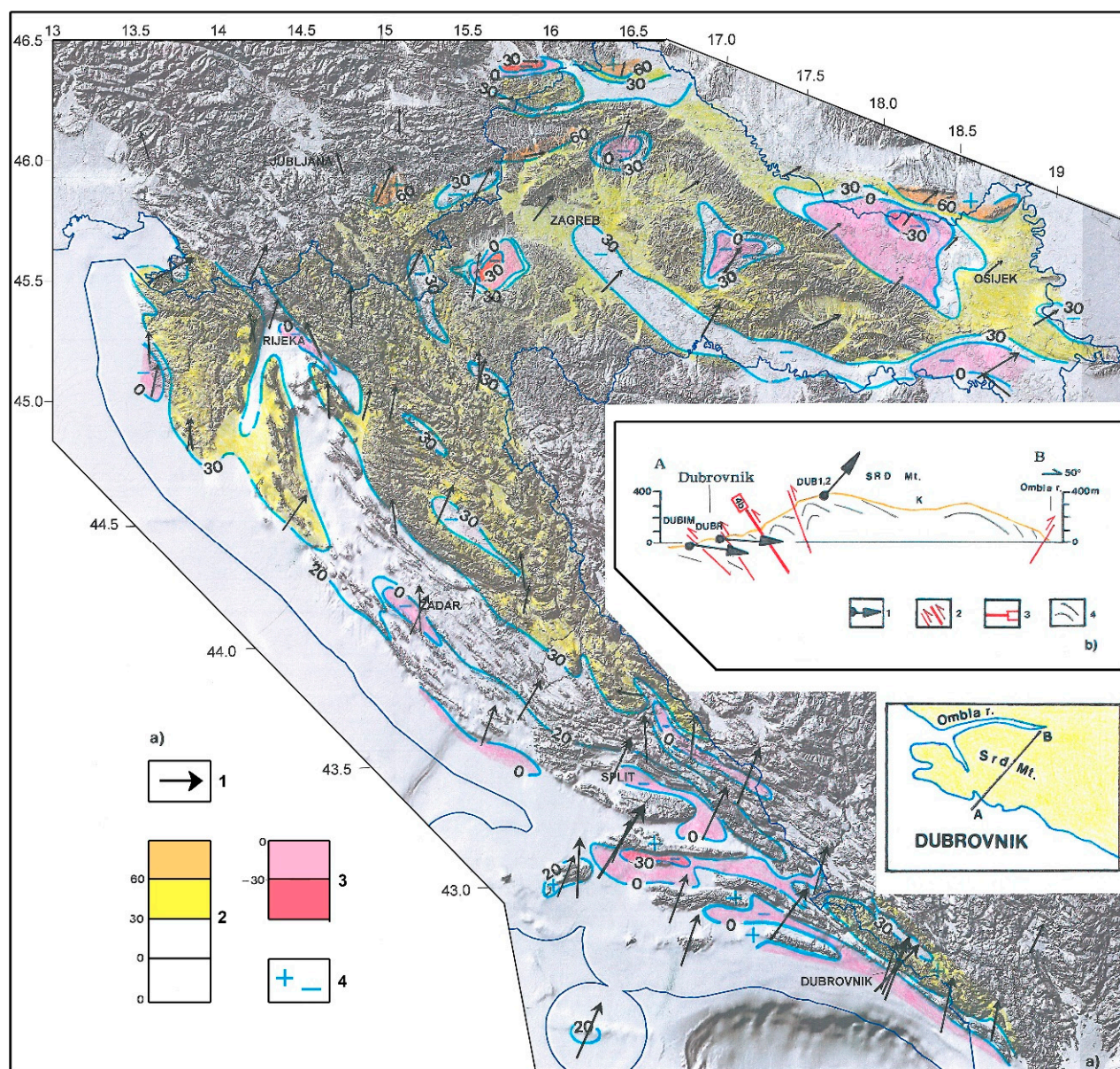


Figure 5. (a) Slope angles and directions of annual velocities at geodetic points (for 2008–2013 period). Legend: 1—directions of annual velocity at geodetic points in mm/yr; 2—spatially positive movements (uplift) greater than 0° , 20° , 30° , and 60° ; 3—spatially negative movements (descending) greater than 0° , -30° ; 4—maximum and minimum slope angles. (b) Slope angles and directions of annual velocities on Mt. Srđ near Dubrovnik. Legend: 1—directions and slope angles of annual velocity at points DUBM, DUBR, DUBI, and DUB2; 2—faults with an indication of reverse movement; 3—main branch of Mosor–Biokovo–Dubrovnik fault (4b); 4—layers of predominantly Cretaceous carbonate sediments.

A good example of the change in the angle of the movement direction measured at the geodetic points can be found in Dubrovnik (Figure 5b). Negative movement directions have been established at the DUBM and DUBR stations. They are found in the footwall of the main branch (4b) of the Mosor–Biokovo–Dubrovnik fault (4a). At the DUBI and DUB2 stations, the movement direction reaches almost 50° . This is a sure sign of the space compression, reverse elevation of the local structure of Mt. Srđ, and recent tectonic activity on the broader Mosor–Biokovo–Dubrovnik fault zone (4a,b).

Figure 6a shows the obtained directions of movement velocities at geodetic points in Croatia, and due to the possible correlation of data, also in parts of Italy and Slovenia. The abundance of data in Italy is highlighted, which are shown separately in Figure 6b [2] (Devoti et al., 2017). A significant coincidence of the movement directions of geodetic points in Italy, and especially in most of the regional structural unit Adriatic (A in Figure 1) and the neighbouring parts of the Dinarides (D), is immediately noticeable. Movements towards NE and NNE prevail. Deviations towards the N and NNW are located around Rijeka, in parts of Istria and along the edge of the Alps. The most important thing is to point out the causes of the formation of structures, their movements and the most active sections of faults. In the regional space, the original regional tectonic movements are the movements of the African plate. There is significant compression of space in Italy, and movements of geological structures towards NE and NNE prevail along the contact with the Adriatic microplate (AMP in Figure 1). The presence of recent tectonic activity is directly indicated by the numerous epicentres of earthquakes that occurred in the period 2004 to 2021 (Figure 4a) (source EMSC) and the Adriatic Microplate (AMP) is moving towards NE, NNE and in Istria towards N.

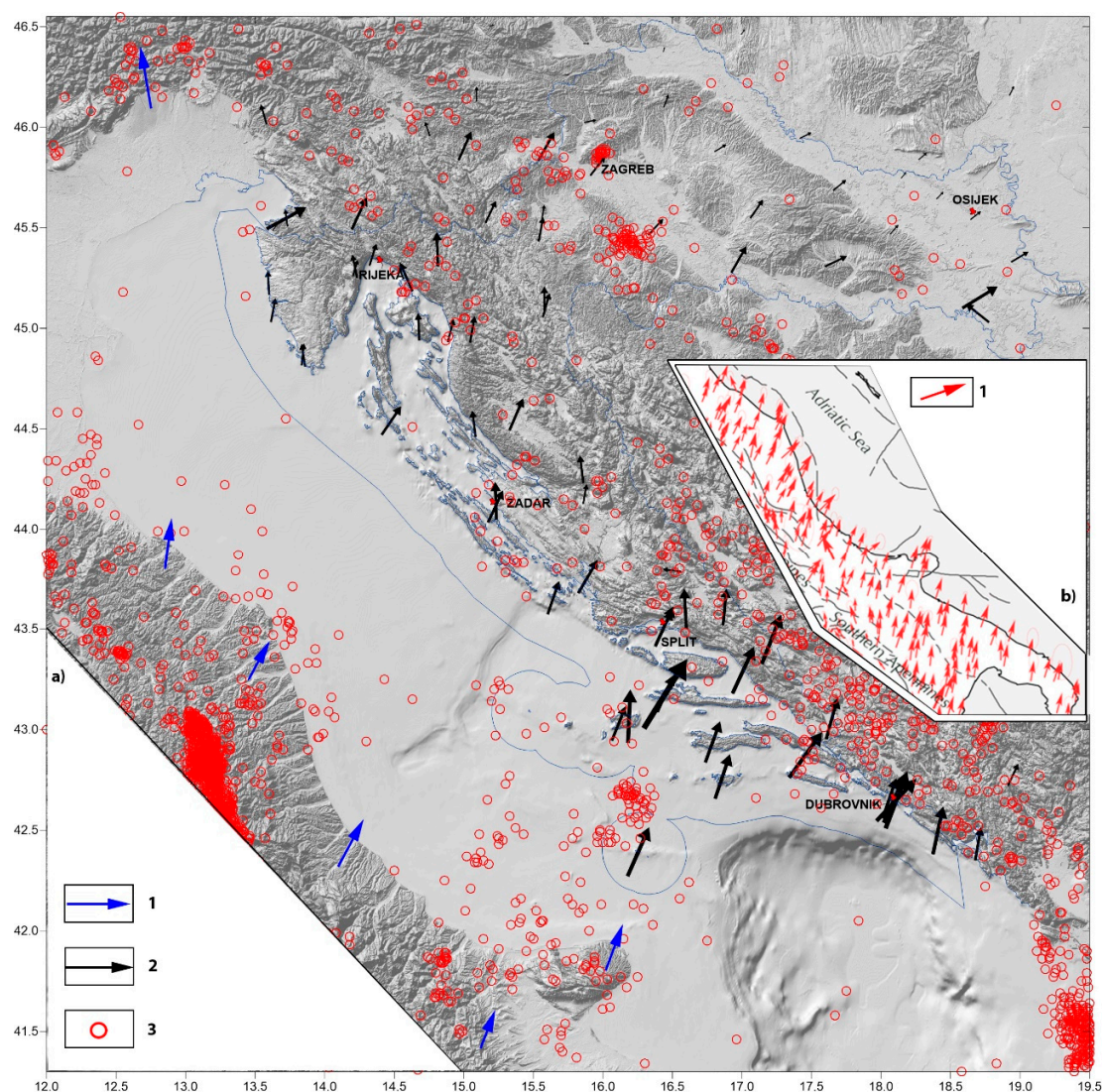


Figure 6. (a) Velocity vectors directions on geodetic points in Croatia, averaged velocity vector directions on geodetic points in Italy and seismic activity from 2004 to 2021. Legend: 1—annual velocity directions on geodetic points in Croatia; 2—averaged velocity directions on geodetic points in Italy; 3—earthquake epicentres in the period 2004—2021 with $M > 3$. (EMSC). (b) velocity directions on geodetic points in Italy—part (from [3]).

Figure 7 shows the recent geological structure setting in the Dinarides (D, SD) and Adriatic (A) regional structural unit. The most important faults of the structural setting that border the regional structural units are emphasized. There are a series of faults within each unit that extend along the particularly large structures and prominent units. The faults are mostly reversed with opposite vergences due to the prevalence of constant space compression.

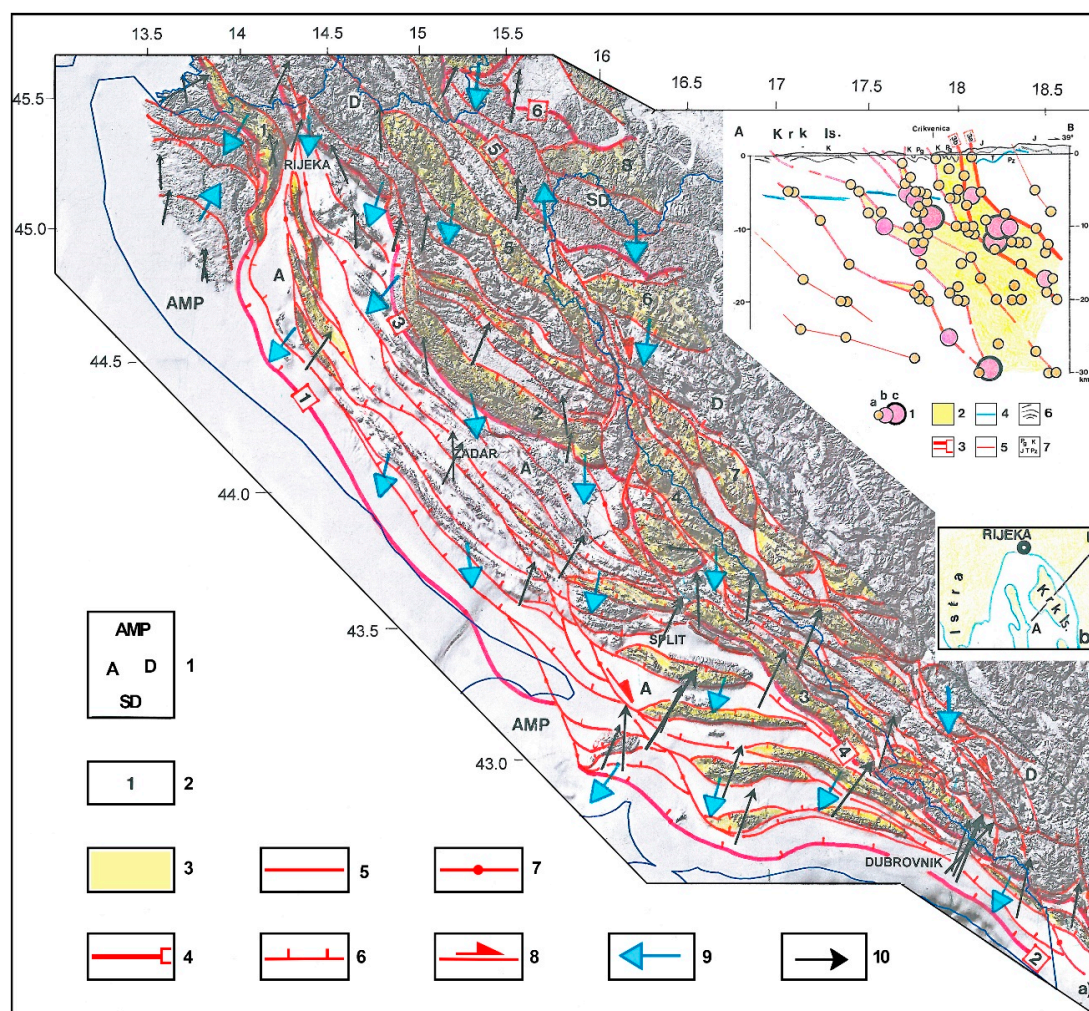


Figure 7. (a) Recent geological structural setting and tectonic activity in Dinaric space and Adriatic regional structural unit. Legend: 1—regional geologic structural units: a—Adriatic microplate (AMP) and Adriatic (A) unit, b—Dinarides: Dinaric (D) and Supradinaric (SD); 2—the most prominent structural units within the regional geological structural units with reverse faults of opposite vergence along fault walls: Čičarija–Učka (1), Velebit (2), Mosor–Biokovo (3), Dinara–Kamešnica (4), Kapela (5), Grmeč (6), Golija (7), Petrova Gora–Kozara (8); 3—major large structures; 4—the most important faults adjacent to regional structural units and parts of the Pannonian Basin, along with the Trieste–Učka–Vis fault (1), Vis–South Adriatic fault (2), Ilirska Bistrica–Rijeka–Vinodol fault and continuation of Velebit–Sinj fault (3), Mosor–Biokovo–Dubrovnik fault (4), Ljubljana–Karlovac–Slunj fault (5), and southern boundary fault of the Pannonian Basin (6); 5—other important faults; 6—reverse faults; 7—faults of indeterminate character; 8—direction of horizontal movement along the fault; 9—direction of movement of structure parts along the surface according to geological data; 10—directions of annual velocity at geodetic points in mm/yr. (b) Seismotectonic profile of Rijeka area. Legend: 1—earthquake hypocenters with a magnitude of (a) <4, (b) 4–5, and (c) >5.2; 2—seismotectonically active area; 3—faults included in the seismotectonically active areas and the most important Ilirska Bistrica–Rijeka–Vinodol fault (3); 4—other seismotectonically active faults; 5—the probable footwall surface of carbonate rock complex; 6—layers of rocks along the surface; 7—rocks on the surface: Pg (Paleogene)—limestones and flysch; K (Cretaceous)—predominantly limestones and dolomites; J (Jurassic)—limestones and dolomites; T (Triassic)—dolomites, limestones, marls, sandstones, and eruptives; and Pz (Paleozoic)—mainly shale, limestones, conglomerates, and sandstones.

It is vital to point out the structures' origins, movements, and the most active sections of faults. The source of the tectonic movements are movements of the Adriatic microplate (AMP). Certain rock complexes with a higher density that are responsible for building the Dinarides resist these movements. Considerable space compression, reverse structures, and faults occur. New geological and geodetic data show the narrowing of the AMP and the existence of southern and northern parts. Each part moves with a rotation predominantly toward the NNE and N. The presence of recent tectonic activity is confirmed by the epicentres of relatively numerous earthquakes. Concentrations of earthquakes, especially around Zagreb, Dubrovnik and the Adriatic microplate, indicate active parts of geological structures in the observed period.

The most crucial task was comparing the obtained directions of the movements of the geodetic stations and the parts of the structures along the surface based on the geological data (Figure 7). The directions obtained at the geodetic points show the basic real movements of the parts of the structural units. The featured geological directions of the movements along the most important reverse faults with vergences toward the SW and SSW in all parts of the structural setting are almost always opposed to the starting directions of the movements at the geodetic points. This is a direct sign of the existence of reactions to the basic directions of tectonic movements. In the detailed comparisons with the amplitudes and angles of the movements, it should be taken into consideration that the intensity of the tectonic movements is oscillating.

The reverse faults with vergences toward the NE and NNE are less reflected in the relief because of the smaller amplitudes of the reverse movements. However, in some places, along the contact between rocks of different densities, the movements of the complexes of rocks with higher density are dominant. Examples can be found in Istria (the AMP and along the Ljubljana–Karlovac–Slunj fault (5)).

Figure 7 shows the changes in the direction of the movements determined by geodetic and geological measurements. The direction changes are always to the left, from the NE direction to the N, around Split and Zadar, or in the NNW direction around Rijeka and in Istria. This is obviously a consequence of the retrograde rotation of particular geological structures or even parts of the structural setting. This is also confirmed by the strikes of faults along whose walls the horizontal component of the movement prevails.

Residual gravimetric anomalies are evidence of the existence of reversing structures and primary reverse movements along the faults with vergences toward the SW and SSW. These show the placement of the structures in the first kilometers of depth. Figure 8 shows anomalies in the area of the southern Adriatic islands. The shifts in the lowered and elevated parts of the structure are distinguished from their surface projections.

Under the conditions of space compression, there is always a reverse penetration of rocks with different densities toward the surface. The resulting reversing structures are clearly reflected in the relief. Figure 9 shows the steep relief created in the Mosor–Biokovo–Dubrovnik fault zone (4a,b). Tectonic movements in the Adriatic unit (A) are transverse to the strike of the fault. Thus, reverse movements along the hanging wall of the fault are very pronounced. The existence of branches of the main faults in the observed zone point to the recent reversal movements and the possible creation of new forms of relief.

It has already been emphasized that, in the Dinarides (D, SD) geological structure setting and in the Adriatic (A) unit, there are structures with reverse faults with opposite vergences along their walls. The appearance of such local structures in the broader zones of particular faults indeed emphasizes their most tectonically active sections. In this respect, the most important faults bordering regional structural units are especially emphasized. As shown in Figure 10, a relatively larger local reverse structure is located around Crikvenica.

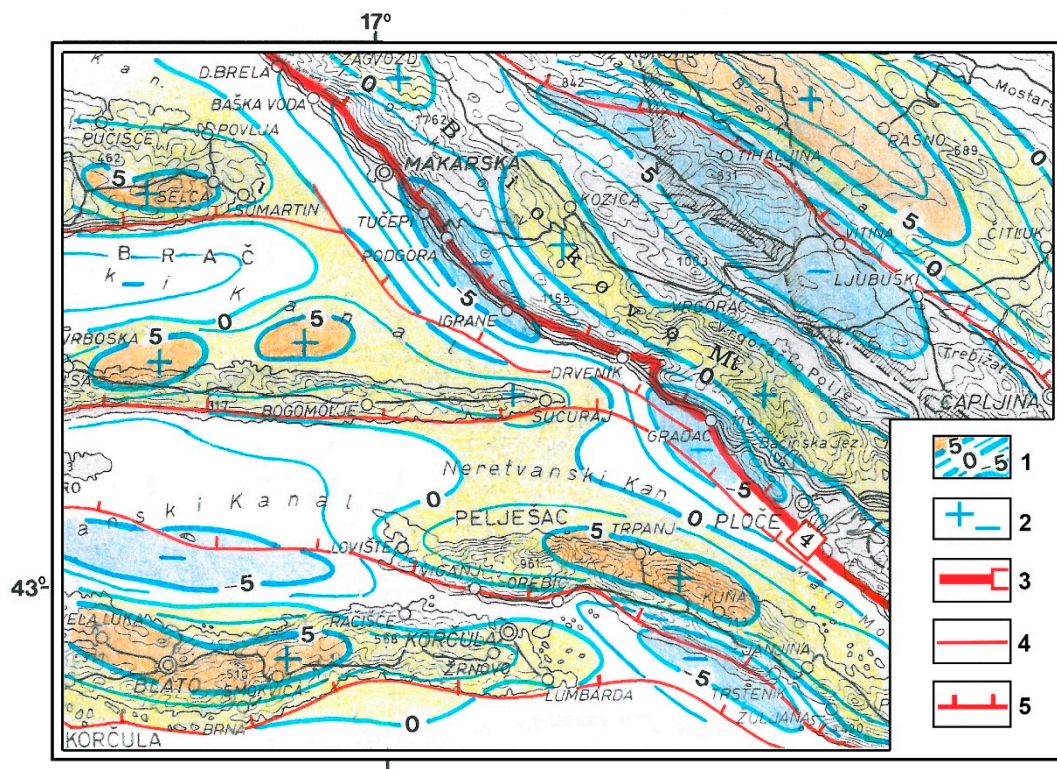


Figure 8. Gravimetric residual anomalies in the area of southern Adriatic islands and Biokovo. Legend: 1—Isolines of anomalies in mgal; 2—the highest positive and negative values of mgal; 3—major Mosor-Biokovo-Dubrovnik fault (4), borders of regional structural units; 4—faults extending along large local elevated reverse structures of vergences toward S and SSW-SW; 5—mark for reverse faults.

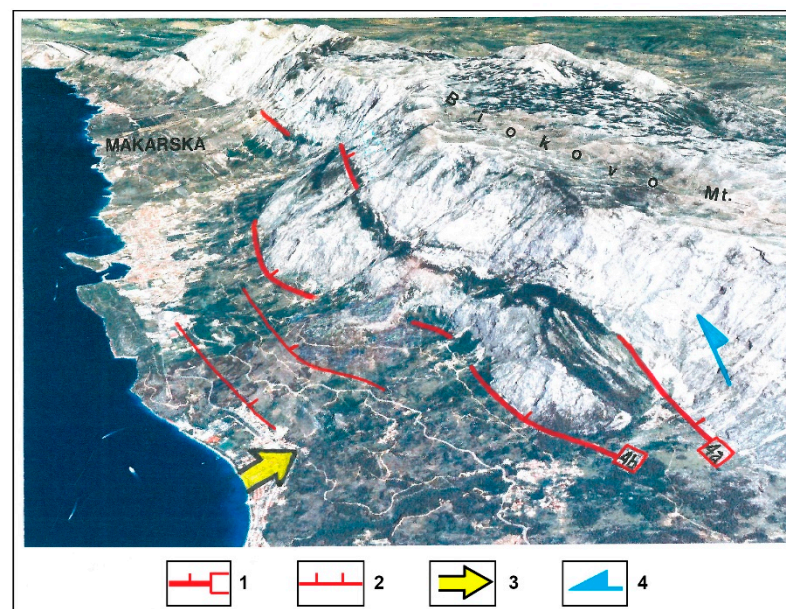


Figure 9. Mosor-Biokovo-Dubrovnik fault zone (4a,b), its branches, and steep relief of Biokovo near Makarska, caused by compression in the contact area of regional structural units and reverse shifts in hanging wall of fault (Google Earth). Legend: 1—Mosor-Biokovo-Dubrovnik fault (4a,b); 2—fault branches; 3—basic direction of movement of parts of the Adriatic regional structural unit based on geodetic data; 4—the reverse movement of the hanging wall of the Mosor-Biokovo-Dubrovnik fault (4a,b).

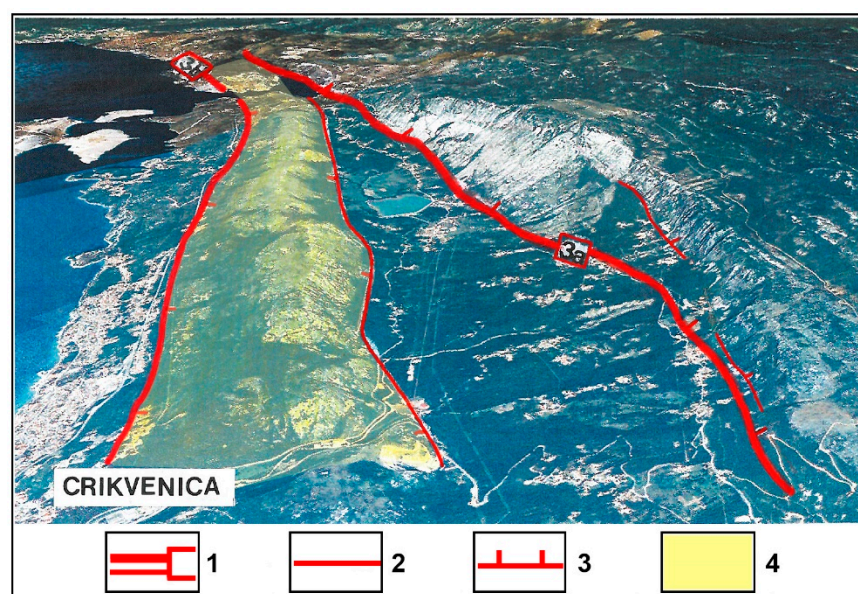


Figure 10. Local reverse structure in Crikvenica area due to compression in the contact area of regional structural units (Google Earth). Legend: 1—Major Ilirska Bistrica–Rijeka fault (3a) and its main branch (3b); 2—other faults in the wider zone; 3—reverse faults; and 4—local elevated structure with reverse faults of opposite vergence along their walls.

Earthquake events always highlight the recent tectonic activity. Notably different is the relatively wide contact between the Adriatic (A) and Dinaric (D) regional structural units. An example of the profile of the seismotectonically active area around Rijeka is shown in Figure 7b. The earthquake focuses reveal the positions of deep faults. These faults are obliquely inclined, and the earthquake focuses reach a depth of 30 km. The same depths were recorded in other places such as Dubrovnik. The Paleozoic rocks in the Ilirska Bistrica–Rijeka–Vinodol fault zone (3) show shifts of several kilometers.

It is necessary to look at the regional area shown in Figure 11 to observe the tectonic activity in the western part of the Pannonian Basin (WPB).

The origins of the tectonic activity in the separated regional area are the movements of the AMP. They show extreme compression in the Southern Alps (SA) and the northern part of the Dinarides (D unit). The regional deformations may result from the reversal movements of the Alps and Dinarides and their transcurrent movements. The WPB and Sava fault (SF) are partially in an enclosed position between the Alps and Dinarides. The consequence is the transpression of space and formation of compression structures in the NNE–SSW and NE–SW directions, along with the rightward tectonic transport. Geological data show the prevalence of the horizontal component of the fault wall movement around Ljubljana and especially along the Periadriatic fault (9) and its branches. Geodetic data also confirm the generally eastward movements at the PTUJ, DONA, and ZABO points. The movement directions of the geodetic points around Ljubljana toward the NNE and NNW indicate the rotation of the Sava fault (SF) structures caused by horizontal movements in the Ljubljana–Karlovac–Slunj (5) fault zone. Tectonic movements are constantly followed by the occurrence of earthquakes (Figure 11b). In particular, the seismotectonically active area is the Žumberak–Medvednica structural unit, which encompasses the most important Zagreb fault (8) and the local structures at Varaždin, along which the Periadriatic fault (9) continues to the Drava fault (9 in Figure 12).

In the SPB, the structures are extended in the WNW–ESE direction (Figure 12). The Sava (14) and Drava Basins (16) are dominant in the geological structure setting, filled with Neogene–Quaternary sediments. Reverse faults with opposite vergences extend along their boundaries, with elevated smaller structural units between them. Reverse faults along their walls indicate the presence of space compression. The units are constructed mostly

of Paleozoic granite, gneiss, and metamorphic rocks of higher density, with quaternary sediments, found only on the surface at Bilogora (13).

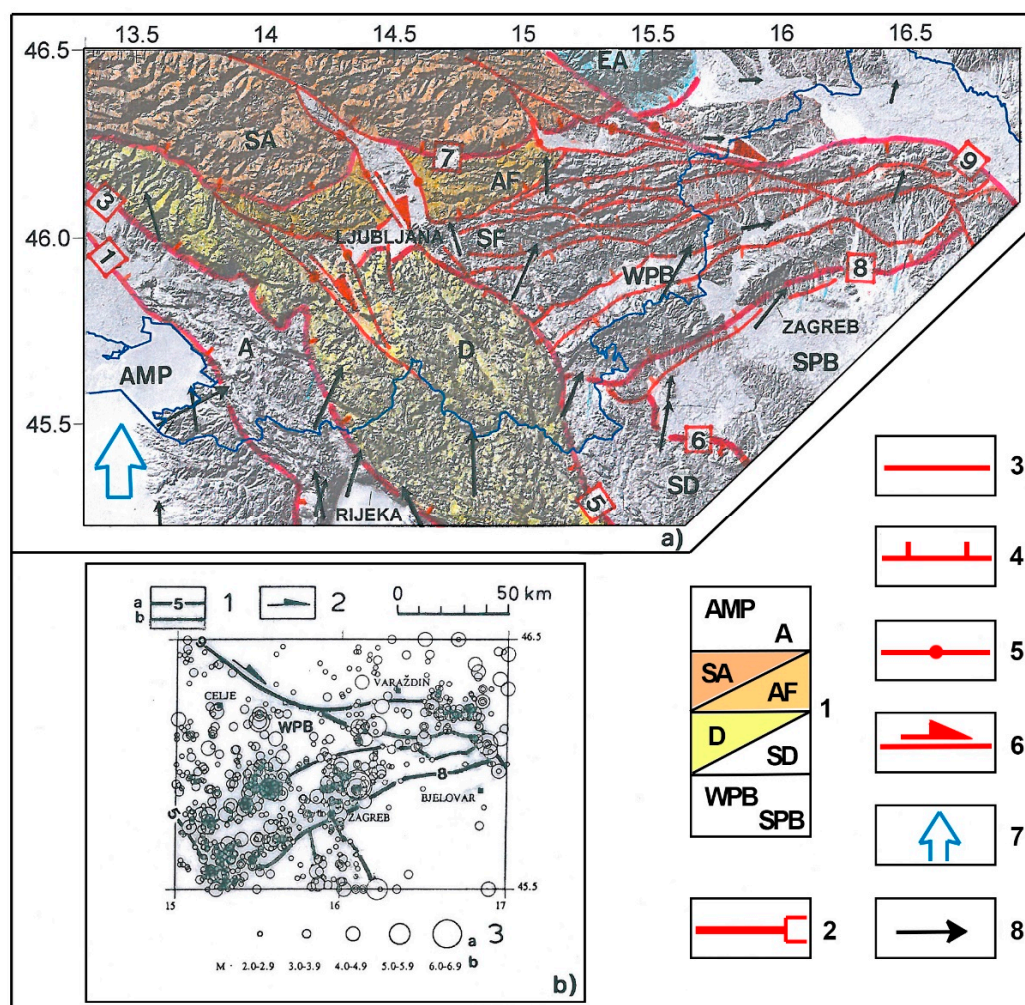


Figure 11. (a) Recent geological structural setting and tectonic activity in the contact area of Adriatic microplate, Alps, Dinarides, and Pannonian Basin. Legend: 1—Regional geological structural units: a—Adriatic microplate (AMP) and Adriatic (A) unit, b—Southern Alps (SA), Eastern Alps (EA), Prealps (AF) and Sava faults (SF), c—Dinarides, and Dinarik (D) and Supradinarik (SD) units, d—Pannonian Basin: Western (WPB) and Southern (SPB); 2—major faults adjacent to regional structural units: Trieste-Učka-Vis fault (1), Ilirska Bistrica-Rijeka-Vinodol fault (3), Fella-Sava fault and continuation of Ljubljana-Karlovac-Slunj (5), southern boundary fault of Pannonian Basin (6), SA fault (7), Zagreb fault (8), Periadriatic fault and continuation of Drava fault (9); 3—other important faults; 4—reverse faults; 5—faults of indeterminate character; 6—the direction of horizontal movement along the fault; 7—movement direction of the Adriatic microplate (AMP); 8—direction of annual velocity at geodetic points in mm/yr. (b) Seismic activity: 1a—major faults: Ljubljana-Karlovac-Slunj fault (5), Zagreb fault (8), Periadriatic fault and continuation of Drava fault (9); 1b—other important faults bordering seismotectonically most active structural units in the western part of the Pannonian basin (WPB); 2—the direction of horizontal movement along the fault; 3—earthquake epicentres (a) and earthquake magnitudes (b).

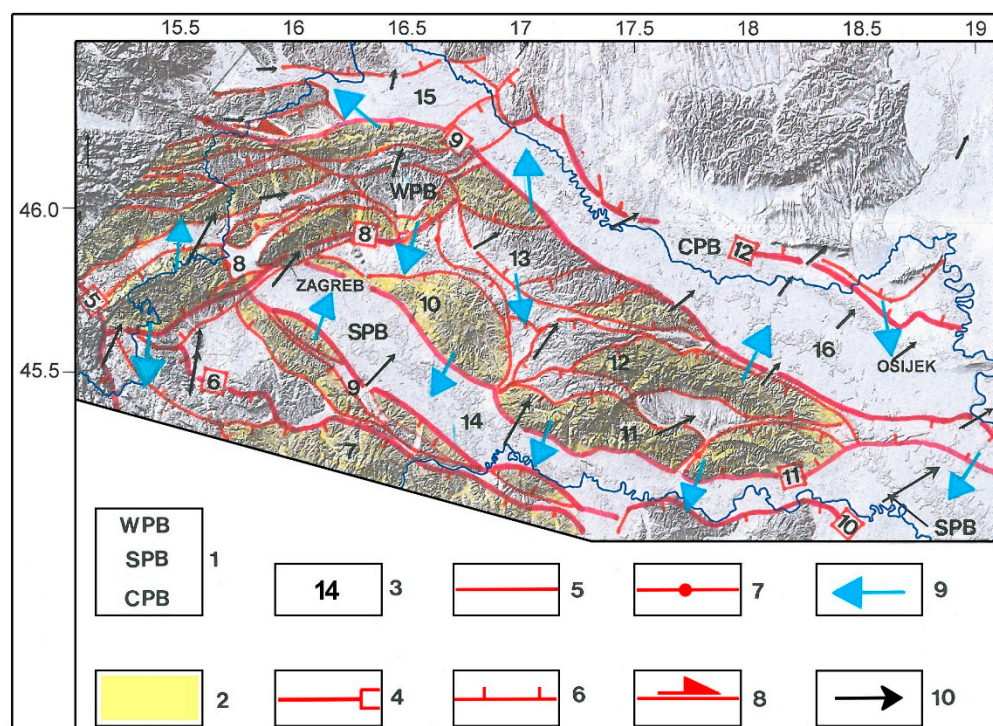


Figure 12. Recent geological structural setting and tectonic activity in the area of the Pannonian Basin. Legend: 1—Regional geological structural units: Pannonian Basin: Western (WPB), Southern (SPB), and Central (CPB); 2—the most prominent structural units within the regional geological structural units along whose wings are reverse faults of opposite vergence: Petrova gora–Kozara (7), Žumberak–Medvednica (8), Vukomeričke gorice–Šamarica (9), Moslavačka gora (10), Psunj–Dilj gora (11), Papuk (12), and Bilogora (13); 3—large basins: Sava (14), Mura (15), and Drava (16); 4—major faults adjacent to regional structural units and the Sava and Drava Basins: the southern boundary fault of the Pannonian Basin, Zagreb fault (8), Periadriatic fault and continuation of the Drava fault (9), Sava fault (10), Zagreb–Vinkovci fault (11), and Barcs–Baranja fault (12); 5—other important faults; 6—reverse faults; 7—faults of indeterminate character; 8—direction of horizontal movement along the fault; 9—direction of movement of parts of structures along the surface according to geological data; 10—direction of annual velocity at geodetic points in mm/yr.

Two observations should be noted. First, the inclination angles of the velocity directions determined at the geodetic stations shown in Figure 3 are notable. In the Drava Basin (16), the eastern part of the Sava Basin (14), and the central part between the elevated structural units, the velocity directions (inclinations) are almost horizontal. In the zones of the Drava fault (9), Zagreb–Vinkovci fault (11), and especially the Barcs–Baranja fault (12), there are elevations with angles greater than 30° and 60°. This points to tectonically active fault sections and the elevation of structures.

Furthermore, reverse movements along the Zagreb–Vinkovci fault (11), mostly toward the SW, are signs of resistance to the regional tectonic movements identified at the geodetic points. This indicates space compression. However, in the Sava fault (10) and especially along the Drava fault (9), the directions of the geological and geodetic movements are identical. This shows the contact of rocks with different densities. This is the case when there are primary reverse movements and a sudden sloping elevation of higher density rocks toward the surface. They then coincide with the regional directions of the tectonic movements.

An example is the seismic reflex profile over Bilogora (13) shown in Figure 13. The position of the Paleozoic rocks at depth is essential. There is a noticeable and gradual reverse in the rise of the rocks toward the NE. In the zone of the Drava fault (9a,b), this is followed by an abrupt discontinuance and lowering of the rocks in depth.

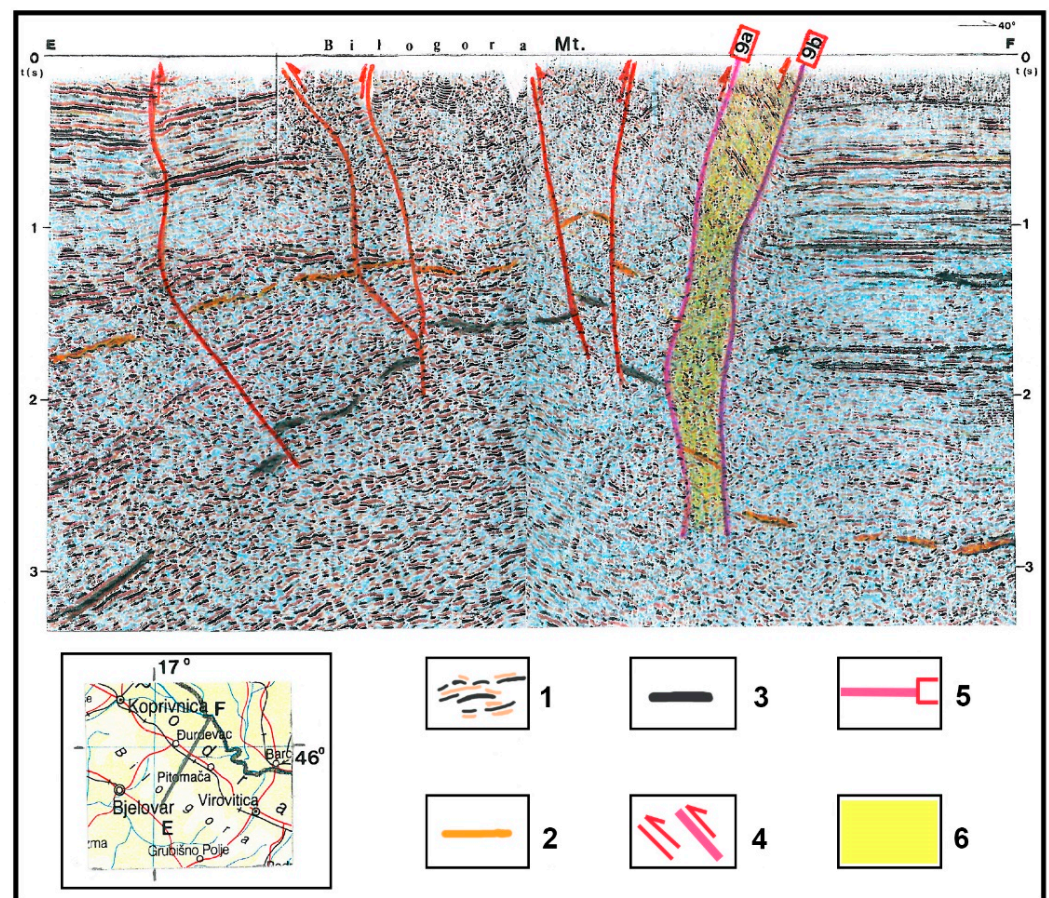


Figure 13. Seismic reflection profile of Bilogora. Legend: 1—Seismic reflexes of rocks in depth; 2—footwall surface of Neogene rocks; 3—the probable footwall surface of Paleozoic rocks; 4—faults indicating the movement of hanging wall; 5—Drava fault (9) borders the central and southern parts of the Pannonian Basin; 6—Drava fault zone (9a,b).

5. Conclusions

GNSS measurements at 83 stations (geodynamic and reference stations of GNSS POSs) distributed over the territory of the Republic of Croatia and neighbouring countries for a period of almost 20 years (1994–2013) were collected and processed in the scientific software Bernese 5.0 for the central epoch on 15 January 2004 (e 2004.04), which resulted in a unique database of the relative velocities for all 83 stations.

The obtained data represent the directions of the recent movement of parts of the geological structures caused by tectonic movements. The amplitudes and angles of the movements shown in this paper point to the tectonically most active areas in the Republic of Croatia. The most crucial task was comparing this geodetic data to previously acquired geological data to observe the present tectonic dynamics of the geological structural setting and determine the causes of the obtained movement directions. Initial are the movements of the Adriatic microplate (AMP). The data indicated the existence of southern and northern parts of the microplate. Each part moves with a retrograde rotation toward the NNE and NE, and in Istria towards N. In the Southern Alps, the compression of space is emphasized, but also the deformation of structures towards E and ESE. The movements also affect the deformations of the northern part of the Dinarides and create the structure of the E–W direction, but NE–SW direction in the Pre-Alps, Sava faults and the marginal, western part of the Pannonian Basin NW of Zagreb. In the Dinarides, complexes of higher density rocks that build the geological structures in depth resist these movements. This results in the compression of space and elevation of structures along whose walls reverse faults stretch. Of primary importance are the reverse movements with vergences toward the SW and S. It

was emphasized that the directions of the structure movements in the broader part of the geological structural setting are the opposite to the directions of the calculated velocities at geodetic points. It is evident that they represent a direct reaction to the initial movements of the AMP. Changes in the movement direction obtained using the geodetic and geological data were also noted. They point to the rotation of particular geological structures or even parts of the structural setting.

In the elaboration of the collected data, a comparison was made with the present seismotectonic activity and the elaboration of structural relationships in depth.

Primarily, the relations between the regional Adriatic (A) and Dinaric (D) structural units, especially around Rijeka and between Split and Dubrovnik, were emphasized. The compression of the space is especially pronounced around Dubrovnik, where the largest amplitudes of movements were recorded on geodetic measurement points. The border area of the western part of the Pannonian Basin (WPB) and zone of the most important faults of the recent structural setting was depicted.

The current research in this project includes the completely new processing of the gathered continuous GNSS data from the CROPOS stations for the period from 2009 to 2019 and their combination with the InSAR data from the Sentinel missions. This should give us insight into the recent and more detailed picture of the geodynamic processes in the research area.

Author Contributions: Conceptualization, A.Đ., M.P., M.M.; methodology, A.Đ., M.P., M.M.; validation, M.P., A.Đ. and M.M.; formal analysis, M.P., A.Đ., M.M.; investigation, M.P., A.Đ., M.M.; resources, M.M., B.P., A.Đ., M.P.; data curation, M.P., M.M., A.Đ.; writing—original draft preparation, A.Đ., M.P.; writing—review and editing, A.Đ., M.P., M.M., B.P.; visualization, M.P., A.Đ.; supervision, B.P.; project administration, B.P., M.M.; funding acquisition, B.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been fully supported by the Croatian Science Foundation under project No. IP-01-2018-8944.

Acknowledgments: Hereby: we would like to thank our dear friend and colleague, Eduard Prelogović, who has unselfishly helped with his immense knowledge and experience while researching and writing this article.

Conflicts of Interest: The authors declare no conflict of interest.

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