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Izvorni znanstveni članak

THE STRUCTURAL FABRIC AND SEISMOTECTONIC ACTIVITY OF NORTHERN VELEBIT: SOME NEW OBSERVATIONS

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A permanent seismotectonic activity is present in the region of northern Velebit. Through history a number of earthquakes magnitudes of VIII° and IX° MCS are reported. In this century the most powerful earthquake of a magnitude of 5.8 occurred in 1916. The key tectonic movements that cause these earthquakes are dislocations of the Adriatic platform towards the north and the resistance of the Dinarides towards these movements. The tectonic dynamics of a structural arrangement depend on the relationship between stress and the deformation of structural units. According to the tectonic measurements performed on outcrops of major faults the following orientation of stress was obtained; from 20/25° to 200/205° in the northern Velebit region and 340 to 160° in the hinterland. Within the structural arrangement compression of space occurs which is well pronounced in the Novi Vinodolski area. Possible deformation of structures is manifested spatial diagonal reverse displacements accompanied by rotation of the structure. In the Velebit hinterland right horizontal tectonic transport was determined. In the zone of the transcurrent fault Žuta Lokva–Otočac–Bunić the spatial opening leads to the formation of pull-apart structures. Seismotectonically active zones occur in the contact region between the Adriatic platform and the Dinarides. Spatially its position is inclined and bent.

Ključne riječi: Potresi, Tektonski pokreti, Stres, Pomaci struktura, Seizmotektonski aktivna zona

U području sjevernog Velebita stalno je prisutna seizmotektonska aktivnost. U povijesti se više puta spominju potresi intenziteta VIIo i IXo MCS. U ovom stoljeću najjači potres dogodio se 1916. godine magnitude 5,8. Ključni tektonski pokreti koji uzrokuju pojavljivanje potresa jesu pomaci Jadranske platforme prema sjeveru i odupiranje Dinarida tim pomacima. Tektonska dinamika strukturnog sklopa ovisi o odnosu stresa i deformacija strukturnih jedinica. Prema podacima terenskog mjerenja u izdancima najvažnijih rasjeda dobivena je orijentacija stresa: u sjevernom Velebitu 20/25o–200/205o i u zaleđu 340–160o. U strukturnom sklopu nastaje kompresija prostora osobito izražena oko Novog Vinodolskog. Moguće deformacije struktura jesu dijagonalni reversni pomaci u prostoru uz rotaciju struktura. U zaleđu sjevernog Velebita utvrđen je desni horizontalni tektonski transport. U zoni transkurentnog rasjeda Žuta Lokva–Otočac–Bunić otvaranjem prostora oblikuju se strukture tipa pull-apart. Seizmotektonski aktivna zona pojavljuje se u prostoru dodira Jadranske platforme i Dinarida. Značajan je njezin kosi položaj u prostoru uz koncentraciju žarišta resa na dubinama do 34 km.

Introduction

Northern Velebit and its proximate hinterland are situated on the edge a seismotectonically active zone that extends through Vinodol and Rijeka towards Friuli. New earthquake data enabled determination of regions with concentrated earthquake focus points. These indicate active zones that can be linked to geological structures. Therefore detailed structural and geological mapping was undertaken in zones of major faults within the structural arrangement. The aim of these investigations was to determine the relationship between stress and the deformation of structures and to obtain data about the tectonically active faults on the surface. The earthquakes are a confirmation of recent tectonic activity. Therefore it is necessary to present the dynamics of the studied structures and its connection with earthquake activity. To obtain the necessary data about the seismotectonic activity, relevant information from previous studies was taken into account. The most comprehensive data on surface geology can be extracted from the Basic Geological Map, sheets Crikvenica (Šušnjar et al., 1970), Rab (Mamužić, et al., (1969) and Otočac (Velić et al., 1974). Also important data is found in the papers that deal with subsurface structural relationships, landscape formation, tectonic movements and regional structural classifications (exp. Aljinović et al., 1987; Labaš, 1987; Skoko et al., 1987; Prelogović, 1989; Blašković, 1990, 1991; Herak, 1991; Faivre, 1992; Prelogović et al., 1981, 1995). Spatial attention was focused on the utilization of data on seismotectonic activity and the stress regime (Ritsema, 1974; Grünthal and Strormeyer, 1986; Anderson and Jackson, 1987; Jamičić et al., 1995; Bada and Horvath, 1998). And finally earthquake data was used from the archive of the Geophysical department »Andrija Mohorovičić« and the latest earthquake catalogue (Herak M. et al., 1996). From all this data it was possible to outline spatial seismotectonically active zones in studied region.

Tectonic movements and earthquakes

There is a high concentration zone of earthquake epicenters that extends approximately from Starigrad through Senj and Vinodol towards Rijeka. A projection of the active zone which can be as wide as 30 km is presented on Fig. 1. There are also historic recordings on earthquake occurrences. The most powerful earthquakes are recorded, especially those of the intensity of VIII° and IX° MCS with epicenters near Rijeka (in 1721 and 1750) and Senj (in 1648 and 1873) The most intensive earthquake in this century occurred near Novi Vinodolski in 1916. The magnitude of the earthquake was 5.8 of the Richter scale. Also earthquakes of 5.2 magnitude (1916) and 5.1 magnitude (1925) were recorded at Novi Vinodolski. To comprehend the frequency of earthquake occurrences it is necessary to refer to the following occurences (Richter scale):

- 1918. Senj, 4.4 magnitude;
- 1925. Bribir in the Vinodol valley, 5.0 magnitude;
- 1926. off the Novi Vinodolski shore, 4.7 magnitude;
- 1939. Dobrinj on the island of Krk, 4.9 magnitude;
- 1494. Starigrad, 5.3 magnitude;
- 1951. island Prvić, 4.5 magnitude;
- 1986. off the Novi Vinodolski shore, 4.7 magnitude.

Apart form the above mentioned earthquakes, a relatively large number of earthquakes of smaller magnitude occurred during this century. This frequency of earth-

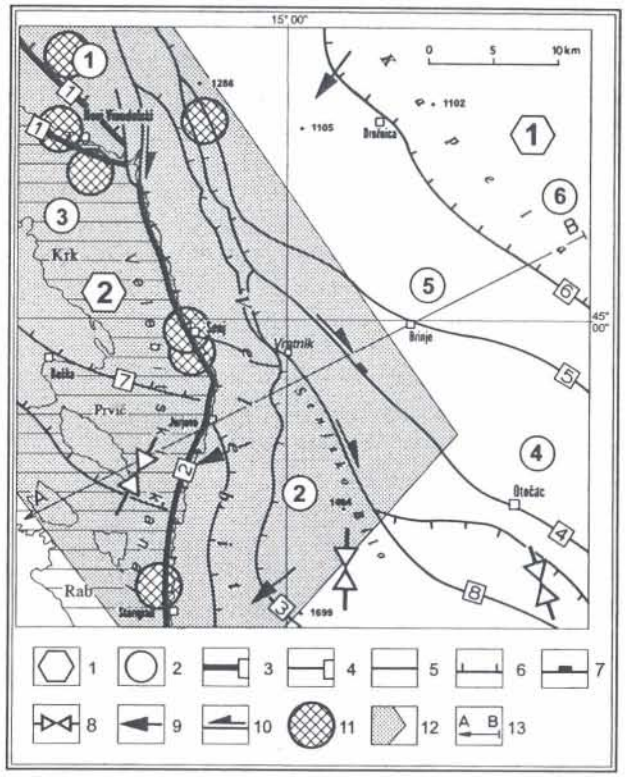

Fig. 1. Structural framework and seismotectonic active zones

Legend

A. Structures. **1. regional structural zones.** Dinaricum (1), Adriaticum (2); **2. structural units:** Dinaric (1), Adriatic (2); **2 – structural units:** Tuhobić–Kobiljak (1), Sjeverni Velebit (2), Rijeka–Krk (3), Gacka (4), Drežnica–Jezerane (5), Velika and Mala Kapela (6);

B. Faults: **3. the most important faults of seismotectonic framework, bordering regional structural units:** Ilirska Bistrica–Rijeka–Vinodol (1), Velebitski fault (2); **4. faults bordering structural units and important faults of structural framework:** fault Krivi put–Vratnik–Oltari–Alan (3), fault Žuta Lokva–Otočac–Bunić (4), fault Brinje–Vrhovine (5), fault of Velika and Mala Kapela (6), fault Rijeka–Omišalj–Baška (7), fault Senjsko Bilo–Kosinjkis vrh (8); **5. satellite faults and faults delimiting the most active scismotectonic parts of structural units; 6. reverse faults; 7. normal faults;**

C. Tectonic dynamic of included area: **8. regional stress; 9. direction of movement of structures close to the surface; 10. faults with distinct horizontal displacement;**

D. The strongest carthquakes and scismotectonic active zone: **11. epicenters of strongest earthquakes in the past, magnitude 5–6; 12. projection of seismotectonic active zone on the surface; 13. seismotectonic profiles**

quake occurrences is indicative of a persisting seismotectonic activity. The key tectonic movements that are responsible for earthquake occurrence are the movement of the Adriatic platform towards the north and the resistance of the Dinaric rock mass. The spatial position and the size of different rock masses are of prime importance. These are geological structural units of different size, and for the area studied are presented in Fig 1. On the surface the structural units are outlined by faults. The role of these faults is of prime importance within the structural and seismotectonic framework. On the surface the reverse fault zone dominates at the contact with the Dinaricum (1), and it consists of: Ilirska Bistrica–Rijeka–Vinodol fault (1), and the Velebit fault (2). In the hinterland of the Dinaricum (1) four fault zones are distinguished, which fan out and have a SE strike. These faults are as follows: Krivi Put–Vratnik–Oltari–Alan fault (3), Žuta Lokva–Otočac–Bunić fault (4), Brinje–Vrhovine fault (5) and Senjsko Bilo–Kosinjski Vrh fault (8). Due to recent tectonic movements it was necessary to perform structural analyses of these faults as well as other faults present within the structural units. It was necessary to determine the position of the fault within the structure, to isolate the most active sections, and the amount of displacement of blocks or units within the structure that are positioned between fault zones.

In the broader area around Senj, Jurjevo and Vratnik and also between Žuta Lokva and Otočac, 80 outcrops where found where the essential structural elements where measured. Folds and faults where studied and analyzed. The faults were classified according to type, importance within the structure, and origin. The relationship of the paraclase and the surrounding rocks was determined. Also it was important to determine the direction of tectonic transport which is a consequence of stress and structural deformation. The orientation of local stress together with the stress within the structural units enabled the determination of most active fault sections and the movement direction of structures at the surface.

The following features characterize the Velebit fault (2): It is parallel to the shore line, the zone boundary fault lies beneath the sea, near Jurjevo diverge faults occur and the zone expands abruptly. At the observation points the orientation of the faults within the zone was measured. The inclination direction varies and has an orientation from 40° to 120°, with dip angles between 45° and 76°. In most cases right tectonic transport was observed with angles between 30° and 40° in relation to the horizontal plane. The average direction of structure displacement in the Senj area is 160°. Between Jurjevo and Starigrad the average direction of structure displacement is towards the SW (235°). It is important to stress that the Velebit fault zone (2) consists of numerous faults of different inclination and character as a consequence of fault bending. The Krivi Put–Vratnik–Oltari–Alan fault (3) is parallel to the Velebit fault (1) and is probably its branch. The measurements performed at Vratnik give an average dip angle of 60° and right tectonic transport. The direction of the hanging wall displacement is towards the SW (248°).

Very interesting data was obtained from the Velebit hinterland. The Žuta Lokva–Otočac–Bunić fault is shown on Fig. 2. Near Brlog a fault diverges from the main zone and extends through Drenovac klanac. The faults between Žuta Lokva and Otočac are normal with steep inclination angles between 75° and 88°. The right, almost horizontal tectonic transport was determined in a majority of cases. The measured angles in relation to the horizontal plane do not exceed 20°.

The horizontal tectonic transport within the studied fault zone causes spatial opening and the formation of pull-apart structures. The horizontal displacement near Brlog and Kompolje measures from 2 to 3 km. The Hrvatsko polje structure developed along the boundary of the main fault zone Žuta Lokva–Otočac–Bunić (4).

From the data presented the orientation of regional stress was calculated. In the coastal area between Senj and Starigrad the approximate orientation is 20/25°–200/205°. In the hinterland between Žuta Lokva and Otočac the direction 340–160° dominates. The local stress around Žuta Lokva and Kompolje has an orientation of 320/340°–140/160°. The fault zone Žuta Lokva–Otočac–Bunić (4) is very favorably positioned towards the stress, which has as a consequence marked right horizontal tectonic transport. It is appropriate to outline

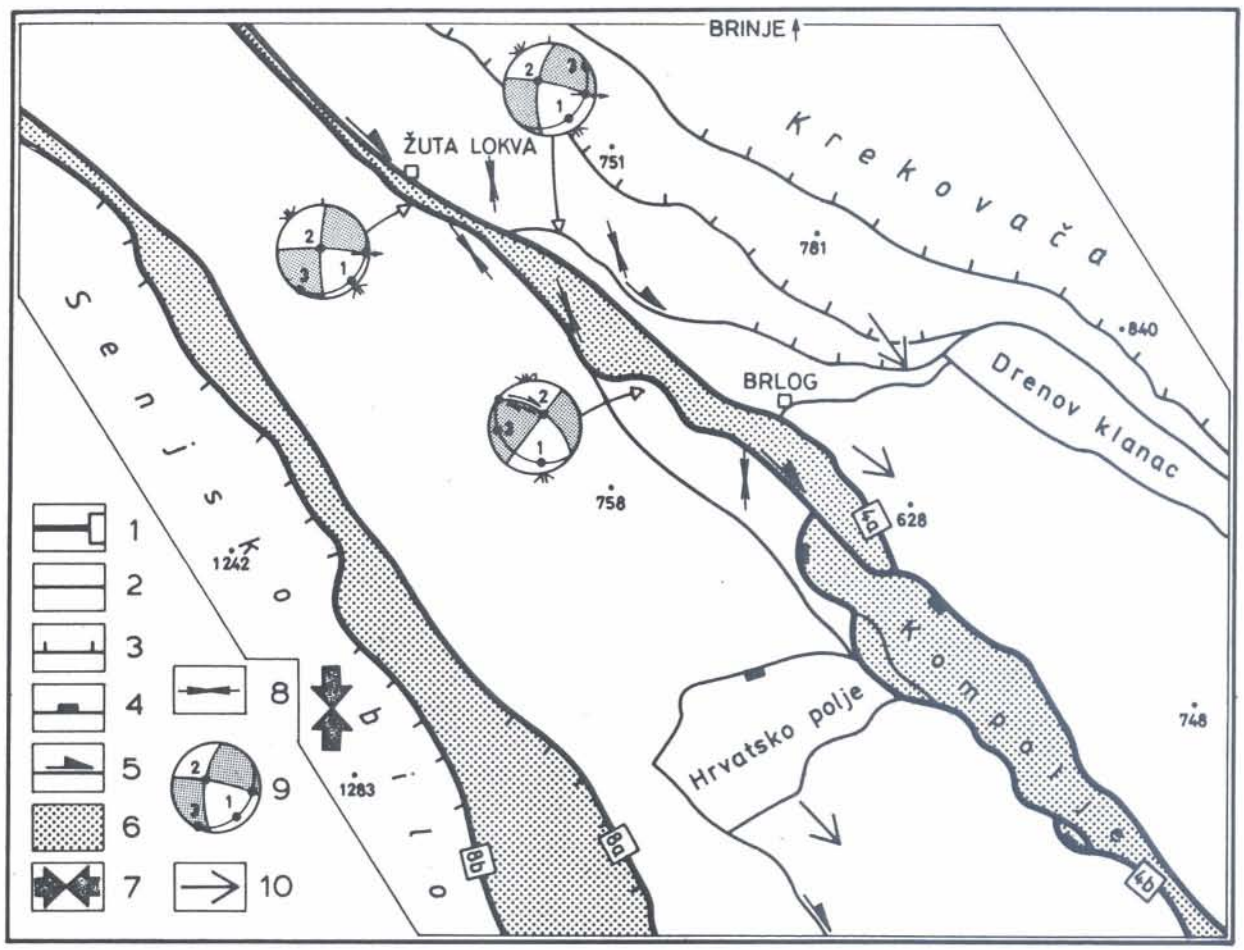

Fig. 2. Zone of faults Žuta Lokva–Otočac–Bunić

Legend
A. Faults: **1 – faults bordering structural units, the most important in seismotectonic framework:** fault Žuta Lokva–Otočac–Bunić (4, a and b – marginal faults of zone); fault Senjsko Bilo–Kosinjski Vrh; **2 – faults bordering structures, branches of the most important zones and important local faults; 3 – reverse faults; 4 – normal faults; 5 – faults with marked horizontal displacement; 6 – important zones of fault;**
B. Stress, displacements of structures: **7 – regional stress; 8 – local stress; 9 – field of local compression and extension; 10 – direction of displacement of structures close to the surface**

some data about the older phases of tectonic activity here. For example at outcrops near Žuta Lokva the major fault Žuta Lokva–Otočac–Bunić (4) indicates reverse tectonic transport at an angle of 70° in relation to the horizontal plane. Also the change in stress orientation is observed. During younger and recent phases the local stress direction has moved 15 to 20° from the north towards the west in comparison with the orientation of stress in older active phases.

Conclusion

The presented surface fault features and displacement of parts of structural units are a consequence of tectonic movements. Due to the movement of the Adriatic platform at the boundary with the Dinarides compression occurs along a spatially inclined zone. Within this zone a high concentration of earthquakes is present (Fig. 3). The inclined position indicates the existence of reverse type of structural relationships. The earthquake epicenters can also be found dislocated along lesser fault zones. These lesser fault zones are often further connected with major fault zones on the surface. It is obvious that the zone that connects with the Velebit fault (2) also in part covers other zones. The most prominent feature is the spatial bending of zones with depth from very inclined, through slightly inclined to almost horizontal at greater depths. The Žuta Lokva–Otočac–Bunić fault is a branch of a distinct seismotectonically active zone which links with the Velebit fault (2).

In order to define the tectonic dynamics of a structure it is necessary to define the orientation of stress. The unfavorable, almost perpendicular stress orientation in relation to the strike of structural units, results in spatial compression and a concentrated occurrence of earthquakes. This is most pronounced in the area around Novi Vinodolski. Away from the main compression zone in the studied area, right transcurrent displacements along faults or tectonic transport of structural units can occur. This is the major feature in the fault zone Žuta Lokva–Otočac–Bunić (4).

Due to its position in relation to the major compression zone and the zones of transcurrent displacement parts of northern Velebit are rotated. In the studied area movements in the occur towards the SW diagonally in relation to the strike of the structures. Seismotectonic

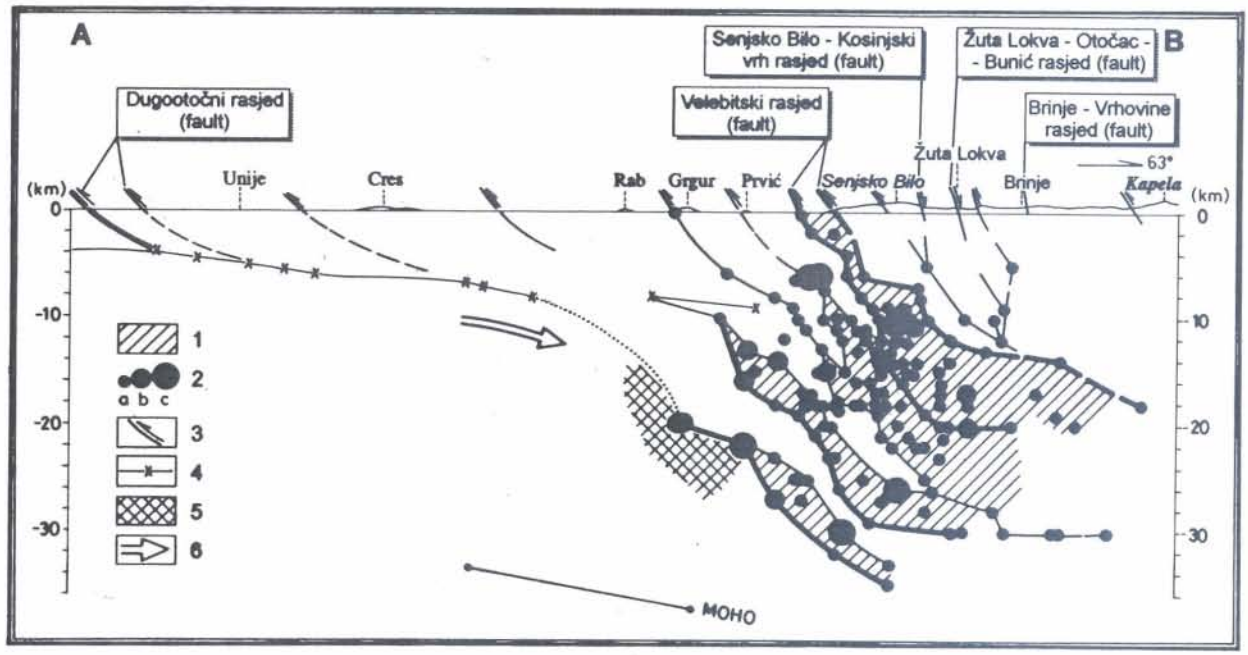

Fig. 3. Seismotectonic profile

Legend
1 – seismotectonic active zone; 2 – earthquakes epicenters with magnitudes: a) <4.0, b) 4.1–5.0, c) 5.1–6.0; 3 – faults; 4 – base of carbonate rocks; 5 – zone of higher gravimetric gradients; 6 – direction of displacement of Adriatic platform

activity is enhanced in the direction of Novi Vinodolski which is the area of maximum compression.

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