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The earthquake of 12 April 1998 in the Krn Mountains (Upper Soča valley, Slovenia) and its seismotectonic characteristics

Potres 12. aprila 1998 v Krnskem pogorju (Zgornje Posočje, Slovenija) in njegove seizmotektonske značilnosti

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Abstract

The earthquake on 12 April 1998 at 10h 55min UTC (12h 55min local daylight-saving time) in the Krn mountains was according to its magnitude (m_b=5.3, M_m=5.3, M_{LV}=5.6, M_w=5.6, M_S=5.7, M_{WA}=6.0) among the strongest in Slovenia in the 20th century. Its epicentre was situated about 8 km south-east from the town of Bovec and its hypocentral depth was 7.6 km. The maximum intensity VII-VIII EMS-98 was observed in four villages. Mainly older buildings, built of rubble and simple stone, were damaged. A temporary network of portable stations deployed immediately after the earthquake has recorded more than 7000 aftershocks. From the earthquake mechanism and the distribution of the aftershock foci, we conclude that the main shock has happened on the dextral strike-slip subvertical fault striking NW-SE. The fault rupture dimensions were approximately 10 km x 7 km; however, no evidence of a surface rupture was found. The seismotectonic analysis of the region is based on the field observations and analysis of aerial photographs, the distribution of aftershocks and the depth distribution of focal mechanisms. These data reveal that recent tectonic activity in western Slovenia is connected to strike-slip faults in NW-SE direction as well as to thrusting along the Southalpine thrust front and parallel thrust planes.

Izvleček

Potres 12. aprila 1998 ob 10. uri in 55 minut po svetovnem času (oz. 12. uri 55 minut po lokalnem poletnem času) z žariščem v Krnskem pogorju je bil po magnitudi (m_b=5,3, M_m=5,3, M_{LV}=5,6, M_w=5,6, M_S=5,7, M_{WA}=6,0) eden od najmočnejših potresov z nadžariščem v Sloveniji v dvajsetem stoletju. Nadžarišče potresa je bilo približno 8 km jugovzhodno od Bovca, žariščna globina potresa pa je bila 7,6 km. Na podlagi žariščnega mehanizma in razporeditve žarišč popotresov sklepamo, da se je glavni potres zgodil ob subvertikalnem prelomu v smeri SZ-JV, ki ima značaj desnega zmičnega preloma. Pretrg v globini, velikosti 10 km x 7 km, ni dosegel površine, saj na površinskih izdankih preloma v domnevni seizmogeni coni ni znakov koseizmičnega premika. Potres je dosegel največje učinke (VII-VIII EMS-98) v štirih krajih. Poškodovani so bili predvsem starejši objekti, grajeni iz obdelanega in neobdelanega kamna. Začasna mreža prenosnih potresnih opazovalnic je zabeležila več kot 7000 popotresov. Seizmotektonski model raziskanega območja je narejen na podlagi terenskih opazovanj ter analize letalskih posnetkov, prostorske porazdelitve popotresov in žariščnih mehanizmov. Na podlagi tega sklepamo, da je tektonska dejavnost na tem območju povezana z narivanjem ob Južnoalpski narivni meji in njej vzporednih narivnih ploskvah ter s premiki ob zmičnih prelomih v smeri SZ-JV.

Introduction

In the past the region of the Upper Soča valley was hit several times by damaging earthquakes, but none of the known strong events originated in the Soča valley region. Two strongest events, the 1348 Villach earthquake and the 1511 Idrija earthquake have caused significant damage in north-western Slovenia. Recent studies have shown that the first one most probably happened in Friuli, Italy (Gutdeutsch & Lenhardt, 1996). However, in the catalogue by Boschi et al. (2000), its epicentre is in the vicinity of Bovec, Slovenia. Uncertain is also the location of the 1511 earthquake. Ribarič (1979) specifies two earthquakes with epicentres near Idrija and Cividale, that happened several hours apart. In Boschi et al. (2000) there is only a single event of magnitude 6.9 with epicentre in the vicinity of Robidišče, Slovenia. These earthquakes have supposedly reached intensity X EMS-98.

In this century the strongest events were again the Friuli ones in 1976 (Ribarič, 1980, 1982, 1992, 1994a,b). Some houses, damaged in 1998, were rebuilt and retrofitted already three times in 20th century: after the World War I (as the Soča front line went just across the 1998 epicentral area, see Ovčak & Vidrih, 1999), after the World War II and again after the 1976 earthquakes.

The epicentre of the earthquake on 12 April 1998 at 10h 55m UTC was situated about 8 km south-east from the town of Bovec in an unpopulated region of the Krn mountains (URSG, 1998-99a, Živčić et al., 1999). The earthquake was also felt in nine European countries (Italy, Switzerland, Germany, Austria, Hungary, Czech Republic, Slovakia, Croatia and Bosnia and Herzegovina). The shaking was felt as far away as Milan (350 km from the epicentre), Sarajevo (450 km) and central Slovakia (500 km). The maximum intensity of the main shock was estimated to be VII-VIII EMS-98 (Cecić et al., 1999a,b). One person in Bovec died of a heart attack. The largest effects were in villages Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne, where the maximum intensity VII-VIII EMS-98 was observed. Mainly older buildings, built of rubble and simple stone, were damaged. Many effects in nature (soil and rock sliding phenomena) were observed (Vidrih & Ribičič, 1999a,b). The highest density of the soil and rock sliding phenomena occurred in fractured fault zones, along fault planes, cracks or bedding. Spatial distribution of major rockfalls is mostly limited to the Krn mountains following the NW-SE direction. The biggest rockfall occurred from the walls of Mt. Veliki Lemež above the Lepena valley, with the estimated volume of 15 x 10^6 m^3 (Gosar, 1999a).

The investigated territory was included in many seismotectonic and seismic hazard studies of broader region (e.g. Slejko et al., 1987, Carulli et al., 1990, Poljak et al., 2000), but very few detailed seismotectonic studies have been done before the earthquake. According to Sikošek (1982) the western part of the Idrija fault zone and parallel faults were assigned capability of generating strong earthquakes.

The aims of this paper are to summarise the results of large amount of data that were collected mainly by the Geophysical Survey of Slovenia (GSS) and to consider the Krn Mountains earthquake within its seismotectonic context. The seismotectonics of the region is based on the field observations and analysis of aerial photographs and the distribution of aftershocks. A new model of seismotectonic setting of this region is presented.

Main event

The main shock occurred on 12 April 1998, at 10h 55m 32.9s UTC (12h 55m 32.9s local time) and was well recorded on seismographs all around the world. At the time of the main shock there were no seismic stations in the nearest vicinity. The nearest station was in Italy, approximately 16 km SW from the epicentre, the nearest station in Slovenia in Vojsko near Idrija. Hypocentral parameters were computed using adapted joint hypocentre determination method (Bajc et al., 1999) based on one-dimensional isotropic velocity model. That method reduces the effects of nonhomogeneities and anisotropy in the Earth that hinder precise hypocentral locations especially in cases where there are no stations close to the epicentre. The hypocentral co-ordinates are 46.309° N, 13.632° E and its depth 7.6 km. The estimated error for the origin time is 0.2 s and for the location 1 km.

From the unclipped vertical component waveforms of four permanent stations of the Slovenian seismic network, the local magnitude $M_{LV}=5.6$ was determined. Wood-Anderson magnitude $M_{WA}=6.0$ was determined from simulated digital seismograms from three stations in Slovenia. United States National Earthquake Information Centre has determined mean values of surface and body wave magnitudes from the global network of seismic stations: $M_S=5.7$ from 71 observations and $m_b=5.3$ from 69 observations. Moment magnitude $M_w=5.6$ was determined at the Harvard University (Harvard CMT Catalog, 1998) from 49 records. Magnitude $M_m=5.3$ was estimated from the areas affected by effects of macroseismic intensities IV, V and VI EMS-98 using the relations derived for the earthquakes in Slovenia (Živčić & Cecić, 1998; Živčić et al., 2000).

The source mechanism of the main shock was determined from the surface wave spectra and P wave polarity data using the method of Bukchin et al. (1994). The obtained results are consistent with the results obtained from the various international research organisations that compute the solutions using the data from the world-wide network of broadband stations for all stronger earthquakes. The earthquake has happened on a vertical fault striking in NW-SE direction. The movement on the fault was purely horizontal in the right-lateral sense. The size and orientation of the ruptured plane is well defined by the spatial distribution of aftershocks.

Macroseismic data

After the main shock, questionnaire forms were distributed by mail to all voluntary observers within the GSS database (more than 4300), and 68% were returned. That is quite high percentage comparing to similar surveys in Europe and elsewhere (Cecić et al., 1999a). Several field trips were made with the aim of collecting the macroseismic data in the wider epicentral area. The data on damage and other earthquake effects were collected in order to be able to evaluate the intensities by means of the European Macroseismic Scale 1998, or EMS-98 (Grünthal ed., 1998a,b). Additional data on damage were later contributed by the damage inspection commissions of the Ministry of the Environment and Spatial Planning.

Macroseismic data for more than 2000 localities were evaluated. The spatial distribution of intensities is shown on the Figures 1a and 1b. Fortunately for the inhabitants, the epicentre was situated in the uninhabited area, that explains the relatively low intensity values. The maximum intensity (VII-VIII EMS-98) was observed in villages Lepena, Magozd, Spodnje Drežniške Ravne and Tolminske Ravne (Cecić et al., 1999a, Zupančič et al., 1999). The comparison of the official seismological map for the return period of 500 years (Seizmološka karta, 1987, Tumač, 1987) with the observed intensities in the wider epicentral area has shown that the predicted values were not exceeded (Cecić, 2000).

The intensity values shown on the maps were evaluated using EMS-98 exclusively on the basis of the questionnaires, telephone calls and the data we collected in the field in April 1998. Intensities for other countries (except for Croatia and Austria, which supplied the “raw” data) were evaluated by the institutions in charge.

The most common type of building structure in the epicentral area is masonry. Older buildings are made of simple and massive stone, with wooden floors. Modern buildings are reinforced masonry with reinforced concrete floors. There are also some industrial or commercial buildings made of reinforced concrete frames or walls. There are no high-rise buildings in this area. Timber structures are rare in the Upper Soča valley, and there are also no steel structures.

More than 3000 houses were examined by civil engineers and the damage was described in detail (Godec et al., 1999). Older fieldstone and simple stone objects with wooden floors and poor quality mortar suffered damage most frequently. In some cases, the partial collapse of walls or corners of the poorly built objects has occurred. Numero-

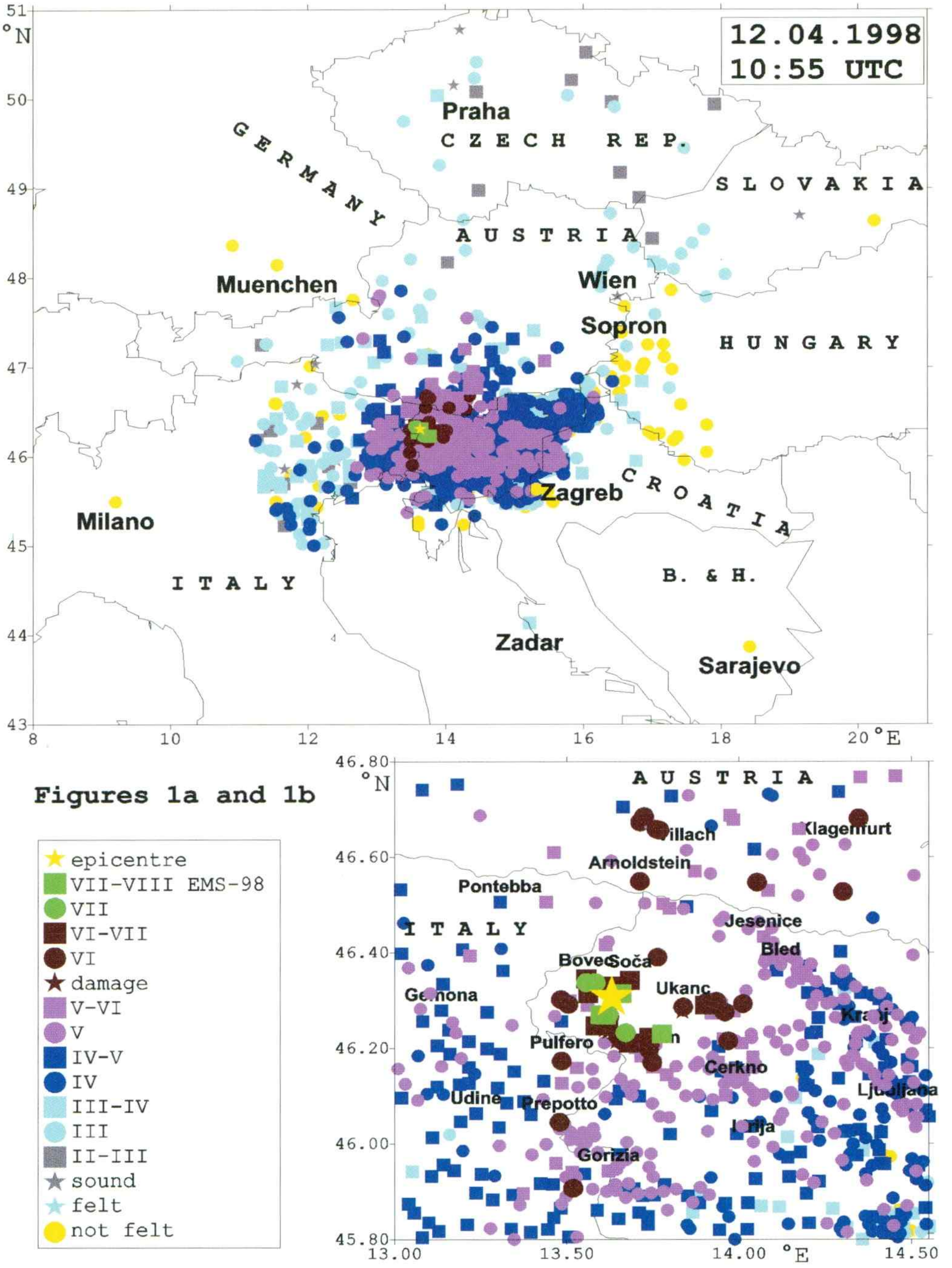


Figure 1a. Intensities of the earthquake on 12 April 1998 at 10:55 UTC.

Slika 1a. Intenzitete potresa 12. aprila 1998 ob 10. uri 55 minut UTC.

Figure 1b. Intensities of the earthquake on 12 April 1998 at 10:55 UTC in western part of Slovenia and the surrounding countries.

Slika 1b. Intenzitete, ki jih je potres 12. aprila 1998 ob 10. uri 55 minut UTC dosegel v zahodni Sloveniji in sosednjih pokrajinah.

us houses had damage on roofs and chimneys, and deep and extensive cracks in walls were often seen. Some recently built buildings were also damaged, in many cases due to unfavourable soil conditions. Sharp damage variations within short distances were among the most prominent characteristics of this earthquake. Only a minor part of this phenomenon may be attributed to different vulnerability of buildings, because the building construction is similar throughout the area. It is therefore likely that most of the variation in damage can be attributed to the amplification effects caused by local geological conditions. A very obvious case was observed in Bovec, where relatively well built new houses in a part of Bovec named Mala vas suffered higher damages compared to the predominantly old buildings in other parts of the town. Geological and geophysical investigations in this area have shown that a large part of Bovec was built on rather heterogeneous glacial (clay, debris) and glaciofluvial (sand, gravel) deposits. Nevertheless, it was not possible to simply correlate variations in damage to any prominent lithological change in the surface layer. Therefore, the effects of local geology on ground motion amplification were studied with microtremor analysis and modelling based on applied geophysical data (Gosar, 1999b). Both methods showed significantly higher amplification in the frequency range of building vulnerability (2-10 Hz) in the Mala vas than in the central part of Bovec. Similar results were observed in several other places. These findings confirmed that large differences in damage to the buildings in the Upper Soča valley could be attributed to variations in the thickness and physical properties of rather heterogeneous Quaternary deposits.

Due to many aftershocks, the damage to buildings was becoming larger over time; therefore, in numerous cases it was not possible to evaluate the damage caused by the first and strongest earthquake but only the cumulative effects of several earthquakes. Many objects had already been damaged in the 1976 Friuli earthquakes, but the retrofitting and reinforcement of the buildings had been done poorly or not at all.

Collaboration with other governmental teams that were collecting and evaluating the damage was established, but the data from the damage database were incorporated into the final version of the intensity map only for a few localities. In the processing of data from the damage database, we took into consideration only that part of the data set for buildings with house numbers. For these, we have complete records of damage, which is not the case for the remaining objects that were not numbered - those were not systematically surveyed. The deficiency of this supposition is that in the statistical processing poorly built buildings (such as stables, hay barns and other auxiliary buildings, that can be placed into vulnerability class A) are not included.

Many monuments of the World War I, that are situated in the epicentral area, were damaged as well (Ovčak & Vidrih, 1999). It has to be pointed out, however, that these are not standard objects, and are not included into EMS-98. Therefore the data on the damage could not be used for estimating the intensity.

Another characteristic consequence of the 12 April 1998 earthquake were extensive effects in natural surroundings. There were several landslides and rockslides. The largest rockslides occurred on Veliki Lemež, Osojnica, Krn and on the Kota 1776 between Vršič and Lipnik (Vidrih & Ribičič, 1999a,b).

There were a few reports of damage on buildings in other countries. An older building in Friuli, Italy was damaged. From Austria, particularly Carinthia, there were also some reports mostly about small cracks in plaster. The shaking was felt in many European countries. The average radii of the areas with the same intensity are given in Table 1. Using the method of Živčić (1984) we obtained the focal depth of 4.4 km and epicentral intensity I_0 of 8.4 EMS-98.

Table 1. Average radii of areas of the same intensity for the main shock on 12 April 1998 (in kilometres).

Preglednica 1. Povprečni polmeri območij z enako intenziteto za glavni potres 12. aprila 1998, v kilometrih.

I EMS-98	VII	VI	V	IV	III
r [km]	13	25	66	180	422

Aftershocks

Time distribution of aftershocks

The first portable seismograph station was installed 9 hours after the earthquake in Trenta. It recorded 107 aftershocks in the first 5 hours of its operation and another 234 in the following 24 hours. Two more stations were installed the day after the main shock. On 18 April additional two stations were installed in Lepena and Drežnica, in the close vicinity of the aftershock zone (S-P arrival times differences approximately 1 second and less). These stations recorded more than 7000 aftershocks till the end of 1998. Figure 2 shows the network of portable stations installed after 12 April 1998, the type of equipment and the period of operation.

The strongest aftershock with M_{LV} =4.2 occurred on 6 May 1998 (23 days after the main shock). Its hypocentre was shallower (5.1 km) and shifted 5 km to the SE as compared to the main shock (Cecić at al., 1999b).

In a year after the main shock, 303 aftershocks with local magnitude larger than 1.0 and 13 aftershocks greater than M_{LV} =3.0 were recorded. Diagram of magnitude-frequency relation with Gutenberg-Richter's function is shown in the Figure 3. The catalogue of aftershocks is complete for the M_{LV} greater than 2.0.

The modified Omori's power law (Utsu, 1962) describes the rate of occurrence of aftershocks. We applied the maximum likelihood method proposed by Ogata (1983) to estimate the parameters of Omori's law implemented in AFT program (Utsu &

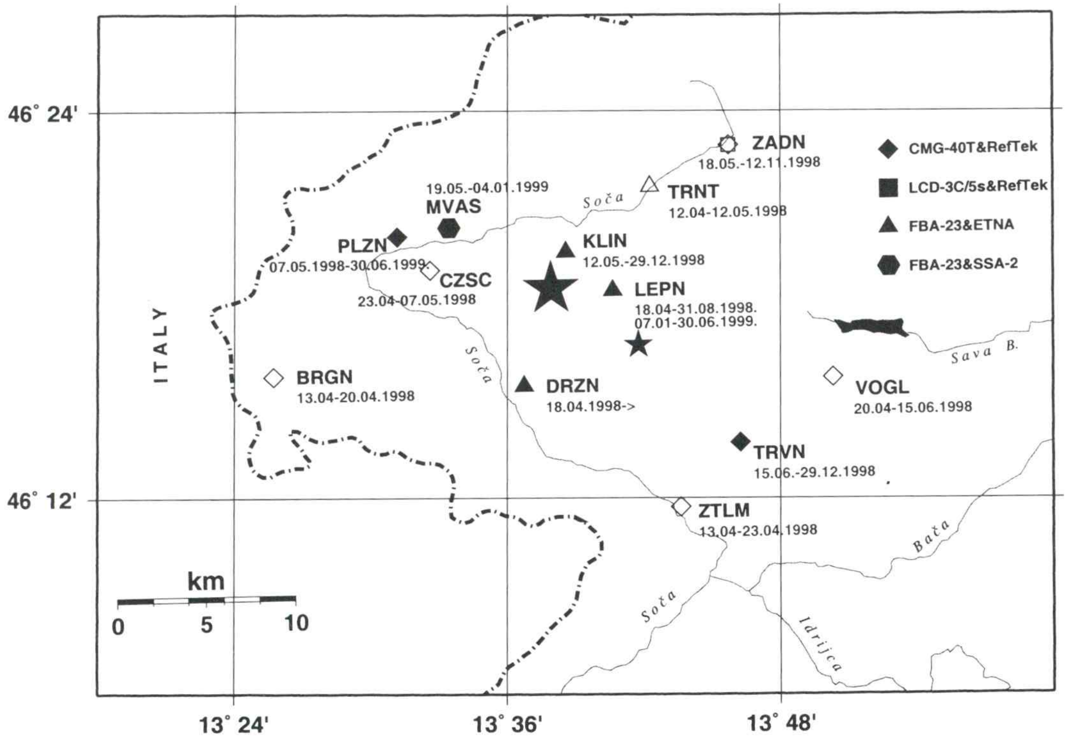


Figure 2. Locations of portable seismic stations; symbols represent type of equipment installed, dates show the period of operation. Full symbols denote stations operating simultaneously for more than 3 months. Larger star is the epicentre of the main shock and smaller one the epicentre of the strongest aftershock.

Slika 2. Lokacije prenosnih opazovalnic. Simboli kažejo tip nameščene opreme, datumi pa obdobje v katerem je opazovalnica delovala. Polni simboli označujejo opazovalnice, ki so sočasno delovale več kot tri mesece. Večja zvezda je lokacija glavnega potresa, manjša zvezda je lokacija najmočnejšega popotresa.

O g a t a , 1997). For the lower bound magnitude, 2.0 was chosen as the value of data completeness, that is clearly seen from Figure 3. The first trial with modified Omori's law has shown that it is not possible to obtain good agreement with actual data without introducing the secondary aftershock sequence starting at the time of the strongest aftershock on 6 May 1998. It is clearly seen as a "step" in the cumulative frequency diagram (Figure 4). Parameters of Gutenberg-Richter's and modified Omori's law are in good agreement with values known from literature (e.g. G o s a r et al., 1998).

Spatial distribution of aftershocks and their fault plane solutions

The hypocentral parameters of aftershocks were obtained using the adapted joint hypocentre determination method (B a j c et al., 1999), and the average estimated location error is approximately 500 m. The spatial distribution of the aftershocks, occurring till the end of September 1998 and having the largest 90% confidence ellipsoid axes smaller than 5 km, is defined. Hypocentres of the majority of the aftershocks stretch in a NW-SE elongated belt (azimuth 307°) that is approximately 10 km long and 3 km wide (Figure 5). The cross-section perpendicular to this direction (Figure 6) shows that the aftershock foci occurred almost from the surface to approximately 7 km in depth. The fault plane is almost vertical. According to this, the estimated size of the ruptured area would be 10 km x 7 km. This estimate is in agreement

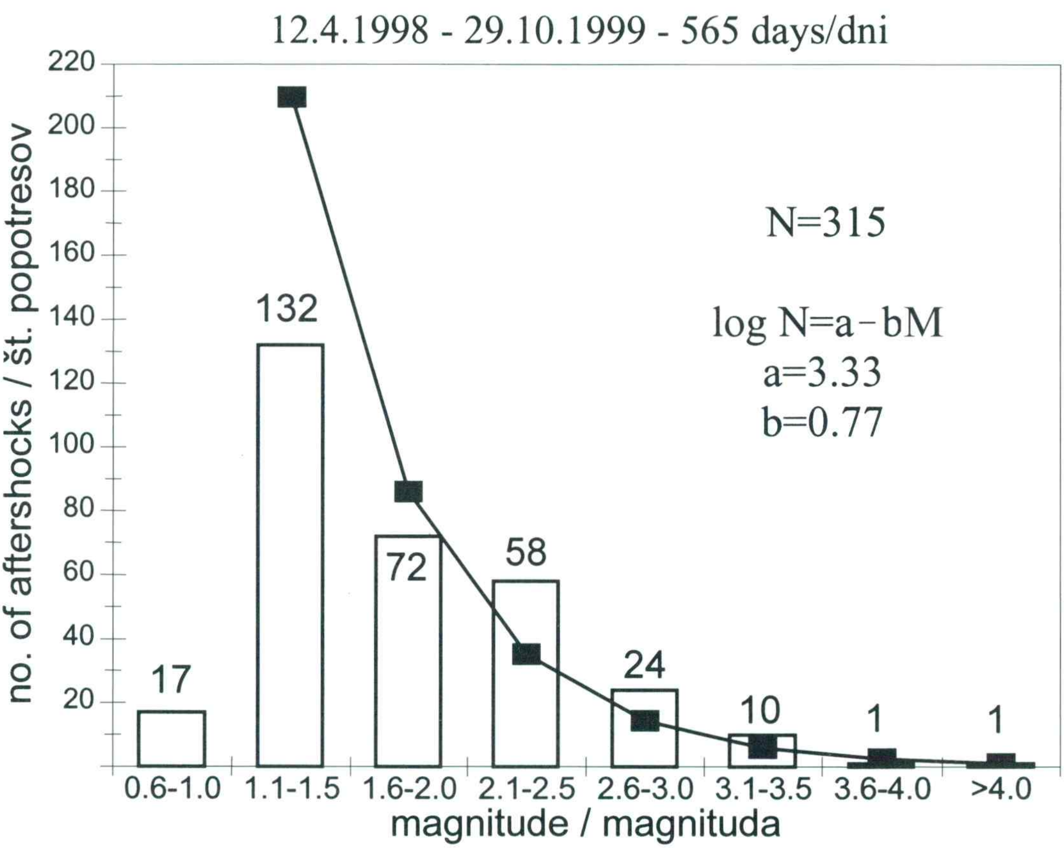
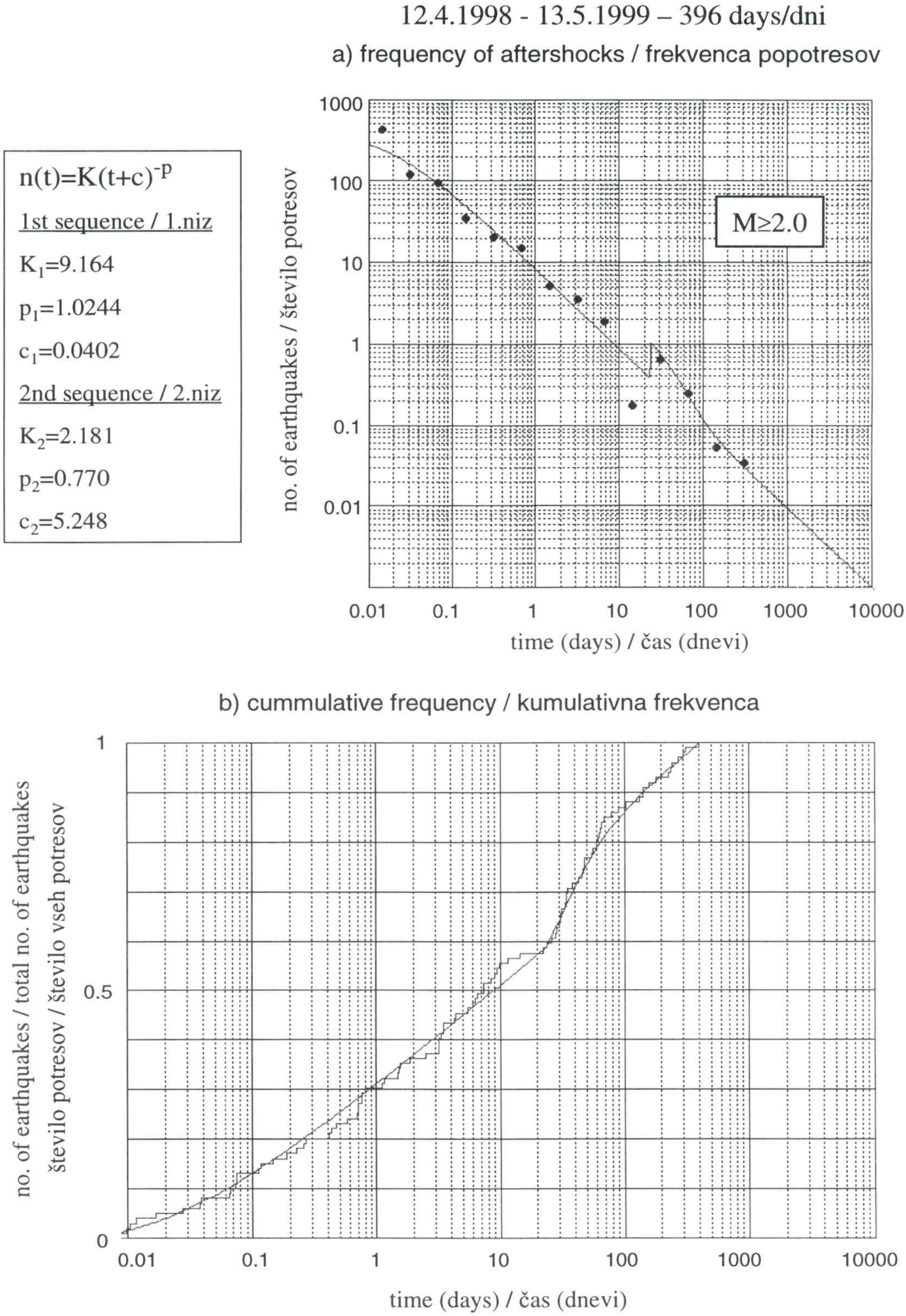


Figure 3. Magnitude-frequency relation (bar) for aftershocks with fitted Gutenberg-Richter's function (line).

Slika 3. Pogostost popotresov v odvisnosti od magnitude (histogram) z Gutenberg-Richterjevo krivuljo, ki se podatkom najbolj prilega (polna črta)


12.4.1998 - 13.5.1999 – 396 days/dni
a) frequency of aftershocks / frekvenca popotresov
n(t)=K(t+c)^-p
1st sequence / 1.niz
K1=9.164
p1=1.0244
c1=0.0402
2nd sequence / 2.niz
K2=2.181
p2=0.770
c2=5.248
M≥2.0
no. of earthquakes / število potresov
1000
100
10
1
0.1
0.01
0.01 0.1 1 10 100 1000 10000
time (days) / čas (dnevi)
b) cummulative frequency / kumulativna frekvenca
no. of earthquakes / total no. of earthquakes
število potresov / število vseh potresov
1
0.5
0
0.01 0.1 1 10 100 1000 10000
time (days) / čas (dnevi)

with some published relations. The length (or area) of active fault plane for the earthquake of magnitude M_w=5.6 or M_s= 5.7 varies from 8 km (or 42 km^2) (Wells & Coppersmith, 1994) to 13 km (or 107 km^2) (Vakov, 1996).

The fault plane solutions of the aftershocks were determined from the waveforms recorded by the digital seismographs in Slovenia (permanent stations and broadband portable seismographs) and from seismographs and accelerographs in Friuli (NE Italy) using the polarities and amplitudes of the first arrival of longitudinal and transversal waves (Snoke et al., 1984). For the main shock the best double couple from the moment tensor solution of Pondrelli et al. (1998) is presented.

Table 2. Fault plane solutions for the main shock and stronger aftershocks.

Preglednica 2. Rešitve prelomne ploskve za glavni potres in močnejše popotrese.

Date Datum	Time Čas (UTC) H:M:S	Co-ordinates Koordinate °N	°E	Depth Globina (km)	M_{LV}	Strike Smer (°)	Dip Naklon (°)	Rake Premik (°)
12.4.1998	10:55:32.9	46.309	13.632	7.6	5.6	132	86	178
12.4.1998	13:35:27.6	46.259	13.554	12.3	3.2	78	55	65
12.4.1998	16:15:39.5	46.310	13.604	7.2	3.0	278	40	84
12.4.1998	20:54:00.9	46.314	13.612	5.7	2.8	44	84	38
12.4.1998	22:13:48.0	46.320	13.612	4.3	3.3	80	58	66
15.4.1998	19:40:30.3	46.273	13.725	4.7	3.3	252	47	50
15.4.1998	22:42:10.0	46.304	13.650	4.2	3.1	267	42	72
16.4.1998	17:21:44.3	46.285	13.660	4.8	2.8	280	37	77
22.4.1998	06:56:28.7	46.274	13.696	3.7	2.9	57	63	49
6.5.1998	02:53:00.1	46.280	13.696	5.1	4.2	51	71	36
8.5.1998	10:11:12.8	46.275	13.694	4.7	2.8	346	40	-82
13.5.1998	01:58:53.5	46.286	13.706	4.3	3.1	54	76	-5
15.5.1998	13:37:47.9	46.302	13.629	5.7	2.7	75	35	0
20.5.1998	06:40:29.8	46.320	13.613	3.8	2.5	75	90	20
24.5.1998	17:45:23.9	46.285	13.694	4.8	2.6	105	56	72
28.5.1998	12:31:53.1	46.277	13.705	3.5	2.6	30	82	6
29.5.1998	22:50:38.0	46.321	13.606	3.7	2.5	83	42	67
10.6.1998	23:32:41.3	46.303	13.631	6.3	3.2	21	32	-17
13.6.1998	18:40:17.4	46.270	13.659	12.7	2.5	33	60	28
29.6.1998	17:33:47.0	46.317	13.612	6.4	2.6	220	68	28
21.8.1998	13:10:41.3	46.253	13.681	4.8	2.5	38	48	-31
30.8.1998	01:18:22.4	46.249	13.691	5.0	3.0	41	78	9

Figure 4. Frequency (a) and cumulative frequency (b) of aftershocks with modified Omori's law function. Secondary aftershock sequence, following the strongest aftershock on 6 May 1998 is included, expressed as a clear step in both diagrams. The data are presented as filled circles (a) or stair curve (b) and exponential fitted functions as solid lines. In (a) data are normalised on number of aftershocks per day.

Slika 4. Frekvenca (a) in kumulativna frekvenca (b) popotresov z modificirano Omorijevo krivuljo, ki se podatkom najbolj prilega. Vključen je sekundarni popotresni niz s pričetkom ob najmočnejšem popotresu 6. maja 1998, ki se odraža v jasnem kolenu v obeh diagramih. Podatki so predstavljeni kot polni krogci (a) ali stopničasta krivulja (b), eksponentni krivulji, ki se podatkom najbolj prilegata pa s polno črto. Na diagramu (a) je število popotresov normirano na en dan.

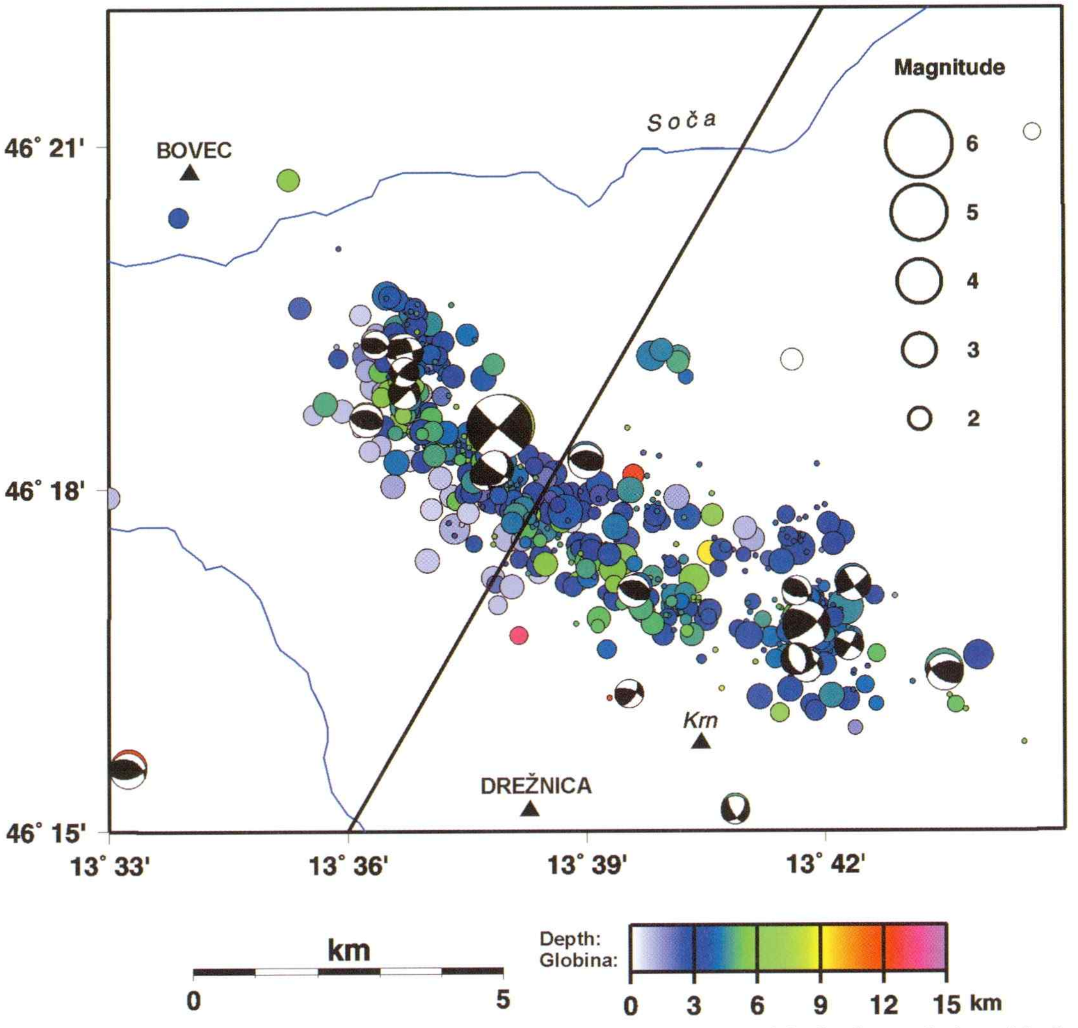


Figure 5: Map of epicentres (circles coloured according to focal depth) and fault plane solutions (black and white circles with compressional quadrant shaded) determined from data of the network of portable seismological stations (Bajc et al., 1999). The line indicates profile shown on the figure 6.

Slika 5: Karta nadžarišč (krogi v barvah odvisnih od žariščne globine) in rešitev prelomne ploskve (črno-beli krogci z zasenčenim kompresijskim kvadrantom), določenih iz podatkov začasne mreže potresnih opazovalnic (Bajc et al., 1999). Označen je profil podan na sliki 6.

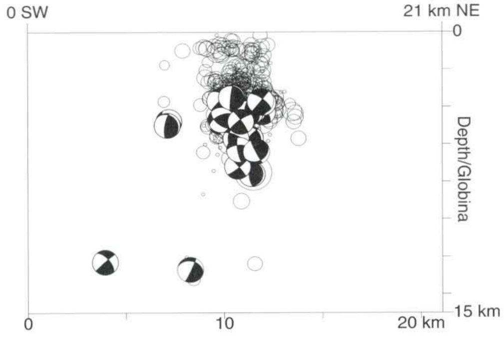


Figure 6: Projection of all hypocentres and fault plane solutions from figure 5, on the plane striking SW-NE.

Slika 6: Profilna projekcija vseh žarišč in žariščnih mehanizmov iz slike 5, pravokotno na dinarsko smer.

Fault plane solutions for many aftershocks are different from that of the main shock. The aftershocks have mainly reverse component, the direction of the plane is WNW-ESE and both possible solutions have a similar dip. The major principal stress component for all earthquakes is almost horizontal and approximately in N-S direction. Most of them were shallower than the main shock.

Macroseismic data of aftershocks

Many of the aftershocks were felt by the inhabitants of the Upper Soča Valley and the intensities were assessed for 102 earthquakes (Cecić et al., 2000). For 47 aftershocks ($1.8 < M_{LV} < 4.2$) in 1998 and 1999 it was possible to draw intensity maps and assess macroseismic epicentres. The macroseismic epicentre was considered to be a centre of mass for the data points in 3 highest intensity classes (where the data for a range of degrees, such as V-VI, were considered as a separate class). The radii of areas with the same intensity (in km) were then assessed. Linear fit between the local magnitude and the size of the zone of certain intensity resulted in better statistical significance than the logarithmic fit. The relations are given in Table 3.

Table 3. The relation between the local magnitude and the size of the zone of a certain intensity, for the aftershock sequence 1998-1999. Parameter *r* denotes the radius of the zone, in km.

Preglednica 3. Odvisnost velikosti con posameznih intenzitet od lokalne magnitude za popotrese v letu 1998 in 1999. Parameter *r* je polmer cone v kilometrih.

I (EMS-98)	No. of events Število potresov	Relation Enačba
III	26	$r_{III} = 25.4\ M_L - 47.1$
IV	35	$r_{IV} = 12.4\ M_L - 21.2$
V	10	$r_V = 7.6\ M_L - 16.1$

In general macroseismic epicentres lay to the south-west from the set of instrumental epicentres. This can be explained with the fact that the foci of the earthquakes were under the vast uninhabited area (high mountains), whereas the majority of settlements in which the aftershocks were felt (and the questionnaires answered), is situated to the south and south-west from the mountains, in the valley of Soča river. The average distance between macroseismic and instrumental epicentres was 6 km.

For the aftershock sequence (from 13 April 1998 to 14 June 2000) GSS has sent 12531 questionnaires to its permanent observers. In total, 8620 questionnaires were returned, that represents 69%. It is important to point out that in some heavily damaged localities observers ceased to answer the questionnaires immediately or soon after the main shock; e.g. in Bovec there were more than 15 observers before the main shock, but majority of them completely stopped answering or returned questionnaires in very rare occasions. It can be explained by the change of the order of priorities - people whose houses were destroyed or damaged in the earthquake surely had more important and urgent things to take care of. Also, large number of aftershocks forced people to get used to it, so they stopped paying attention to individual events.

Study of aerial photographs and digital elevation models (DEM)

The cyclic aerial photogrammetry survey of the north-western Slovenia was performed in July 1998. From these images a new 25 meter resolution digital elevation model (DEM) was produced. We analysed and compared the aerial photographs taken in the previous cyclic survey (1995) and those taken after the main shock. The study area covered approximately 750 km^2 between 13.42°E - 13.80°E and 46.17°N - 46.38°N. On aerial photographs, morphological elements (rockfalls, rockslides, landslides, talus) and structural elements (crack systems and faults) were outlined. Since the epicentre lies in the remote part of the Krn Mountain range, the analysis gave a lot of additional data about the effects to the nature and their spatial distribution (Figure 7).

The instability phenomena, like rockfalls and landslides are not uncommon in this area due to very steep slopes built mainly of fractured carbonate rocks. Rock failures have been observed after heavy rainfall and seasonal temperature changes (two larger events have been observed in Julian Alps in last 10 years). The most rock failure events were triggered by the main shock, and the

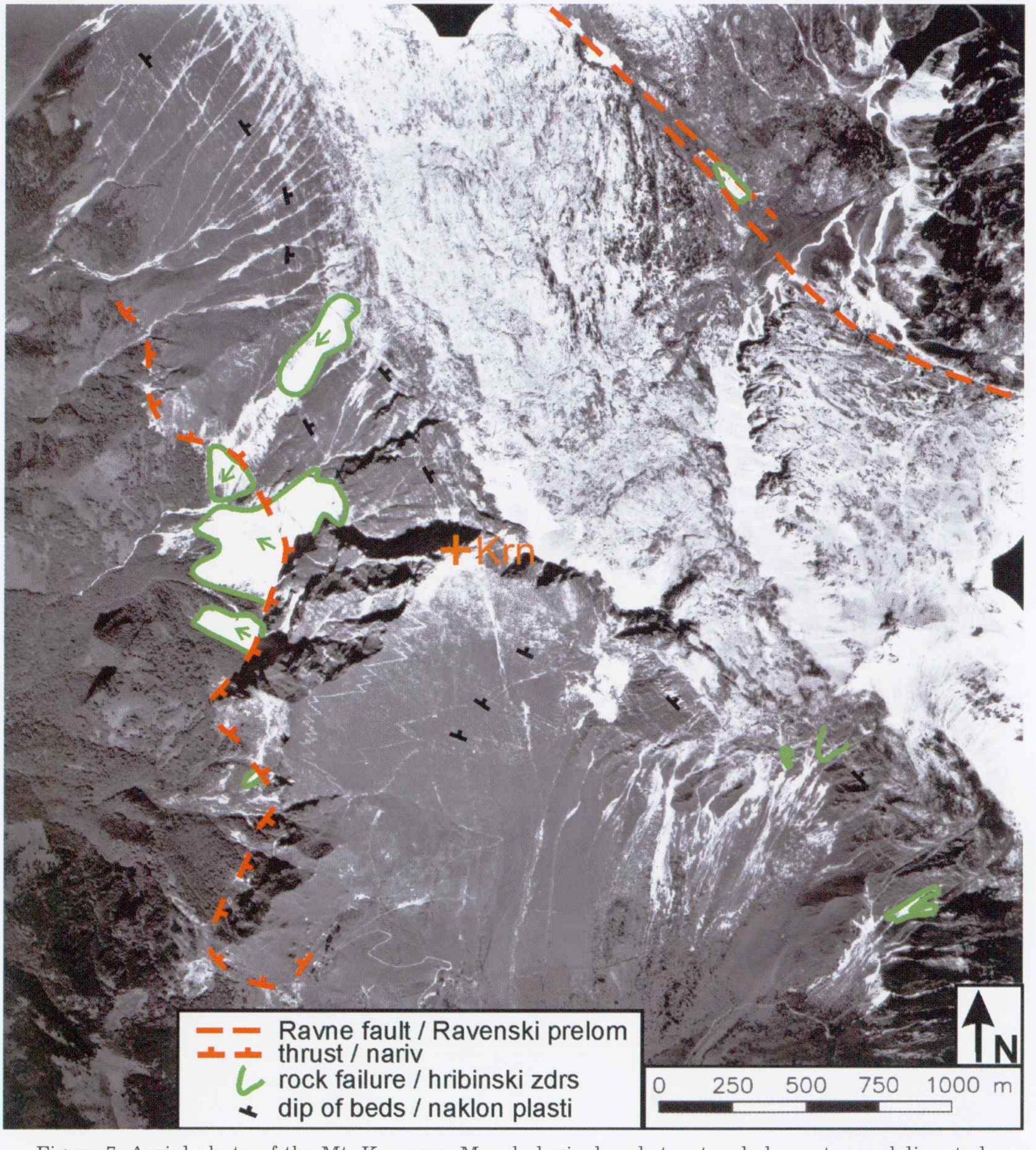


Figure 7: Aerial photo of the Mt. Krn area. Morphological and structural elements are delineated. (Cyclic aerial photography survey of Slovenia 1:17 500, 1998, © Surveying and Mapping Authority of the Republic of Slovenia).

Slika 7: Letalski posnetek območja Krna. Na sliki so prikazani morfološki in strukturni elementi. (Ciklično aerosnemanje Slovenije v merilu 1:17 500 iz leta 1998, © Geodetska uprava Republike Slovenije).

aftershocks only increased the damage to the nature. The highest density of the soil and rock sliding phenomena occurred in fractured fault zones, along fault planes, cracks or bedding. A few slides were observed also in unconsolidated material like moraine sediments near Drežnica village and glacio-fluvial terraces of the Soča river near Bovec (Poljak, 1998; Vidrih & Ribičič, 1999a,b). Spatial distribution of major rockfalls is mostly limited to the Krn Mountains following the NW-SE direction.

By comparison of two digital elevation models that represent the terrain before

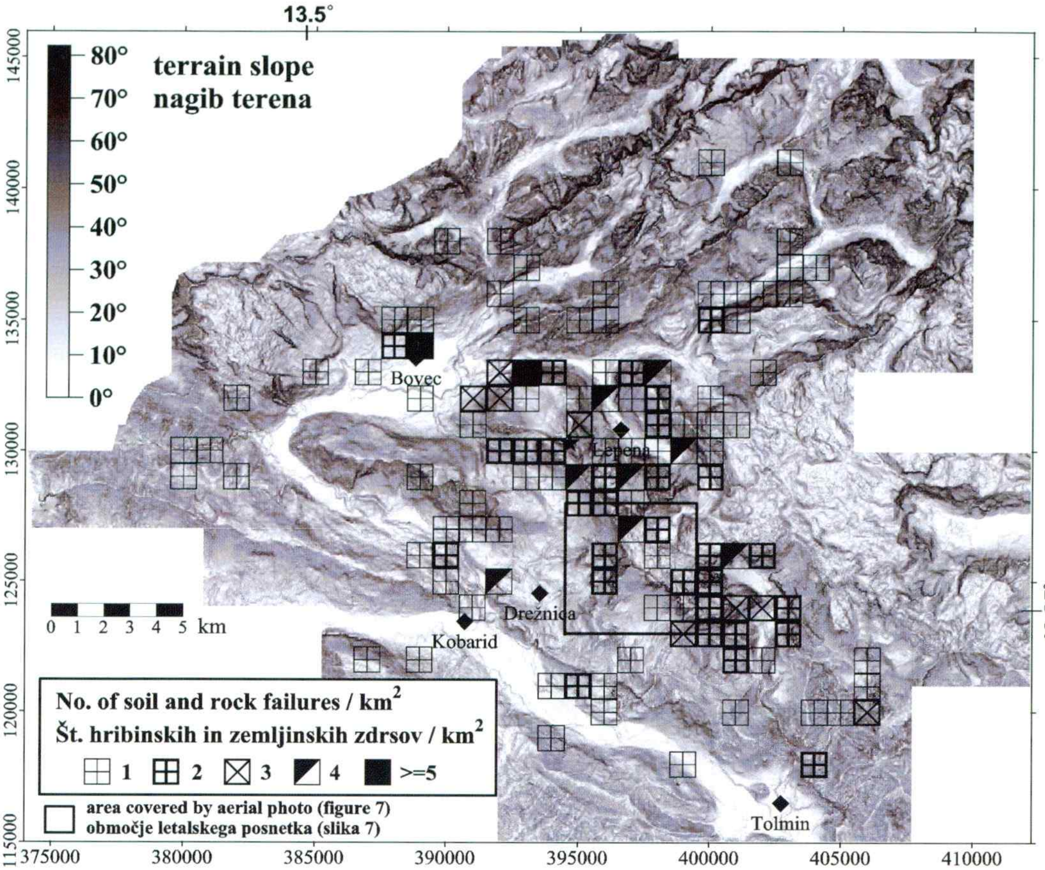


Figure 8: Density of rock and soil sliding phenomena (no. of sliding phenomena per km^2) in the investigated area.

Slika 8: Gostota hribinskih in zemljinskih zdrsov (število zdrsov na km^2) na raziskanem območju.

(DEM 100) and after the earthquake (DEM 25) the volumes of two larger massive rockfalls in Krn mountains were estimated (Gosar, 1999a). For the one of most spectacular massive rockfall of complete southeast wall of Osojnica Mountain above the Tolminka valley, the volume of fallen rock of 3 x 10^6 m^3 was estimated. The largest was the rockfall in north and west walls of Veliki Lemež above the Lepena valley with the estimated volume of 15 x 10^6 m^3. Some systematic errors and low resolution of DEM 100 reduced the accuracy of analysis in some areas or even precluded estimation of rockfall volume. The spatial distribution of rock and soil failure events is shown in Figure 8.

Seismotectonic setting

Regional geological setting

Regional geological setting of the investigated area is presented on Figure 9. The most prominent feature is the Periadriatic lineament which separates Austroalpine (Eastern Alps) from the Dinarides. Dinarides are divided into the E-W oriented Southern Alps and NW-SE striking Internal and External Dinarides. Their different orientation is of tectonic origin. The Southern Alps are thrusted towards the south onto the External Dinarides (Southalpine thrust front). The thrusts in External Dinarides are NW-SE oriented. The External Dinarides are thrusted onto the Adriatic - Apulian foreland (External Dinaric thrust front) in the same direction. The External Dinaric thrust front has different names: in Friuli it is called the Palmanova line (no. 12a. on Figure 9) and in Istria the Karst thrust brink (no. 12b. on Figure 9). The Pannonian basin basement is built of tectonic blocks of Austroalpine and Dinarides tectonic blocks. The main neotectonic deformations are defined by three tectonic zones (Placer, 1999b): the E-W oriented Periadriatic zone situated between the Periadriatic lineament and Sava fault, the WSW-ENE oriented Mid-Hungarian tectonic zone with Zagreb lineament being its main feature, and the NW-SE oriented Idrija tectonic zone. The main features of the Periadriatic tectonic zone are right-lateral strike-slip faults and transpressional regime. The main features in Mid-Hungarian tectonic zone are reverse faults and left lateral strike-slip faults of lesser extent. In the Idrija tectonic zone, the main features are right-lateral strike-slip faults and in its SW part they are combined with reverse faults. The intersecting area between inner part of Idrija (no. 8b on Figure 9) and Mid-Hungarian (no. 7 on Figure 9) tectonic zones, is called the Idrija - Mid-Hungarian transsection zone (no. 9 on Figure 9). It is characterised by typical parquet structure. All three tectonic zones form a triangle called the Sava compressive wedge where the Sava folds are formed.

The relationship between the Idrija tec-

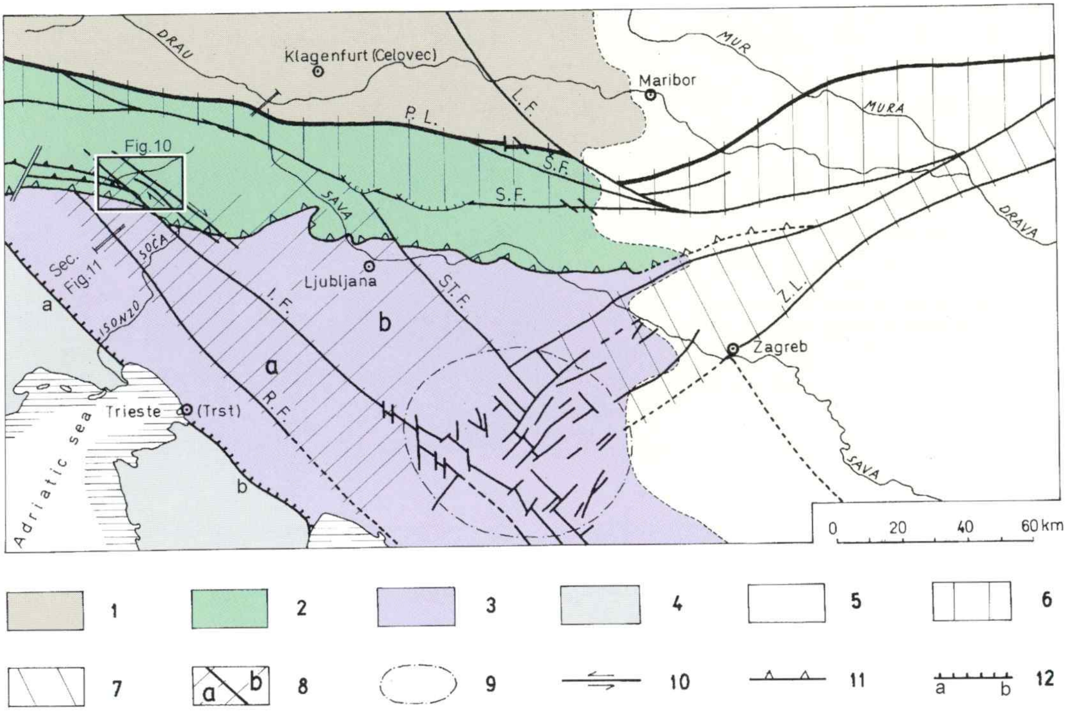


Figure 9: Neotectonic map of Slovenia and adjacent regions (after Placer 1999a,b). 1. Eastern Alps (Austroalpine); 2. Southern Alps; 3. External and Internal Dinarides; 4. Adriatic - Apulian foreland; 5. Pannonian basin; 6. Periadriatic tectonic zone; 7. Mid-Hungarian tectonic zone; 8. Idrija tectonic zone, a - outer part, b - inner part; 9. Idrija - Mid-Hungarian Transsection zone; 10. recent active strike-slip fault; 11. Southalpine thrust front; 12. External Dinaric thrust front (a - Palmanova line, b - Karst thrust brink); **P.L.** Periadriatic lineament; **S.F.** Sava fault; **Š.F.** Šoštanj fault; **L.F.** Lavant fault; **Z.L.** Zagreb lineament; **ST.F.** Stična fault; **I.F.** Idrija fault; **R.F.** Raša fault.

Slika 9: Neotektonska skica Slovenije in sosednjih območij (po Placerju 1999a,b). 1. Vzhodne Alpe (Avstroalpin); 2. Južne Alpe; 3. Zunanji in Notranji Dinaridi; 4. Jadransko - Apulijsko predgorje; 5. Panonski bazen; 6. Periadriatska tektonska cona; 7. Srednjemadžarska tektonska cona; 8. Idrijska tektonska cona, a - zunanji del, b - notranji del; 9. Idrijsko - Srednjemadžarska presečna cona; 10. recentno aktivni zmični prelom; 11. Južnoalpska narivna meja; 12. Zunanjedinarska narivna meja (a - mejna črta Palmanove, b - Kraški narivni rob), **P.L.** Periadriatski lineament; **S.F.** Savski prelom; **Š.F.** Šoštanjski prelom; **L.F.** Labotski prelom; **Z.L.** Zagrebški lineament; **ST.F.** Stiški prelom; **I.F.** Idrijski prelom; **R.F.** Raški prelom.

tonic zone and the Southalpine thrust front is important for the understanding of the seismotectonic pattern of the investigated area. Some strike-slip faults in NW-SE direction of External Dinarides can be traced only to the Southern Alps thrust, and the other cross the Southalpine thrust front and continue further north-westwards. The displacement along the faults that cross the Southalpine thrust front is smaller than it is along the same faults in the External Dinarides. This suggests that the thrusting of the Southern Alps is younger than the faulting of the External Dinarides. However, we suppose that some of the External Dinarides faults exist below the Southern Alps. The most prominent faults that cross the Southalpine thrust front are the Idrija, Kneža and Ravne faults (Placer et al., 1999).

Geologic and tectonic framework of the Upper Soča valley region

The investigated area lies at the southern rim of the Southalpine thrust front (Placer, 1999a,b). The most comprehensive study of the area was done for the Geologic Map of SFRY 1:100 000, presented on sheets Tolmin and Videm (Udine) (Buser, 1986, 1987), and Beljak and Ponteba (Jurkovšek, 1987a,b).

The mountainous regions are almost entirely built up of limestone of the Dachstein formation. It gradually transits into lithologically similar Lower Jurassic limestone. The area of the Bovec basin is composed of clastic sediments. The most prominent are Cretaceous turbidites and the scaglia type limestone and marl. They lie normally on Middle and Upper Jurassic carbonates and clastites. The slopes of the Bovec basin are covered by the remnants of Quaternary glacial sediments, and its central part is filled with glacio-fluvial sediments that form several river terraces.

According to Jurkovšek (1987b), the northern part of the terrain presented on Figure 10 belongs to the Julian Alps overthrust. The most prominent structures here are the Rombon anticline (no. 1), the Kanin syncline (no. 2), as well as the Mojstrovka (no. 3), Soča (no.4) and Vrata (no. 5) faults. Towards the south, Buser (1986) distinguished several thrusts of the Julian Alps among which the Krn overthrust (no. 6) is the most prominent one. The distinct structures of this area are furthermore the Polovnik anticline (no. 7) and a series of NW-SE oriented faults, among which the Ravne (no. 8), Kneža (no. 9) and Idrija (no. 10) faults are marked on Figure 10.

Regarding the tectonic structure of the Bovec basin, Kossmat (1913) proposed a steep syncline in E-W direction. On the contrary, both Buser (1986) and Jurkovšek (1987b) described it as a half-tectonic window following Winkler's (1924) concept. Recent investigations of this area (Poljak et al., 1998) suggest that the Bovec basin represents a steep syncline that stretch in ENE-WSW direction (no. 11 on Figure 10). Mountain slopes that surround the basin are built up of normally superimposed beds of Upper Triassic to Upper Cretaceous age, and these form a distinct fold, i.e. the syncline. The syncline axis itself is covered by glacio-fluvial to glacio-limnic sediments of Upper Pleistocene to Holocene age that have no signs of structural deformations. Kuščer et al. (1974) presented, on the basis of geological mapping and drilling data, the Bovec basin as a syncline. According to Poljak et al. (1998) the Cretaceous clastic rocks of syncline axis are additionally folded, whereas the Mesozoic rocks that form its limbs are partially thrusted towards the main syncline axis, i.e. towards north-west and south-east respectively. The main thrust front of the Krn overthrust stretches most probably in NW-SE direction under the Quaternary sediments of the Bovec basin.

The position of described syncline that is roughly perpendicular to the other NW-SE oriented Dinaric structures is supposedly a consequence of horizontal displacement along the main Dinaric faults. This is otherwise not an exception, because a series of NE-SW oriented folds are well expressed in the vicinity of regional Dinaric faults in the western part of Slovene External Dinarides (Jurkovšek et al., 1996).

Regarding geology of the epicentre area, it has the same characteristics as the above described wider region. The Mt. Krn is built up of Upper Triassic carbonate series that consist mainly of limestones with dolomites

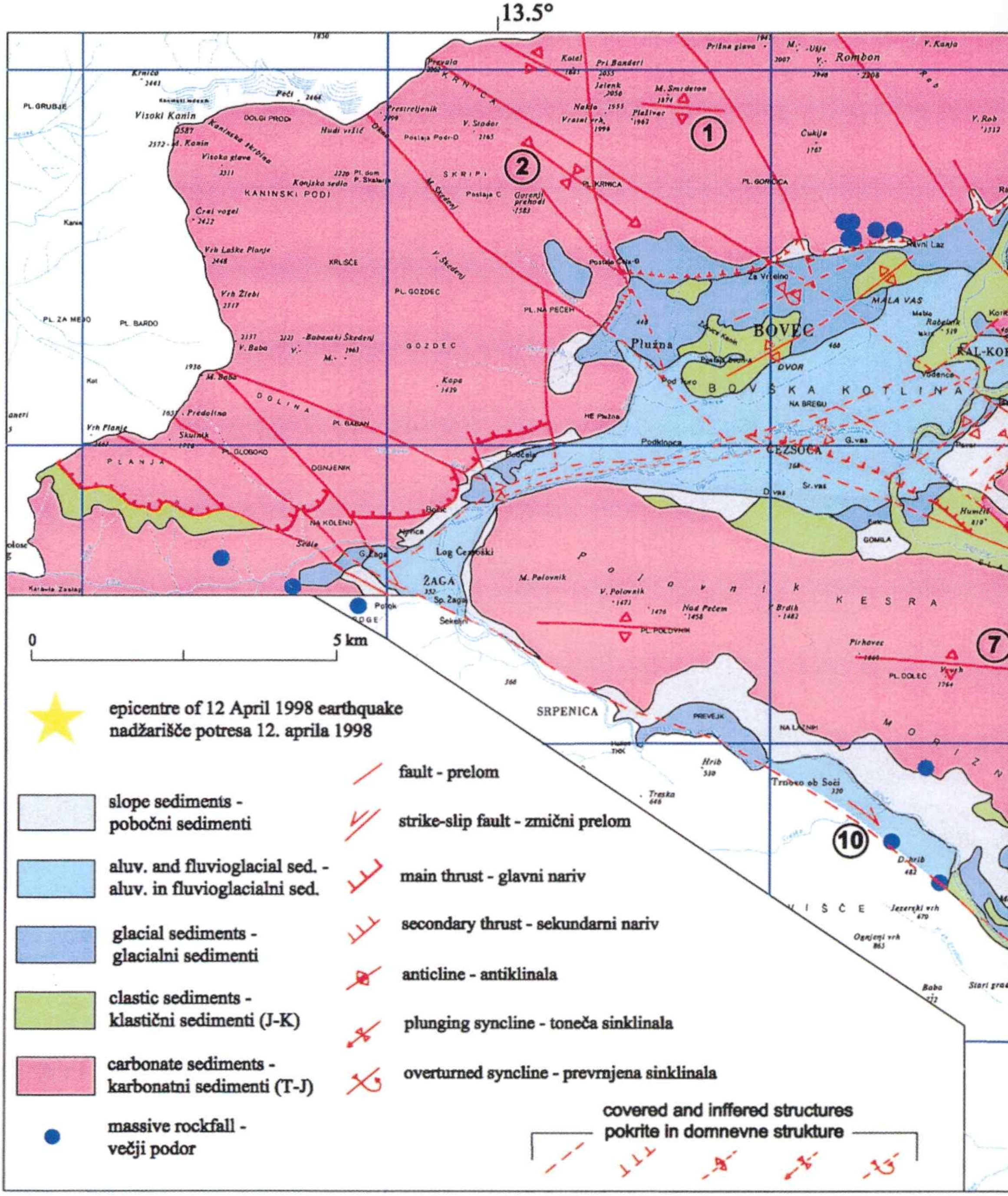
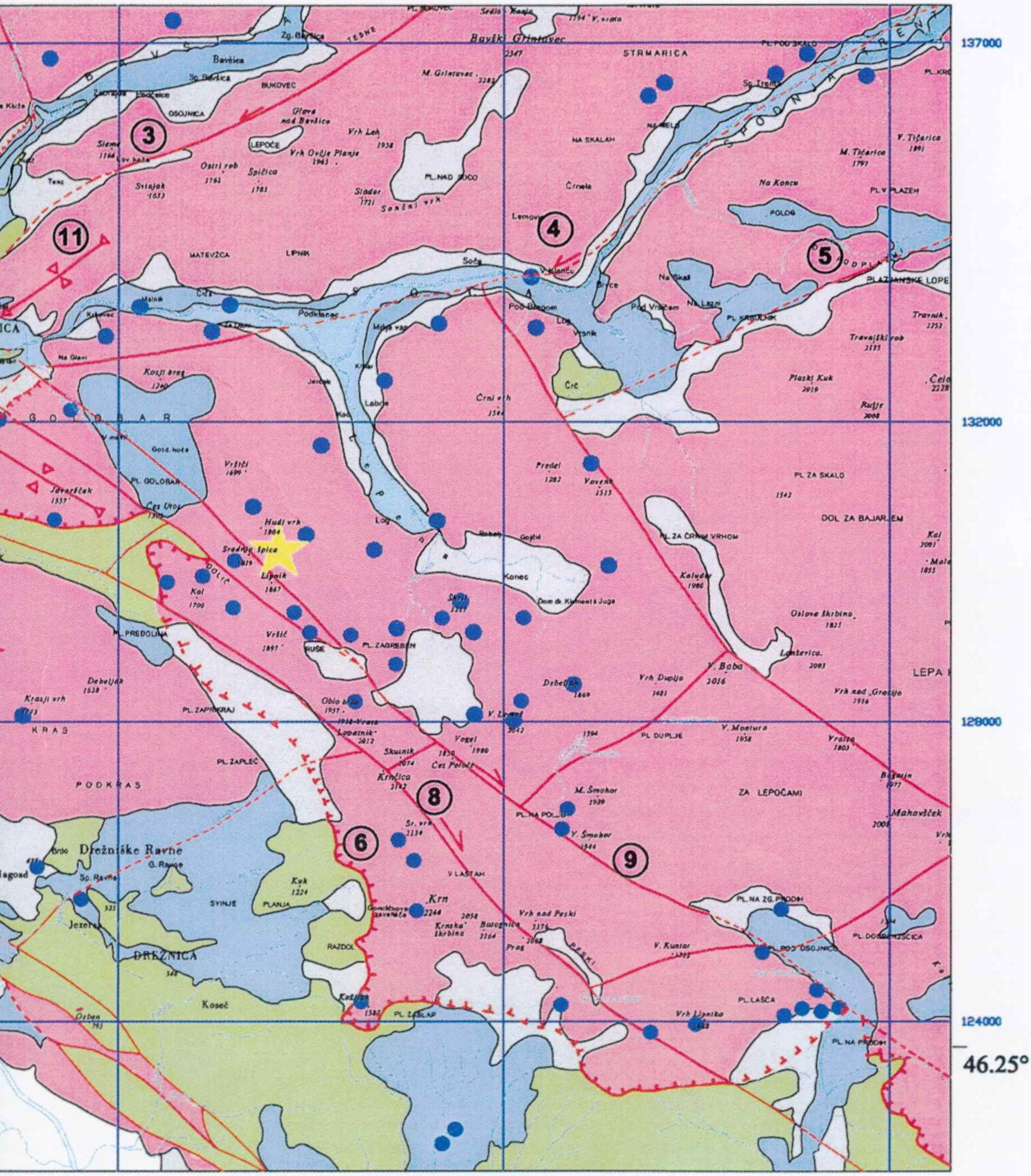


Figure 10: Generalised geological map of Upper Soča Valley (after Kuščer et al., 1974, Buser, 1987, Jurkovšek, 1987a, Poljak et al., 1998). Numbers in open circles: 1. Rombon anticline, 2. Kanin syncline, 3. Mojstrovka fault, 4. Soča fault, 5. Vrata fault, 6. Krn overthrust, 7. Polovnik anticline, 8. Kneža fault, 9. Ravne fault, 10. Idrija fault, 11. Bovec syncline



Slika 10: Pregledna geološka karta Zgornjega Posočja (po Kuščer et al., 1974, Buser, 1987, Jurkovšek, 1987a, Poljak et al., 1998). Številke v krogih: 1. Rombonska antiklinala, 2. Kaninska sinklinala, 3. Mojstrovški prelom, 4. Soški prelom, 5. prelom Vrata, 6. Krnski nariv, 7. Polovniška antiklinala, 8. Kneški prelom, 9. Ravenski prelom, 10. Idrijski prelom, 11. Bovška sinklinala

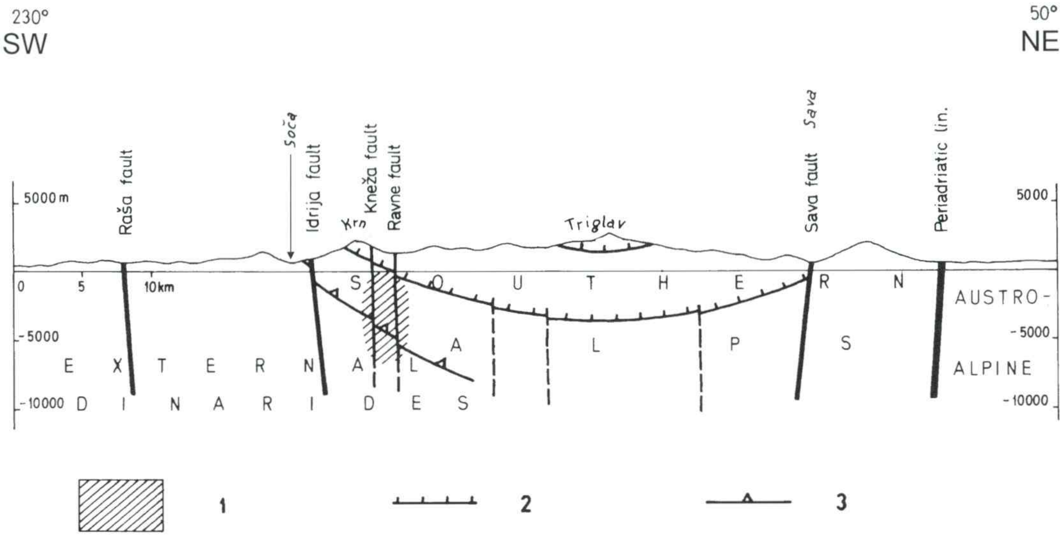


Figure 11: Regional profile across the seismogenic area. 1. Area of the earthquake hypocenters, 2. Overthrust, 3. Southalpine thrust front.

Slika 11: Regionalni profil prek potresnega območja. 1. območje žarišč potresov, 2. meja pokrova znotraj Južnih Alp, 3. Južnoalpska narivna meja.

in its upper part. Both, the limestones and the dolomites are well bedded and only partially massive. their total thickness exceeds 1000 m. Overlying carbonates, there are some outcrops of transgressively deposited Jurassic and Cretaceous clastic rocks. Their thickness varies but does not exceed 100 m. Some areas of the Mt. Krn slopes are covered by loose sediments of glacial origin few tens of meters thick.

Model of structural deformations

The interpretation of the earthquake from 12 April 1998 mechanism is based on the study by Carulli et al. (1990) in which former ideas of recent underthrusting of the Adriatic - Apulian foreland together with a part of External Dinarides under the Southern Alps were improved. According to seismological data of the main shock and numerous aftershocks within the framework of structural relationship between the Southalpine thrust front and the Idrija tectonic zone, we suppose that the recent tectonic activity in the western Slovenia follows two mechanisms. The first one is related to the Southern Alps thrusting along particular thrust planes, and the second one to dextral strike-slip horizontal displacements along NW-SE oriented faults. Both mechanisms can take place at the same time or in alternation.

The main shock from 12 April was generated in the tectonic zone of the Kneža and Ravne faults. Geological interpretation of the entire region from the External Dinarides to the Eastern Alps is presented in the Figure 11, and it also explains the structural mechanism along above mentioned Kneža and Ravne faults. Dotted area marks spatial distributions of all shocks. Calculated fault plane solutions express right-lateral horizontal and oblique displacements as well as reverse faulting. Having in mind that the structural zone of both faults is composed of numerous variously oriented fault planes of the second order, we believe that all the hypocentres can be placed within the fault zone between the Kneža and Ravne faults. This is consistent with results of three GPS campaigns in western Slovenia, two before the earthquake (in 1994 and 1995) and one in August 1998. Computed differences in locations between first and third campaign revealed displacements in the order of 10 millimetres (Mišković et al., 1999). The sense of motion shows right-lateral movement along strike slip faults. Modelling the rupture on the extended source from the strong motion records revealed the same area on which bilateral faulting has occurred (B a j c et al., 2001). It should be pointed out that the described right-lateral tectonic displacement is the only one that is evident north-eastward of the Idrija fault.

Conclusions

The fault plane solution of the main shock is a pure horizontal right-lateral strike-slip. The further analysis shows that the main tectonic displacement happened within a fault zone determined by the Kneža and Ravne faults. Hypocentres of the majority of aftershocks stretch in a NW-SE elongated belt that is approximately 10 km long and 3 km wide. A cross-section constructed perpendicularly to the seismic zone indicates that the hypocentres lie in a vertical plane that extends from near the surface down to approximately 7 km in depth. The main event happened at the 7.6 km in depth. Coseismic deformation according to our investigation, is distributed in the aforementioned fault zone, and did not reach the surface. Fault plane solutions for many aftershocks deviate from that of the main shock, having mainly reverse component. The direction of the plane is WNW-ESE with southward direction of thrusting. Most of them were shallower than the main shock. The major principal stress component for the main shock and majority of aftershocks is almost horizontal in N-S direction.

On the basis of seismological data and geological relationship between the Southern Alps thrust front and the Idrija fault zone of the External Dinarides, we conclude that the recent tectonic activity in the western part of Slovenia is related with shearing along the NW-SE oriented faults as well as with thrusting along the Southalpine thrust front. Both mechanisms may occur simultaneously or in alternation.

In earthquake catalogues there are no major earthquakes in the investigated area, although the region was devastated many times in history by earthquakes originating either in the south-east (Idrija region) or in the west (Friuli, Italy). The earthquake mechanism is in agreement with previous seismotectonic and seismic hazard studies, where the western part of the Idrija fault zone and parallel faults were assigned capability of generating strong earthquakes. But the earthquake of 12 April 1998 and its aftershock sequence also revealed many new aspects of seismicity and seismotectonics of this region. This knowledge will also help to improve the seismic hazard assessments for this region.

Acknowledgements

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Potres 12. aprila 1998 v Krnskem pogorju (Zgornje Posočje, Slovenija) in njegove seizmotektonske značilnosti

Glavni potres

Potres 12. aprila 1998 ob 10. uri in 55 minut po svetovnem času (oz. 12. uri 55 minut po lokalnem poletnem času) z žariščem v Krnskem pogorju je bil po magnitudi (m_b=5,3, M_m=5,3, M_{LV}=5,6, M_w=5,6, M_S=5,7, M_{WA}=6,0) eden od najmočnejših potresov z nadžariščem v Sloveniji v dvajsetem stoletju. Nadžarišče potresa je bilo približno 8 km oddaljeno od Bovca. Žariščni parametri so izračunani na podlagi metode hkratnega določanja žarišč (B a j c et al., 1999) in enodimenzionalnega izotropnega hitrostnega modela. Žariščne koordinate so 46,309° S, 13,632° V in globina 7,6 km. Ocenjena napaka žariščnega časa je 0,2 s in lokacije 1 km. Žariščni mehanizem glavnega potresa je določen na podlagi površinskih valov in prvih premikov pri vstopu P-valov z metodo po Bukchin et al. (1994). Rešitev kaže na čisti desni zmik ob SZ-JV usmerjenem navpičnem prelomu.

Makroseizmični podatki

Po glavnem potresu je Uprava RS za geofiziko (URSG) po pošti poslala vprašalnike na naslove vseh aktivnih prostovoljnih opazovalcev (več kot 4300), ki sodelujejo z URSG. Vprašalnike nam je vrnilo 68% opazovalcev. Terenske raziskave smo izpeljali v najbolj prizadetih naseljih. Zbirali smo podatke o poškodbah in drugih učinkih potresa na način, ki nam je omogočal vrednotenje podatkov s pomočjo EMS-98, evropske potresne lestvice iz leta 1998 (Grünthal ed., 1998a,b). Dodatne podatke so nam posredovale komisije za popis poškodb, ki so podrobno pregledale več kot 3000 objektov. Poškodovali so se predvsem starejši objekti, grajeni iz obdelanega in neobdelanega kamna. V posameznih primerih je prišlo do delnih porušitev sten ali vogalov slabo grajenih hiš. Pri novejših, solidno grajenih objektih so na obseg poškodb bistveno vplivala slaba tla. Zaradi številnih popotresnih sunkov so se poškodbe na hišah s časom večale.

Z obdelavo makroseizmičnih podatkov smo dobili vrednosti intenzitete potresa 12. aprila 1998 v več kot 2000 krajih (sliki 1a in 1b). Potres je dosegel največje učinke (VII-VIII EMS-98) v krajih Lepena, Magozd, Spodnje Drežniške Ravne in Tolminske Ravne (Cecić et al., 1999a; Zupančič et al., 1999). Glavni potres so, razen v Sloveniji, čutili še prebivalci Italije, Švice, Avstrije, Nemčije, Češke, Slovaške, Madžarske, Hrvaške ter Bosne in Hercegovine.

Prebivalci Posočja so čutili številne popotresne sunke. Za 102 popotresa smo lahko opredelili intenzitete. Makroseizmične epicentre je bilo mogoče določiti za 47 popotresov. Za popotrese v obdobju med 13. aprilom 1998 in 14. junijem 2000 je URSG poslala 12531 vprašalnikov in prejela 8620 odgovorov (69%).

Časovna in prostorska porazdelitev popotresov ter žariščni mehanizmi

Prva začasna opazovalnica, postavljena v Trenti 12. aprila (9 ur po glavnem potresu), je v prvih petih urah zapisala 107 potresov, v naslednjih 24-ih pa še 234. Skupaj so tri prenosne opazovalnice (poleg Trente še v Lepeni in Drežnici) do konca leta 1998 zaznale več kot 7000 popotresov.

Najmočnejši popotres je bil 6. maja 1998 (23 dni po glavnem potresu) ob 2. uri 53 minut 0,1 sekunde UTC z žariščem približno 5 km jugovzhodno od žarišča glavnega potresa na globini 5,1 km in je imel magnitudo M_{LV} = 4,2 (Cecić et al., 1999b).

V enem letu po glavnem potresu smo zabeležili 303 potrese z lokalno magnitudo večjo od 1,0 in 13 popotresov z magnitudo večjo od 3,0. Katalog popotresov je kompleten za magnitudo večjo od 2,0. Opredeljeni parametri Gutenberg-Richterjevega (slika 3) in modificiranega Omorijevega zakona (slika 4) se dobro ujemajo z vrednostmi iz literature (e.g. Gosar et al., 1998).

Žariščni parametri za popotrese so izračunani na podlagi metode hkratnega določanja žarišč (Bajc et al., 1999). Žarišča večine popotresov so razporejena v 3 km širokem in 10 km dolgem pasu, razpotegnjenem v smeri severozahod-jugovzhod (azimut 307°) (slika 5). Profil v smeri SV-JZ kaže, da so potresi razporejeni od skoraj površine pa do globine približno 7 km (slika 6). Prelomna ploskev je skoraj navpična. Ocenjena velikost aktivirane prelomne ploskve je 10 km x 7 km.

Žariščne mehanizme popotresov smo opredelili iz zapisov digitalnih potresnih opazovalnic v Sloveniji (stalne potresne opazovalnice in prenosne širokopasovne opazovalnice) in severovzhodni Italiji. Za izračune smo uporabili smeri prvih premikov pri vstopu vzdolžnega in prečnega valovanja in razmerja med amplitudami SH in P valov (Snoke et al., 1984). Žariščni mehanizmi popotresov so večinoma narivnega tipa, smer nariva je približno ZSZ-VJV, pri čemer imata obe možni ploskvi približno enak naklon. Vsem mehanizmom je skupno, da je največja napetost skoraj horizontalna in je njena približna smer sever-jug.

Analiza letalskih posnetkov ter digitalnega modela reliefa

Na letalskih posnetkih smo določili morfološke elemente kot so podori in plazovi ter melišča in strukturne elemente t.i. fotogeološke prelome, ki predstavljajo razpoklinske sisteme in geološke prelome (Poljak, 1998). Primerjali smo posnetke v merilu 1: 17.500, ki so bili posneti leta 1995 s tistimi, ki so bili posneti po potresu poleti 1998, s čemer smo dobili veliko dodatnih podatkov o pojavih v naravi (podori, zdrsi) v hribovitem svetu Krnskega pogorja, ki jih je drugače težko evidentirati (slika 7).

Največje število podorov je nastalo v apnencih in dolomitih na območju Krnskega pogorja: v dolini Lepene in v okolici izvira Tolminke. Posamezni podori in plazovi so nastali tudi v Spodnji Trenti in na južnem delu Kaninskega pogorja (Vidrih & Ribičič, 1999). Podori so praviloma nastali ob tektonskih strukturah in sicer v zdrobljenih prelomnih conah, ob prelomnih ploskvah, ob različnih razpokah in po ploskvah plastovitosti. V manjšem številu je potres sprožil tudi drsenje nesprijetega materiala, na primer v morenskem materialu pri Drežnici in v rečno-ledeniških terasah Soče pri Bovcu. Ponekod so se aktivirali tudi stari plazovi. Prostorska porazdelitev teh pojavov kaže usmeritev SZ-JV (slika 8). Na podlagi digitalnih modelov reliefa pred potresom (DMR 100) in po potresu (DMR 25) smo ocenili prostornino dveh večjih podorov v Krnskem pogorju na 3 in 15 milijonov m^3 (Gosar, 1999a).

Regionalna geološka zgradba

Najbolj izrazita geotektonska linija širšega območja (slika 9) je Periadriatski lineament, ki loči Avstroalpin (Vzhodne Alpe) od Dinaridov. Dinaride sestavljajo Južne Alpe, ki se raztezajo v smeri vzhod-zahod in Zunanji ter Notranji Dinaridi v smeri SZ-JV. Južne Alpe so ob Južnoalpski narivni meji od severa proti jugu narinjene na Zunanje Dinaride. Narivi znotraj slednjih so usmerjeni od severovzhoda proti jugozahodu. V isti smeri so tudi Zunanji Dinaridi ob Zunanjedinarski narivni meji (linija Palmanova in Kraški narivni rob) narinjeni na Jadransko - Apulijsko predgorje (Placer, 1999b).

Za mehanizem nastanka potresa v Krnskem pogorju je pomembno razmerje prelomov Idrijske tektonske cone do Južnoalpske narivne meje. Mejo nekateri prelomi sekajo, drugi pa so ob njej odrezani. Tisti prelomi, ki jo sekajo, v Južnih Alpah kmalu zamrejo, premiki pa so ob njih manjši kot v Zunanjih Dinaridih. Zato sklepamo, da je narivanje Južnih Alp mlajše od prelomov Idrijske tektonske cone, premiki ob teh prelomih v Južnih Alpah pa so po vsem sodeč nasledstvenega značaja. Zaradi tega domnevamo, da segajo nekateri med njimi dlje pod Južne Alpe, kot je to videti na površju. Najbolj izrazito sekajo Južnoalpsko narivno mejo po Buserju (1987) Idrijski prelom ter v manjši meri Kneški in Ravenski prelom, ki potekata preko Krnskega pogorja (Placer et al., 1999).

Geološka zgradba Zgornjega Posočja

Kaninsko in Krnsko pogorje sta skoraj v celoti zgrajena iz zgornjetriasnega apnenca v dachsteinskem razvoju. Ta na robovih Bovške kotline postopno prehaja v facialno podoben spodnjejurski apnenec. Bovško kotlino gradijo na površju klastične kamnine, ki ležijo normalno na karbonatno-klastičnih kamninah doggersko-malmske starosti. Razvite so v obliki turbiditnega faciesa ali kot apnenci v razvoju scaglia. Pobočja Bovške kotline pokrivajo ostanki glacialnih morenskih sedimentov, medtem ko je njen osrednji del zapolnjen z glacio-fluvialnimi sedimenti, ki oblikujejo rečne terase. Ponekod je v podlagi le-teh jezerska kreda (Buser, 1987).

Jurkovšek (1987b) uvršča severni del ožjega raziskanega območja (slika 10) v nariv Julijskih Alp. Najbolj pomembne strukture na tem območju so antiklinala Rombona, Kaninska sinklinala ter Mojstrovški in Soški prelom ter prelom Vrata. Proti jugu opisuje Buser (1986) več narivov Julijskih Alp, najpomembnejši med njimi je Krnski nariv. Pomembne strukture južnega dela območja so še Polovniška antiklinala in niz prelomov usmerjenih SZ-JV med katerimi so najbolj izraziti Ravenski, Kneški in Idrijski prelom. Novejše raziskave Bovške kotline kažejo na to, da je le-ta strma sinklinala v smeri VSV-ZJZ. Zapolnjena je z ledeniško-rečnimi in ledeniško-jezerskimi usedlinami pleistocenske do holocenske starosti, ki niso deformirane. Kredne klastične kamnine v jedru sinklinale so dodatno nagubane, mezozojske kamnine v krilih gube pa so narinjene proti severo-zahodu oziroma jugo-vzhodu. Glavni narivni rob Krnskega nariva se verjetno nadaljuje v smeri SZ-JV pod kvartarnimi usedlinami Bovške kotline. Lega opisane sinklinale, ki leži približno pravokotno na SZ-JV usmerjene dinarske strukture, je verjetno posledica vodoravnih premikov vzdolž glavnih dinarskih prelomov (Poljak et al., 1998).

Model strukturnih deformacij in sklepi

Razlaga potresa 12. aprila 1998 v Krnskem pogorju temelji na delu Carulli et al. (1990). Na podlagi seizmoloških podatkov za glavni potres in popotrese ter strukturnih odnosov med Južnoalpsko narivno mejo in Idrijsko tektonsko cono domnevamo, da recentna tektonska aktivnost v zahodni Sloveniji nastaja na dva načina. Prvi mehanizem nastanka je povezan z narivanjem Južnih Alp po različnih narivnih ploskvah. Drugi mehanizem je povezan z desnimi zmiki vzdolž SZ-JV usmerjenih prelomov. Oba mehanizma se lahko pojavljata skupaj ali izmenično.

Glavni potres 12. aprila 1998 je nastal v območju Ravenskega in Kneškega preloma. Na sliki 11 je prikazana geološka interpretacija celotnega ozemlja med Zunanjimi Dinaridi in Vzhodnimi Alpami. Žariščni mehanizmi (slika 5) kažejo desne vodoravne in poševne zmike ter reverzne zmike. Ob upoštevanju dejstva, da je prelomna cona sestavljena iz notranjih, veznih in spremljajočih prelomnih ploskev različnih smeri, lahko večino potresov pripišemo prelomni coni med Kneškim in Ravenskim prelomom. To potrjujejo tudi rezultati geodetskih GPS meritev v zahodni Sloveniji. Izračunani regionalni premiki so reda velikosti 10 mm (Mišković et al., 1999). Meritve kažejo na premike ob desnih zmičnih prelomih. Modeliranje pretrga s ploskovnim žariščem iz zapisov močnejših potresov kaže enako področje pojavljanja potresov (Bajc et al., 2001). Opisani desni zmik je edini dokazan zmik severovzhodno od Idrijskega preloma.

Analiza podatkov je pokazala, da se je glavni premik zgodil v prelomni coni med Kneškim in Ravenskim prelomom. Žarišča večine popotresov so razporejena v 3 km širokem in 10 km dolgem pasu, razpotegnjenem v smeri severozahod-jugovzhod (slika 5). Profil pravokotno na dinarsko smer (slika 6) kaže, da so popotresi razporejeni od bližine površine pa do globine približno 7 km in so nastali plitveje kot glavni potres, ki je bil v globini 7,6 km. Prelomna ploskev je skoraj navpična. Koseizmične deformacije so se zgodile znotraj prelomne cone, pretrg pa ni dosegel površine. Žariščni mehanizmi popotresov kažejo večinoma na narivni tip v smeri približno ZSZ-VJV, s smerjo narivanja proti jugu.

V potresnem katalogu na obravnavanem območju ni zabeleženih večjih potresov, kljub temu pa je bilo Zgornje Posočje že večkrat v zgodovini prizadeto zaradi potresov, ki so nastali na območju Idrije ali na območju Furlanije. Tudi študije seizmotektonike in potresne nevarnosti tega območja pripisujejo zahodnemu delu Idrijske prelomne cone in vzporednim dinarskim prelomom zmožnost nastanka močnejših potresov, toda potres 12. aprila 1998 in njegovi popotresi so razkrili mnoge nove poglede na seizmičnost in seizmotektoniko tega območja.

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