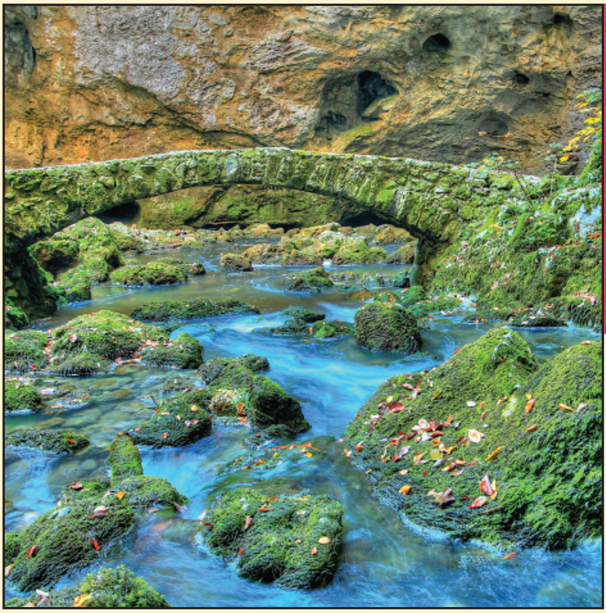
ACTA GEOGRAPHICA SLOVENICA

GEOGRAFSKI
ZBORNIK



2019
59
1

ACTA GEOGRAPHICA SLOVENICA
GEOGRAFSKI ZBORNIK
59-1 • 2019

Contents

Maja KOCJANČIČ, Tomislav POPIT, Timotej VERBOVŠEK
Gravitational sliding of the carbonate megablocks in the Vipava Valley, SW Slovenia 7

Małgorzata KIJOWSKA-STRUGAŁA, Anna BUCAŁA-HRABIA
Flood types in a mountain catchment: the Ochotnica River, Poland 23

Irena MOCANU, Bianca MITRICĂ, Mihaela PERSU
Socio-economic impact of photovoltaic park: The Giurgiu county rural area, Romania 37

Andrej GOSAR
The size of the area affected by earthquake induced rockfalls: Comparison of the 1998 Krn Mountains (NW Slovenia) earthquake (M_w 5.6) with worldwide data 51

Matej GABROVEC, Peter KUMER
Land-use changes in Slovenia from the Franciscean Cadaster until today 63

Mojca FOŠKI
Using the parcel shape index to determine arable land division types 83

Mateja FERK, Matej LIPAR, Andrej ŠMUC, Russell N. DRYSDALE, Jian ZHAO
Chronology of heterogeneous deposits in the side entrance of Postojna Cave, Slovenia 103

Special issue – Green creative environments

Jani KOZINA, Saša POLJAK ISTENIČ, Blaž KOMAC
Green creative environments: Contribution to sustainable urban and regional development 119

Saša POLJAK ISTENIČ
Participatory urbanism: creative interventions for sustainable development 127

Jani KOZINA, Nick CLIFTON
City-region or urban-rural framework: what matters more in understanding the residential location of the creative class? 141

Matjaž URŠIČ, Kazushi TAMANO
The importance of green amenities for small creative actors in Tokyo: Comparing natural and sociocultural spatial attraction characteristics 159

ISSN 1581-6613
9 771581 661010

ACTA GEOGRAPHICA SLOVENICA

59-1
2019

ISSN: 1581-6613
COBISS: 124775936
UDC/UDK: 91

Issued by/izdajatelj: Geografski inštitut Antona Melika ZRC SAZU
Published by/založnik: Založba ZRC
Co-published by/sozaložnik: Slovenska akademija znanosti in umetnosti

Address/Naslov: Geografski inštitut Antona Melika ZRC SAZU, Gosposka ulica 13, SI – 1000 Ljubljana, Slovenija

The papers are available on-line/prispevki so dostopni na medmrežju: http://ags.zrc-sazu.si (ISSN: 1581–8314)

Ordering/naročanje: Založba ZRC, Novi trg 2, p. p. 306, SI – 1001 Ljubljana, Slovenija; zalozba@zrc-sazu.si

Annual subscription/letna naročnina: 20 € for individuals/za posameznike, 28 € for institutions/za ustanove.
Single issue/cena posamezne številke: 12,50 € for individuals/za posameznike, 16 € for institutions/za ustanove.

Cartography/kartografija: Geografski inštitut Antona Melika ZRC SAZU
Translations/prevodi: DEKS, d. o. o.
DTP/prelom: SYNCOMP, d. o. o.
Printed by/tiskarna: Tiskarna Present, d. o. o.
Print run/naklada: 350 copies/izvodov

The journal is subsidized by the Slovenian Research Agency and is issued in the framework of the Geography of Slovenia core research programme (P6-0101)/revija izhaja s podporo Javne agencije za raziskovalno dejavnost Republike Slovenije in nastaja v okviru raziskovalnega programa Geografija Slovenije (P6-0101).

The journal is indexed also in/revija je vključena tudi v: SCIE – Science Citation Index Expanded, Scopus, JCR – Journal Citation Report/Science Edition, ERIH PLUS, GEOBASE Journals, Current geographical publications, EBSCOhost, Geoscience e-Journals, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google scholar, and CrossRef.

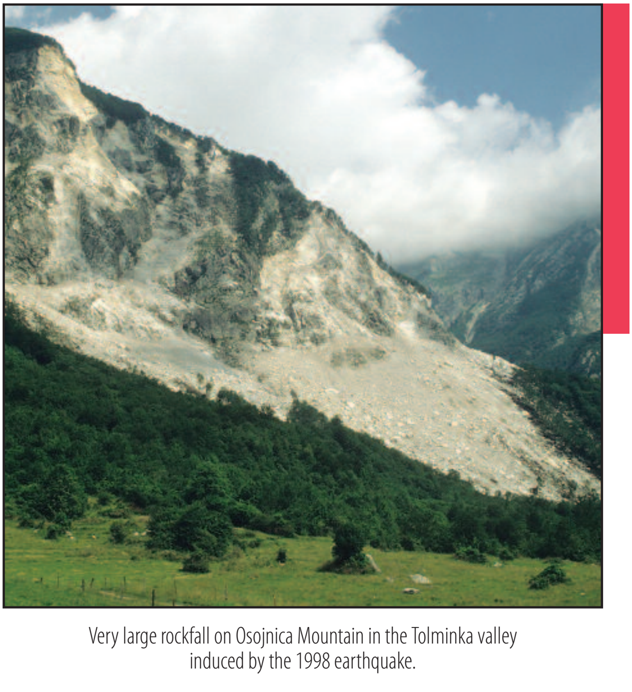
Oblikovanje/Design by: Matjaž Vipotnik.

Front cover photography: Stone bridge over the Rak River on the outskirts of the Rakov Škocjan polje, which is otherwise known for its beautiful natural bridges (photograph: Matej Lipar).
Fotografija na naslovnici: Kamniti most čez reko Rak na obrobju kraškega polja Rakov Škocjan, ki je sicer bolj znano po čudovitih naravnih mostovih (fotografija: Matej Lipar).

Acta geographica Slovenica, 59-1, 2019, 51–61

THE SIZE OF THE AREA AFFECTED BY EARTHQUAKE INDUCED ROCKFALLS: COMPARISON OF THE 1998 KRN MOUNTAINS (NW SLOVENIA) EARTHQUAKE (M_W 5.6) WITH WORLDWIDE DATA

Andrej Gosar



ANDREJ GOSAR

Very large rockfall on Osojnica Mountain in the Tolminka valley induced by the 1998 earthquake.

DOI: https://doi.org/10.3986/AGS.4845
UDC: 550.348.435(497.4)
COBISS: 1.01

The size of the area affected by earthquake induced rockfalls: Comparison of the 1998 Krn Mountains (NW Slovenia) earthquake (M_w 5.6) with worldwide data

ABSTRACT: The 1998 Krn Mountains M_w 5.6 earthquake had widespread effects on the natural environment, among which rockfalls prevail. All rockfalls were evaluated to estimate the total affected area. The 180 km^2 area (r = 7.6 km) was established and compared with two worldwide datasets. The affected area is considerably below the upper bound limit established from both datasets. The same is valid for the nearby 1976 Friuli M_w 6.4 earthquake with a 2050 km^2 affected area. However, comparison with the ESI 2007 scale definitions has shown that the area affected by the 1998 I_{max} VII–VIII event is significantly larger than the one proposed by this scale, but smaller for the 1976 I_{max} X event. This could not be explained by differences in hypocentral depth or focal mechanisms of both events. The results of the study have implications for seismic hazard assessment and for understanding environmental effects caused by moderate earthquakes in mountain regions.

KEY WORDS: earthquake effects, intensity, rockfall, macroseismic investigations, Environmental Seismic Intensity scale, Krn Mountains, Slovenia

Velikost območja pojavljanja skalnih podorov zaradi potresa: primerjava potresa M_w 5,6 leta 1998 v Krnskem pogorju (SZ Slovenija) s svetovnimi podatki

POVZETEK: Potres leta 1998 v Krnskem pogorju z M_w 5,6 je imel obsežne učinke v naravnem okolju, med katerimi so prevladovali skalni podori. Vse podore smo raziskali z namenom ocene velikosti celotnega območja pojavljanja. Ugotovili smo 80 km^2 veliko območje (r = 7.6 km) in ga primerjali z dvema svetovnima zbirkama podatkov. Celotno prizadeto območje ob Krnskem potresu je znatno manjše od zgornje meje pojavljanja ugotovljene za obe zbirki. Enako velja za bližnji potres leta 1976 v Furlaniji z M_w 6,4, pri katerem je bila velikost prizadetega območja 2050 km^2. Po drugi strani pa je primerjava z ESI 2007 pokazala, da je celotno prizadeto območje ob potresu leta 1998 z I_{max} VII–VIII izrazito večje od opredelitve v tej letvici in manjše za potres leta 1976 z I_{max} X. Te razlike ni mogoče pojasniti z razliko v globini žarišča ali razliko v žariščnem mehanizmu obeh potresov. Rezultati te študije so pomembni za ocenjevanje potresne nevarnosti in za razumevanje učinkov na okolje pri srednje močnih potresih v goratih območjih.

KLJUČNE BESEDE: učinki potresa, intenziteta, skalni podor, makroseizmične raziskave, lestvica Environmental Seismic Intensity, Krnsko pogorje, Slovenija

Andrej Gosar
Slovenian Environment Agency, Seismology and Geology Office
and
University of Ljubljana, Faculty of Natural Sciences and Engineering
andrej.gosar@gov.si

The article was submitted for publication on January 4th, 2017.
Uredništvo je prejelo prispevek 4. januarja 2017.

1 Introduction

Earthquakes have long been recognized as an important trigger of slope movements in areas with pronounced topography. For some earthquakes, especially in Asia and Latin America, they have more dramatic consequences than ground shaking itself, through damming narrow valleys (e.g. Komac and Zorn 2016) or burying complete settlements (Guerrieri and Vittori 2007). In areas with unfavourable geomorphic and geologic settings landslides or rockfalls can become a primary source of damage and death toll. For example, in the Peruvian earthquake in 1970, almost half of the 54,000 fatalities were due to an immense landslide that descended from Nevado Huascaran, burying two villages (Reiter 1990).

In spite of their geomorphic and economic significance, earthquake-induced slope movements are still poorly understood, especially how do the number, size and distribution of landslides or rockfalls depend on the magnitude and intensity. For hazard assessment, it is necessary to establish correlations between seismic ground shaking and landslides or rockfalls in different geological, topographical, and climatic conditions. One of the first systematic studies was done by Keefer (1984) who analysed 40 strong historical earthquakes distributed worldwide in the period 1811–1980 with the magnitude range of 5.2–9.5 in order to determine the characteristics, geological environments, and hazards of slope movements. He identified 14 types of slope movements and found out that rockfalls, disrupted soil slides, and rock slides were the most common. Correlations between earthquake magnitude and slope movements distribution show that the maximum affected area increases from approximately 0 km^2 at M = 4.0 to 500.000 km^2 at M = 9.2. Keefer also discovered that each type of earthquake-induced slope movement occurs in a particular geological environment. The work of Keefer (1984) was extended by Rodriguez, Boomer, and Chandler (1999) who studied additional 36 earthquakes in the magnitude range of 5.4–7.8 which occurred between 1980 and 1997 and compared the results of both studies. Their correlation between earthquake magnitude and the total area affected by slope movements differs somewhat from Keefer's. For the intermediate magnitude range of 5.4–7.0, a modified relation was suggested. However, the scatter of data from which the correlation was derived was greater than that found by Keefer.

Both studies analysed the world's largest earthquakes with relatively few examples of weaker events in the magnitude range of 5.2–6.0 or intensities smaller than VII. However, recent studies in Spain have shown that landslides also resulted from lower magnitude (M_w<5.0) earthquakes (Delgado et al. 2011). They were observed at greater distances (> 10 km) in comparison to previous studies. Another study of a M_w 4.7 earthquake with the I_{max} V EMS-98 in central Spain (Delgado et al. 2015) has shown that this event triggered many small rockfalls at distances of 20–30 km from the epicentre. Weak ground-motion attenuation was identified as the most probable reason for occurrence of slope instability at large distances. Maximum epicentral distance of landslide occurrence and the total affected area were both far above the upper bound curves derived by Keefer (1984) or Rodriguez, Boomer, and Chandler (1999). Identification of variations in ground-motion attenuation or areas which are especially prone to slope movements due to geological setting is important for realistic seismic hazard assessment in problematic areas (Papanikolaou 2011).

Various macroseismic scales developed during the 20th century (MCS, MSK, MM, EMS-98) only partly included the effects of earthquakes on the natural environment. But recent studies offered new evidence that coseismic environmental effects (e.g. Komac 2015) provide precious information on the earthquake intensity field, complementing the damage-based macroseismic scales. Therefore, the definition of the higher intensity degrees can effectively take advantage of the diagnostic characteristics of the environmental effects (Guerrieri and Vittori 2007).

The EMS-98 scale, which is predominantly used in Europe, considers four categories (Grünthal 1998): the effect on humans and objects, as well as the damage to buildings and the natural environment. However, environmental effects are only briefly described. The main problem is that the same phenomenon is attributed to a very wide range of intensity degrees, which prevents its practical application.

In 2007, the ESI 2007 was introduced as a scale based only on the effects on the natural environment (Guerrieri and Vittori 2007). According to this scale, secondary effects induced by the ground shaking include ground cracks, slope movements, liquefaction, anomalous waves, and hydrogeological anomalies. The ESI 2007 describes each type's characteristics and size (volume) as a diagnostic feature in a range of intensity degrees. One of the diagnostic characteristics for intensities higher than VI is also the total affected area (Table 1).

Table 1: Extraction from the ESI 2007 scale with a description of slope movements characteristic for each intensity degree (after Guerrieri and Vittori 2007).

Intensity		Slope movements	Total affected area
IV	Largely observed	Exceptionally, rocks may fall and small landslide may be (re)activated, along slopes where the equilibrium is already near the limit state, e.g. steep slopes and cuts, with loose and generally saturated soil.	–
V	Strong	Rare small rockfalls, rotational landslides and slump earth flows may take place, along often but not necessarily steep slopes where equilibrium is near the limit state, mainly loose deposits and saturated soil.	–
VI	Slightly damaging	Rockfalls and landslides with volume reaching ca. 10^3 m^3 can take place, especially where equilibrium is near the limit state, e.g. steep slopes and cuts, with loose saturated soil, or highly weathered/ fractured rocks.	–
VII	Damaging	Scattered landslides occur in prone areas, where equilibrium is unstable (steep slopes of loose/saturated soils), while modest rockfalls are common on steep gorges, cliffs). Their size is sometimes significant (10^3–10^5 m^3); in dry sand, sand-clay, and clay soil, the volumes are usually up to 100 m^3.	10 km^2
VIII	Heavily damaging	Small to moderate (10^3–10^5 m^3) landslides are widespread in prone areas; rarely they can occur also on gentle slopes; where equilibrium is unstable (steep slopes of loose/saturated soils; rockfalls on steep gorges, coastal cliffs) their size is sometimes large (10^5–10^6 m^3).	100 km^2
IX	Destructive	Landsliding is widespread in prone areas, also on gentle slopes; where equilibrium is unstable (steep slopes of loose/saturated soils; rockfalls on steep gorges, coastal cliffs) their size is frequently large (10^5 m^3), sometimes very large (10^6 m^3).	1,000 km^2
X	Very destructive	Large landslides and rockfalls (>10^5–10^6 m^3) are frequent, practically regardless of equilibrium state of slopes, causing temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse.	5,000 km^2
XI	Devastating	Large landslides and rockfalls (>10^5–10^6 m^3) are frequent, practically regardless of equilibrium state of slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Significant landslides can occur even at 200–300 km distance from the epicenter.	10,000 km^2
XII	Completely devastating	Large landslides and rockfalls (>10^5–10^6 m^3) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Significant landslides can occur at more than 200–300 km distance from the epicenter.	50,000 km^2

The 12 April 1998 earthquake in Krn Mountains (Figures 1 and 2) had prominent effects on the natural environment, mainly expressed as massive rockfalls. The earthquake magnitude (M_w) was 5.6 and its I_{max} was VII–VIII EMS-98 (Zupančič et al. 2001). It caused severe damage to buildings in the Upper Soča valley but no casualties. Some of its effects have already been discussed in this journal (e.g. Zorn 2002). The affected area is predominantly a sparsely inhabited mountainous environment. The application of the EMS-98 scale for intensity assessment was therefore limited to only a few settlements in the epicentral area. There was an early attempt to also use environmental effects to assess the intensities using the EMS-98 scale (Vidrih, Ribičič, and Suhadolc 2001), but it was determined that this scale is not sufficiently detailed in descriptions of effects characteristic for particular intensity degrees. After the ESI 2007 was presented, Gosar (2012) performed a study aimed to evaluate its applicability to this event. It was proved that the ESI 2007 can be successfully applied in the epicentral area to supplement the EMS-98 scale for intensity assessment, although the ESI 2007 is mainly aimed to evaluate much stronger earthquakes.

The 1998 earthquake, an event with a relatively moderate magnitude, was not expected to cause such a large number of rockfalls, including some large and very large ones. Since the damage was concentrated mainly to buildings with poor seismic design (Komac, Zorn, and Kušar 2012) or to areas with pronounced site effects (Gosar 2007), rockfalls were the most prominent characteristic of this event (Vidrih and Ribičič 1998). It is therefore a challenge to compare the extent of environmental effects with other earthquakes worldwide and especially with the nearby 1976 Friuli Mw 6.4 earthquake. The latter occurred 35 km to the West in NE Italy (Aoudia et al. 2000; Carulli and Slejko 2005) in mountains with a similar geological setting (Govi and Sorzana 1977). Since the type of environmental effects depends largely on the geological setting (for

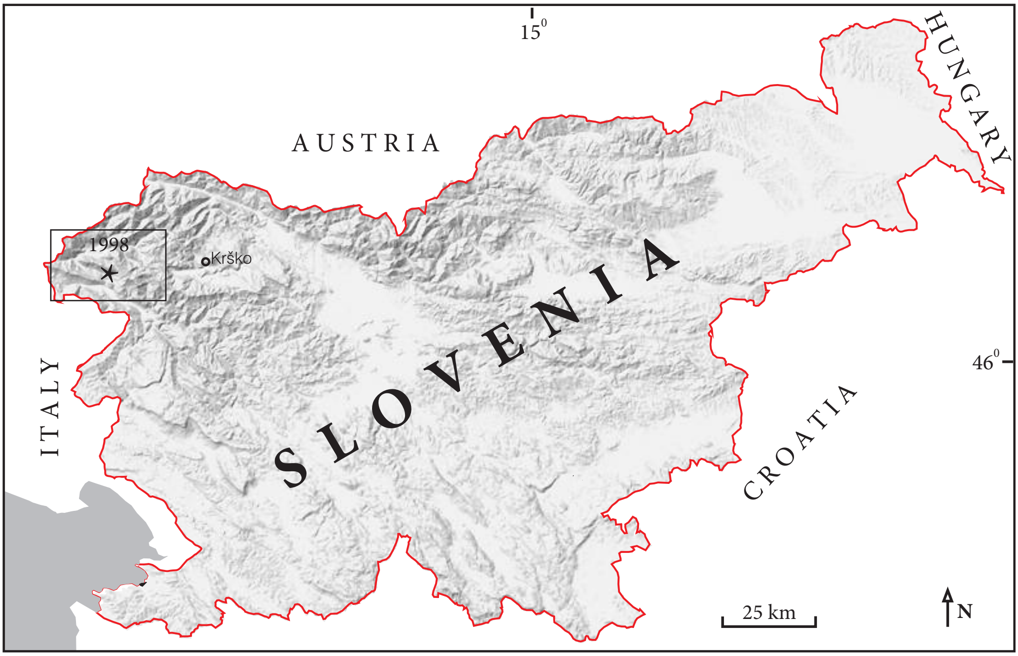


Figure 1: Location map of the study area with the epicentre of the 12th April 1998 earthquake in Krn Mountains.

example landslides prevail in looser rocks and rockfalls in harder rocks), one of the possibilities for comparison included in the ESI 2007 scale is the size of the total affected area. The aim of this study was therefore to compare the total affected area of the 1998 earthquake with available data from worldwide studies to see if this earthquake deviates from established relationships between the magnitude or maximum intensity of the event and the total area affected by slope movements.

2 Methods

The extensive effects of the 1998 earthquake on the natural environment were spread over a large area and therefore required a systematic approach in data collection and analysis. Soon after the earthquake occurred it became apparent that rockfalls were the most frequent phenomenon and the only one spread over the total affected area (Vidrih and Ribičič 1998). A systematic approach was particularly important because the wider epicentral area is situated in high mountains, where access roads are only available in certain valleys. Data collection and analysis were therefore based on a combination of field surveys and analyses of aerial photographs.

Rockfalls and landslides were surveyed in the field in the months following the earthquake and a database of rockfalls was prepared. A regular aerial photography survey of the NW part of Slovenia was carried out in July 1998, just three months after the earthquake, which was very useful for this study. Rockfalls were clearly visible on these images because the newly exposed surfaces or rock debris and blocks were still fresh, before lichens and vegetation started to change their surfaces. Stereo pairs of aerial images were analysed using stereo glasses while Digital Ortho Photos were analysed with GIS software.

Quantitative assessment of the rockfall and landslide size (volume) is important for the application of various criteria in the ESI 2007 scale, but not so much for the assessment of the total affected area. For landslides this is normally easier, because it is possible to measure the area and estimate the average thickness of the landslide body. Rockfalls are much more irregular than landslides, which is why estimation of their volume is usually more difficult and requires more experience. Krn Mountains are built of Mesozoic carbonates, predominantly of Upper Triassic limestones and dolomites (Zupančič et al. 2001). The area is cut by several faults which extend mainly in the NW-SE direction. In general the rocks are highly fractured, loose, and prone to slope movements.

3 Rockfalls induced by the 12th April 1998 earthquake

Detailed investigations showed that the earthquake caused at least 78 rockfalls (Figure 2). These were classified into five groups according to their estimated volume (Table 2). The distribution of very small rockfalls, which predominate in number (53), is quite uneven. On the other hand, medium to very large rockfalls are clearly distributed in a zone approximately 5 km wide and 9 km long, which extends in a NW-SE direction, along the seismogenic Ravne fault (Figure 2). The termination of rockfalls occurrence is very sharp to the SE of the epicentre, in the Tolminka valley, but more gradual to the NW, W, and N. The strong motion data inversion revealed that the Ravne fault ruptured in a length of 12 km between the Bovec basin and the Tolminka valley (Bajc et al. 2001). The majority of the medium, large, and very large rockfalls occurred along the same segment.

Table 2: Distribution of rockfalls caused by 12 April 1998 earthquake according to their size.

Size of rockfall	Estimated volume (m^3)	Number
Very small	10^2	53
Small	10^3	13
Medium	10^4	6
Large	10^5	4
Very large	$>10^6$	2

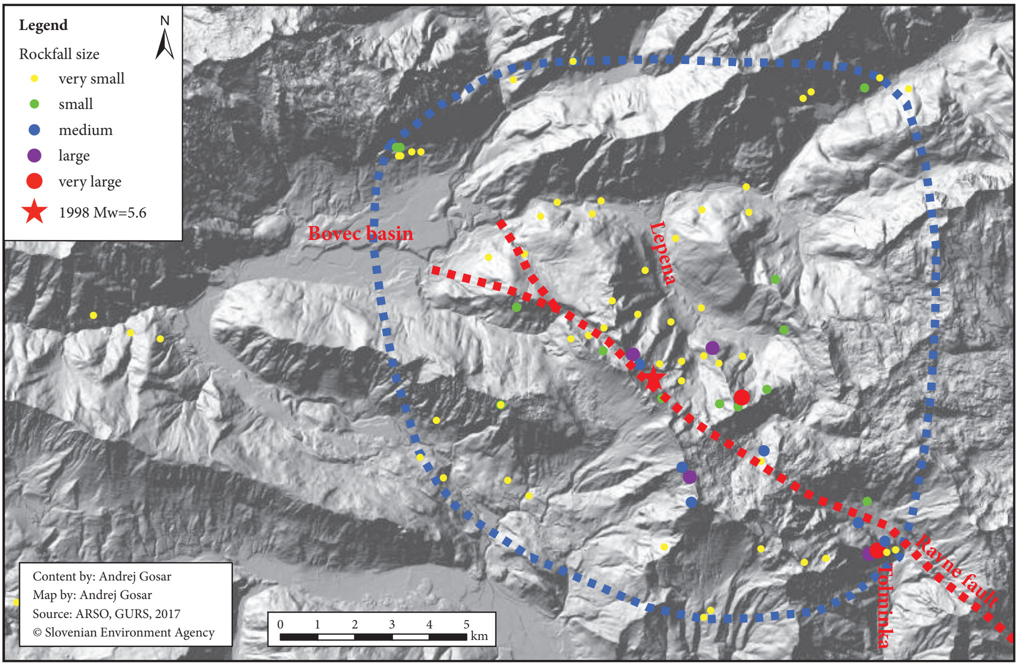
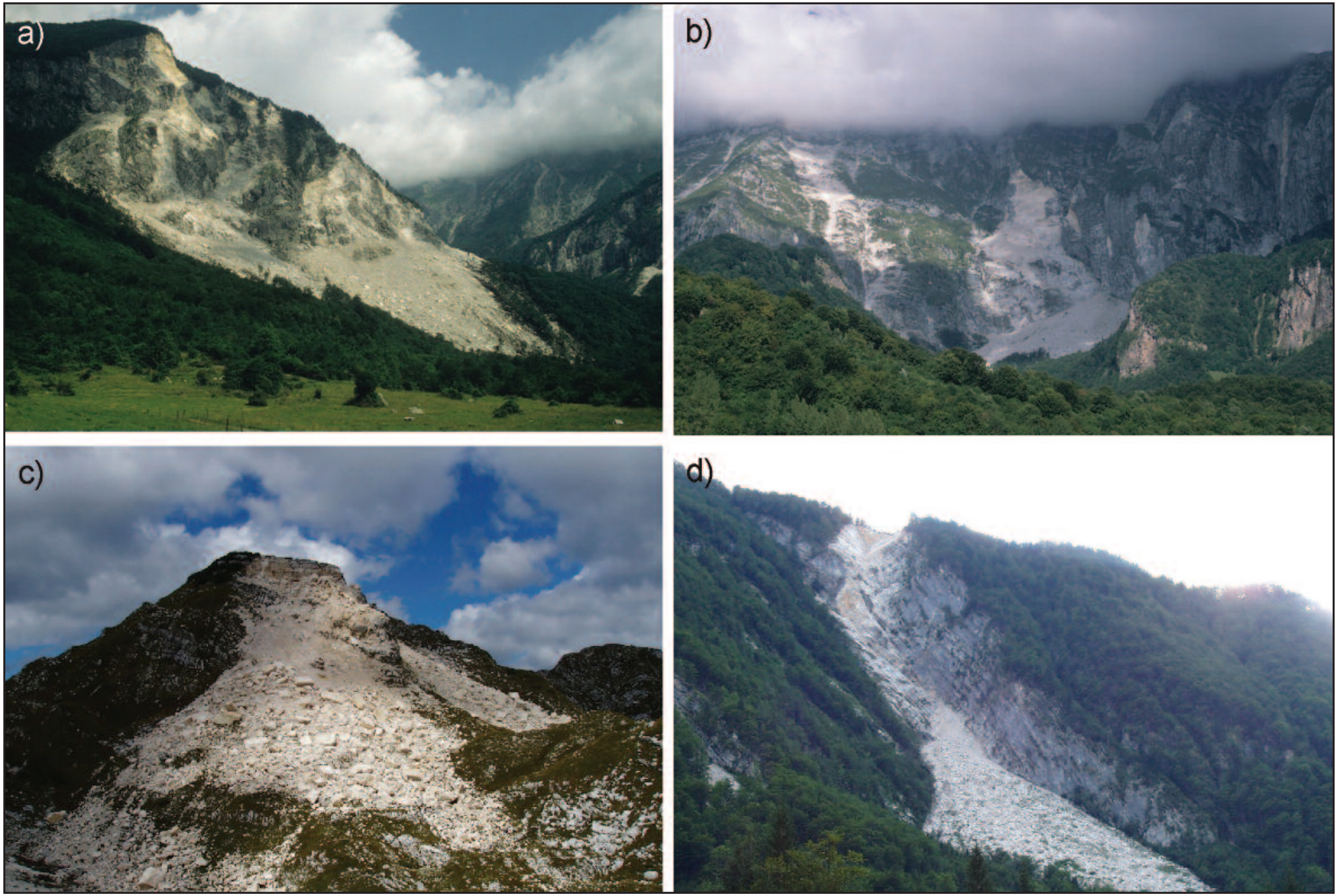


Figure 2: Locations of rockfalls in the Upper Soča valley caused by the 12 April 1998 earthquake with a contour of the total affected area (blue dashed line) and the trace of the seismogenic fault (red dashed line).

Figure 3: Larger rockfalls in Krn Mountains: a) Osojnica in Tolminka valley, b) Krn and Krnčica, c) Veliki Šmohor, d) Škril in Lepena valley. ➤


a)
b)
c)
d)

The largest rockfall occurred on Veliki Lemež in the Lepena valley. Its volume was estimated as 15×10^6 m^3 by comparing two digital elevation models which show the topography of the area before and after the earthquake. The second largest rockfall with the estimated volume of 3×10^6 m^3 occurred on Osojnica Mountain above the Tolminka valley (Figure 3a). Four rockfalls were classified as large. On the slopes of Krn and Krnčica Mountains several massive planar rockslides occurred (Figure 3b), developed along cracks or bedding planes within limestone dipping downslope. The Škril rockfall (Figure 3d) is a typical example of a wedge-shaped rockslide (Vidrih 2008). There were six rockfalls of medium size. An example is the Veliki Šmohor rockfall (Figure 3c), where the top of the mountain collapsed even though the slope is not very steep.

4 Comparison of the total area affected by rockfalls induced by the 1998 earthquake with worldwide data and the ESI 2007 intensity scale

Figure 2 shows the distribution of all 78 rockfalls classified according to their volume. The density of rockfalls over the affected area is quite uneven, depending on the spatial distribution of slope failure prone areas. On average there were three rockfalls per km^2, but the number ranges from one rockfall at larger distances from the epicentre to more than five rockfalls per km^2 in the closest epicentral area. A detailed analysis has

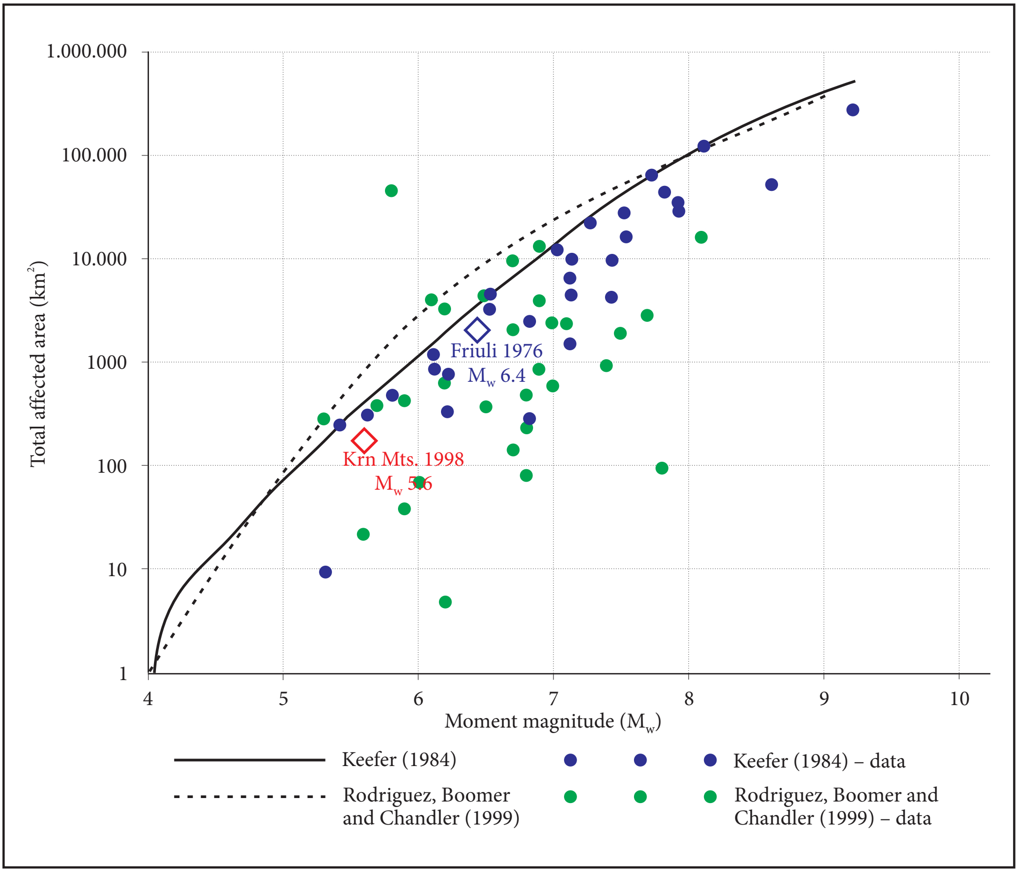


Figure 4: The area affected by rockfalls or landslides as a function of earthquake magnitude for 40 events which occurred worldwide in 1811–1980 (Keefer 1984) and 36 events in 1980–1997 (Rodriguez, Boomer and Chandler 1999), and the data for the 1976 Friuli and 1998 Krn Mountains earthquakes. The solid line is the upper bound determined by Keefer (1984) and the dashed line is the one determined by Rodriguez, Boomer, and Chandler (1999).

shown that all very small rockfalls (10^2 m^3) cannot reliably determine the total affected area because some of them occurred quite far from other observed phenomena. Such examples are the very small rock slides that occurred in the westernmost part of the investigated area (Figure 2). Therefore, we decided to draw a contour which delimits the total affected area as a limit of continuous (nearly spaced) observations of rockfalls which includes all small (10^3 m^3) and large (10^5 m^3) rockfalls (Figure 2), missing only a few very small ones. The area is nearly circular with a radius of approximately 7.6 km and a size of 180 km^2. As already mentioned, the distribution of medium, large, and very large rockfalls clearly shows an elongated shape along the strike of the seismogenic Ravne fault (NW–SE) terminating sharply in the SE. The distribution of small and very small rockfalls is more uniform, with fewer observed occurrences only in the eastern part, characterized by karstified surfaces and less prominent topography and thus less prone to slope failures.

The obtained results were first compared with the 1976 Friuli Mw 6.4 earthquake for which Govi and Sorzana (1977) made a detailed evaluation of slope movements based on aerial photo interpretation and field mapping. They discovered that photo interpretation is a very effective method, that rockfalls occurred mainly in places where they had already occurred in the past, and that the weakening of rocks by tectonic fracturing is an important factor for rockfall distribution. However, this study does not include a map of rockfall distribution. The total affected area was estimated by Keefer (1984), based on studies of Ambraseys (1976) and Govi (1977), to be 2050 km^2 large. This corresponds to a circle with $r = 25.5$ km. A significantly stronger earthquake in a geologically similar area where Mesozoic carbonates prevail resulted in the considerably larger affected area, as expected (Govi and Sorzana 1977).

The results of the 1998 earthquake were then compared with the results for worldwide datasets, and established relations for the upper bound limit in the relation between the total affected area and earthquake magnitude according to Keefer (1984) and Rodriguez, Boomer, and Chandler (1999). Even though rockfalls were the most prominent and widespread phenomenon of this earthquake, the total affected area (180 km^2) is still much smaller than the established upper bound limits (Figure 4). For the Mw 5.6 earthquake the upper bound limit of the affected area is 430 km^2 according to Keefer (1984) and 880 km^2 according to Rodriguez, Boomer, and Chandler (1999).

Comparison of the relation between the total affected area and the macroseismic intensity using the ESI 2007 scale has shown that the area affected by the 1998 earthquake with I_{max} VII–VIII significantly exceeds the value expected from the ESI 2007 scale (Figure 5). According to the ESI 2007 an area of about 30 km^2 is expected at this intensity, interpolated between 10 km^2 at intensity VII and 100 km^2 at intensity VIII (Table 1, Figure 5). On the other hand, the area of 2050 km^2 affected by the 1976 earthquake with I_{max} X (Giorgetti 1976) is lower than the value expected from the ESI 2007, which assigns a total affected area of 5000 km^2 to intensity X (Table 1, Figure 5).

The affected area depends not only on the magnitude of the earthquake but also on its hypocentral depth. When comparing the 1998 and the 1976 earthquakes, the difference in hypocentral depth is minimal, namely 7.6 km for the former and 6 km for the latter. For the Friuli event the focal depth was first estimated at 25 km (Console 1976) due to the large distance from the epicentre to the nearest seismic station in Trieste. However, the relocation study of Aoudia et al. (2000) estimates it at 6 km. The second parameter which can affect the shape and size of the affected area is the focal mechanism which influences the radiation of seismic energy from the source. It was a reverse one (a W–E trending fault) for the Friuli event (Console 1976) and almost a pure dextral strike-slip (a NW–SE trending fault) for the Krn Mountains event (Zupančič et al. 2001). The elongated shape of the area affected by medium to very large rockfalls in Krn Mountains is related to the direction of the strike-slip fault, but the total affected area seems to be more or less circular (Figure 2).

5 Conclusion

Although the 1998 Krn Mountains earthquake was an event with a relatively moderate magnitude (Mw 5.6), it had prominent and widespread environmental effects expressed mainly as rockfalls of different sizes. Nevertheless, comparison of the total affected area of 180 km^2 with established relations for worldwide datasets of mainly stronger earthquakes has shown that this area is still considerably below the upper bound limit determined by Keefer (1984) and Rodriguez, Boomer, and Chandler (1999). The same is true for the 1976 Friuli Mw 6.4 earthquake which had a total affected area of 2050 km^2. However, comparison with the ESI 2007

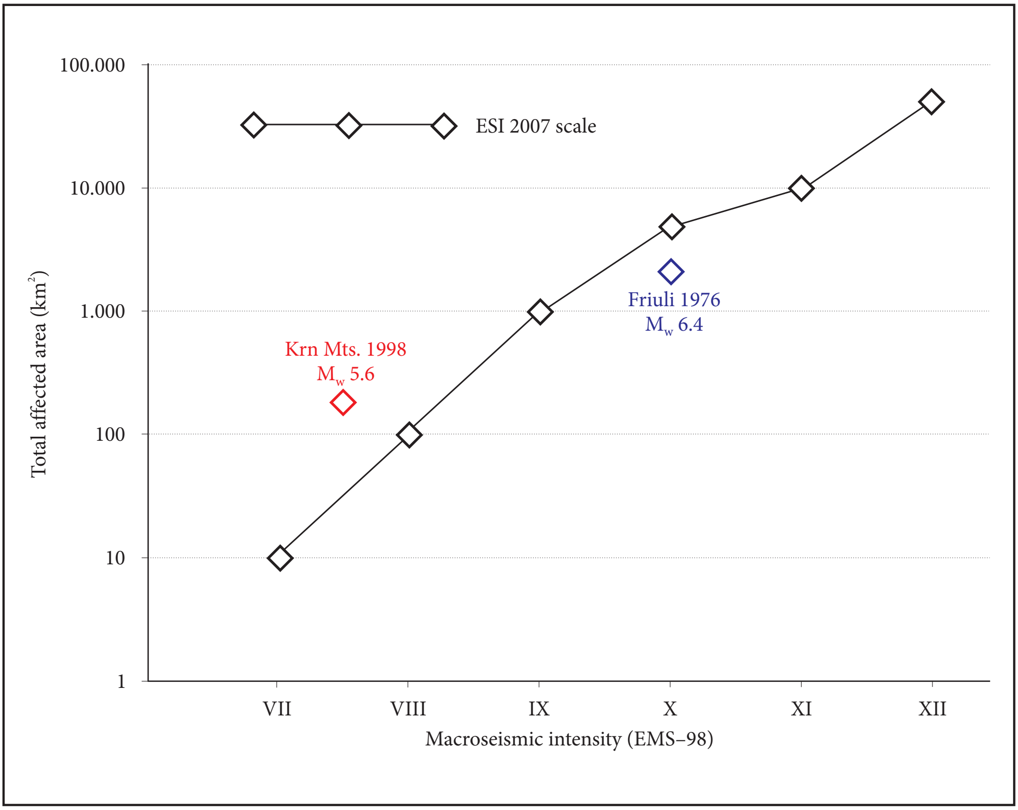


Figure 5: The area affected by earthquake environmental effects as a function of maximum intensity according to the ESI 2007 scale (Guerrieri and Vittori 2007) and the data for the 1976 Friuli and 1998 Krn Mountains earthquakes.

scale has shown that the total affected area in the Krn Mountains earthquake is significantly larger than what this scale proposes for an I_{max} VII–VIII event. For the Friuli I_{max} X earthquake, the affected area is much lower than expected from the ESI 2007 scale. This difference could not be explained by diffeences in hypocentral depth or focal mechanisms of the two earthquakes. The results of this study have implications for realistic seismic hazard assessment – identification of slower ground-motion attenuation or areas prone to slope movements due to geological setting. They also provide insight into environmental seismic effects caused by moderate magnitude earthquakes in mountain regions, built of carbonate rocks prone to slope failures.

ACKNOWLEDGEMENTS: The study was realized with the support of the research program P1-0011 financed by the Slovenian Research Agency. The author is grateful to Mihael Ribičič, Marko Kočevar, and Tomaž Beguš for their contribution in field documentation of rockfalls.

6 References

Ambraseys, N. N. 1976: The Gemona di Friuli earthquake of 6 May 1976 UNESCO Technical Report RP 1975-76. Paris.

ARSO 2017: Database of earthquake induced rockfalls in Krn Mountains. Ljubljana

Aoudia, A., Sarao', A., Bukchin, B., Suhadolc, P. 2000: The Friuli 1976 event: a reappraisal 23 years later. Geophysical Research Letters 27-4. DOI: https://doi.org/10.1029/1999GL011071

Bajc, J., Aoudia, A., Sarao, A., Suhadolc, P. 2001: The 1998 Bovec-Krn mountain (Slovenia) earthquake sequence. Geophysical Research Letters 28-9. DOI: https://doi.org/10.1029/2000GL011973

Carulli, G. B., Slejko, D. 2005: The 1976 (NE Italy) earthquake. Giornale di Geologia Applicata 1. DOI: https://doi.org/10.1474/GGA.2005-01.0-15.0015

Console, R. 1976: Focal mechanism of some Frioul earthquakes (1976). Bollettino di Geofisica Teorica ed Applicata 19.

Delgado, J., Palaez, J. A., Tomas, R., Garcia-Tortosa, F. J., Alfaro, P., Lopez-Casado, C. 2011: Seismically-induced landslides in the Betic Cordillera (S Spain). Soil Dynamics and Earthquake Engineering 31-9. DOI: https://doi.org/10.1016/j.soildyn.2011.04.008

Delgado, J., Garcia-Tortosa, F. J., Garrido, J., Loffredo, A., Lopez-Casado, C., Martin-Rojas, I., Rodriguez, M. J. 2015: Seismically-induced landslides by low-magnitude earthquake: The Mw 4.7 Ossa De Montiel event (central Spain). Engineering Geology 196. DOI: https://doi.org/10.1016/j.enggeo.2015.07.016

Giorgetti, F. 1976: Isoseismal map of the May 6, 1976 Friuli earthquake. Bollettino di Geofisica Teorica ed Applicata 19.

Gosar, A. 2007: Microtremor HVSR study for assessing site effects in the Bovec basin (NW Slovenia) related to 1998 Mw5.6 and 2004 Mw5.2 earthquakes. Engineering geology 91, 2-4. DOI: https://doi.org/10.1016/j.enggeo.2007.01.008

Gosar, A. 2012: Application of Environmental Seismic Intensity scale (ESI 2007) to Krn Mountains 1998 Mw=5.6 earthquake (NW Slovenia) with emphasis on rockfalls. Natural Hazards and Earth System Sciences 12-5. DOI: https://doi.org/10.5194/nhess-12-1659-2012

Govi, M. 1977: Photo-interpretation and mapping of the landslides triggered by the Friuli earthquake (1976). Bulletin of the International Association of Engineering Geology 15-1.

Govi, M., Sorzana P. F. 1977: Effetti geologici del terremoto: frane. Rivista Italiana di Paleontologia e Stratigrafia 83.

Grünthal, G. 1998: European Macroseismic Scale 1998. Luxemburg.

Guerrieri, L., Vittori, E. 2007: Intensity scale ESI 2007. Memorie Descritive della Carta Geologica d'Italia 74. Rome.

GURS 2017: Digital elevation model of Slovenia – 5 m resolution. Surveying and Mapping Authority of Slovenia. Ljubljana.

Keefer, D. K. 1984: Landslides caused by earthquakes. Geological Society of America Bulletin 95. DOI: https://doi.org/10.1130/0016-7606(1984)95%3C406:LCBE%3E2.0.CO;2

Komac, B., Zorn, M., Kušar, D. 2012: New possibilities for assessing the damage caused by natural disasters in Slovenia - The case of the real estate record. Geografski vestnik 84-1.

Komac, B. 2015: Modeliranje obpotresnih pobočnih procesov v Sloveniji. Geografski vestnik 87-1. DOI: https://doi.org/10.3986/GV87107

Komac, B., Zorn, M. 2016: Naravne in umetne pregrade ter z njimi povezani hidro-geomorfni procesi. Geografski vestnik 88-2. DOI: https://doi.org/10.3986/GV88204

Papanikolaou, I. D. 2011: Uncertainty in intensity assignment and attenuation relationships: How seismic hazard maps can benefit from the implementation of the Environmental Seismic Intensity scale (ESI 2007). Quaternary International 242-1. DOI: https://doi.org/10.1016/j.quaint.2011.03.058

Reiter, L. 1990: Earthquake hazard analysis. New York.

Rodriguez, C. E., Boomer, J. J., Chandler, R. J. 1999: Earthquake-induced landslides: 1980-1997. Soil Dynamics and Earthquake Engineering 18. DOI: https://doi.org/10.1016/S0267-7261(99)00012-3

Vidrih, R., Ribičič, M. 1998: Slope failure effects in rocks at earthquake in Posočje on April, 12 1998 and European Macroseismic Scale (EMS-98). Geologija 41. DOI: https://doi.org/10.5474/geologija.1998.019

Vidrih, R., Ribičič, M., Suhadolc, P. 2001: Seismogeological effects on rocks during 12 April 1998 upper Soča Territory earthquake (NW Slovenia). Tectonophysics 330. DOI: https://doi.org/10.1016/S0040-1951(00)00219-5

Vidrih, R. 2008: Seismic activity of the upper Posočje area. Ljubljana.

Zorn, M. 2002: Rockfalls in Slovene Alps. Acta Geographica Slovenica 17.

Zupančič, P., Cecić, I., Gosar, A., Placer, L., Poljak, M., Živčić, M. 2001: The earthquake of 12 April 1998 in the Krn Mountains (Upper Soča valley, Slovenia) and its seismotectonic characteristics. Geologija 44-1. DOI: https://doi.org/10.5474/geologija.2001.012