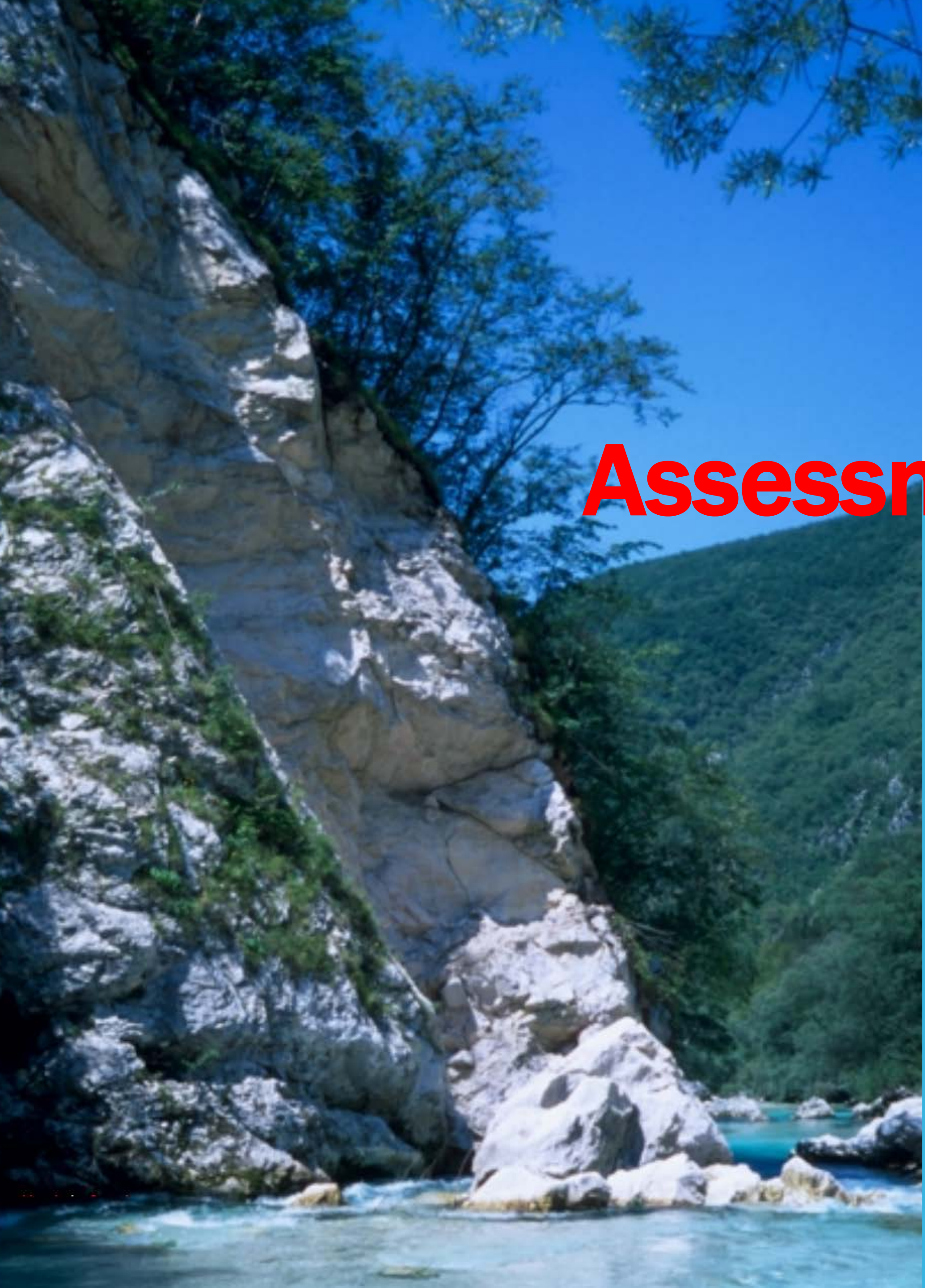

Assessment of co-seismic slope processes in Slovenia

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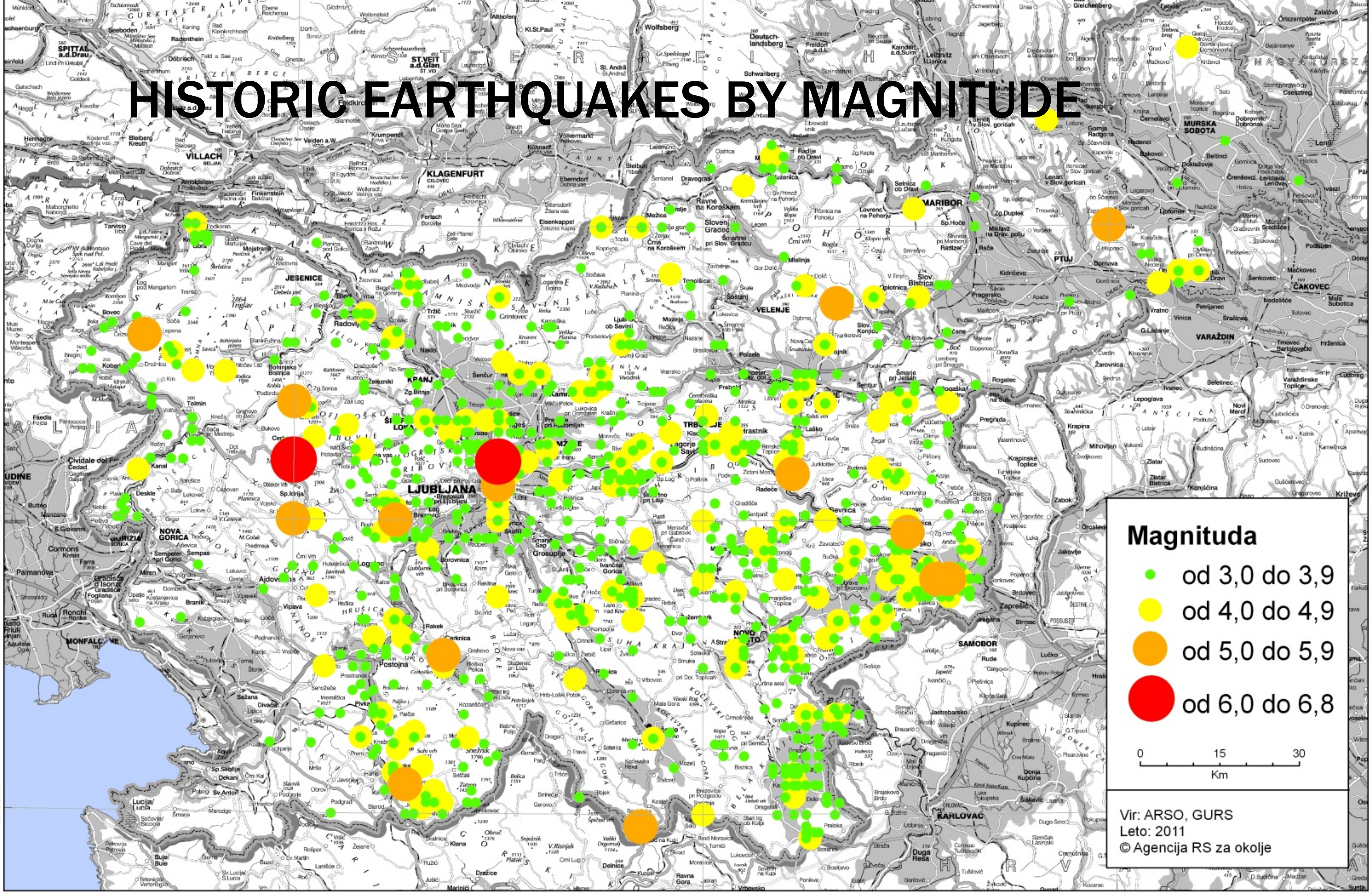
Earthquakes are frequent phenomena in Slovenia

- Contact of Alpine & Dinaric tectonic systems
- Adriatic tectonic plate
- Number of faults (Idrija fault, Sava fault)

Several large earthquakes hit the area in history

- The first strong known earthquake was in 1348
- The last strong earthquakes were in 1976 (M6.5), 1998 (M5.7) and 2004 (M4.9)

HISTORIC EARTHQUAKES BY MAGNITUDE



CO-SEISMIC SLOPE PROCESSES

The most frequent co-seismic geomorphological features:

- cracks (30%),
- landslides (20%) and
- rockfalls (14%).

Co-seismic slope processes (1/3) cause most of the damage during earthquakes.

(Keefer 1984; Prestininzi &Romeo 2000; Yin, Wang &Sun 2009)

Earthquakes lower the cohesion and shear strength of rocks.

The magnitude of earthquake-triggered slope processes depends on earthquake magnitude:

- **VI** EMS: Stones and rocks are falling, small cracks form
- **VII** EMS Middle-size rockfalls
- **VIII** EMS Rockfalls and large rockfalls, large cracks
- **IX** EMS Regional rockfalls

(Keefer 1984; Vidrih, Ribičič &Suhadolc 2001)

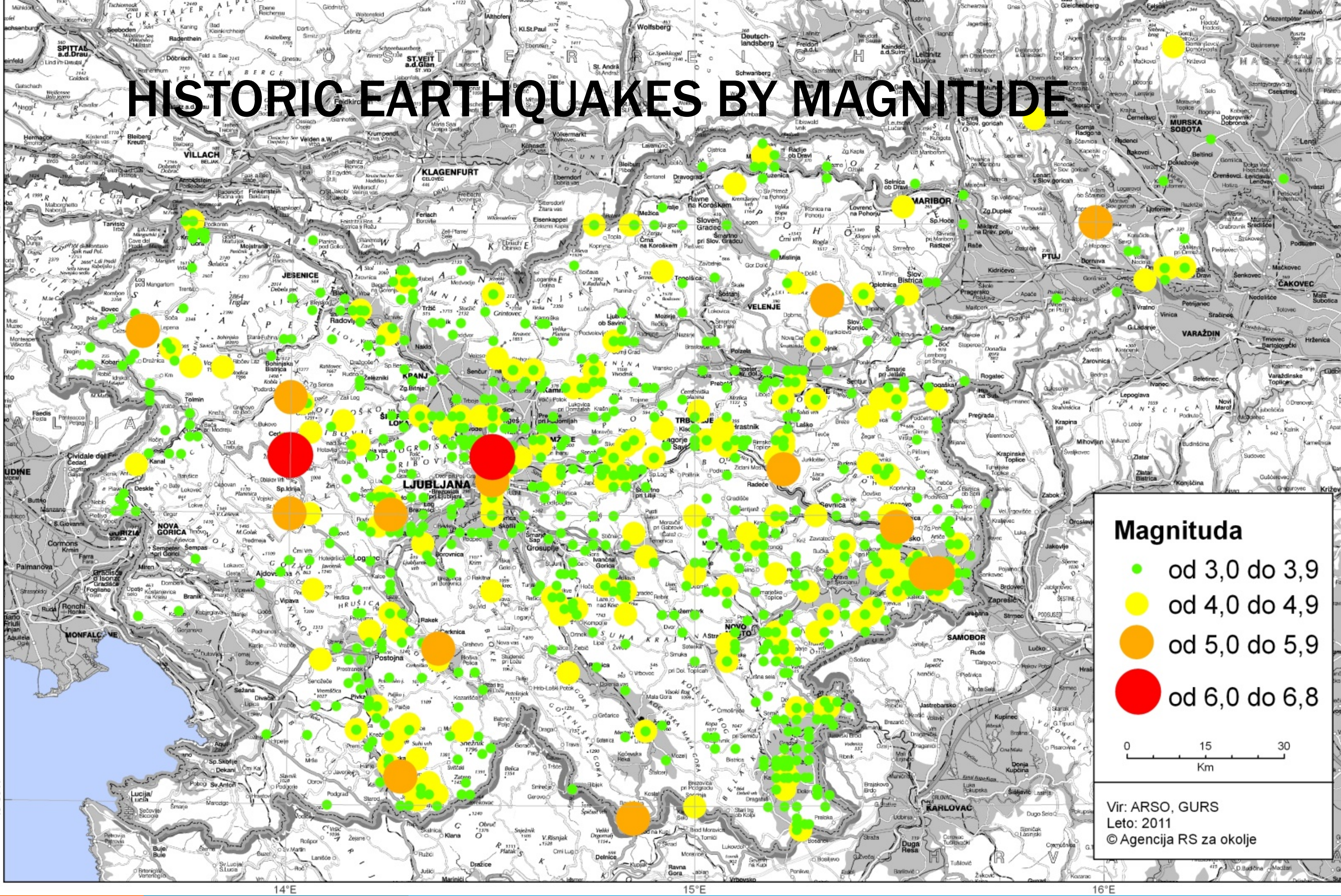
VII EMS may trigger small rockfalls

50 earthquakes of this size in Slovenia since 16C

15 earthquakes in 20C only

1348 Pontebba, Italija	**6**.4	VIII-IX	Large/reginal
1511 Idrija - Cerkno	**6**,8	X	Regional
1690 Villach, Avstrija	**5**,9	VIII	Large
1880 Zagreb, Hrvaška	**6**,2	VII	Middle-size
1895 Ljubljana	**6**,1	VIII-IX	Large-regional
1976 Gemona, Italija	**6**,5	VIII-IX	Regional
1998 Bovec	**5**,7	VII-VIII	Large
2004 Bovec	**4**,9	VI-VII	Middle-size

HISTORIC EARTHQUAKES BY MAGNITUDE



Earthquake-triggered slope processes received global attention during the Wenchuan earthquake in 2008.

Slovenia experienced them 10-15 years ago when approximately 150 large rockfalls were triggered in the Bovec region:

- 12.4.1998, M 5.7 VII-VIII EMS: **100**
- 12.7.2004, M 4,9 VII EMS: **50**

(Vidrih & Ribičič 1998; Vidrih, Ribičič & Suhadolc 2001; Komac & Zorn 2002; Zorn 2002a; Natek, Komac & Zorn 2003; Mikoš, Fazarinc & Ribičič 2006)

Rockfall size (m^3)	1998		2004	
	Number of rockfalls	Total/average volume of rockfalls (m^3)	Number of rockfalls	Volume of rockfalls (m^3)
100–1000	28	14.000/**500**	**32**	16.000
1000–10.000	**13**	26.000/**2000**	**6**	12.000
10.000-100.000	**4**	100.000/**25,000**	0	1
Above 100.000	**5**	800.000/**160,000**	0	1
Total	**50**	**940.000**	**38**	**28.000**

(Vidrih & Ribičič 1998; Vidrih, Ribičič & Suhadolc 2001; Komac & Zorn 2002; Zorn 2002a; Natek, Komac & Zorn 2003; Mikoš, Fazarinc & Ribičič 2006)

DISTANCE TO FAULTS

Most of earthquake-triggered slope-process lie close to faults which present zones of tectonic tension.

- Example from Italy: 60% < 10 km, max. distance to the nearest fault was 25 km
- Slovenia (1998): **60% < 400 m**, max. distance to the nearest fault was 2 km

(for Italian case: Gasparini et al. 1997; Esposito et al. 2000; Prestininzi & Romero 2000)

TOPOGRAPHIC EFFECT

The topographic effect causes larger oscilation of the upper parts of slopes

- Coalinga, California M6.7 ground acceleration at the top of slope was 0.5g, while 0.25g at the bottom.
- Whittier Narrows, California, erthquake waves amplitude was 10x higher on 60m hill than in the nearby plane.
- Northridge, California, 17.1.1994, M6.7: 56% of 11.000 shallow landslides occured in the upper ¼ of slopes

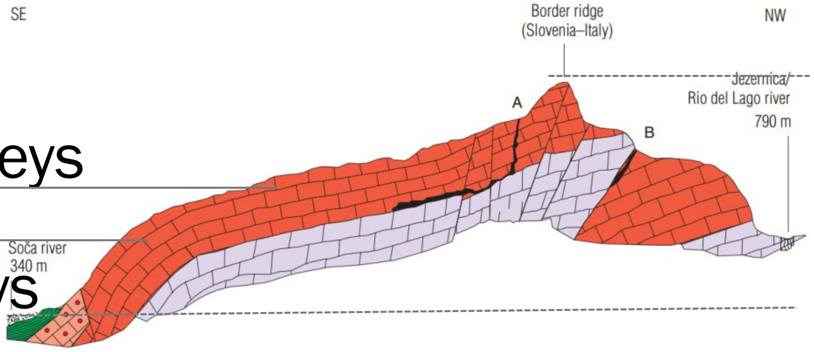
(Murphy et al. 2000; Petley & Murphy 2001; Davis in West 1973; Bouchon 1973; Geli, Bard in Julien 1988; Natek, Komac in Zorn 2003; Spudich, Hellweg & Lee 1996)

During the Soča Valley earthquake 12.4.1998, M5.7

Most of the slope processes were triggered a few hundred metres above the valley bottom. Approximately half of them were rockfalls.

¼ of rockfalls 1000 m above valleys

¾ of rockfalls 700 m above valleys



(max relative height is about 2200m)

(Natek, Komac &Zorn 2003)

Co-seismic slope processes are an important geomorphological factor in the reshaping of slopes and mountain ridges.

The 1998&2004 earthquakes released almost 1Mm^3 of material:

30% remained on the slopes

20% ended in watercourses

50% can **connect to watercourses**

(About the same amount of material was released by the Stovžje debris flow.)

ROCKFALL & LANDSLIDE DAMS

The released sediments can block watercourses

The Wenchuan earthquake caused 828 landslide (and rockfall) dams

40 % of them were partial and 60 % full blockage

60 % of the dams are spilled-over in one month time,
14 % remain in long-term

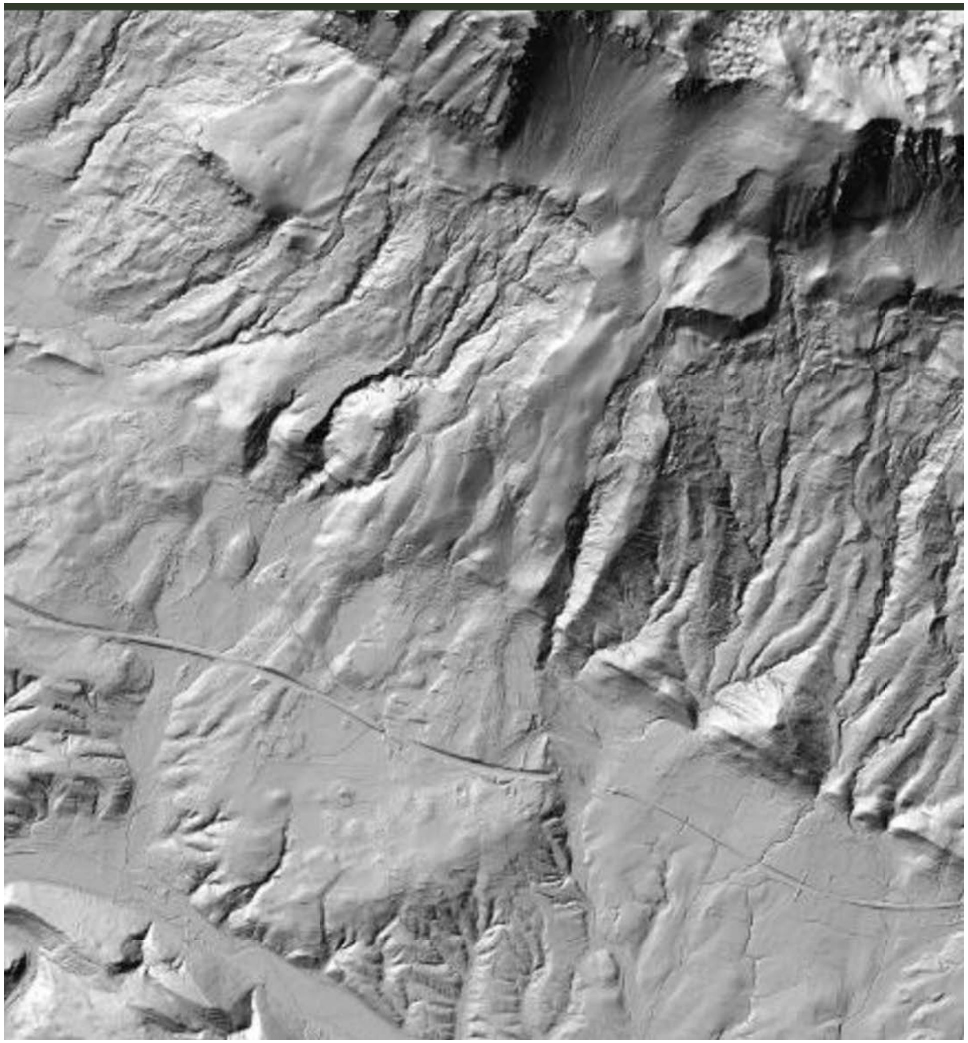
(Costa & Schuster 1988; Korup 2002; Korup, McSaveney & Davies 2004; Komac, Natek & Zorn 2008; Fan et al. 2012).

LANDSLIDE DAMS IN SLOVENIA

In Slovenia about 10% of known slope processes can connect to watercourses. Some examples:

Time	Region	Event	Cause
15,000 BP	Julian Alps	rockfall dam	unknown
1511	Julian Alps	rockfall dam	earthquake
1511	Julian Alps	possible rockfall dam	earthquake
1348	Gailtal/Zilja Alps	rockfall dam	earthquake
1990	Kamnik-Savinja Alps	landslide dam	floods
2004	Julian Alps	rockfall dam	unknown

(Košir & Cecić 2011; Cecić 2011; Komac & Zorn 2009; Komac, Natek & Zorn 2008; Buser 1986; Zorn 2002a; Bavec et al. 2004; Zorn 2002b)

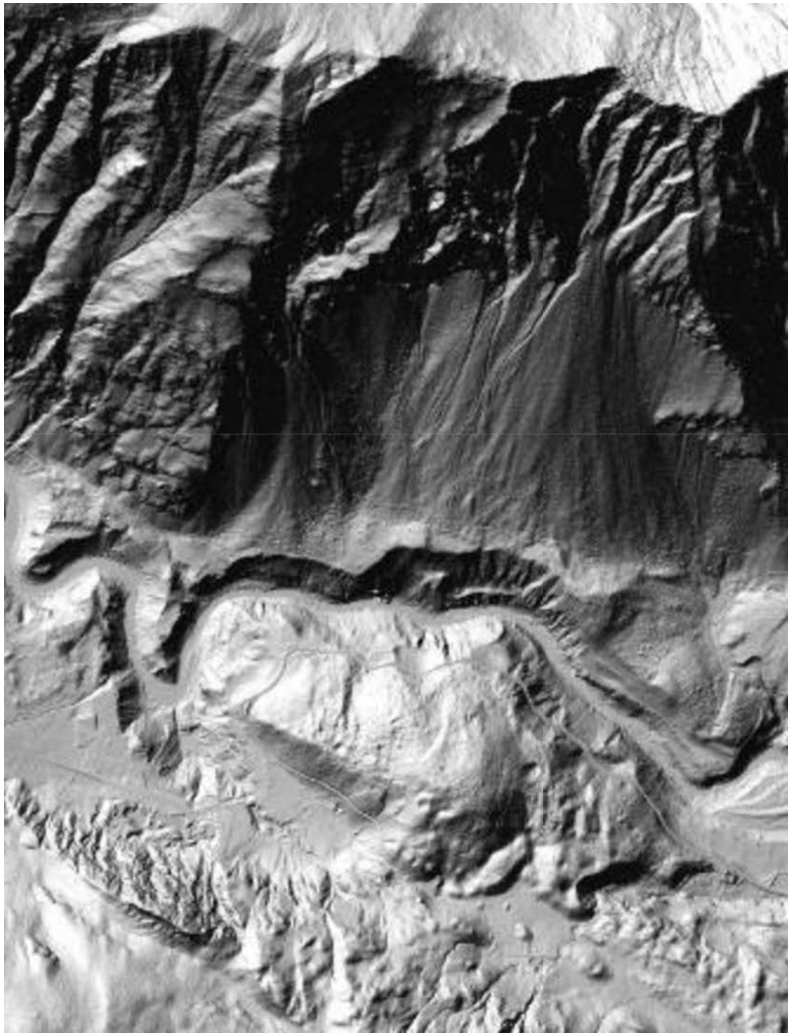


Vipava valley, Selo

Rockfall

15,000 BP

150 M m^3, 10 km^2



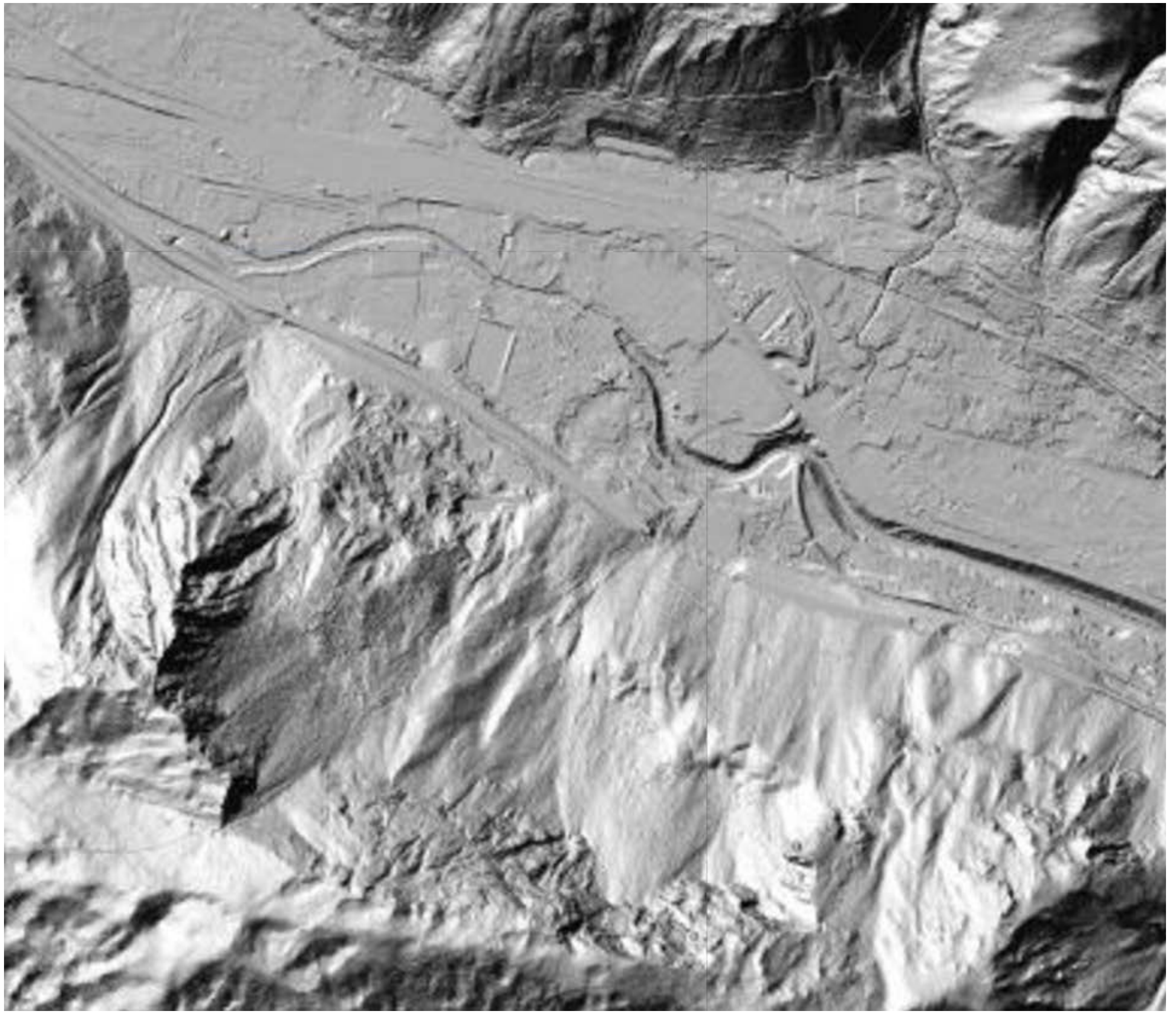
Soča valley, Kuntri

The largest rockfall in Slo. Alps

12,790 BP

200 M m^3

Dam and lake formation

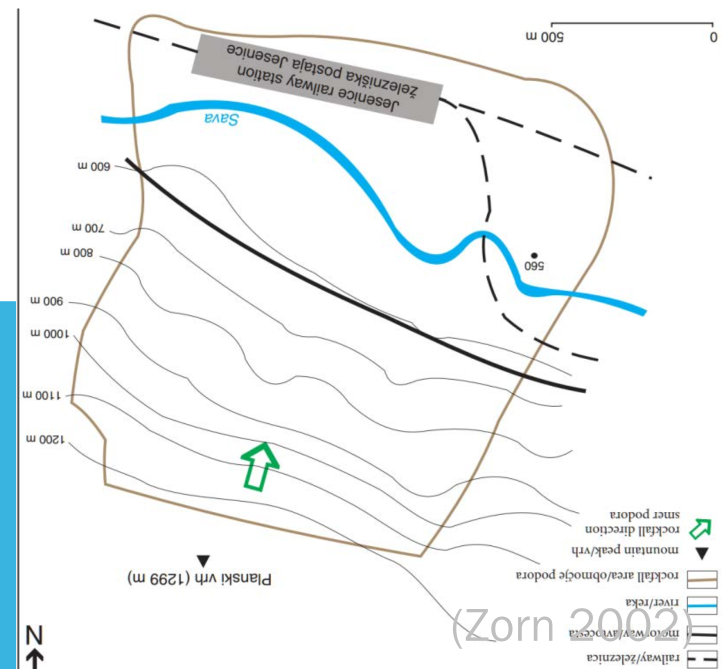


Sava valley, Mirca

12,790 BP

10 M m^3

Dam (20 m) and lake formation



(Zorn 2002)

Idrija valley

1511

Rockfall

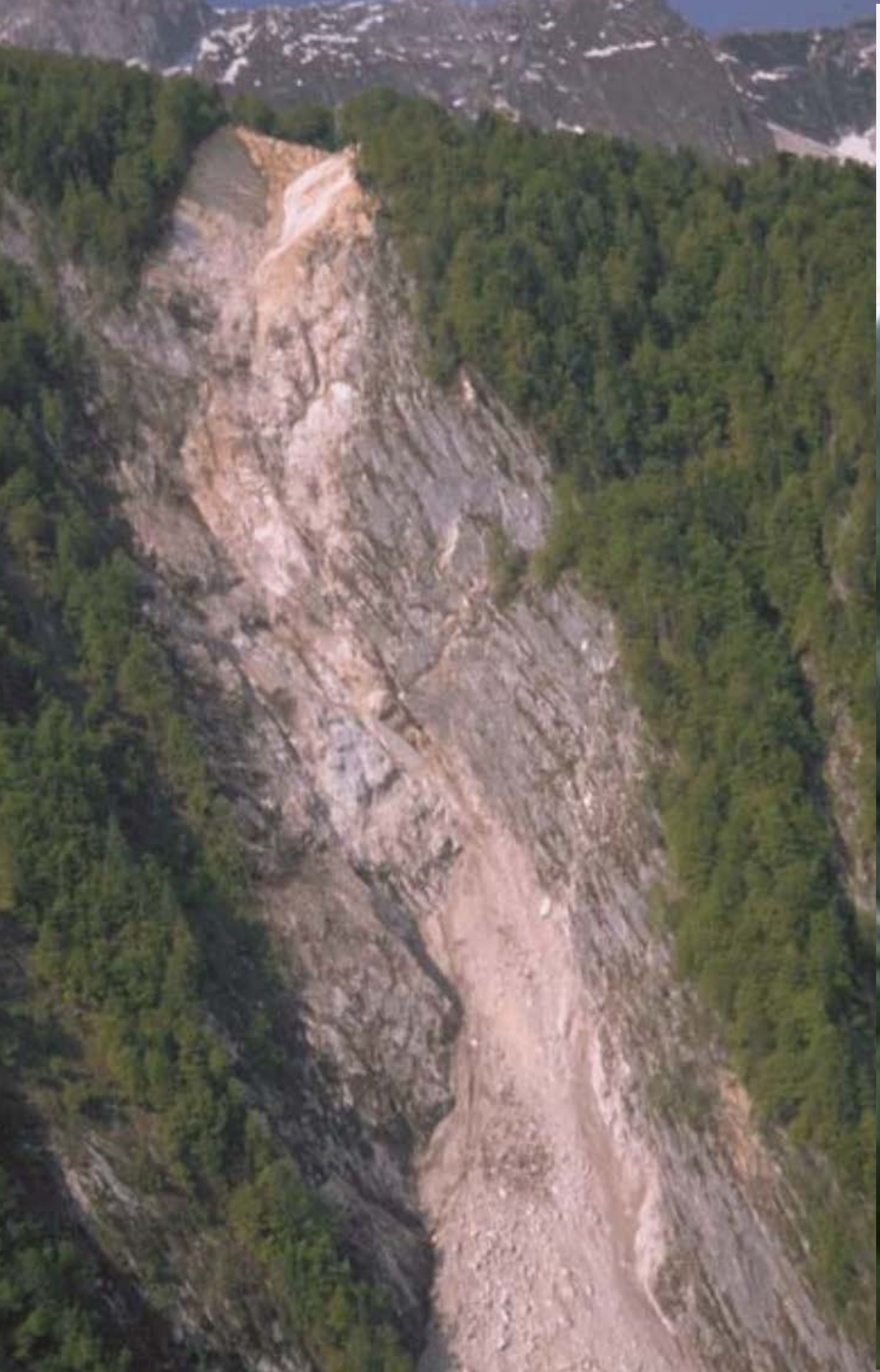
Dam formation (the Idrija settlement supposed do be flooded)

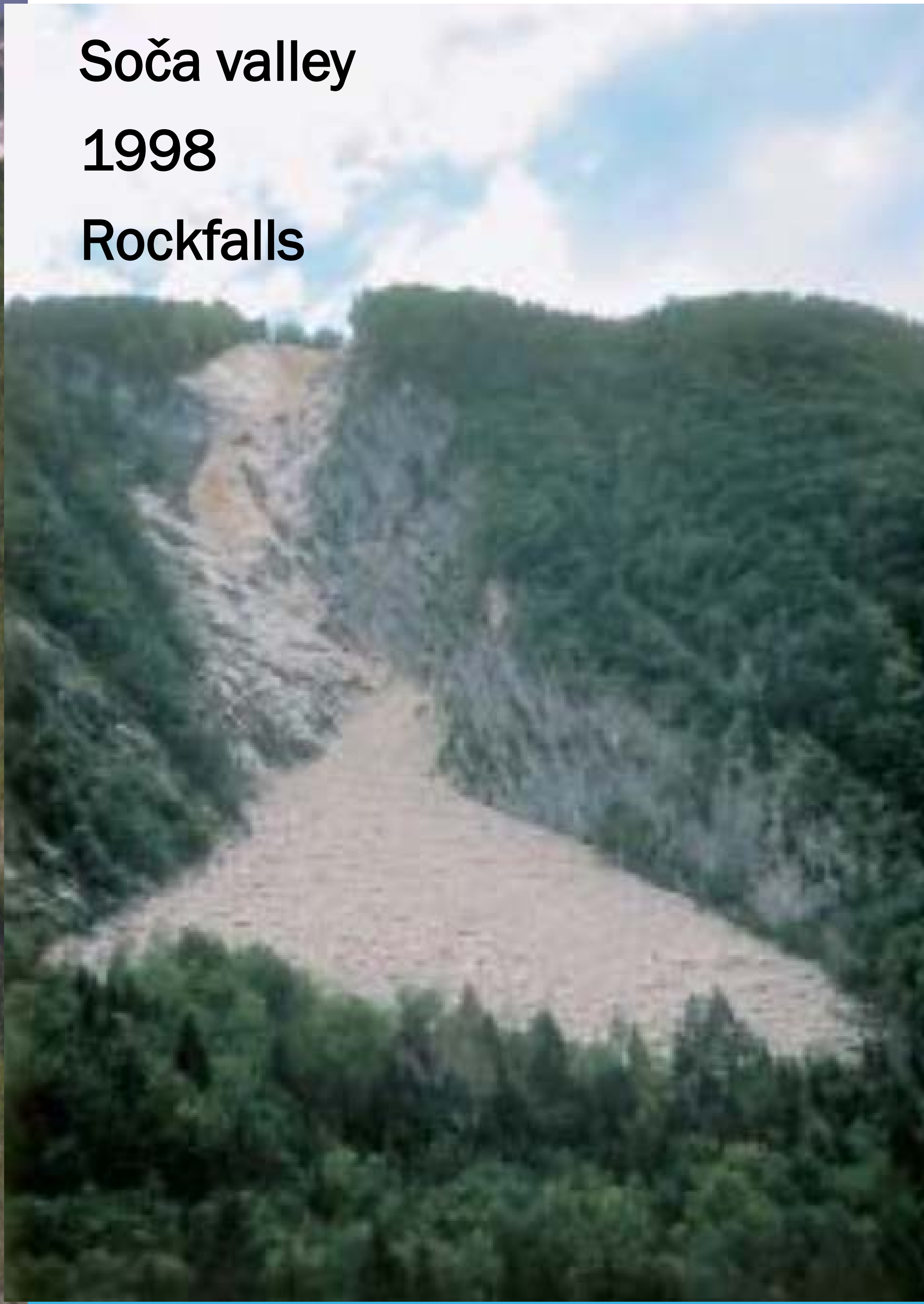
(Cecić 2011)

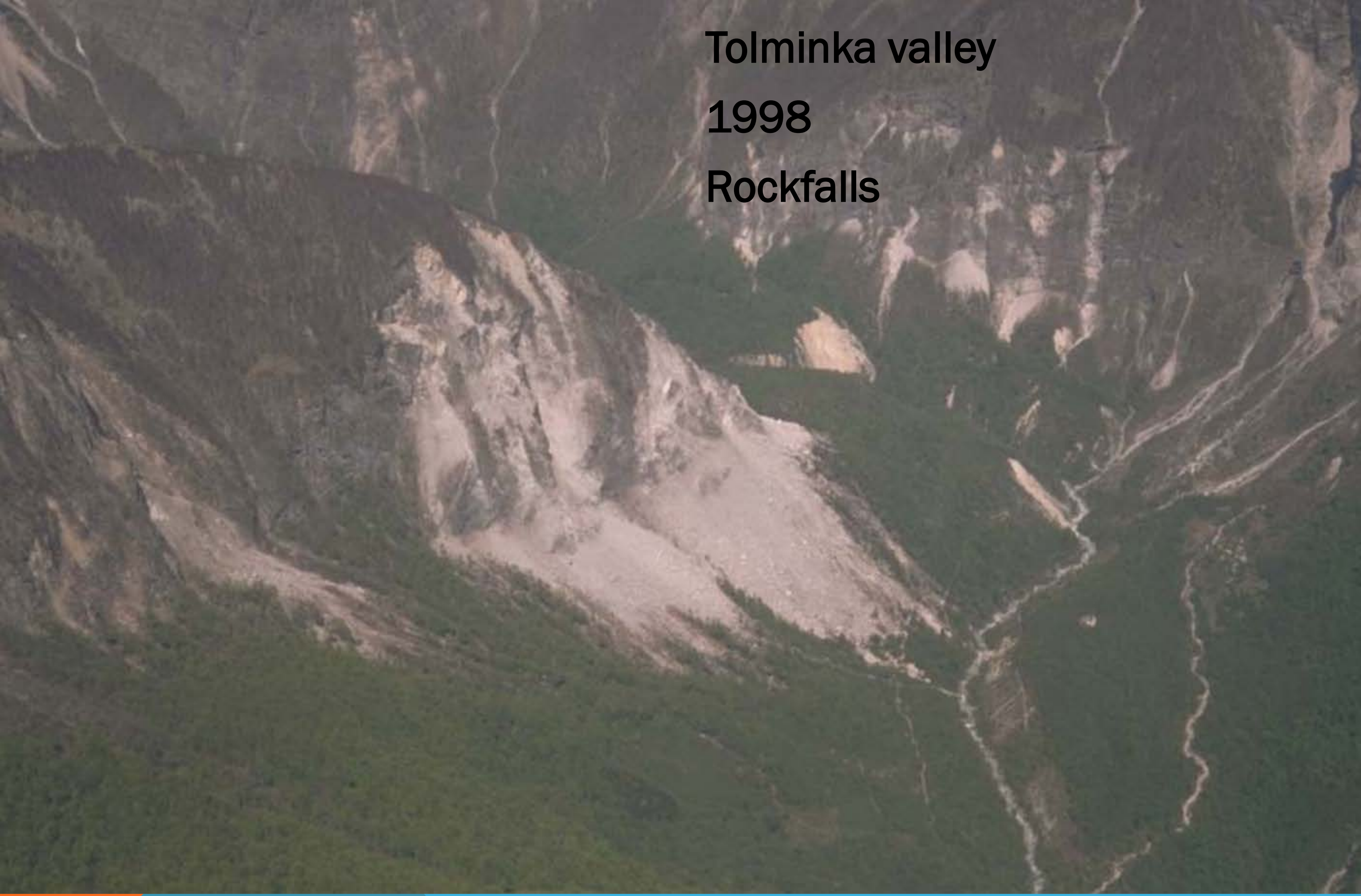
1994

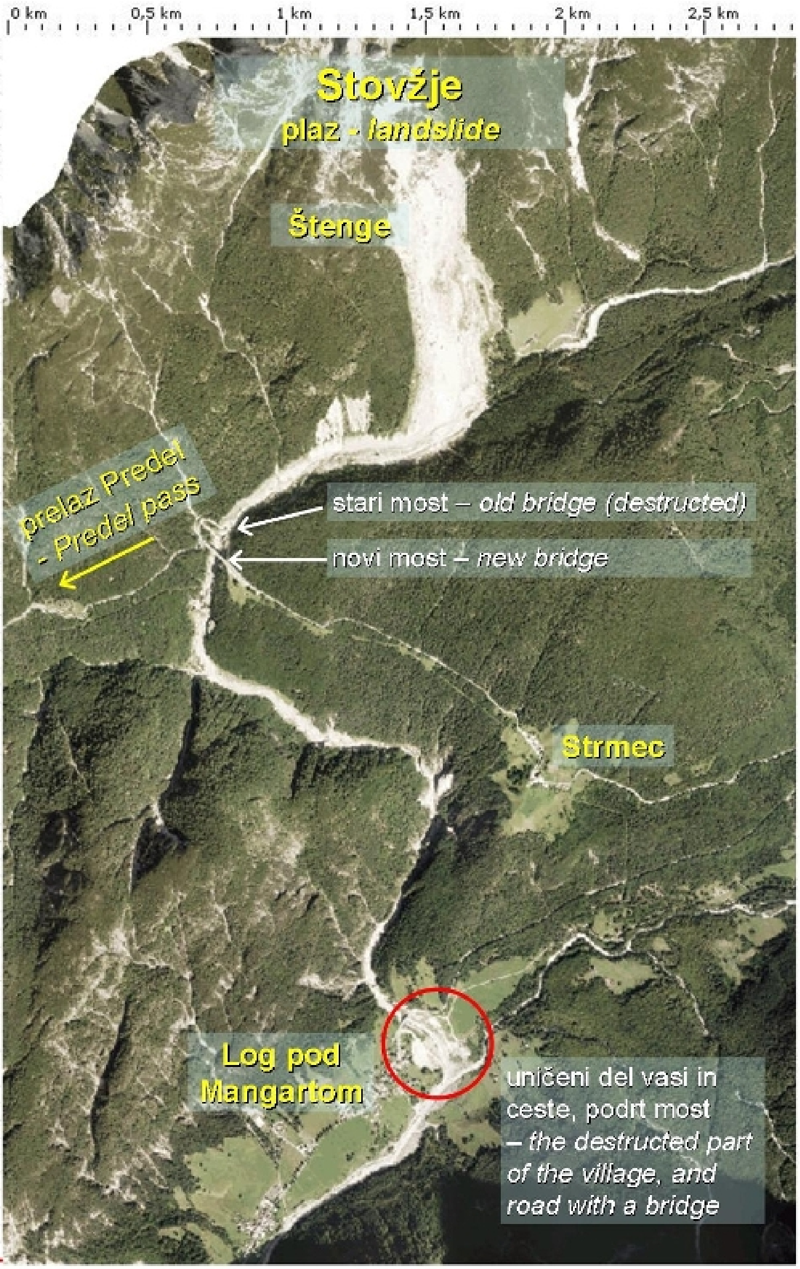
Twin rockfalls

(Zorn 2002)



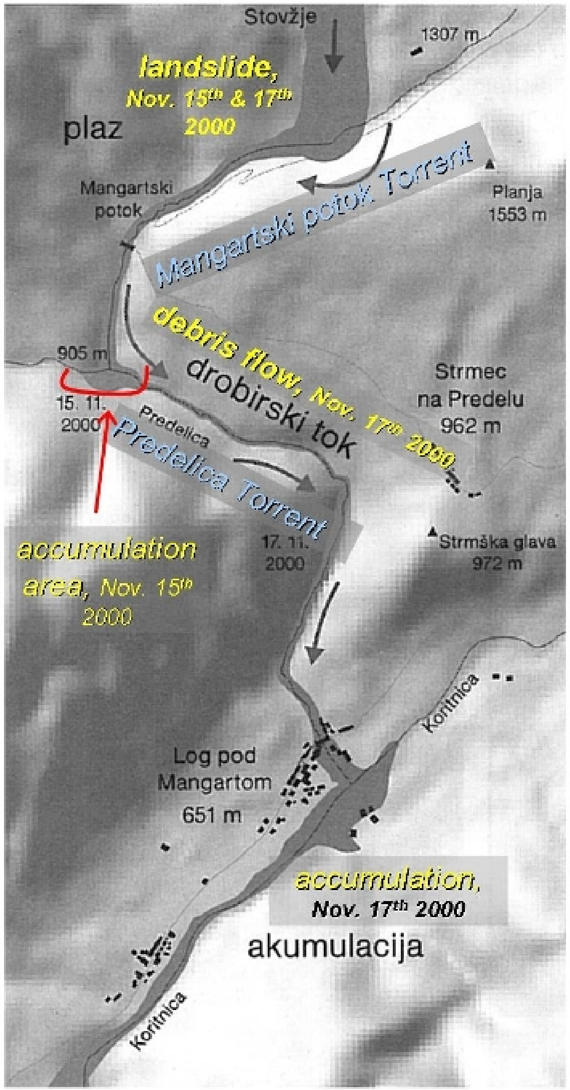

Soča valley
1998
Rockfalls


Tolminka valley
1998
Rockfalls



Plaz Stovžje, pot drobirskega toka in del mesta akumulacije;

Stovžje landslide, debris flow path and part of the accumulation area;



Vsebina skice in kartografija / *Content and cartography*:

Blaž Komac

stavba / *building*

vzpetina / *elevation*

vodotok / *stream*

cesta / *road*

smer drobirskega toka / *debris flow direction*

območje plazu, drobirskega toka in odlaganja gradiva / *landslide area, debris flow and accumulation*

Tolminka valley

2004

Rockfalls, dam

(Komac & Zorn 2009)

Čedca rockfall

2008

Rockfalls, debris flow

ASSESSMENT BY THE NEWMARK METHOD

We assessed the probability of such events using the Newmark method which defines the relations between:

- rock strength,
- relief (slope inclination), and
- ground movements.

The method is known in geotechnical analysis. Here it was used at regional/national scale. The possibility of sliding was calculated from the critical acceleration - acceleration of the quake which could lead to rock displacement by exceeding rock shear strength, defined by Factor of safety.

(Keefer 1984; Harp & Jibson 1996; Keffer, Wasowski & Del Gaudio et al. 2006; Carson & Kirkby 1972; Wilson & Keefer 1985; Miles & Ho 1999; Jibson, Harp & Michael 2000; Miles & Keefer 2001a; 2001b; Jibson & Michael 2009; Chen et al. 2014)

Critical acceleration (a_c):

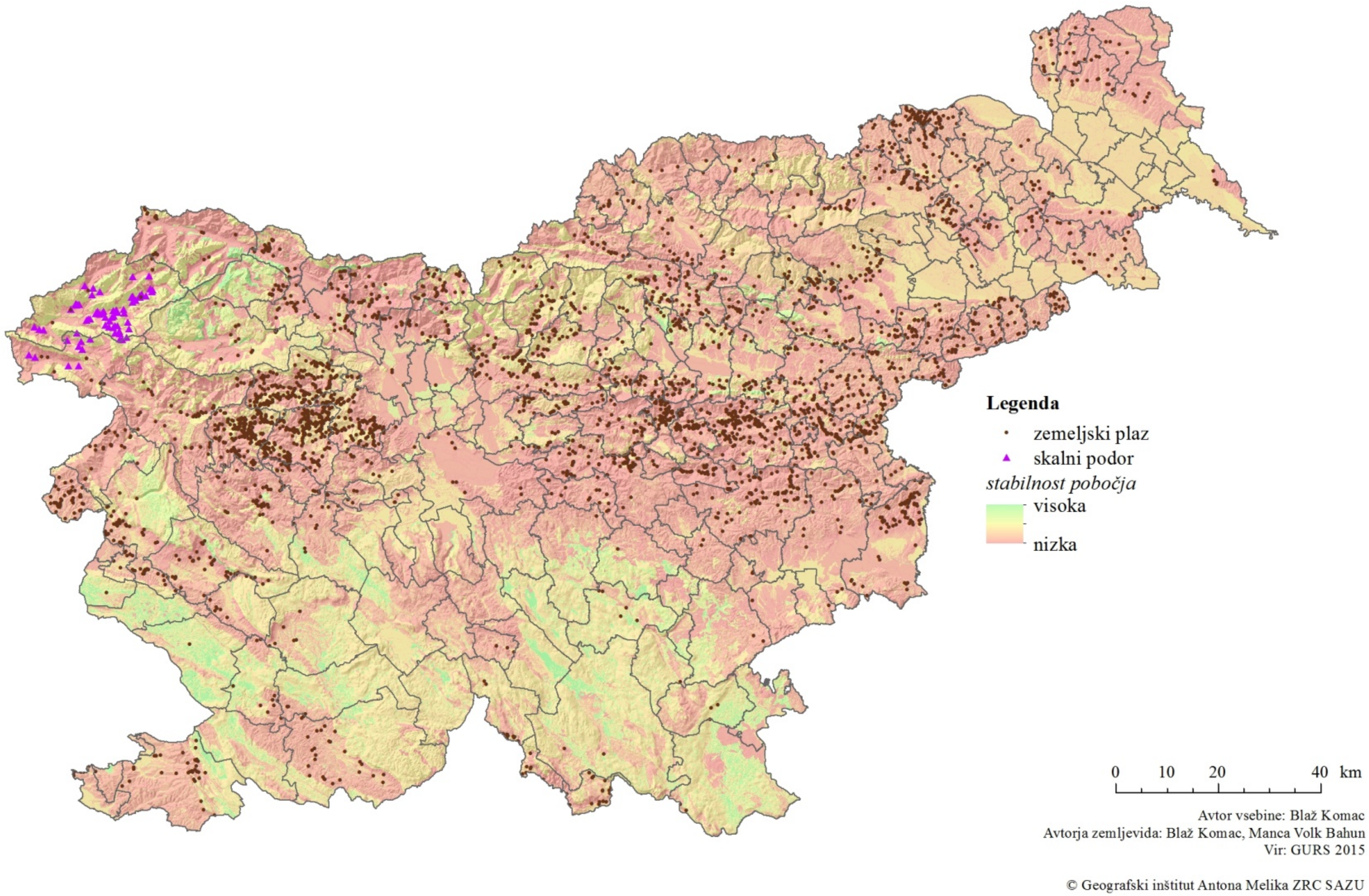
$$a_c = \left(\frac{c'}{\gamma t \sin\alpha} + \frac{\tan\varphi'}{\tan\alpha} + \frac{m\gamma_w \tan\varphi'}{\gamma \tan\alpha} - 1 \right) g \sin\alpha$$

$F_{s'}$

Factor of safety

α – slope inclination [rad.],
φ' – effective shear slope [rad.]
c' - effective cohesion (kPa)
α - slope inclination [radian], γ (**γ_w**) – specific weight [kN/m^3]
t – thickness of mobile mass [m]
m - share saturated rock [%]

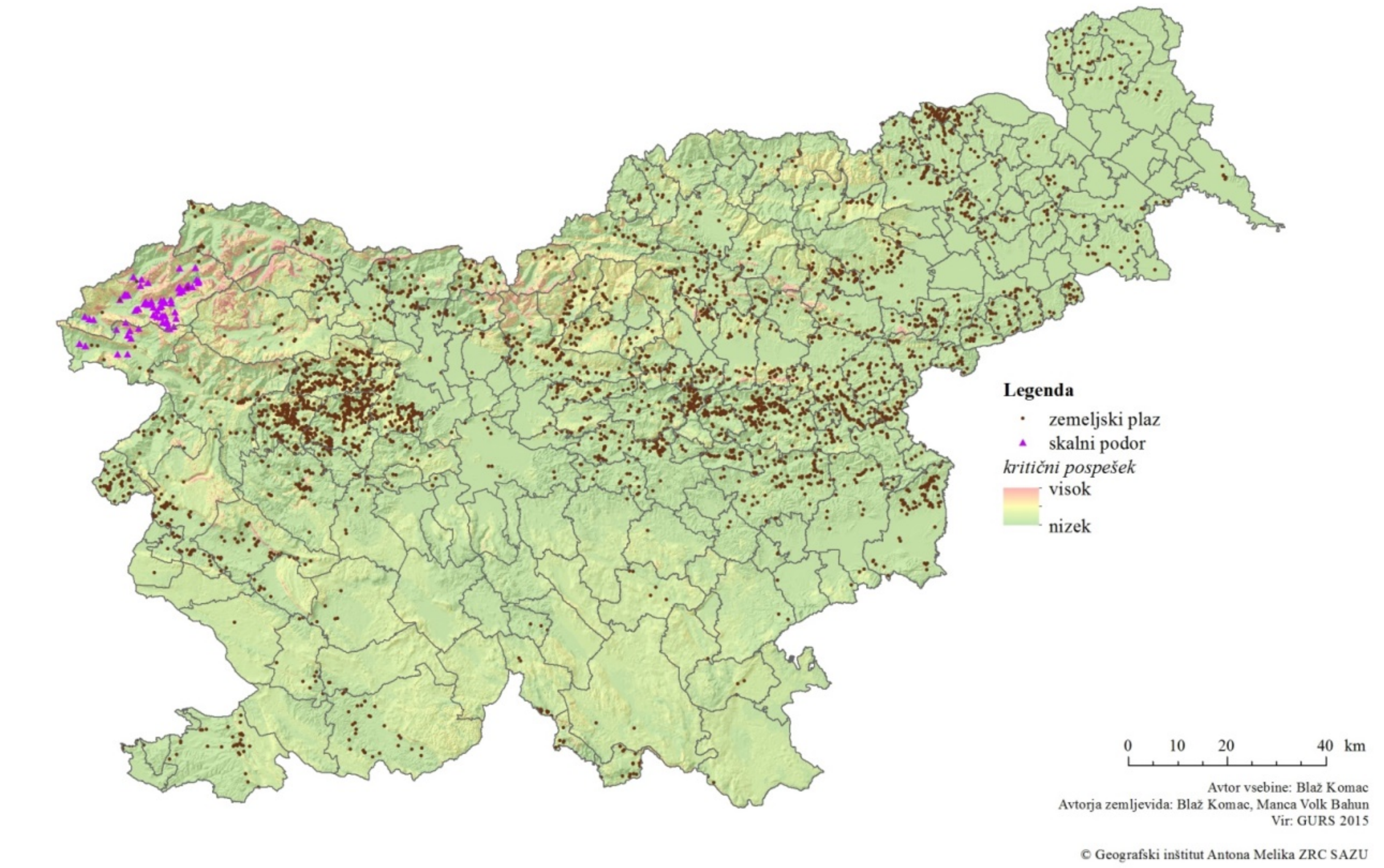
The calculated critical acceleration was compared to the expected seismic acceleration for Slovenia.



Factor of safety

About 60% of landslides are in unstable areas, 4% in relatively stable areas and 36% in stable areas.

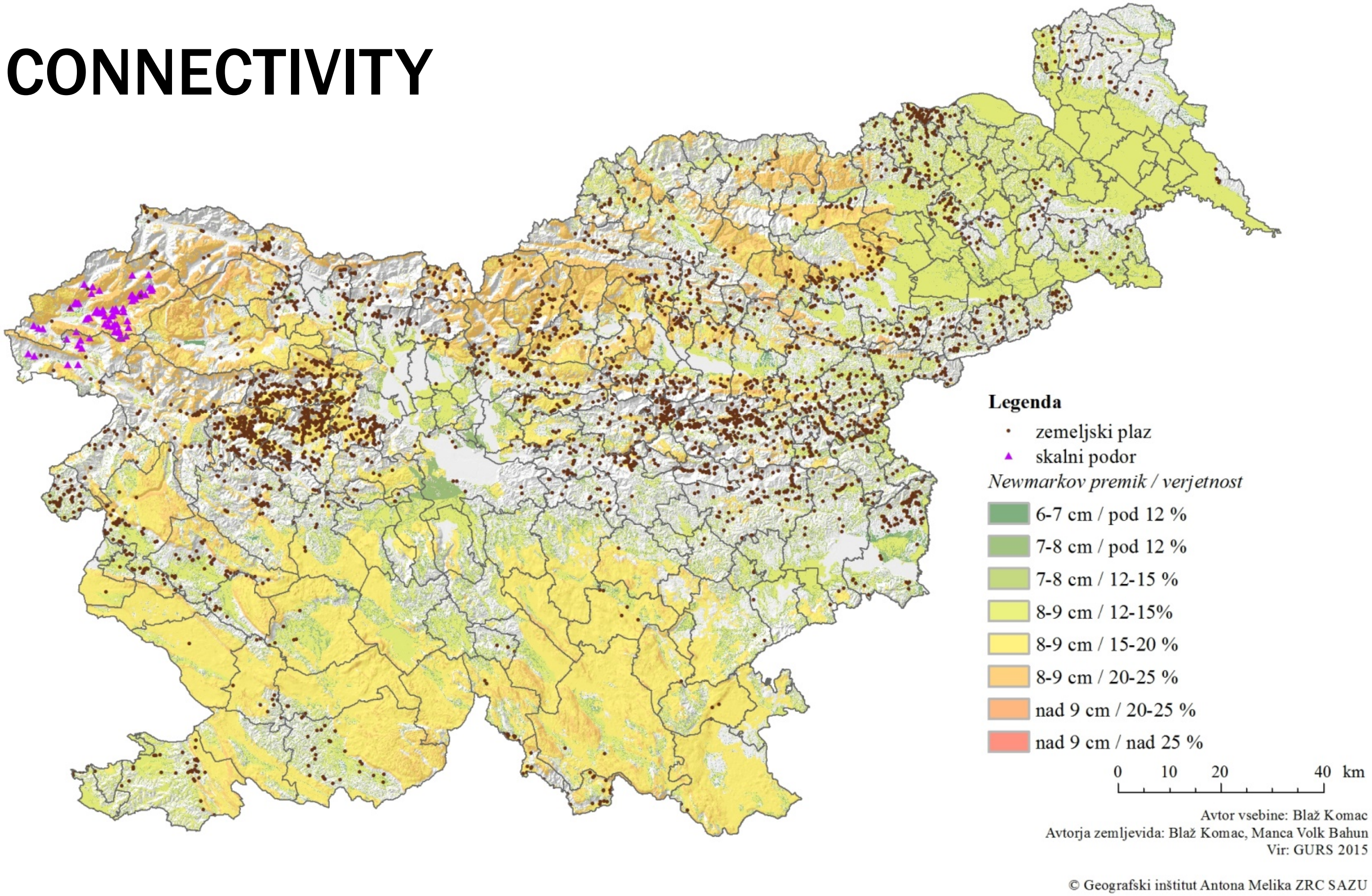
The database, therefore, also includes rockfalls.



Landslides occur at low values of a_c.

High a_c means that stronger force is needed to activate the movement. 75% of the recorded slope processes have been triggered at low critical acceleration values, less than 10% at moderate values and 25% at high values.

CONNECTIVITY



Comparison of a_c & earthquake g: during an earthquake with a return period of 475 years, the a_c of slopes is reached in mountain areas: Julian Alps, Kamnik-Savinja Alps, the Sava Hills, Strojna, Kozjak and Pohorje, Slovenske gorice, Cerkno, Škofja Loka, Polhov Gradec and Rovte hills.

CONCLUSION

Four different but related natural hazards were discussed: earthquake, landslides & rockfalls, and floods.

The risk of landslide and rockfall activation on regional level during in the event of an earthquake was estimated using the Newmark method.

About 50% of the 1998 earthquake-triggered rockfalls were located in high hazard areas and close to faults.

Large-scale & low frequency events may release and move large amounts of sediment. In Slovenia, this applies to strong earthquakes and extreme precipitation events.

The 1998 & 2004 earthquakes released almost the same amount of material (1Mm^3) as the debris flow (500 y return period).

About 50% of the material can connect to watercourses sometime in future.

About 10 % of Slovenian streams are subject to possible landslide or rockfall dam formation.

THANK YOU FOR YOUR KIND ATTENTION

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