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The space and time pattern of local seismicity in Slovenia

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The territory of Slovenia is subdivided into five seismogenetic regions according to their geological, tectonical, and geophysical properties. The seismicity of these regions is determined on the basis of more than 3000 earthquakes contained in the catalogue for Slovenia. Seismically most active part is concentrated in central, southeastern and southwestern Slovenia (zones B_2, B_3, and A_2).

Temporal energy release, strain release and indexes of seismic activity $\bar{A}_{10}$ have been determined for all characteristic regions. Introducing parameter $\Sigma = \Sigma E^{2/3}$ it is shown that a temporal dependence of the activity exists, and further, that an increase of the activity in southwestern and southeastern Slovenia is accompanied by a decrease of activity in its central part, and vice versa.

Variations of *b*-value in the relation $\log N = a - bM$ have been determined for the three characteristic regions A_2, B_2 and B_3. They have been correlated with times of occurrence of strong earthquakes. It is shown that most events occurred in time intervals when the *b*-value was 0.9 or less, or when the trend of the *b*-value was negative.

Prostorna i vremenska razdioba lokalne seizmičnosti u Sloveniji

Teritorij Slovenije podijeljen je na pet seizmogenetskih područja na osnovi njihovih geoloških, tektonskih i geofizičkih svojstava. Seizmičnost tih područja određivana je na temelju više od 3000 potresa koji su analizirani u katalogu potresa Slovenije. U seizmičkom pogledu najaktivniji dio koncentriran je u srednjoj, jugoistočnoj i jugozapadnoj Sloveniji (zone B_2, B_3 i A_2).

Za sva karakteristična područja određene su sume oslobađanja seizmičke energije, oslobađanje deformacija i indeksi seizmičke aktivnosti $\bar{A}_{10}$. Uvodeći parametar $\Sigma = \Sigma E^{2/3}$ pokazano je postojanje vremenske zavisnosti seizmičke aktivnosti, te da je porast aktivnosti u jugozapadnoj i jugoistočnoj Sloveniji popraćen smanjenjem aktivnosti u srednjoj Sloveniji. Vrijedi i obrnuto.

Varijacije vrijednosti *b* u odnosu $\log N = a - bM$ određene su za tri karakteristična područja A_2, B_2 i B_3. One su korelirane s vremenima pojavljivanja jačih potresa. Pokazano je da se većina potresa dogodila u vremenskim intervalima kad je vrijednost *b* bila 0,9 ili manje, odnosno, kad je trend ove vrijednosti bio negativan.

1. Introduction

The territory of Slovenia is subdivided into five seismogenetic regions (A-E) by characteristic fault systems (a-f) and further into ten smaller subregions or seismogenetic zones. Some of them exhibit higher seismicity with respect to the other zones. A region with low seismicity is situated in the southwestern (A_0) and partly in the western territory (A_1), and other regions of lower seismicity are in the northeast Slovenia (C, D, E). Seismic activity is concentrated mainly in the seismogenetic zones of Javorniki - Snežnik (A_2) which is a part of the region between tha faults of Kozina and Idrija, further, in the central seismogenetic zone of Ljubljana depression (B_2) between the faults of Idrija and Sava which is followed by the Krško-Brežice zone (B_3) to the southeast (Figure 1).

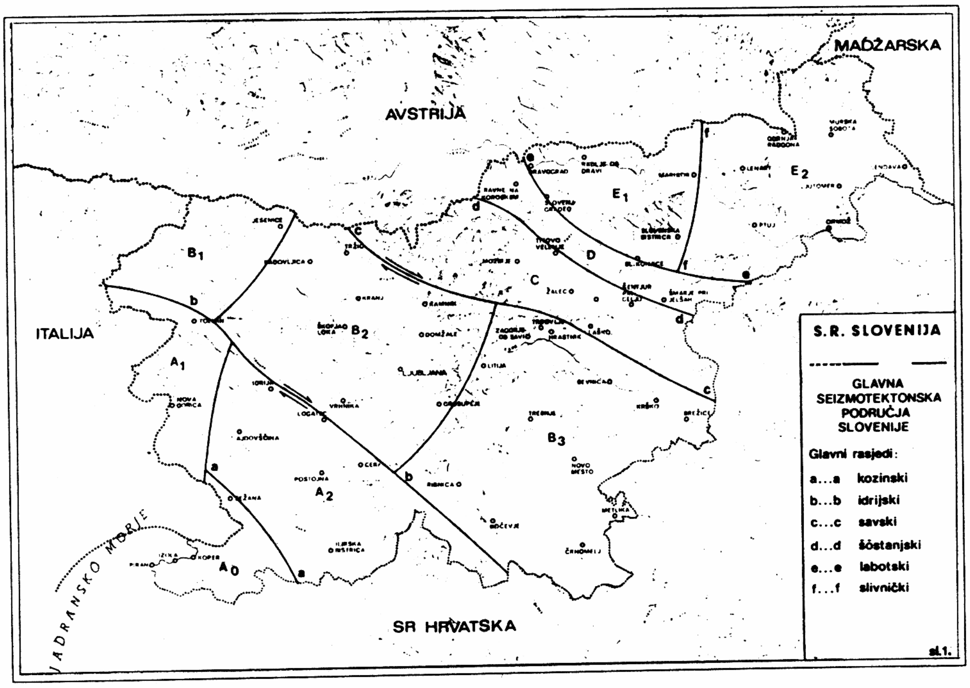

Figure 1. Principal seismotectonic zones in Slovenia
Faults: a ... a fault of Kozina
b ... b fault of Idrija
c ... c fault of Sava
d ... d fault of Šoštanj
e ... e fault of Labot
f ... f fault of Slivnica

Both zones, B_2 and B_3 are separated by a narrow aseismic belt along the line Ribnica- Titovo Velenje which includes minor groups of epicentres of low magnitudes. The purpose of this paper is to present some basic facts concerning the space and time pattern of local seismicity of Slovenia as a comlex unit and separately for the individual characteristic regions.

2. The sums of released seismic energy ΣE and strain release $\Sigma E^{1/2}$

2.1. The determination of released seismic energy ΣE and strain release $\Sigma E^{1/2}$ after Benioff

Data contained in the catalogue of earthquakes for Slovenia (Ribarič, 1982) comprise the time period from the year 792 to 1981 and are based mainly upon macroseismic observations. Following relations have been used :

$$M_m = 0.66\, I_o + 1.7 \log_{10} h - 1.6 \tag{1}$$

$$\log E = 11.5 + 1.5\, M_m \quad \text{(Solov'jev, 1957)} \tag{2}$$

$$K = 4.5 + 1.5\, M_m \tag{3}$$

$$K = \log_{10} E \quad (E \text{ in J}). \tag{4}$$

where M_m is macroseismic magnitude, I_o – epicentral intensity in MSK-64 scale , h – focal depth in km, $\log E$ – released seismic energy in ergs, K – energetic class.

For the territory of Slovenia the sum of released seismic energy during the period 792 – 1981 amounts to $3.1329 \cdot 10^{16}$J, which is equivalent to total magnitude $\hat{M} \cong 8.0$.

Introducing an areal measure of conditional specific seismicity being equal to $\Sigma E/F{\cdot}t$ and further a volume measure of conditional specific seismicity $\Sigma E/F{\cdot}h_a{\cdot}t$, where the symbols are : F – area, t – time, h_a – thickness of the seismically active zone in the Earth's crust ($h_a = h_m + 2\sigma_h$) , where h_m is the mean focal depth of all events and σ_h their standard deviation, we obtain the following value of the conditional specific seismicity for the area of Slovenia (20251 km^2) with normalization to one year:

$$\Sigma\, E/F{\cdot}\, t = 1.30003 \cdot 10^{19} \text{ J/km}^2 \cdot \text{ year} \tag{5}$$

Introducing the volume measure of conditional specific seismicity which is defined also as a mean specific seismic power $\overline{N}_m$ we find :

$$\overline{N}_m = \Sigma\, E_i \,/\, (V{\cdot}t) = 5.023 \cdot 10^{-12} \text{ J/m}^3 \cdot \text{ s} \tag{6}$$

normalizing the values to m^3 and seconds (s) in order to allow for comparisons with other published data (Šenkareva, 1973). Results obtained by Šenkareva (1973) for the Apennine peninsula are in the range 10^3 - $10^{\ 4} \cdot 10^{-12}$ J/cm^3 · s, and are consistent with the data in formula (6). They are valid for the axial part of the mega-anticlinorium of the Apennines and Calabro-peloritanian structures.

2.2 *Regional investagations of ΣE and $\Sigma E^{1/2}$*

The availability of homogeneous data for individual seismogenetic zones provides for a reduction of the observational time interval to 1810–1980. Normalizing the values to 100 years and 10000 km^2 we obtain results as shown in Table 1.

Table 1. Sums of the released seismic energy and total strain release for the time period 1810-1980 (in J, or $J^{1/2}$, normalized to 100 years , and 10000 km^2).

Seismogenetic zones Area(km^2)	ΣE J	$(\Sigma E)_n$ J	$(\Sigma E)^{1/2}$ J$^{1/2}$	$(\Sigma E)_n^{1/2}$ J$^{1/2}$
A_0, A_1, A_2 5853.92 km^2	$3.265 \cdot 10^{14}$	$3.065 \cdot 10^{14}$	$1.807 \cdot 10^7$	$1.752 \cdot 10^7$
B_1, B_2 4188.51 km^2	$2.079 \cdot 10^{15}$	$2.717 \cdot 10^{15}$	$4.556 \cdot 10^7$	$5.222 \cdot 10^7$
B_3 5427.01 km^2	$1.405 \cdot 10^{15}$	$1.422 \cdot 10^{15}$	$3.748 \cdot 10^7$	$3.771 \cdot 10^7$
C + D + E 9026.26 km^2	$1.043 \cdot 10^{14}$	$6.350 \cdot 10^{13}$	$1.021 \cdot 10^7$	$7.969 \cdot 10^6$

Taking the value of $(\Sigma E)_n^{1/2}$ in (C + D + E) as an unit, we obtain a ratio 1 :2.02 for regions A, (A_0, A_1, A_2), 1 : 5.5 for combined regions B_1 and B_2 and 1 : 4.03 for seismogenetic region B_3. These are representative relative measures for the intensity of generating earthquakes in particular zones.

2.3. *Strain release and seismic activity $\bar{A}_{10}$ in Slovenia (1810-1980)*

Graphically the strain release for the territory has been represented for the time period from 1810 on. Due to the better defined data from 1875 on, it was decided to carry out the numerical calculations from this year to 1980. The following relation was found :

$$\Sigma E^{1/2} \, (J^{1/2}) = (4.478 + 1.112 \, \Delta t) \cdot 10^{10} \, / \, \sqrt{10^7} \, (J^{1/2}) \qquad (7)$$

for: $1875 \leq t \leq 1980$.

The value of Δt is 10 years. The results are presented in Figure 2.

The parameters for determination of seismic activity in Slovenia have also been selected for the time period from 1818-1980, i. e. 171 years, using magnitudes $M \geq 3.1$ transformed into energetic classes K, taking individual frequencies of events N_i (K), and normalizing the values with respect to one year and 10000 km^2 of area in order to enable comparisons with other data. Raw data are presented in Table 2.

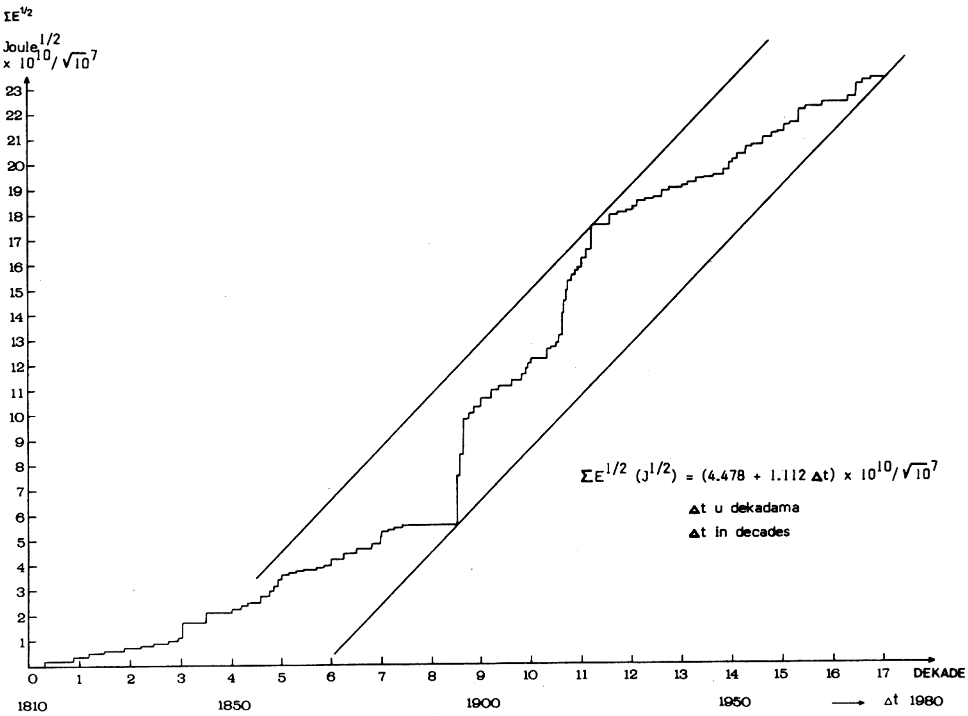

Figure 2. Strain release in Slovenia 1810-1980 (1875-1980)

Table 2. Parameters for determination of seismic activity in Slovenia (1810-1980), normalized to 1 year and 10000 km^2

Energetic class	M	$\overline{M}$	K	N_i	log ($F \cdot N_i$)
2	3.1-3.5	3.3	9.45	414	-0.9148001
3	3.6-4.0	3.8	10.2	167	-1.3090939
4	4.1-4.5	4.3	10.95	85	-1.6023815
5	4.6-5.0	4.8	11.7	20	-2.2307704
6	5.1-5.5	5.3	12.45	5	-2.8328304
7	5.6-6.0	5.8	13.2	1	-3.5318004
8	6.1-6.5	6.3	13.95	1	-3.5318004

By the method of linear regression the mean value of the index of the seismic activity $\bar{A}_{10}$ was calculated being equal to :

$\bar{A}_{10} = 0.065.$

The slope $\gamma = -0.644$ and the coefficient of correlation $r = -0.987$.
Genarally the relation is the following :

$$\log N_i = -1.187 - 0.644\ (K - 10) \qquad (8)$$

The result is presented in Figure 3.

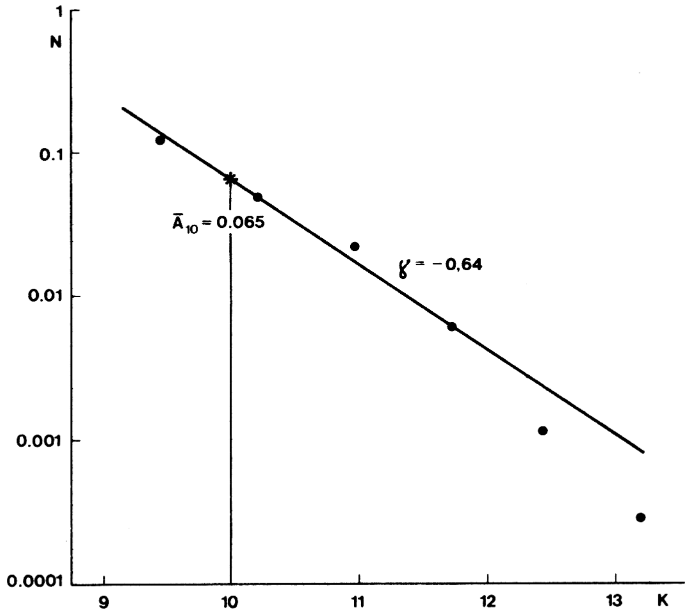

Figure 3. $N = f(K)$, for Slovenia, 1810-1980, normalized to 1 year and 1000 km2

2.3.1. Seismic activity of individual seismogenetic zones

Because of the nonuniform distribution of data in various regions the observational time interval was shortened to the interval of 1850-1979. Energetic classes $K \geq 8$ have been used as well as individual frequencies N_i of the events. Data have been normalized to 100 years and 10000 km^2.

In continuation the mean seismic activity $\bar{A}_{10}$ for $K = 10$ has been determined introducing normalized values for 1 year and 1000 km^2 in order to comply with results obtained by some authors who performed studies for the adjacent region of Friuli (Riuscetti and Slejko, 1984; Slejko, 1985). The results are shown in the last column of Table 3.

Table 3. Individual frequencies N_i vs. $K(K \geq 8)$ for seismogenetic regions in Slovenia (1850-1979), normalized to 100 years and 10000 km^2

Region	n	A_i	γ_i	$\log N_i^*(K_{10})$	Coeff. of correlation r	$\bar{A}^*_{10}$
A_0,A_1,A_2	5	5.4926	-0.38	1.6911	-0.92	0.0755
B_1,B_2	6	6.9463	-0.49	2.0315	-0.95	0.1709
B_3	6	7.3801	-0.55	1.8741	-0.97	1.1103
C,D,E	5	5.1738	-0.38	1.3499	-0.98	0.0329

*normalized to 1 year and 1000 km^2, n = number of observations

Parameters for determination of seismic activity have been determined also for cumulative frequencies N_c of earthquakes in four groups of seismogenetic zones. They exhibit the same trends, but, as expected, higher values of A_c and γ. The results are presented in Table 4.

Table 4. Cumulative frequencies N_c vs. $K(K \geq 8)$ for seismogenetic regions in Slovenia (1850-1979), normalized to 100 years and 10000 km^2.

Region	n	A_c	$\gamma c/r$	$\log N^*_c(K_{10})$	$\log N_c^*(K_{13})$	K for $N_c^* = 1.0$
A_0,A_1,A_2	5	6.8461	-0.50/-0.98	1.8780	0.3876	13.780
B1, B2	6	7.9605	-0.57/-0.98	2.2328	0.5144	13.898
B_3	6	8.0213	-0.60/-0.98	2.0424	0.2488	13.416
C,D,E	5	6.0614	-0.45/-0.99	1.5185	0.1556	13.343

n = number of observation

2.4. Discussion

Riuscetti and Slejko (1984) and Slejko (1985) presented results of determination of the indexes of seismic activity $\bar{A}_{10}$ for Friuli and Venetia-Giulia regions which amount to $\bar{A}_{10}$ = 0.1 and more. In the western part of Carnic and Julian Alps the values of $\bar{A}_{10}$ are between 0.1 and 0.05. Their results are compatible with our findings.

3. Parameter "sigma" - Σ

The introduction of the parameter Σ has a physical explanation in statistical procedures. Under certain conditions the rupture areas S_r in seismic sources are proportional to $E^{2/3}$. Parameter $\Sigma = \Sigma\, E^{2/3}$ determines herewith the total square of ruptures of seismic sources of seismic events which occurred during the time t. Temporary changes of this parameter are significant for the preparation time for a stronger earthquake, as its maximum value is reached before the stronger event (Keilis-Borok, Malinovskaya, 1964).

Statistical analysis of Σ is based upon the fact that the earthquakes show comparable $\Sigma E^{2/3}$ in a broad spectrum of magnitudes, whereas the total value of released energy depends mainly on the contributions of stronger events. The mean annual number of earthquakes N with energies in the range from E to $c \cdot E$ is :

$$N \cong c \cdot E^{-\beta}. \tag{9}$$

Parameter $\beta \cong 2/3$. We can write $N \cdot E^{2/3} = c$ which means that this value is constant and does not depend on E (Kondorskaya et al., 1985).

The values of $\Sigma E^{2/3}$ have been determined for three decades (1950-1979) using $M \geq 2.5$ for four regions (A_0 - A_2), (B_1- B_2), (B_3), and (C - D - E). Data have been subjected to normalization to 30 years and 10000 km^2. The following criteria have been used in analysis of trends of the values of Σ :

1) The value of Σ in the 3rd decade is significantly higher than the mean value of the sum of the 1st and 2nd decade (sign "+") which represents the zero line.

2) The mean value of the sum of 2nd and 3rd decade represents the zero line and the value of Σ in the first decade is significantly above this zero line (sign "-").

Numerical values of Σ for the time period 1850-1979 without normalization and normalized values for three decades I (1959-1959), II (1960-1969), and III (1970-1979) are shown in Table 5, separately for four combined seismogenetic zones. Annexed to this table is a scheme of the signs showing relative maximum and minimum values for the particular regions.

Table 5. Sigma - Σ for the time period 1850-1979, and separately for decades 1950-1979, normalized to 10000 km^2, in $J^{2/3}$, Slovenia, $M \geq 2.5$

Region	$E^{2/3}$ (1850-1979)	I(1950-1959)	II(1960-1969)	III(1970-1979)
A_0-A_2	$1.2332 \cdot 10^9$ $J^{2/3}$	$3.1799 \cdot 10^8$ $J^{2/3}$	$1.4763 \cdot 10^8 J^{2/3}$	$1.2983 \cdot 10^8$ $J^{2/3}$
B_1-B_2	$2.6153 \cdot 10^9$	$2.6451 \cdot 10^7$	$1.2995 \cdot 10^8$	$2.1825 \cdot 10^8$
B_3	$1.6013 \cdot 10^9$	$1.1459 \cdot 10^8$	$3.0287 \cdot 10^8$	$3.2908 \cdot 10^7$
C-D-E	$7.9267 \cdot 10^8$	$1.0549 \cdot 10^8$	$5.4833 \cdot 10^6$	$1.1053 \cdot 10^8$

	I	II	III
A_0-A_1	+	-	-
B_1-B_2	-	+	-
B_3	-	+	-
C-D-E	+	-	+

3.1. Discussion

A working hypothesis of a quasi-periodicity of the events based upon this scheme could imply, using the moving-window method, an extrapolation of the signs for the 4^{th} decade (1980-1989), indicating a "+" sign for zones (A_0 - A_1 - A_2), a "-" for (B_1 - B_2), "+" for B_3, and a "-" for (C - D - E). This would mean an increase of seismic activity in southern and southeastern Slovenia in the current decade. Results of present monitoring of seismic activity confirm this thesis. It is important to note that, owing to short observational intervals and other reasons (e. g., because these systems are interdependent), these conclusions may be only provisional and have primarily orientational character.

4. Regional temporal changes of the coefficient b in selected areas (A2, B2 and B3) in Slovenia.

A study of time variations of b-values in the formula $\log N = a - bM$ has beeen carried out for the past 130 years using events with $M \geq 3.0$ for selected areas A_2, B_2 and B_3. In the calculations cumulative frequencies N_c have been used, as well as magnitude intervals of $\Delta M = 0.1$. The values of N_c have not been normalized with respect to unit areas. The time intervals used are Δt = 30 years with overlapping $\Delta t' = 10$ years. Foreshocks and aftershocks have been excluded from the observational material. The values of a and b in Table 6 have been determined with the linear regression method, and the standard deviation SD (b) of the b-value was calculated using the formula :

$$SD\ (b) = \sigma = 1.96\, b/\sqrt{n} \quad \text{(Aki, 1965)}, \tag{10}$$

where n represents the number of magnitude intervals. Formula (10) is valid for the 95 % confidence limit.

The results are presented in Table 6 and graphically in Figure 4. A further step in this procedure was an insertion of times of appearance of some significant earthquakes to the curves for regions A_2, B_2 and B_3.

4.1. Discussion

Most events occurred during time intervals of decreasing or relatively constant values of the parameter b, only the Ljubljana earthquake in 1985 occurred during the time of a slight increase of this value. It seems important to note that all values of the coefficient b during the periods of stronger events have been less than $b = 0.9$.

The value of b indicates a general state of the stress in the crust of the seismogenetic zones. Decrease of b – value towards a lower limit means an approach of the stresses to some final values. The changes of b or of the ratio a/b and their regional interrelations are therefore a measure for the individual behaviour of seismogenec zones.

Table 6. *Temporary trends of b-values changes ($M \geq 3.0$, foreshocks and aftershocks omitted). Time period : 1850 - 1979, Δt = 30 years overlapping $\Delta t'$ = 10 years.*

Time period	Region A_2				Region B_2				Region B_3				Remarks
	b	$\sigma(b)$	a	n	b	$\sigma(b)$	a	n	b	$\sigma(b)$	a	n	
1850-1879	0.975	0.854	4.113	5	0.653	0.320	3.558	16	0.613	0.380	3.067	10	Smallest b in B_2 and B_3
1860-1889	0.505	0.495	2.236	4	0.878	0.477	4.231	13	0.626	0.388	3.095	10	Smallest b in A_2
1870-1899	1.205	0.787	5.149	9	0.769	0.355	4.319	18	0.777	0.246	3.658	10	
1880-1909	1.440	0.892	6.058	10	0.824	0.371	4.565	19	1.224	0.692	5.444	12	
1890-1919	1.124	0.636	5.167	12	0.855	0.384	4.728	19	0.766	0.375	4.151	16	
1900-1929	0.737	0.373	3.849	15	1.392	0.757	6.241	13	0.793	0.377	4.383	17	1st maximum in B_2
1910-1939	0.683	0.346	3.614	15	1.292	0.731	5.744	12	0.750	0.536	4.209	17	
1920-1949	0.623	0.339	3.258	13	1.142	0.746	4.847	9	0.790	0.387	4.286	16	
1930-1959	0.871	0.569	4.179	9	1.790	1.326	6.996	7	0.747	0.391	3.962	14	very high b in B_2
1940-1969	0.822	0.465	4.085	12	0.940	0.651	4.098	8	0.821	0.430	4.050	14	
1950-1979	0.855	0.484	4.278	12	0.822	0.486	3.833	11	0.801	0.435	3.941	13	

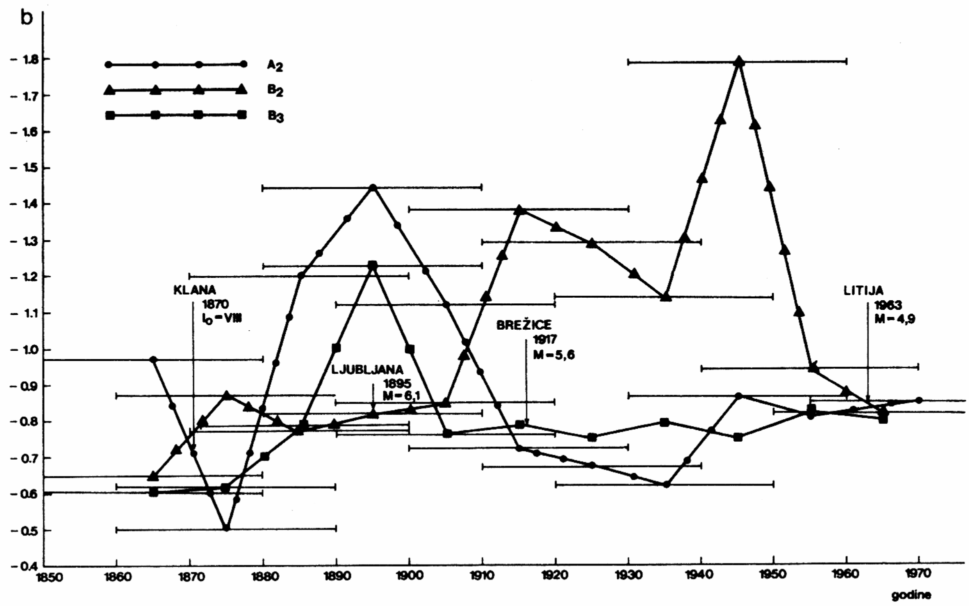

Figure 4. Temporary changes of *b* – value for three seismogenetic regions in Slovenia

5. Conclusions

The seismic activity in Slovenia is concentrated mainly in the central part in the seismogenetic zones A2, B2 and B3. It is demonstrated that the quantities of released seismic energy, and consequently strain energy, vary significantly from region to region and they also show important temporal variations. An analysis of the parameter Σ results in the conclusion that the seismic activity in the three main zones has an interactive character. The activity trends seem to be related in A2 and B3 only. Increasing activity in B2 means an opposite trend in both other zones.

Seismicity of Slovenia is moderate and can be defined according to definition of C.F. Richter as a sporadic seismicity. This is also based upon the fact that this territory is situated in a transitional zone between the seismically very active Dinarides and relatively stable middle Europe.

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