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The Kresna earthquake of 1904 in Bulgaria

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Abstract
The Kresna earthquake in 1904 in Bulgaria is one of the largest shallow 20th century events on land in the Balkans. This event, which was preceded by a large foreshock, has hitherto been assigned a range of magnitudes up to $M_s = 7.8$ but the reappraisal of instrumental data yields a much smaller value of $M_s = 7.2$ and a re-assement of the intensity distribution suggests 7.1. Thus both instrumental and macroseismic data appear consistent with a magnitude which is also compatible with the fault segmentation and local morphology of the region which cannot accommodate shallow events much larger than about 7.0. The relatively large size of the main shock suggests surface faulting but the available field evidence is insufficient to establish the dimensions, attitude and amount of dislocation, except perhaps in the vicinity of Krupnik. This downsizing of the Kresna earthquake has important consequences for tectonics and earthquake hazard estimates in the Balkans.

Key words *Bulgaria – Balkans – seismicity – magnitude*

1. Introduction

The purpose of this paper is to set down what is known about the Kresna earthquake and its sequence, locate their epicentral areas, assess their magnitude and record what is know about their effects on the ground and on man-made structures. No attempt is made to associate these events with local tectonics or to evaluate the associated seismic hazard.

The Kresna earthquake of 4 April 1904 ($M_s = 7.2$) and its large foreshock twenty minutes earlier ($M_s = 6.8$), originated in the upper reaches of the Struma valley with an epicentral region which straddles the border between modern Bulgaria and Macedonia. It caused extensive damage and the geological effects included landslides, rockfalls, liquefaction of the ground, changes in water and stream flow, and surface faulting.

Until relatively recently this earthquake remained so little known that it is not even mentioned in seismological and geological works such as of de Ballore (1906, 1924), Louis (1930), Richter (1958), while Sieberg (1932) refers to it in passing, devoting to it only four lines. What probably accounts for this is the small impact, that at the beginning of the 20th century, this earthquake had in a region which had virtually no towns and only a few villages in the mountains or foothills with no connections with the few urban centres in the region.

What revived general interest in this earthquake, that soon classed it as the largest shock in the Balkans, was the large magnitudes of $m_B = 7.5$ and $M_s = 7.8$ that Gutenberg and Richter (1954), and later Christoskov and Grigorova (1968), assigned to it, that influenced seismo-

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logical thinking of seismic hazard and on the largest earthquake that might occur in the region.

Following the destructive earthquake at Skopje in 1963 ($M_s = 6.2$) in neighbouring Macedonia, what was then part of Jugoslavia, and during the re-construction of the city, reappraisal of the Kresna earthquake became an important issue, and UNESCO organised a reassessment of the event, a task entrusted to a team consisting of the late Prof. A. Zatopek, Dr. V. Karnik and of the writer, who undertook to prepare a concise report of the instrumental and macroseismic aspects of the earthquake. During the period

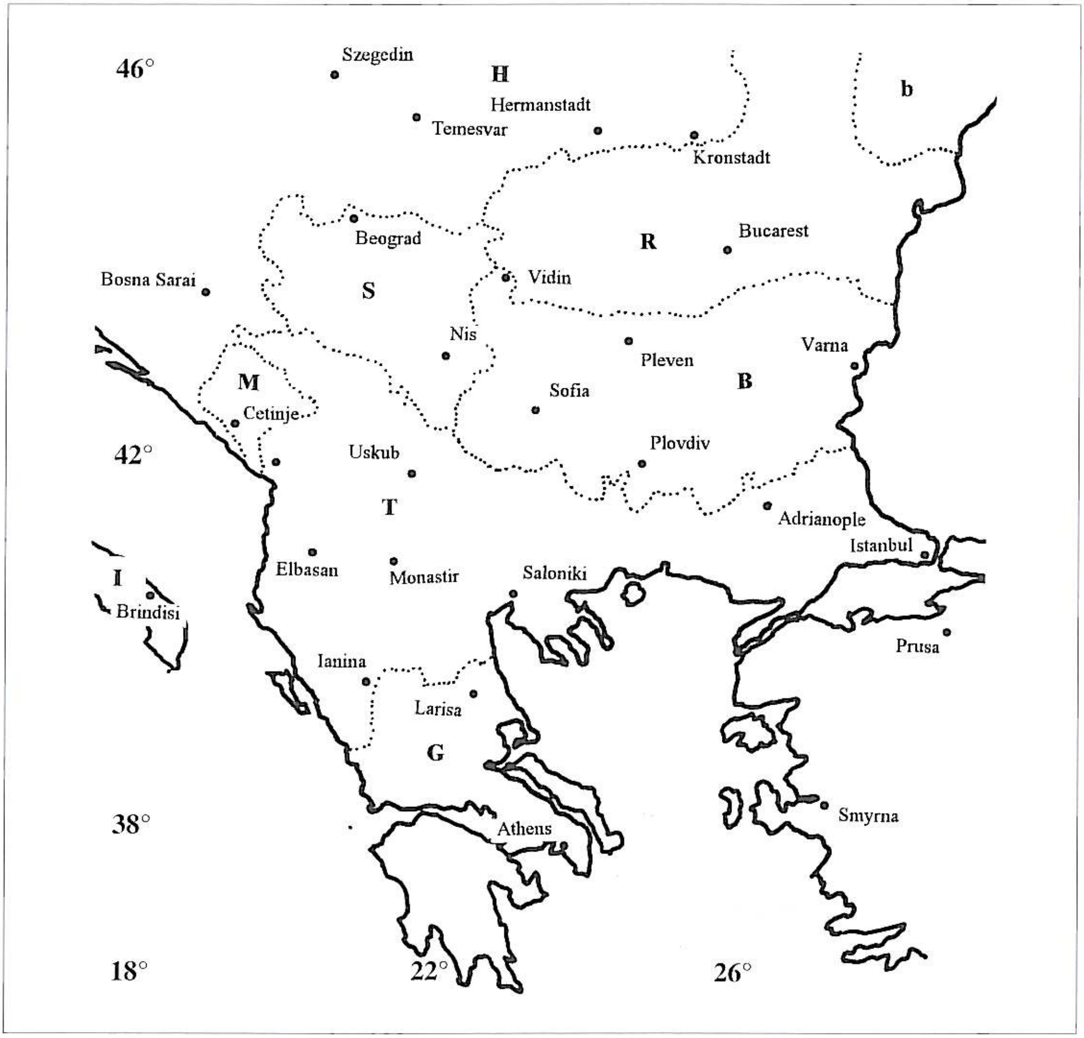


Fig. 1. The Balkans at the turn of the 20th century with place-names in the style used in Europe at the time. B = Bulgaria; b = Bessarabia; G = Greece; H = Hungary; I = Italy; M = Montenegro; R = Romania; S = Serbia; T = Ottoman Empire.

1965 to 1970, members of the team made cursory field trips in the regions of Struma and Bregalnica, the purpose of which was to collect local information and instrumental data regarding the event and to identify recent surface faulting that could be associated with the 1904 earthquake. For a variety of reasons, the report of the team was never completed. This paper is based on the observations made and notes kept by the writer during the period 1965 to 1970, on macroseismic data collected more recently, and on some of the more recent field work in the Krupnik area.

The 1904 earthquake happened in what was then the Ottoman Empire, in an area, shown in fig. 1, in which modern national boundaries were quite different at the time of the earthquake. Throughout this paper I use old names, those mentioned in contemporary sources, some of which differ from modern place-names.

2. Regional seismicity

The general area most affected by the earthquakes of 4 April 1904 is not known to have been damaged in the past by a severe earthquake, but this may well be due to lack of information rather than lack of earthquakes. The epicentral area was removed from large towns and trade routes, and any large earthquake in the area would have been felt and reported at outlying urban centres, but its location would have remained uncertain. Instrumental records of recent years, in this area as in others, show that minor shocks originate at points rather than generally spread over the area, with no relation to known tectonics. Geological field evidence of fault segmentation and local morphology is in agreement with the imperfect historical record, which indicates that no very great earthquake was likely to have originated in the region.

Epicentres of all important earthquakes on land in the general area (40°-43°N and 21°-25°E) before 1960 are macroseismic, and surface-wave magnitudes for the whole period, and locations after 1960, are instrumental (*e.g.*, Ambraseys *et al.*, in preparation); they are listed in table I and they are shown in fig. 2.

3. Instrumental data

Instrumental data for the foreshock of 4 April come from 47 stations in the distance range 8° to 90° and for the main earthquake from 54 stations in the range 3° to 120°. Additional data from undamped seismographs of the Russian network (*e.g.*, Rosenthal, 1907; Levitski, 1906), and a crude teleseismic location agrees with the general area of the event.

We could find only one usable seismogram for the shocks of 4 April, 1904 made by a Wiechert instrument at Leipzig (Etzold, 1904) which is shown in fig. 3a. Other Wiechert seismograms from German stations and from Budapest are now lost. Records from undamped instruments from European stations, such as those from Rocca di Papa, written by an Agamennone pendulum (Monti, 1907), are either clipped soon after the onset or they are not readable. Examination of the N component of the Leipzig record in fig. 3a shows four sizable foreshocks of M_s between 5.7 and 6.4, occurring between the large foreshock and the main shock. A usable recordings for the aftershock of 10 April, 1904 is shown in fig. 3b.

4. Magnitude and seismic moment

The first estimate of the magnitude of the 1904 earthquake was made by Gutenberg. His work sheet (#87:1053) shows that for this he made use only of the maximum amplitude from the undamped Omori seismograph in Osaka (OSA), and the P and S amplitudes from a Wiechert in Göttingen (GTT) from which he calculated m_B = 7.4 and 7.6 respectively, and from which he gives, not a very robust estimate of a long-period body-wave magnitude, of about 7.5.

Karnik (1968), using the original Prague formula and ground amplitudes from Göttingen (GTT), Leipzig (LEI) and Potsdam (POT), calculated the surface-wave magnitude of the larger shocks of the Struma sequence. For the main shock he gives M_s = 7.8.

He was followed by Christoskov and Grigorova (1968) who, using trace amplitudes recorded by 10 undamped penduli in Russia

Table I. Significant earthquakes within 40° to 43°N and 21° to 25°E.

	Y	M	D	OT	N	E	h	M_s	log*M*	*r*	M_w	q	Location
1	1902	07	05	1456	40.79	23.05	00	6.31	25.67	0	6.38		Assiros G
2	1904	04	04	1003	41.80	22.70	00	6.90	26.49	0	6.93		Kresna B
3	1904	04	04	1026	41.80	23.00	00	7.18	26.91	0	7.21	0.5F	Kresna B
4	1904	04	10	0852	41.90	22.80	00	6.18	25.51	0	6.28		Kresna B
5	1904	04	19	1814	41.90	23.10	00	5.64	24.89	0	5.87		Kresna B
6	1905	10	08	0727	41.90	23.20	00	6.35	25.72	0	6.42		Kresna B
7	1921	08	10	1410	42.33	21.37	00	5.72	24.98	0	5.92		Urosevac K
8	1928	04	14	0859	42.15	25.40	00	6.91	26.51	0	6.94		Plovdiv B
9	1928	04	18	1922	42.25	25.00	00	7.02	26.67	0	7.05	0.6F	Plovdiv B
10	1928	04	25	0925	42.10	26.00	00	5.60	24.85	0	5.84		Plovdiv B
11	1931	03	07	0016	41.33	22.43	00	6.14	25.46	0	6.24		Valandovo M
12	1931	03	08	0150	41.32	22.51	00	6.70	26.19	0	6.73	0.2	Valandovo M
13	1932	09	26	2126	40.50	23.80	00	5.82	25.09	0	6.00		Ierissos G
14	1932	09	26	1920	40.50	23.80	00	6.82	26.37	0	6.85	0.5F	Ierissos G
15	1932	09	28	1652	40.75	23.40	00	5.72	24.98	0	5.92		Ierissos G
16	1932	09	29	0357	40.77	23.48	00	6.32	25.68	0	6.39		Ierissos G
17	1932	11	01	1619	40.55	23.75	00	5.58	24.83	0	5.82		Ierissos G
18	1933	05	11	1909	40.70	23.67	00	6.28	25.63	0	6.36		Ierissos G
19	1958	07	17	0537	40.72	23.39	19	5.48	24.72	0	5.75		Volvi G
20	1963	07	26	0417	41.99	21.43	10	6.23	25.04	1	5.96		Skopje M
21	1978	05	23	2334	40.70	23.25	08	5.76	24.76	1	5.78		Volvi G
22	1978	06	20	2003	40.73	23.25	07	6.41	25.43	1	6.22	0.3F	Volvi G
23	1978	07	04	2223	40.75	23.11	05	5.12	24.36	0	5.51		Volvi G
24	1990	12	21	0657	40.86	22.35	15	6.12	25.23	1	6.09		Gumenisa G
25	1994	09	01	1612	41.10	21.19	12	5.78	25.05	0	5.97		Bitola M
26	1995	05	13	0847	40.10	21.65	11	6.51	25.88	1	6.52	F	Kozani G

q = per cent of the seismic moment of the main shock released by the larger foreshocks and aftershocks of the sequence; F = event associated with normal surface faulting; location: B = Bulgaria, G = Greece, K = Kossovo, M = Macedonia.

(Levitski, 1906) and three seismographs in Europe at (GTT), (LEI) and (POT), calculated surface-wave magnitude of the main earthquake M_s = 7.8, and of the shocks of 4 April 1904, M_s = 7.3, and of 8 October 1905 M_s = 7.3. Doubts about the large size assigned to this earthquake were expressed by Miyamura (1988) on the grounds that the data used were not reliable.

We find that much of this over-estimation of M_s in these calculations was due to the use of peak-to-peak rather than zero-to-peak trace or ground amplitudes which, before the mid-1910s, was the commonly reported amplitude in station bulletins. This inflated M_s estimates by + 0.3 magnitude units, while an additional inflation was introduced by failing to apply station corrections to station magnitudes derived from

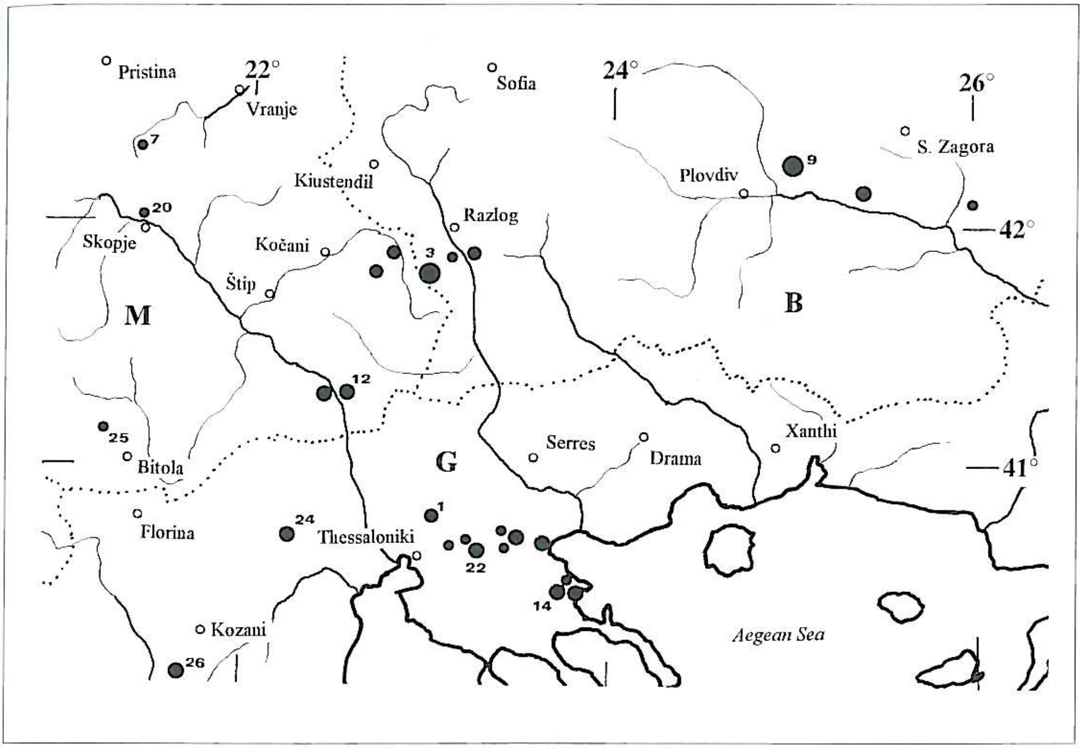


Fig. 2. Distribution of significant earthquakes within 40° to 43°N and 21° to 25°E; numbers refer to larger shocks in table I. Present day national boundaries: B = Bulgaria; G = Greece; M = Macedonia.

a small number of stations, which adds another 0.2 to 0.4 magnitude units (*e.g.*, Ambraseys and Douglas, 2000).

There are a number of methods we can use to bracket the magnitude of the main earthquake. One would be to use trace amplitudes from Milne recorders. The earthquake was recorded by 23 standard Milne instruments in the range of distances 12° to 159° from which we have trace amplitudes (*e.g.*, BAAS, nos. 10-12). Using the calibration relationship

$$M_{SM} = 4.36 + \log A_M + 1.25 \log(\Delta°) \quad (4.1)$$

in which A_M is the single trace amplitude in millimetres and Δ the geocentric distance in degrees (*e.g.*, Ambraseys and Melville, 1982) we find that from 23 stations we have $M_{SM} = 7.1 \pm \pm 0.27$.

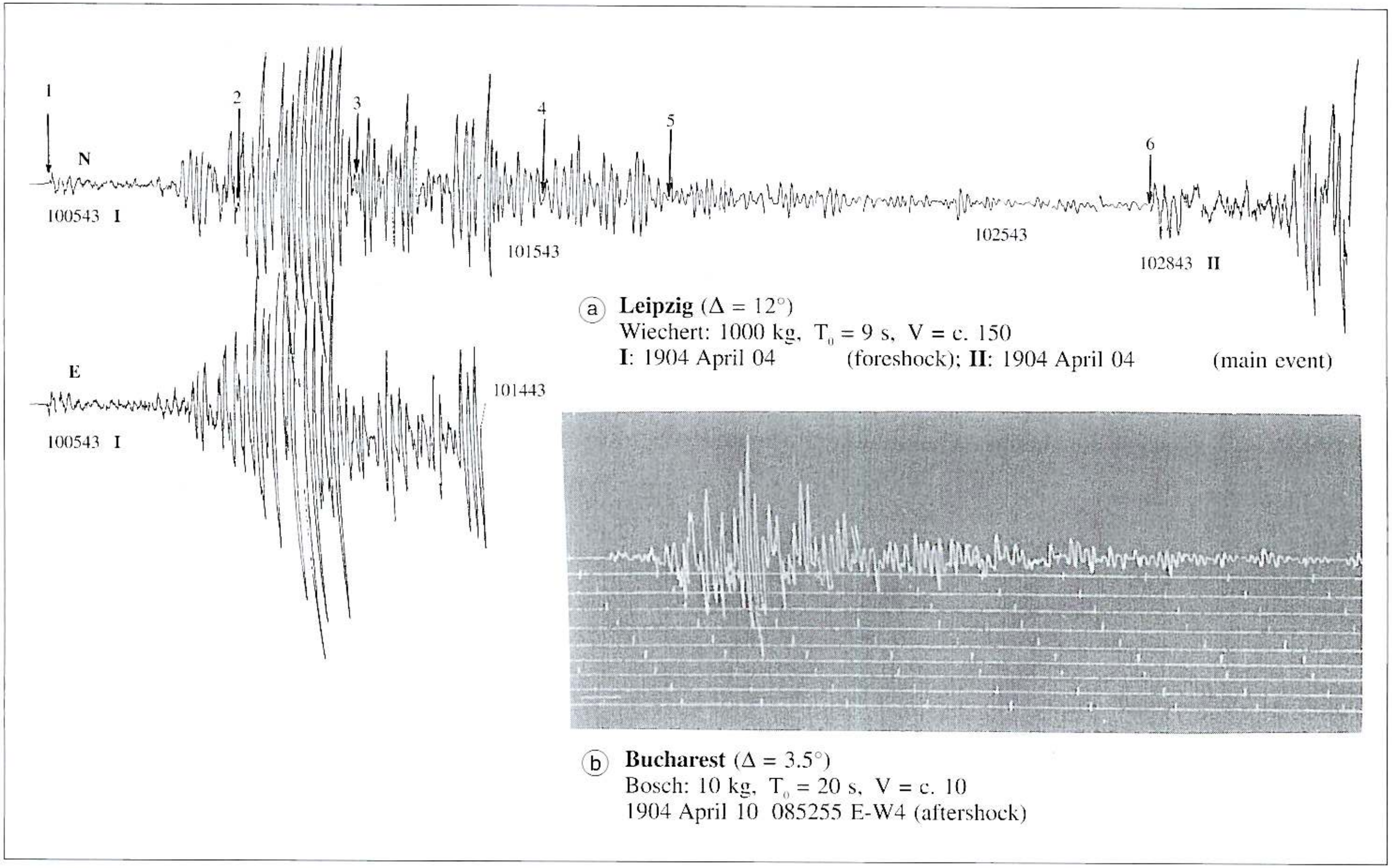
Alternatively, for the same data set, Abe's relationship (*e.g.*, Abe, 1988)

$$M_{SA} = 3.63 + \log A_M + 1.66 \log(\Delta°) \quad (4.2)$$

gives a very similar value of $M_{SA} = 7.0 \pm 0.30$.

Another method would be to use the Prague formula with distance and station corrections (*e.g.*, Ambraseys and Douglas, 2000). From three stations operating Wiechert seismographs, we get $M_S = 7.3 \pm 0.14$ which is close to the values 7.3 and 7.1 obtained from the network of Milne instruments by Abe (1981) and Abe and Noguchi (1983), respectively.

Finally, we can estimate the surface-wave magnitude M_S from macroseismic data using



ⓐ **Leipzig** (Δ = 12°)
Wiechert: 1000 kg, T_0 = 9 s, V = c. 150
I: 1904 April 04 (foreshock); **II**: 1904 April 04 (main event)

ⓑ **Bucharest** (Δ = 3.5°)
Bosch: 10 kg, T_0 = 20 s, V = c. 10
1904 April 10 085255 E-W4 (aftershock)

Fig. 3a,b. a) Facsimile of seismograms of the main foreshock (I) and main earthquake (II) recorded at Leipzig. Other shocks between I and II are marked with: 2) at 10 h 09 min 16 s, M_S = 6.4; 3) 10 h 11 min 59 s, M_S = 6.0; 4) 10 h 16 min 09 s, M_S = 5 3/4; 5) 10 h 18 min 53 s, M_S = 5 3/4. b) Facsimile of the aftershock of 10 April recorded at Bucarest.

Table II. Estimates of isoseismal radii for the main shock (in km).

r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}	
500	330	230	190	120	065	038	020	Grigorova and Palieva (1968)
600	–	300	–	–	–	–	–	Karnik (1968)
–	520	370	250	165	075	045	018	Shebalin (1974)
–	–	–	345	185	106	057	–	Papazachos (1992)
460	–	240	–	–	045	–	–	This study

the following empirical relation

$$M_{Sm} = -\,1.54 + 0.65\,(I) + 0.0029\,(r) + \\ + 2.14\log(r) + 0.32\,p \tag{4.3}$$

which has been derived from 488 isoseismals of about 9000 intensity points associated with 123 shallow (< 26 km) earthquakes of uniformly recalculated M_s in Greece and Western Turkey, for intensities less than VIII MSK and source distances r up to 500 km. In eq. (4.3), p is 0 for mean values and 1 for 84-percentile.

For the main shock, different authors have assess different intensity radii, table II. Using our assessments or those from the isoseismal map of Grigorova and Palieva (1968), eq. (4.3) gives $M_{Sm} = 7.36 \pm 0.13$, a value comparable to the magnitude obtained from instrumental data, or M_0 3.1×10^{19} Nm ($M_w = 6.9$) and 8.1×10^{19} Nm ($M_w = 7.2$) for the foreshock and main earthquake respectively (*e.g.*, Ekström and Dziewonski, 1988). This assessment of M_0 allows us to estimate the probable length of the co-seismic fault rupture, and it may be informative to make this estimate from a combination of first principles and more closely constrained empirical relationships, along the following lines (Ambraseys and Jackson, 1998). For earthquakes that rupture the entire thickness (w) of the seismogenic upper crust, the downdip width of the fault is $w/\sin\theta$, where θ is the fault dip, and the moment is then

$$M_0 = (\mu\alpha w/\sin\theta)L^2 \tag{4.4}$$

where μ is the rigidity modulus and α is the ratio of average displacement (u) to fault length (L), which for intra-continental earthquakes is observed to be close to $5\times10^{-5}\times L$ (*e.g.*, Scholz, 1982). Both observationally and theoretically, it is known that for such earthquakes the relationship between moment and magnitude (M, that is M_s or moment magnitude $\boldsymbol{M}$) is of the form

$$\log(M_0) = A + BM \tag{4.5}$$

where A and B are constants, with $B = 1.5$ for events with M not smaller than about 6.0. Combining these expressions gives a relationship between moment and fault length of the form

$$M_s = \log(\mu\alpha w/\sin\theta)/B - A/B + 2\,(\log L)/B. \tag{4.6}$$

For illustration, if we take $\mu = 3\times10^{11}$ dcm^{-2}, $\alpha = 5\times10^{-5}$, $A = 16.14$ and $B = 1.5$, then for a seismogenic layer of thickness $w = 15$ km and a normal fault ($\theta = 45°$), for the foreshock and earthquake of 4 April 1904 of magnitude M_s 6.8 and 7.2, the rupture lengths would be 32 and 51 km.

5. Macroseismic information

The main shock, its large foreshocks and aftershocks were widely felt and their far-field effects, although somewhat exaggerated when compared with other sources of information, are well reported in the regional press (*e.g.*, *Dnevnik, Gazetiia Sviedenia, Journal de Salonique, Levant Herald, Sabah, Stambul, Vechera Posta, Viesti*).

Additional detailed information for Bulgaria is also available in Watzov (1904, 1905a,b, 1906), for Macedonia and Serbia in Mihailovic (1906, 1911a,b), for Romania in Hepites (1905), for Hungary in Rethly (1905), Halasz (1908), information which is supplemented by the material that covers the whole of the Balkans published by Levitski (1906), Oddone (1907) and Rudolph (1905).

Primary information for the epicentral region is relatively limited and comes chiefly from few field reports of inspections made in April and May 1904 by Austrian engineers in the Ottoman service, in charge of the construction and maintenance of the road along the Struma valley which had been completed shortly before the earthquake, as well as from diplomatic dispatches (Hoernes, 1904; Paillares, 1909; Hubka, 1910; Anonymous, 1911). Information about damage to church property was found in the Exarchate of the Bulgarian Church (Sbornik ot dokumenti i spomeni; Ilčiev, 1910; Christov *et al.*, 1958) as well as in letters published in the local press sometime after the earthquake (Watzov, 1905b).

Contemporary overviews were also published by Belar (1904a,b), Criticos (1932), Eginitis (1909), Hörnes (1905), Husserl (1904) and Moureaux (1904) which, however, add little original information.

Information from interviews with local people collected during the period 1965 to 1970 is of little value. The reason for this is perhaps that no tradition of the earthquake has survived, many of the older local people, in the mid-1960s, being first-generation locals who had immigrated after the 1904 earthquake and after the exchange of populations following the Balkan wars of 1912-1913.

In spite of their relative large number, most of the published reports contain little information from the epicentral region which centers near Kresna, in the Struma valley, and extends for at least 80 km in an E-W direction, an area which at the turn of the last century was remote and relatively inaccessible. The reason for this is that during the period 1903 to 1905 this was a «no-go» area and part of the revolutionary territory controlled by Sandanski's partisan movement. One can only assume that the lack of mention of the earthquake in the sources is due to the relative unpopulated nature of the territory affected. The defeat of the Ilinden uprising of 2 August 1903 and its aftermath were apparently uppermost in people's minds and clearly affected more of them than the earthquake, even though this earthquake was the most serious in this region for generations.

6. Foreshocks

There was little prelude to the double shock of 4 April 1904. No large shocks are known to had occurred in the area and the one true foreshock occurred on 25 November 1903. It was a small earthquake, for which we calculated $M_s = 5.0$, that caused some damage over a small area between Razlog, Rila, and Kocherinovo where a number of houses and churches were damaged without loss of life. The earthquake was felt throughout Bulgaria and in Southeastern Serbia but it was not reported from Northern Greece. It was followed by other small shocks which did some additional damage.

A second, damaging foreshock ($M_s = 6.9$) occurred on 4 April 1904, about twenty minutes before the main earthquake. It did considerable damage but as most accounts do not report its effects and those of the main earthquake separately, it is difficult to discriminate clearly their respective epicentral regions. The general impression from the available information, however, is that the regions mostly affected by the foreshock was in the mountainuous region between Blatec, Berovo and Pehcevo in Macedonia, where there is some evidence that the first shock caused widespread, and in places serious, damage with casualties.

The foreshock was felt throughout Bulgaria, as far south as Volos and Larissa in Greece, throughout Macedonia, Serbia and in some parts of Southern Romania.

7. The main shock

The main shock on 4 April 1904 ($M_s = 7.2$) added to the damage which now extended over an area of about 40 km radius, from west of Kocani in the west to Razlog in the east, Dzu-

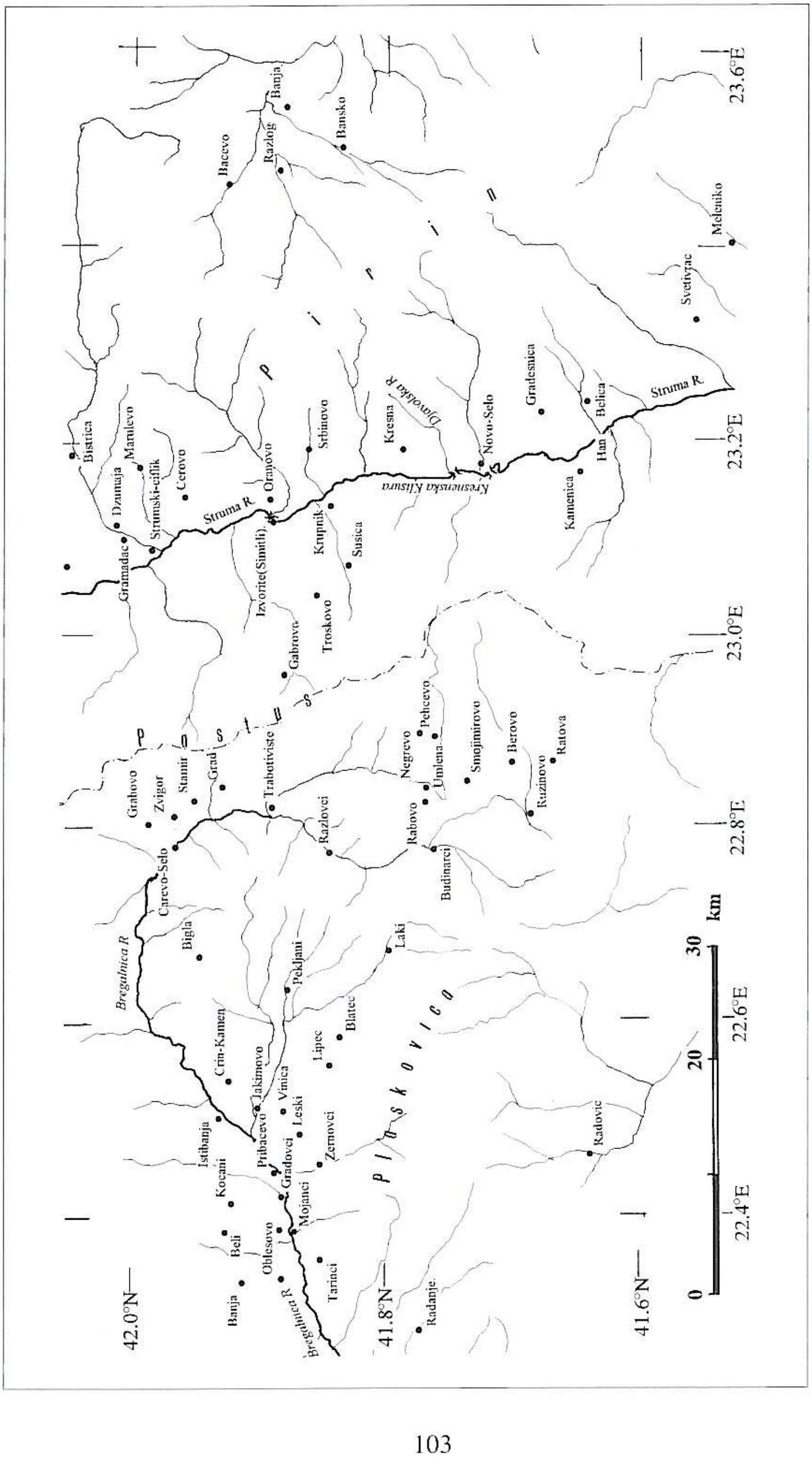


Fig. 4. Location map of epicentral area showing localities mentioned in the text.

maja and Carevo Selo in the north, to Berovo and Novo Selo in the south, an area which straddles the modern Macedonia-Bulgaria border, fig. 4.

In what follows, the information retrieved is presented in a geographic sequence, beginning in the epicentral region and continuing in the far-field. Locations not shown in fig. 4 can be found in 1:100000 scale topographic maps of 1923 and 1954 issued by GIJNA (Geograf. Inst., Jugoslav. Narod. Arm.)

Starting from the eastern extremity of the epicentral region, at Banja damage was not very serious: a few houses and a minaret collapsed killing one person, many chimneys and old walls fell over, and some houses became uninhabitable. Also at nearby Bansko, only one house caved in, chimneys toppled and a number of rural houses suffered different degrees of damage.

The large village of Razlog (Mehomija), particularly its lower part on either side of the Bela Reka, was more damaged. Not a single house was left undamaged and four houses collapsed killing three and injuring 4 people. Sheds, the tobacco warehouses, a minaret, the walls and gate structure and the upper part of an old tower also collapsed. Total losses in the region were estimated at 8000 TL (1.0 Turkish Lira = £ 0.90 of 1901). North of Razlog, on higher ground, damage at Bacevo was relatively small and only a minaret fell over. There is no information from the mountainous tract of land to the west of Razlog for about 20 km until we reach the river Struma, an area relatively thinly inhabited.

Reverting now to the region in the north of the epicentral region, and starting from the upper reaches of the Struma river, the earthquake and its foreshock did some damage at Bistrica where the church and some houses were ruined. At Dzumaja (Blagoevgrad) damage was widespread and in places serious, particularly in the lower part of the town, where about 100 houses damaged by the first shock were ruined, including one mosque, three minarets, the barracks and the military hospital, killing two and injuring four people. Damage in the upper, eastern, part of the town was less widespread and most houses and the church survived the shocks with reparable damage. The loss of public buildings was estimated at 5000 TL.

In the plain south-west of the town, where at Gramadac the Struma Klisura (defile) opens up into a valley, ground motions were so severe that pebbles on the ground were thrown up in the air and large areas in the valley floor liquefied as far Strumski Ciflik a few kilometres to the south. At Gramadac only a few houses were left standing , but people having been warned by the foreshock there were no casualties. Further to the south at Cerovo, destruction was complete and only seven houses were left standing.

Damage along the Struma valley to the south of these localities increased rapidly. From Karasu Ciflik to Izvorite (Simitli), the road along the river was segmented by ground cracks and elsewhere it was blocked by the rubble of masonry retaining walls which had collapsed. Izvorite was almost totally destroyed: out of 200 stone masonry houses, only three were left standing, a minaret fell and the barracks were damaged beyond repair. Five people were killed and 10 injured. A wooden bridge across Struma settled on one side by 0.3 m but did not fell over. On higher ground, Oranovo (Urehovo) was somewhat less affected but with the exception of a few timber-framed houses which survived the shock, all the other houses and the church were totally ruined. In Krupnik, out of 250 houses few survived, and the barracks and church were destroyed. Also Srbinovo (Brezani) was destroyed but details are lacking.

Beyond this point the road to the south along the river and the 12-km long Struminska Klisura (defile), became impassable to carts from rockfalls and what was left of the road could be followed only on foot or on horseback. Kresna, on higher ground east of the defile, was totally destroyed. South-west of Krupnik on the hills, Susica was seriously damaged, probably destroyed, but details are lacking.

Damage was less heavy south of Djavolska Reka (Sejtandere). At Novo Selo (Yeniköy), only seven houses fell in and the church and a minaret were damaged. The bridge over the Struma was left intact. Damage at Gradesnica, just east of the Struma river, was small. Also at Kamenica and Han Belica damage was repairable.

East of the Struma, in Svetivrac, only a few rural houses were seriously damaged. Also in the town of Meleniko damage was relatively small. The earthquake caused great panic, and the collapse of a few dilapidated old houses and walls together with four dwelling. The school suffered some damage as well as the nearby monastery of Spileo which is built at the top of a cliff.

To the west of the Struma, the mountainous region between the river and the Pastusa range was sparsely populated and the few hamlets in the region are said to have been heavily damaged. In Troskovo, all the houses, the school and church were totally ruined. In Gabrovo, what was left standing after the foreshock was totally destroyed by the earthquake.

On the west side of the Pastusa range, and along the Bregalnica river, damage was serious.

Starting from the upper reaches of the river, Ratova was badly damaged. In nearby Ruzinovo, the church fell in. Berovo was almost totally ruined with the collapse of 180 houses and loss of one life. At Smojimirovo (Ismojmir), a number of houses were ruined and the church was damaged. At Umlena, many houses were shattered with no loss of life. The town of Pehcevo (Osmaniye or Malesovo) was almost totally ruined by the foreshock, and what was left standing was destroyed by the main shock. Churches, mosques and schools either collapsed or became uninhabitable. The foreshock killed 12 people in the town and 38 in the surroundings, injuring about 100. Loss of life in the main earthquake was very small because people had fled their houses after the first shock. At Negrovo, Rabovo and Budinarci many houses collapsed without loss of life. Further north, Razlovci was totally destroyed, but details are lacking. The greater part of Trabotiviste with the exception of a few wooden houses the rest were ruined with some loss of life. In Grad, almost all the houses became unihabitable and two people were killed. Stamir, Zvigor and Grabovo were totally destroyed. In Carevo Selo (Carova, Delcevo), on the Bregalnica river, old houses collapsed and new ones were damaged. The church was almost totally demolished and the minaret of the mosque fell. Long cracks along the river banks and liquefaction of river deposits abounded.

Further west on the foothills of Cavka, Bigla, Crin-Kamen (Vinicka Gumma) and Jakimovo survived the shock with very little damage. In contrast, neighbouring Vinica, Leski, Zernovci and Lipec were much damaged with loss of life. Damage was more serious at Blatec (Blaca) where 103 of its 138 houses and three mosques were destroyed and one person killed. Also much of Pekljani was destroyed and the rest of the village was damage, while at Laki (Liska), with the exception of one, all 80 houses of the village were shattered and one person was injured.

Damage to villages in the Bregalnica marshy plain, chiefly due to liquefaction and spreading of the ground, was serious. In Pribacevo, Mojanci, and Oblesevo and neighbouring Gradovci, and Podlog, most houses were ruined and some people were killed. The banks of the Bregalnica river slumped in places and there is evidence of liquefaction of the ground in the villages.

Kocani, the chief town situated on slightly higher ground to the north of the Bregalnica plain, suffered overall small damage. In all, about 40 houses in the lower part of the town were ruined, as well as the church, the barracks, a minaret and the school, but in the upper part most houses remained intact. An inspector who visited the town a few weeks after the earthquake reports that he could not find a badly damaged house to photograph. No one was killed in the town but in the district of Kocani the earthquake killed 14 and injured 11 people.

West of Kocani, in Beli and Banja two thirds of the houses were damaged and a few houses fell in causing casualties. Further to the south damage was patchy. At Radanje, 69 houses and a mosque became uninhabitable, and at Radovic a few old dwellings collapsed killing three people. In the town of Stip, only two houses collapsed and about 20 were damaged, otherwise damage in the town and in its suburb of Novo Selo was insignificant (these sites are to the west of Kocani and outside fig. 4). The bridge on Bregalnica, a multiple arch stone masonry construction, suffered absolutely no damage.

Further away from the epicentral area, damage was sporadic, and at sites on alluvium or river deposits damage was serious, in places accompanied by liquefaction of the ground.

To the north of the epicentral area, the large monastery of Rila, 35 km to the north of Kresna, already damaged by the earthquake of 25 November 1903, suffered additional but repairable damage: the walls of almost all buildings and churches were cracked and 74 chimneys of the main monastery complex fell. Also the Tower of Khrel and the tall external walls of the monastery opened up in places and they had to be repaired and supported with large stone masonry buttresses. The floor of the central court of the monastery cracked and settled but rockfalls from nearby clifs did no damage.

To the south of the epicentral area, in Thessaloniki, 130 km from Kresna, the shock was strongly felt. Contrary to exaggerated press reports, only a few dilapidated houses were ruined, and only one life was lost from the fall of a cornice in the Serbian school. Some of the damage to other buildings was due to the weak state in which they had been left in after the local earthquake of 5 July 1902 ($M_s = 6.5$) while two public buildings that fell in during the 1904 earthquake had already been weakened by separatists bomb attacks shortly before the earthquake.

The earthquake caused no damage to the Istanbul - Thessaloniki - Skopje - Beograd railway line which skirts the epicentral area to the south and west, keeping at an epicentral distance of about 50 km, but it did some damage to station and service buildings.

With no national census, the number of people killed in this earthquake is not known even approximately, which is also an indication of the lack of interest by the authorities to assess damage and rehabilitate the epicentral region.

Damage to public and religious buildings and to the newly built road along the Struma was serious enough to warrant the Turkish authorities taking relief measures, among which were tax relief and interest free loans issued by the Agricultural Bank in the districts of Edirne, Thessaloniki, Iannina, Monastir, and Kossovo to townspeople for repairs, giving priority to public buildings. There is no evidence that these measures were extended to farmers or to those living in the Struma region.

8. Aftershocks

The largest aftershock of the series occurred on 10 April 1904 for which we calculated from instrumental data $M_s = 6.2$. Much of the destruction was done in the area between Kocani, Carevo Selo and Razlovci where a number of houses collapsed with casualties.

Another damaging aftershock (M_s = 5.6) occurred in the region of Oranovo on 19 April 1904.

Aftershocks continued intermittently, the last occurring on 8 October 1905 ($M_s = 6\ .4$). It was strong in the Pirin mountains, but neither instrumental nor macroseismic information is enough to allow with certainty the determination of its epicentral area. It is said that in Bulgaria, near Eltepe or Elova (not identified), in the sparsely populated Pirin Planina, this shock was so violent that people could not stand up and in the Predela Derbent rockfalls blocked the pass and communications with Razlog. Further west, in the region of Malesevo at Pehchevo, houses were totally ruined and a few walls collapsed. The shock shuttered the barracks on the Macedonian frontier, probably at Dzami Tepe.

Damage extended further away as far as the Meleniko area where a few walls collapsed and at Dzumaja where the shock added to the damage already done by the earthquake of 1904, causing the collapse of a minaret which was still standing after the main shock.

The aftershock of 8 October 1905 was rather strong as far as Thessaloniki, Kumanovo, Dzep and Sofia. It was felt over much of the Principal-

Table III. Kresna earthquake sequence 1903-1905.

	Y	M	D	OT	N	E	M_s
1	1903	Nov.	25	2316	42.0	23.4	5.0
2	1904	Apr.	04	1005	41.8	22.7	6.9
3	1904	Apr.	04	1028	41.8	23.0	7.2
4	1904	Apr.	10	0852	41.9	22.8	6.2
5	1904	Apr.	19	1814	41.9	23.1	5.6
6	1905	Oct.	08	0727	41.9	23.2	6.4

ity of Bulgaria, in Greece and it was reported from Romania south of the Carpathian mountains.

Table III summarises the characteristics of the Kresna sequence.

9. Ground effects

9.1. *Liquefaction*

As a result of the shocks, numerous areas in the epicentral area, as well as at some distance from it, were intensely fractured. From the description of the effects of the earthquake it is clear that liquefaction of the ground had an important effect on damage and on the intensities assigned to these places. These areas are irregularly scattered and they show a tendency to concentrate in small valleys at the confluence of rivers and valleys controlled by grabens. Despite the large number of varied and strong foreshocks and aftershocks occurring over a period of a few days, eyewitness reports suggest these features had been almost entirely the result of the large foreshock. Figure 5 shows the distribution of liquefied site with numbers referring to the text.

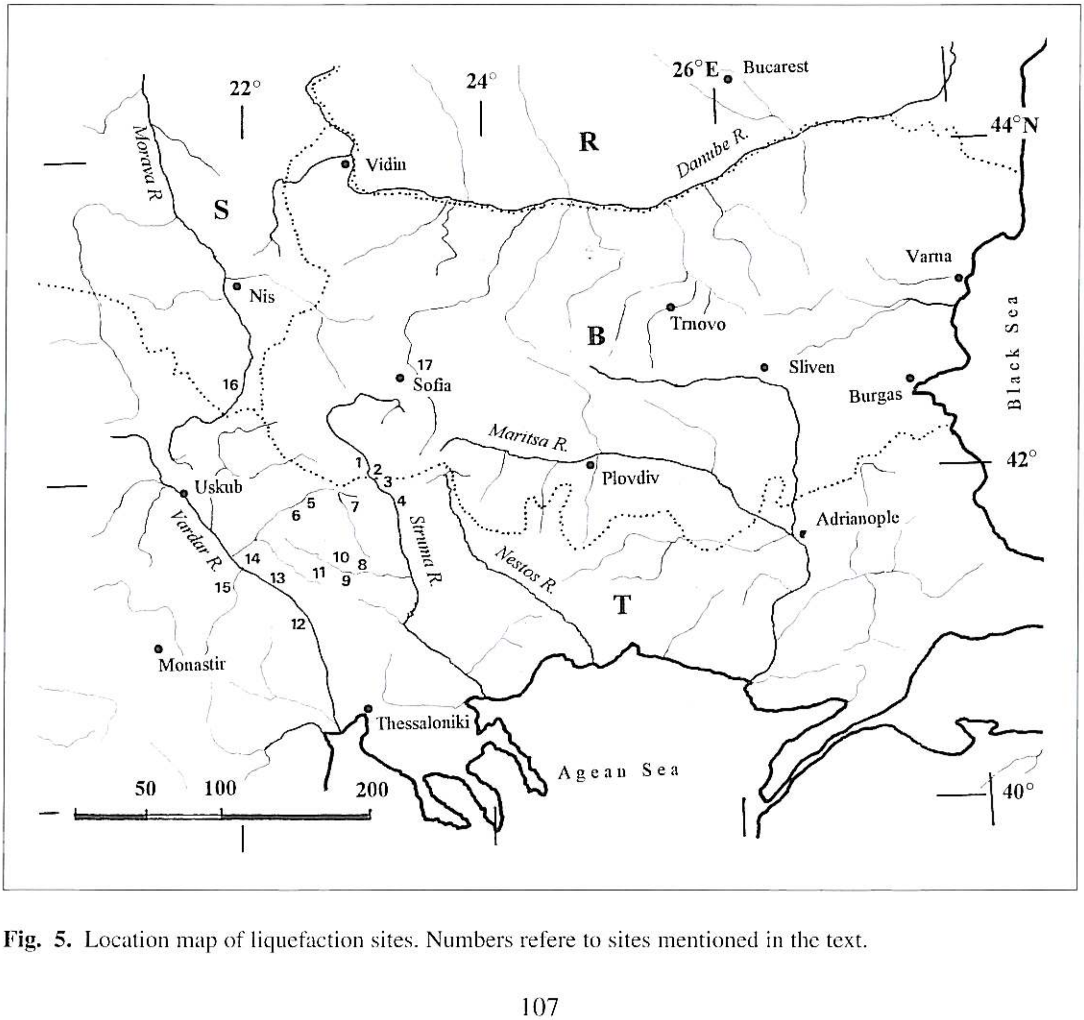


Fig. 5. Location map of liquefaction sites. Numbers refere to sites mentioned in the text.

The northermost point along the Struma river from which liquefaction was reported is in the fields about 2 km south-east of Bobochevo (1) and the Stuma river where sand craters were formed and water was seen ejected from the ground at great heights. Further south at Barakovo (2), the plain at the confluence of the Struma with the Rilska Reka was flooded by the ground water rising above the ground, presumably being responsible for the damage of the bridge on the Rilska Reka.

Wide spread liquefaction was also reported from south-west of Dzumaja, where in the small valley which is confined between the town and the Struma river and includes the village of Gramadac (3), the ground opened up and in places the ground water flooded the fields as far south as the Strumski Ciflik.

Ground spreading, slides and liquefaction were also reported from the east side of the Struma, in the plain between the river and Srbinovo (Brezani) (4). Shortly after the earthquake, warm water oozing up from the ground in the fields south-east of Simitli (Izvorite), caused large patches of snow to melt away.

Another region where liquefaction was widspread is the Bregalnica plain south of Kocani. For a distance of 12 km, from near Jakimovo to Oblesevo, the valley floor liquified and in places jets of water spurted from the ground to heights of two to three metres. Some of the villages around Pribacevo (5) were flooded temporarily by the water table which rose well above the ground. At Gradovci, Mojanci, Podlog and Oblosevo, many of the houses became uninhabitable because of ground failure. Localised liquefaction of the ground was also reported from the upper reaches of the Bregalnica river, near Trabotiviste (7), where the shock caused slumping of the river banks and cracking along terraces, triggering liquefaction of river deposits.

Outside the epicentral region liquefaction was reported from a number of places, along the 20 km long Strumica valley, about 50 km south of Krupnik: from Yenikoy (Novo Selo) (8), Kolesimo (9), Sekirnik (10), Hamzali (Serai), to Angelci (11).

Liquefaction was also reported from areas adjacent to the Vardar river, areas accessible because of the Thessaloniki to Nis railway line which follows the river. The southernmost site from which liquefaction was reported is the Negorci plain (12) west of the Vardar river, about 60 km south of the epicentral area. Further north, there was sporadic liquefaction in the fields east of the Vardar river between Demir Kapija (13) and Negotino (14), 60 km west of the epicentral area. Also west of Negotino at the confluence of Crna and Vardar rivers, ground failures and liquefaction were reported from the area between Rosoman and Palikura (15).

The area outside the epicentral region of most extensive liquefaction was further north at the confluence of the Kostanacka and Davidovacka rivers with the Morava, at Ristovac and Vranje (16), about 70 km northwest of the epicentral area. Damage to a number of villages, due to ground failures was so serious that some authors, unaware of the real location of the earthquake placed prematurely its origin at Vranje (*e.g.*, Mihailovic, 1911b).

Other isolated sites of liquefaction of the ground were reported from the Panega Reka at Ruptsi, and from Gniliane (17) on the Iskr river and from Zihna (?) in Bulgaria.

Flow in many of the streams and cold and hot springs over a large area increased temporarily as a result of the earthquake.

10. Intensity assessment

10.1. *Existing intensity maps*

There are a number of intensity distribution maps available for the Kresna earthquake. One of the first of these maps which was published by Nedeljković (1950) is too crude to be of any use and will not be discussed here. A more reliable map, drawn in the Medvedev-Sponheuer-Karnik (MSK) intensity scale was published by Grigorova and Grigorov (1964, p. 36) who used Watzov's (1905a,b) original data in the Rossi-Forel scale. This map covers only Bulgaria, but a subsequent map extended the coverage over almost the whole of the affected area (*e.g.*, Grigorova and Palieva, 1968).

Karnik (1968) did not publish his map for the main shock which was drawn on the Mercalli-Sieberg (MS) scale and which was also based on Watzof's (1905a,b) data. He reported only the radii of perceptibility and of intensity V, which he estimated at 600 and 300 km respectively.

Another set of isoseismal maps drawn in the Mercalli-Cancani-Sieberg scale (MCS) were prepared by a team of seismologists from Bulgaria, Macedonia, Romania and Jugoslavia. These maps were combined by Shebalin (1974) who produced a map of «generalised» intensity contours in the (MSK) scale. In this map higher isoseismals, which are important because they define the epicentral region, are drawn with a fine detail which is not warranted by the available volume and quality of information and their values are inflated. The reasons for this are that most of the criteria for higher intensities in the (MCS) scale are of limited value and irrelevant when applied to vulnerable structures, and also that intensities for the main shock are contaminated by the effects of its large foreshock (Ambraseys and Melville, 1982, pp. 22-33) Thus, in the conversion of intensites from different scales into the (MCS) scale, and by «generalising» the contouring of isoseismals, intensities $I \leq$ VII (MSK) have been inflated by at least one intensity unit.

More recently, Papazachos *et al.* (1997) published intensity maps for the main shock, for its foreshock and aftershocks, which they constructed using synthetic isoseismals of elliptical shape (*e.g.*, Papazachos, 1992). The input data used are not given and mapping is done for intensities $\geq$ VII (MM) which are affected by the foreshock.

10.2. *Intensity distribution*

The problem with the different intensity scales used by different authors is that these scales have been devised for earthquakes in Central Europe and for earthquakes affecting a built environment which differs considerably from that at the turn of the 20th century in rural Balkans. At that time, houses in the plains were of mud-wall or adobe brick construction covered with flat and heavy roofs, consisting of a rough boarding covered with tamped earth. In mountain villages, houses were build with rubble-stone masonry, laid in clay mortar, built close together in clusters, separated by narrow, winding alleys.

With the majority of the rural building stock being highly vulnerable, maximum intensity above a certain value appears to be effectively the same because at this level all rural houses are damaged beyond repair or destroyed, and any village or town would thus appear equally, but no more, damaged at so-called higher intensity. It becomes practically impossible to determine how strong or light a shock would be necessary to cause heavy damage or destruction. The same comment applies to secondary effects such as landslides, rockfalls and soil failure, which are used as criteria for higher intensities, which are of limited value, and which in the case of the Kresna earthquake are misleading. As a consequence, with damage statistics totally lacking and descriptions being brief and stereotyped, any attempt to assess higher intensities would be too subjective. It is only for sites at some distance from the epicentral area and for which there is sufficient information that it is possible to assess intensities smaller than VIII (MSK), a level at which intensity estimates saturate.

For the Kresna earthquake, there is also another problem which we may discuss briefly. This is the systematic overestimation of far-field intensities and of the radius of perceptibility which leads to inflated estimates of the size of the earthquake. This arises from the misinterpretation of exaggerated press reports which allude to the earthquake having been felt with intensities III to V in Austria, Hungary, at Trieste in Northern Italy, and as far as Mineo in Sicily at epicentral distances of up to 1100 km. In Austria, the earthquake was reported only from the observatory of Graz, at an epicentral distance of 840 km, where the shock was not felt but where a suspended lamp at the observatory was set swinging for a few seconds from which the observer deduced that it was the result of the Kresna earthquake (Belar, 1904a,b). Otherwise, the shock was not felt. Oddone reports that both shocks of 4 April 1904 were felt with an intensity III (RF) at Mineo in Sicily and at Spinea in Venezia, 940 and 1100 km to the north-west of Kresna respectively (Oddone, 1907: 103, 130). In reality the shocks were not felt at these places, but they were only recorded by undamped penduli (*e.g.*, Monti, 1907: 144, 145, 168). Also in Ljubljana, at an epicentral distance of 830 km, the shock was not felt. However at the observatory the earthquake caused suspended lamps to swing for which the staff could not find an explanation before they saw the record made by their undamped seismograph (Belar, 1904a,b).

The earthquake was perceptible in the alluvial plains of Tiszantul, along the southeastern border of present-day Hungary and Romania,

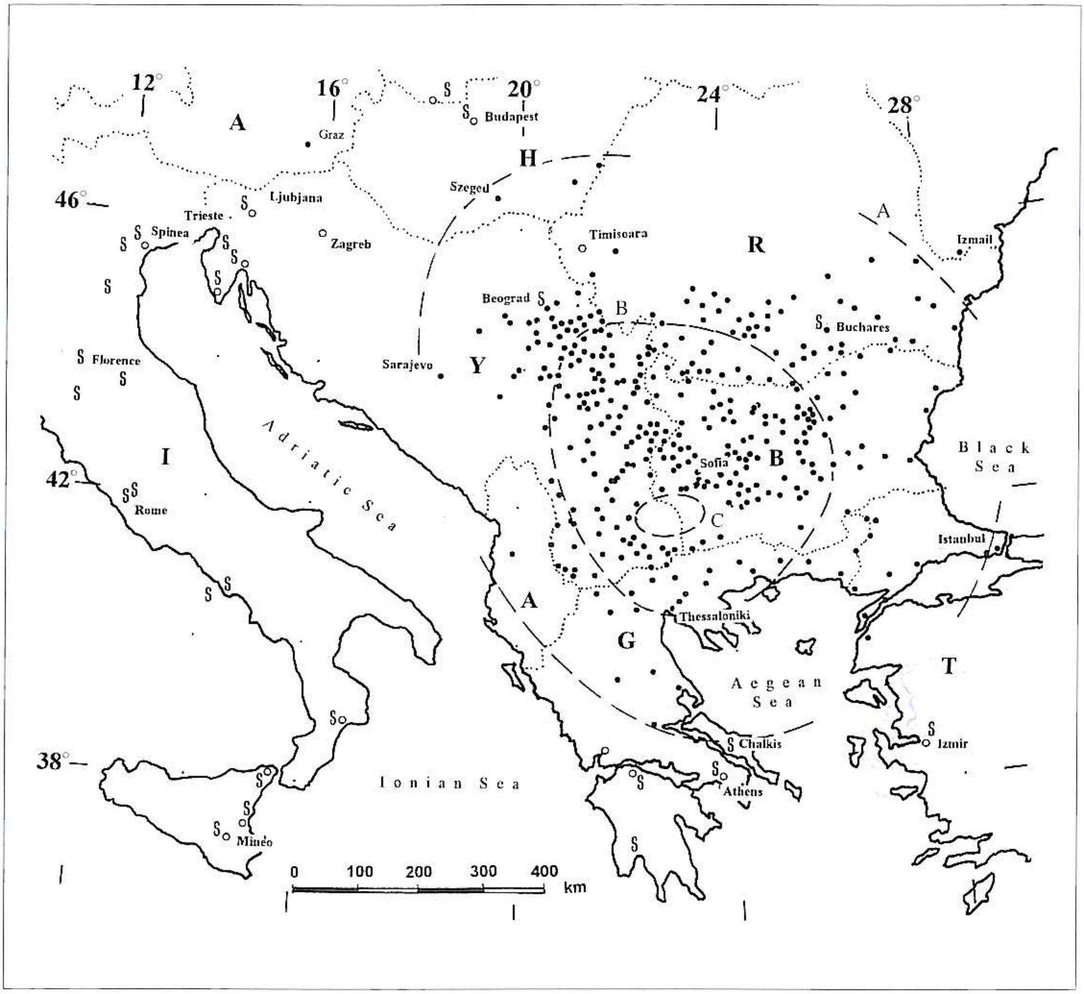


Fig. 6. Intensity distribution map, showing national boundaries in the early 1990s. A = Albania; A = Austria; B = Bulgaria; G = Greece; H = Hungary; I = Italy; R = Rumania; T = Ottoman Empire; Y = Yugoslavia. Solid dots are sites where the shock was felt and for which macroseismic information is available. Open circles are sites where the shock was not felt. S stands for seismographic station in operation at the time of the earthquake. Contour A defines felt area, B area if intensity ≥ V, and C epicentral area.

520 km from the epicentre. Again here the effects were chiefly due to the long-period and long duration of the ground motions, causing suspended objects to swing, stopping pendulum clocks, and causing nausea to some persons at a few places. The intensities of V to VI that Oddone (1907) and Shebalin (1974) assign to these places are grossly overestimated. In fact these effects were noticed and reported because they were first thought to be due to a local shock which occurred in the time of the Kresna earthquake (Hoernes and Seidl, 1905; Rethly, 1905).

Long-period ground motions were also reported from the plains of the Danube and from the Danube delta in Romania and Bessarabia, about 450 to 650 km north-east of Kresna, where intensities, according to Oddone (1907), varied between II and IV (RF) or between IV and VI (CS), according to Florinesco (1958). In one instance the earthquake set up waves in a river and in ponds and in another caused sloshing from a pond.

Also, there is no evidence that the earthquake was felt with an intensity IV (RF) at Athens, at an epicentral distance of 450 km (*e.g.*, Oddone, 1907: 130). We could find no mention of this in the local press, except that the shock was recorded in Athens by an Agamennone undamped pensulum (*e.g.*, Eginitis, 1909). We know that in Greece the Kresna earthquake was not felt south of Volos, at an epicentral distance of 290 km (*e.g.*, Criticos, 1932).

The eastermost locality at which the two shocks of 4 April 1904 were generally felt was the marshy area of Çekmece, today a suburb west of Istanbul, 500 km east of Kresna, but they were barely perceptible in the city (*Sabah* 5.04.1904; *Lev. Her.* 6.04.1904).

There is no evidence that the shock was felt along the densely populated Adriatic coast of Croatia, Montenegro and Albania, at an epicentral distance of about 320 km (*e.g.*, Morelli, 1942; Mihailovic, 1951).

In view of these problems, a more satisfactory method for the assessment of intensity distribution would be to resort to the original material and reappraise intensities uniformly in the (MSK) scale, rather than rely on estimates made by others in different scales (FR), (MS), (MCS) or (SMK). The distribution of the 330 sites for which we have macroseismic information is shown in fig. 6. The overall intensity distribution is rather erratic with pockets of high intensity scattered throughout the region, which is chiefly due to the effect of local soil conditions, a typical far-field characteristic of large earthquakes. An examination of this information shows that intensities could be assessed reasonably well, without being unduly subjective, only at 85 sites, chiefly outside the epicentral region which is defined by $I \geq$ VIII (MSK), shown in fig. 6. This is a sufficiently large sample to define intermediate isoseismals for V and for the radius of perceptibility (III MSK).

11. Faulting

Although there are no modern earthquakes in the precise epicentral region of the 1904 earthquakes, the single focal mechanism available in the general area and the regional morphology indicate normal faulting, with strikes varying between WNW and WSW, fig. 7.

The relatively large size of the two shocks on 4 April 1904 clearly suggests extensive surface faulting for which, however we could find no information in contemporary accounts. It is said that, as result of the earthquake the Struma river was dammed at Krupnik by the southern block being upthrown by 1.5 m, causing the river to stop flowing for ten minutes and forming a lake (P. Petrov, personal communication). However, it is not clear whether this was actually observed or deduced from the recent field exploration of the alluvial cover of the downthrown block (Shanov *et al.* 1999; Shanov and Pavlides, 2000).

The only possible reference to ground deformations in contemporary field reports is the formation of long ground cracks between Krupnik and Simitli which ran parallel with, as well as at right angles to the road, with throws of a few tens of centimetres. Some of these cracks crossed the road and ran in an east-west direction on either side of the road into the fields.

Another set of ground cracks was reported from Simitly (Izvorite). They ran by the river in a SW-NE direction, along a 6 m high terrace, degenerating into a strand of cracks which passed right through the village with a maximum throw

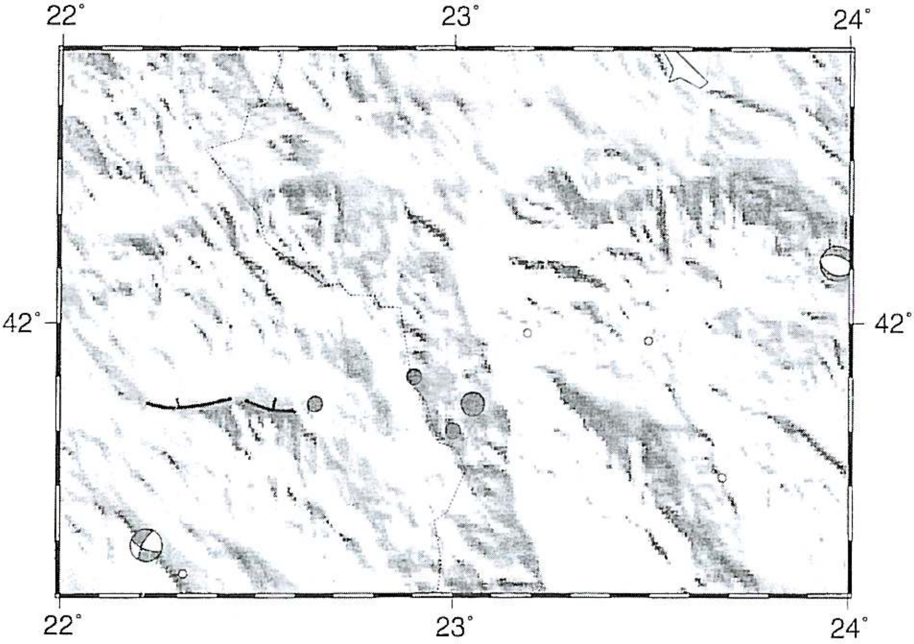


Fig. 7. Topographic map of areas shown in fig. 4 with CMT solutions data given in table I.

of about 1 m. There, timber-framed houses which stradled these cracks withstood the shaking, but in spite of the fact that were distorted by the ground displacements, they were left standing. These are the only two cases of ground deformations reported in contemporary reports. The former I could not locate in 1970, and the latter, from the general morphology of the region I attributed to ground slumping.

Guided by early geological reports (*e.g.*, Louis, 1930), a field examination was made during 1968-1970 of the faults in the Kresna-Srbinovo-Krupnik area. The most important fault segments found extend from west Srbinovo and run in the direction of Krupnik, striking 210°, fig. 8. This is a narrow fracture zone of steep normal faults, basically in gneiss and schists dipping to the north-west that can be followed for five to six kilometres, from west of Srbinovo along and to the south of Rzana Reka to the Struma plain. Because of lack of time no reliable measurement of the characteristic throw on these scarps could be made; erosion and sliding of the footwall grabens masked actual throws which I reckoned to be not more than one metre.

From south of Krupnik, the fault trace turns more to the west and for a few kilometres strikes 240° (R. Armijo, personnal communication, who mapperd these features). The trace seems to extend further west, probably as far as near Susica, an area which was not visited.

Also it was not possible to ascertain whether these surface fault breaks were associated with the 1904 earthquakes or with an earlier, historical event, and if they were the result of the 1904 sequence, whether they were due to the large foreshock or to the main shock.

Since the late 1960s, these faults in the Krupnik-Kresna area have been studied extensively (*e.g.*, Shanov *et al.*, 1999; Zagorchev, 1995a,b) but it seems that there is no consensus about the attitude, location, and length of the surface break actually seen on the ground. Dobrev (1999a,b) gives a rupture length of 15 km, and Yeats *et al.*

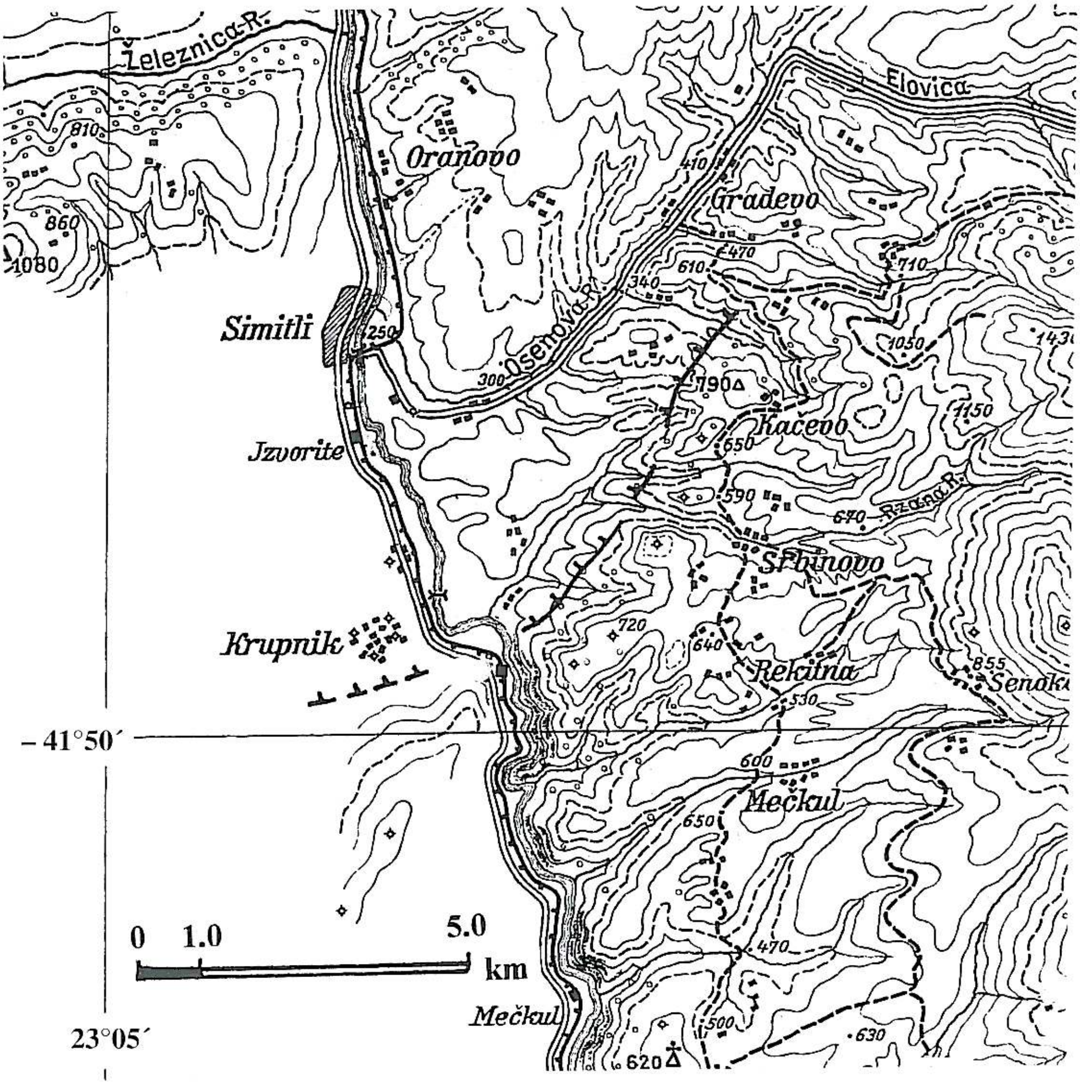


Fig. 8. Sketch of general features of a segment of the 1904 surface fault break mapped in 1969.

(1997) give 60 km or 40 km on Rejanov and Shanov's personal communication, and Ambraseys and Jackson (1998) on second hand information give 25 km. Other writers give different estimates.

Reverting to the area east of Krupnik, at the time of our field studies we were aware of other recent fault scarps to the east of Srbinovo which run along the northeast pediment of the Pirin mountain. They are in a basin-range setting, and they can be associated with one or more of the ranges which are bounded by normal faults. However, macroseismic information does not support their activation in 1904 and we did not examine this region.

We also examined the region north of the Plaskovica range in the Bregalnica valley, 40 km west of Krupnik in Macedonia, where damage in 1904 was as heavy as in the Struma region. Remnants of a series of recent normal scarps were found running along the Osojnica valley in the vicinity of Vinica. They can be followed for about 10 km, from just south of the village of Zernovci to near Blatec striking N-280-E. While it is possible to trace these features eastward by ordinary geological or physiographic evidence, it may be more of a coincidence that they traverse a country heavily damaged in 1904. Although one can take it for granted, we could find no evidence to associate any of these features to the Kresna earthquakes with certainty .

Thus both instrumental and macroseismic data appear consistent with $M_s = 7.2$, a value which also agrees with the degree and extent of damage caused by the earthquake in the epicentral area. This magnitude class is also compatible with the degree of fault segmentation and local morphology of the region (*e.g.*, Zagorchev, 1995a,b) which implies that local tectonics could not have accommodated a single, shallow normal event much larger than about M_s 7.0. From eq. (4.4), $L = [M_0 \sin\theta/\mu w\alpha/]^{0.5}$; assuming normal faulting ($\theta = 45°$), with $\mu = 3\times10^{10}\,\mathrm{Nm}^{-2}$, $\alpha = 5\times10^{-5}$ and a seismogenic depth of $w = 10^4$ m we find that a magnitude 7.4 to 7.8 earthquake would have required rupture lengths of 100 to 190 km respectively, associated with sizeable throws, remnants of which should have been still visible in the ground, but for which so far there is no evidence.

Results from geodetic measurements across the segment of the Krupnic surface fault break on the left side of the Struma river (240°E), which began in 1982, show an oblique left-lateral slip rate of about 3 mm/year (*e.g.*, Dobrev and Kostak, 2000) which does not support these large events in the region.

12. Conclusions

The Kresna earthquake is one of the largest known shallow event on land in the Balkans. It originated in a region in which no known historical or modern large earthquakes have occurred and which was, and still is not regarded by geologists as one of those more active areas in which most large shocks develop.

The reappraisal of the published material for the Kresna earthquakes demonstrated serious shortcomings in the interpretation of macroseismic and instrumental data in existing publications. We find that in rural areas in the Balkans the assessment of intensities $I \geq$ VII (MSK) in the near-field of large shocks becomes judgemental and quite often unduly subjective, and that the drawing of isoseismals contains an element of arbitrariness. This arises from the fact that the data are not always good enough at most sites, not only to allow the assessment of intensity, but also to discriminate between the effects of the main shock and of its large foreshocks or aftershocks. Moreover, rockfalls and landslides are often used to assess intensity; these effects are not indicators of high intensity and they occur more often without the help from earthquakes. We find that the indiscriminate use of intensities assessed in different scales without scrutiny of the original data has caused inflation of the isoseismal contours drawn by different authors.

The Kresna earthquakes triggered liquefaction and liquefaction-induced ground failures, chiefly of saturated fluvial deposits, up to 70 km from the assumed fault zone. Much of the damage reported at relatively large epicentral distances was due to liquefation and associated ground spreading.

The Kresna earthquake was preceded by a destructive foreshock which released a seismic moment half the size of the moment released by the main shock. This multiplicity of shocks seems to be typical of most large shallow earthquakes in the region, their foreshocks/aftershocks releasing about half as much moment as the main event table I (*e.g.*, Ambraseys and Jackson, 1998).

The 1904 earthquake has hitherto been assigned a range of magnitudes up to $M_s = 7.8$, a value which has resulted in an overestimation of the apparent seismic hazard in the region (van Eck and Stoyanov, 1996). The reappraisal of the instrumental data yields a much smaller size of $M_s = 7.2$ and a re-assement of the intensity distribution suggests 7.1. The combined epicentral area generated by the foreshock and the main earthquake extends in an almost E-W direction for about 65 km, form Krupnik to near Kocani in Macedonia. This is consistent with a 7.2 magnitude earthquake and a seismogenic depth of 10 km (for 15 km the associated length of rupture would have been 50 km). Also the relatively large size of the main shock suggests surface faulting but the available evidence is insufficient to establish its full dimensions, attitude and amount of dislocation, except in the vicinity of Krupnik, where recent fault scarps five to less than ten kilometres in total length, have been preserved. It may be argued that the Krupnik earthquake was a multiple event on a partly blind fault and that the surface rupture seen today at Krupnik is associated with one of the constituent shallow breaks.

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REFERENCES

Press reports

Dnevnik no. 664, 1904, Sofia

Gazetiia Sviedenia 05-07.1904, Moscow

Journal de Salonique 09-30, 01-08.05.1904, Thessaloniki

Levant Herald 04.12.1903, 06-23.04, 01-16.05.1904, 23.10.1905, Istanbul

Sabah 05-17.04, 01-13.05.1904, Istanbul

Stambul 23.10.1905, Istanbul

Vechera Posta no. 1133, 1904, Sofia

Viesti nos. 36,38,39,44, 1904, Istanbul

Abe, K. (1981): Magnitude of large shallow earthquakes from 1904 to 1980, *Phys. Earth Planet. Inter.*, **27**, 72-93.

Abe, K. (1988): Magnitudes and origin times from Milne seismograph data, in *Historical Seismograms and Earthquakes of the World*, edited by W. Lee, H. Meyers and K. Shimizaki (Academic Press), 37-50.

Abe, K. and S. Noguchi (1983): Revision of magnitudes of large shallow earthquakes 1897-1912, *Phys. Earth Planet. Inter.*, **33**, 1-11.

Ambraseys, N. and J. Douglas (2000): Reappraisal of surface-wave magnitudes in the Eastern Mediterranean region and the Middle East, *Geophys. J. Int.*, **141**, 357-373.

Ambraseys, N. and J. Jackson (1998): Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region, *Geophys. J. Int.*, **133**, 390-406.

Ambraseys, N. and C. Melville (1982): *A History of Persian Earthquakes* (Cambridge University Press), 122-123.

Ambraseys, N., J. Jackson and C. Melville: *The Seismicity of the Eastern Mediterranean and the Middle East* (Imperial College Press), vol. 1 (in preparation).

Anonymous (1911): *Petritsi-Meleniko-Nevrokopi*, GES/DIS Rapor, Section des Affaires Politiques, G.Q.G de l'Armèe Hellèniques, Athens.

BAAS: *Circulars of the Seismological Committee*, nos. 10, 12, 13, British Association for the Advancement of Science for the years 1904a, 1905a and 1905b, London.

Ballore, Count F. de Montessus de (1906): *La Géographie Séismologique* (A. Colin, Paris), 256-257.

Ballore, Count F. de Montessus de (1924): *La Géologie Séismologique* (A. Colin, Paris).

Belar, A. (1904a): Das Erdbeben vom 4 April 1904, *Die Erdbebenwarte*, **3**, 139-141; 208-218, Laibach.

Belar, A. (1904b): Das Erdbeben vom 4 April 1904, *Die Erdbebenwarte*, **4**, 23-27, Laibach.

Christoskov, L. and L. Grigorova (1968): Energetitsna i prostranstveno vremenna harakteristka na razrushitelnite zemletresennia v Biulgatia sled 1900 godina, *Izv. Geofiz. Inst.*, **12**, 79-107, Sofia.

Christov, C., G. Staikov and K. Mijatev (1958): *Le Monastère de Rila*, vol. 6, p. 144, Sofia.

Criticos, N. (1932): Sur la séismicité de Macédoine, *Ann. Observ. Natl. Athènes*, vol. 12, 149-159.

Dobrev, N. (1999a): Geological hazard processes in the Simitli graben, *Ph.D. Thesis*, Geolog. Inst. Bulgarian Acad. Sci., Sofia (in Bulgarian).

Dobrev, N. (1999b): Fault pattern in the southern part of the Simitli graben, SW Bulgaria, in *2nd Balkan Geophys. Congress*, Abstracts, 292-293.

Dobrev, N. and B. Kostak (2000): Monitoring tectonic movements in the Simitli graben, SW Bulgaria, *Eng. Geol.*, **57** (4).

Eginitis, D. (1909): Etude de sismes survenus en Grèce pendant les annèes 1904-1908, *Ann. Obs. Natl. Athènes*, vol. 5, 562.

Ekström, G. and A.M. Dziewonski (1988): Evidence of bias in estimations of earthquake size, *Nature*, **332**, 319-323.

Etzold, F. (1904): Vierte Bericht der Erdbebenstation Leipzig, *Bericht Verhand. K. Sächs. Gesell. Wissen. Leipzig*, vol. 46, 291-295.

Florinesco, A. (1958): *Catalogue des Tremblements de Terre Ressentis sur le Territoire de la R.P.R*, 130-134, Bucuresti.

Grigorova, E. and B. Grigorov (1964): Epicentrite i seizmichinte linii v NR Biulgaria, *Pub. Inst. Geophys. Bulgarian Acad. Sci.*, Sofia.

Grigorova, E. and K. Palieva (1968): Macroseismichna harakteristika na razrushitelnoto zemletresenie ot 4 April 1904, *Izv. Geofiz. Inst.*, **22**, 109-111, Sofia.

Gutenberg, B.: Unpublished work-notes, Millikan Memorial Library, California Institute Technology.

Gutenberg, B. and C. Richter (1954): *Seismicity of the Earth and Associated Phenomena*, p. 212, Hafner, N.Y.

Halász, R. (1908): *Az 1904 apr. 4-iki balkani földrengès*, Turul, Budapest.

Hepites, S. (1905): Materiale pentru seismografia Romanici 1904, *Analele 1905 Acad. Romane*, n.p., Bucarest.

Hoernes, R. (1904): Berichte ueber das makedonische Erdbeben vom 4 April 1904, *Mittheil. Erdbeben-Comm. Akad. Wissen.*, Wien, **24**, 1-54.

Hoernes, R. (1905): Das Erdbeben vom 4 April 1904, *Die Erdbebenwarte*, **4**, 23-27, Laibach.

Hoernes, R. and F. Seidl (1905): Bericht über das Erdbeben in Untersteiermark und Krain am 31 März 1904, *Mittheil. K. Akad. Wissen*, Wien, NF **23**, 42, Vienna.

Hubka, G. (1910): *Die österreichisch-ungarische Offiziernmission in Makedonien 1903-1909*, Teil: Briefe und Dokumente zur Innen- und Aussenpolitik, n.p., Vienna.

Husserl, A. (1904): Das Erdbeben vom 4 April 1904, *Neueste Erdbeben Nachrichten*, **3** (6-9), 7-8, Leibach.

Ilčiev, D. (1910): *Turskite documenti na Rilskija nonastir*, 34-38, Sofia.

Karnik, V. (1968): *Seismicity of the European Area*, Publ. Academia Praha, part 1, 116-122.

Levitski, G. (1906): *Biulleten postoiannoi Tsentranoi Seismichiskoi Kommissii 1902-1907*, Imperat. Akad. Nauk, **2**, 69-71, **3**, *sub ann.*, St. Petersbourg.

Louis, H. (1930): *Morphologische Studien in Südwest-Bulgarien*, Engelhorns, Stuttgart, pp. 86.

Matova, M., H. Spiridonov, B. Rangelov and P. Petrov (1996): Major active faults in Bulgaria, *J. Earthquake Prediction Res.*, **5**, 436-439, Beijing.

Mihailovic, J. (1906): Zemljotresi u Serbiji u 1904 g.; kritichki pregled sa narochitom obradom potresa od 2 aprila, *Spomen. Srpska Kralj. Akad.*, **43**, pp. 167, Beograd.

Mihailovic, J. (1911a): Katalog der in Jahren 1901-1906 in Serbien vorgekommenen Erdbeben, *Geol. An. Balk. Poluostrva*, **6**, 90-102, 138-202, Beograd.

Mihailovic, J. (1911b): Data über die Folgen der Erderschütterung von 4 April 1904 im Pleistoseistengebiet auf den Territorium von Serbien, *Geol. An. Balk. Poluostrva*, **6**, 121-139, Beograd.

Mihailovic, D. (1951): Catalogue des tremblements de terre epiro-albanais, Travaux Inst. Seism. Beograd, *Arch. Seism.*, no. 1, Beograd.

Miyamura, S. (1988): Some remarks on historical seismograms and the microfilming project, in *Historical Seismograms and Earthquakes of the World*, edited by W. Lee, H. Meyers and K. Shimizaki, 401-419.

Morelli, C. (1942): Carta sismica dell'Albania, *Commiss. Ital. Studio Problemi Soccorso Popolaz.*, **10**, 32-33, Firenze.

Monti, V. (1907): Notizie sui terremoti osservati in Italia durante l'anno 1905, *Pub. Uff. Centr. Meteor. e Geodin., sub ann.*, Roma.

Moureaux, M. (1904): Sur le tremblement de terre des Balkans, 4 avril 1904, *Compt. Rend. Acad. Sci.*, **138**, 997-998, Paris.

Nedeljković, R. (1950): *Seizmološka karta Jugoslavije*, Rad. Seizm. Zavod, Beograd.

Oddone, E. (1907): Les tremblements de terre ressentis pendant l'année 1904, *Publ. Bureau Centr. Assoc. Intern. Seism.*, ser. B, *sub ann.*, Strassburg

Paillarès, M. (1909): *L'imbroglio Macédonien*, 172-177; 207, Paris.

Papazachos, C. (1992): Anisotropic radiation modelling of macroseismic intensities for estimation of the attenuation structure of the upper crust in Greece, *Pageoph*, **138**, 445-469.

Papazachos, B. and C. Papazachou (1997): *The Earthquakes of Greece* (Ziti, Thessaloniki), 255-256.

Papazachos, B., Ch. Papaioannou *et al.* (1997): Atlas of isoseismal maps for strong shallow earthquakes in Greece and surrounding area, *Pub. Geophys. Lab., University of Thessaloniki*, no. 4, p. 19, Thessaloniki.

Rethly, A. (1905): Az 1904-ik evi aprilis 4-iki földrenges, *Termeszettud. Kozl.*, **37**, 47-51, Budapest.

Richter, C. (1958): *Elementary Seismology*, Freeman.

Rosenthal, E. (1907): Katalog der im Jahre 1904 registrierten Seismischen Störungen, *Veröff. Zentr. Bureaus Intern. Seism. Assoz.*, Ser.B, *sub ann.*, Strassburg.

Rudolph, E. (1905): *Katalog der im Jahre 1903 bekannt gewordenen Erdbeben*, Keiserl. Hauptst. Erdbebenforschung Strassburg, 598-612, Leipzig.

Scholz, C.H. (1982): Scaling laws for large earthquakes; consequences of physical models, *Bull. Seismol. Soc. Am.*, **72**, 1-14.

Shanov, S. and S. Pavlides (2000): Co-seismic deformations from the 4 April 1904 Kroupnik earthquake, SW Bulgaria, $M = 7.8$, and their tectonic interpretations, in *Proceedings 31st Intern. Geol., Congress, Rio*, n.p., Brasil.

Shanov, S., A. Boykova and D. Stoev (1999): Geophysical model of the co-seismic rupture from the April 4th 1904, Krupnik earthquake, $M = 7.8$, SW Bulgaria, in *2nd Balkan Geophys. Congress*, Abstracts, 232-233, Istanbul.

Shebalin, N. (Editor) (1974): *Catalogue of Earthquakes*, part III Atlas of isoseismal maps, UNDP-UNESCO Survey Seismicity of the Balkan Region, REM/70/172, p. 36, Skopje.

SIEBERG, A. (1932): Die Erdbeben, in B. Gutenberg's *Handbuch der Geophysik*, vol. 4, p. 757, Berlin.

VAN ECK, T. and T. STOYANOV (1996): Seismotectonics and seismic hazard modelling for Southern Bulgaria, *Tectonophysics*, **262**, 77-100.

WATZOV, S. (1904): Zemletrsenia v Bulgaria 1903, no. 4, 11-44, *Tsentr. Meteor. Stan.*, Sofia.

WATZOV, S. (1905a): Zemletrsenia v Bulgaria 1904, no. 5, 11-83, *Tsentr. Meteor. Stan.*, Sofia.

WATZOV, S. (1905b): Materiali po zemletresenieto v Makadonia na 22 Mart/4 Aprili 1904, no. 5, 173-180, Sofia.

WATZOV, S. (1906): Zemletrsenia v Bulgaria 1905, no. 6, 22-40; 81-82, *Tsentr. Meteor. Stan.*, Sofia.

YEATS, R., K. SIEH and C. ALLEN (1997): *The Geology of Earthquakes* (Oxford Univ. Press, Oxford), p. 487.

ZAGORCHEV, I.S. (1995a): Structure and tectonic evolution of the Pirin-Pangaion structure zone, *Geol. J.*, **29**, 241-268.

ZAGORCHEV, I.S. (1995b): Neotectonics and seismogenic factors in the Central Balkan neoteconic region, in *Proceedings Seminar on Active Faults, Athens*, n.p.

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