The Kupa Valley (Croatia) Earthquake of 8 October 1909—100 Years Later

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INTRODUCTION

The Kupa Valley (Croatia) earthquake of 8 October 1909 belongs to a group of milestone events in the history of geophysics and seismology. Also known as the Kulpa Valley, Pokuplje or the Pokupsko earthquake, it is often mentioned in textbooks, encyclopedias, and historical overviews of science as the earthquake whose seismograms provided key data for Andrija Mohorovičić's proof of the existence of the crust-mantle boundary that was later named after him. The earthquake occurred at just the right time and place to inspire research that resulted in one of the most-cited seismological papers (Mohorovičić 1910a, 1910b, 1910c) from the beginning of the last century. The paper itself was remarkable, as it contained much more than just the discovery it is mostly known for (see, *e.g.*, Herak and Herak 2007). As Kanamori (1986) noted in his Seismological Society of America presidential address, "having been motivated by this finding, Mohorovičić made an extensive study on reflection and refraction of seismic waves at a discontinuity to strengthen his conclusion. In fact, his study of this problem seems to have as strong an impact on seismology as his discovery of the discontinuity itself."

The time was right because the theory had been there for a long time, but the instruments had just gotten good enough to record seismograms with the needed detail. In particular, the Kupa Valley earthquake occurred only a year after the first Wiechert seismograph replaced the Vicentini instrument at the Zagreb observatory, which was already equipped with the first-class Riefler clock. The place was right because the earthquake occurred close to Zagreb (about 30 km to the south) where Mohorovičić lived, and it was strong enough to cause some damage in the city. Earthquakes had been of interest in Zagreb for some time, as seismicity around the capital was at its long-time maximum ever since the large earthquake of 1880. Indeed, it seems that this intense earthquake activity played an important role in Mohorovičić's decision to shift his scientific interest from meteorology toward seismology around the turn of the century.

After the earthquake, Mohorovičić exchanged correspondence with phase readings and comments with many prominent seismologists of that time. The letters from Giovanni Agamennone (Rocca di Papa, Italy), Hans Bendorf (Graz, today Austria), Victor Conrad (Vienna, today Austria), Julius Fenyi (Kalocsa, today Hungary), Ludwig Geiger (Göttingen, Germany), L. Grabowski (Lemberg; today Lviv, Ukraine), Thomas Heath (Edinburg, U.K.), Boris Kondriatzev (Nikolaieff; today Mykolayiv, Ukraine), J.B. Messershmitt (Munich, Germany), John Milne (Shide, Newport, Isle of Wight, UK), Maurycy P. Rudzki (Krakau; today Kraków, Poland), and Spas Vatsov (Sofia, Bulgaria) are still kept in our archives. All together, Mohorovičić received data from 41 stations, of which he used 36.

The Kupa Valley earthquake is cited in seismological literature almost exclusively in the context of the discovery of the Moho. However, it was the strongest event known to have ever occurred in the Kupa Valley epicentral region, and it plays a key role in defining the hazard there. The fact that this region lies only a few tens of kilometers from the Zagreb metropolitan area, with over a million inhabitants, makes its importance even greater. It is therefore somewhat surprising that no dedicated seismological study was ever performed to learn more about this important event. To correct this, and to mark the centennial of the Kupa Valley earthquake, we will use all available archival material—seismograms, station books and bulletins, macroseismic questionnaires, correspondence and manuscripts, newspaper reports, etc.—to relocate the focus, compute the magnitude, reinterpret the intensity data, and estimate the fault-plane solution.

LOCATION AND MAGNITUDE

The Kupa Valley epicentral region (within the white rectangle in Figure 1) is located in northwest Croatia. The seismicity and tectonic framework of northwest Croatia were recently described by Herak *et al.* (2009), who relocated all earthquakes using quasi-simultaneous inversion for hypocentral locations and the velocity model, followed by computation of regional station corrections and final relocation of all events. Here we have adopted their model to relocate 443 events from the Kupa Valley area with recomputed station corrections corresponding to this smaller dataset. The phase onset data for the 1909 mainshock were carefully reexamined, and location was obtained by nonautomatic interactive procedure using 24 arrival times reported in Mohorovičić's 1910 work (Table 1). This led to a

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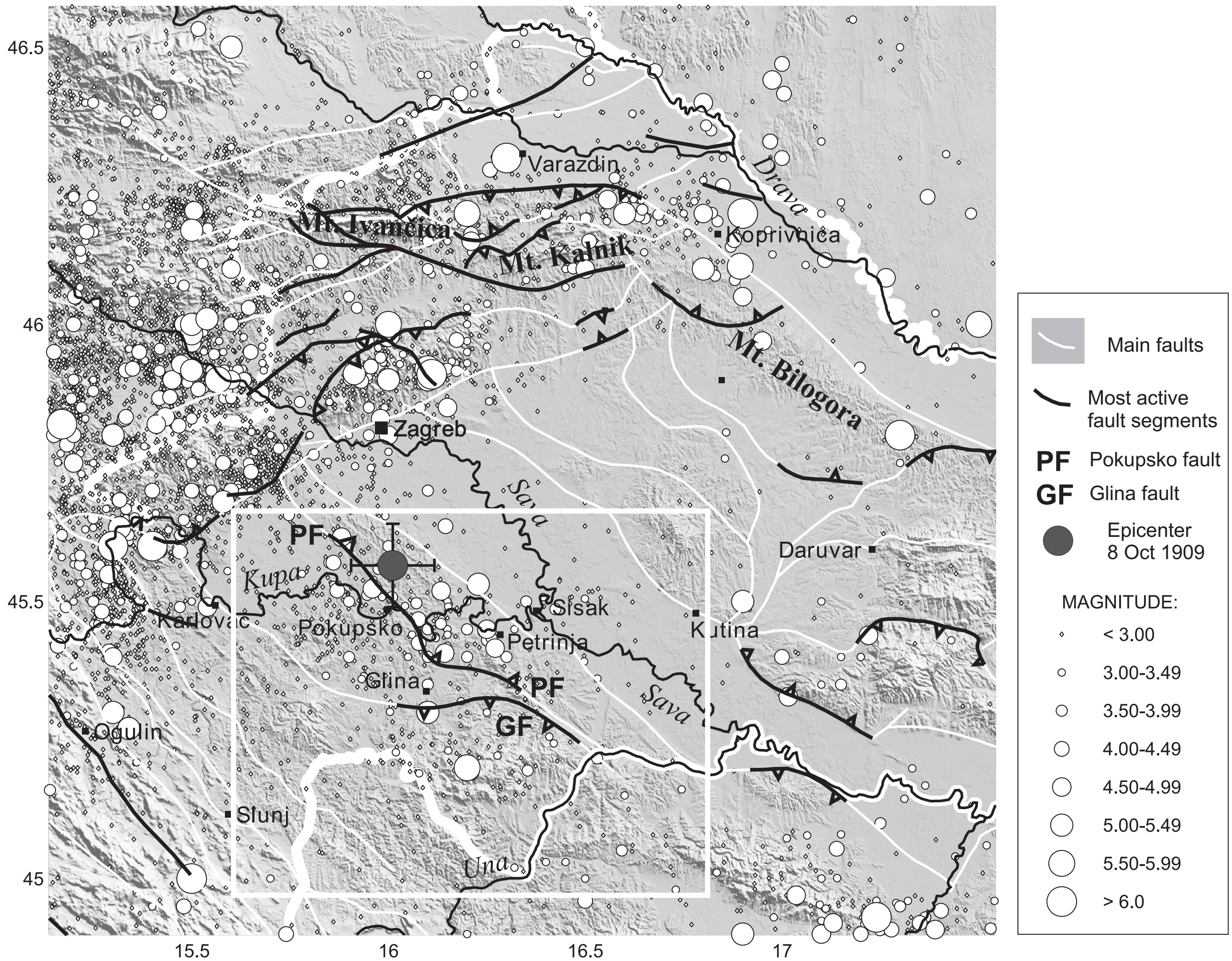


▲ **Figure 1.** Overview map of northwest Croatia, with the Pokupsko epicentral area marked by a white rectangle. Epicenters are from the Croatian Earthquake Catalogue (relocated here for the Pokupsko area). The 1909 mainshock is shown as dark gray circle with 1σ-error bars.

somewhat changed epicentral position (45.57 ± 0.06°N, 16.01 ± 0.08°E) of the Kupa Valley earthquake, which we relocated about 8 km to the north with respect to the location in Herak *et al.* (2009). The estimated focal depth is 14 ± 7 km. Due to poor time-keeping at most of the stations of that time, the standard errors of coordinates are quite large. The epicenter falls into the northeast part of the meisoseismal area (see below), and its position indicates that the earthquake was most probably generated by the Pokupsko fault (PF in Figure 1).

For magnitude estimation we used all available seismograms (see Table 2 and Figure 2). We have strictly followed the procedure for M_S determination as described in the *Manual of Seismological Observatory Practice* (Willmore 1979). These rules are different than those adopted by, *e.g.*, the International Seismological Centre (ISC) or the National Earthquake Information Center (NEIC), as no limits are imposed *a priori* to the period at which measurements are taken (see also Bormann *et al.* 2009). Instead, they give distance-dependent period intervals, outside of which M_S computation is not advised. The instrument response was computed using the calibration data from available sources (Table 2). For the Vicentini seismograph in Rijeka, we assumed that its properties were not significantly different from those of the similar instrument operating in Zagreb from 1906 to 1908, and that effective damping due to friction may be estimated as proposed by Herak, Allegretti, and Duda (1996). Computed magnitudes are remarkably stable with a mean of M_S = 5.78 ± 0.14. The median is M_S = 5.75. This is lower than the magnitude given in Shebalin *et al.* (1974) (M_{LH} = M_S = 6.0), which was the value adopted also in the Croatian Earthquake Catalogue (updated version of the catalog first described in Herak, Herak, and Markušić 1996).

MACROSEISMIC ANALYSIS

The macroseismic analysis relies mostly on the 430 questionnaires sent out and collected by Mohorovičić immediately after

TABLE 1
Data Used to Locate the Kupa Valley Earthquake

08 Oct 1909—08:59:11.95
Lat. = 45.57°N (± 0.06°)
Lon. = 16.01°E (± 0.08°)
Depth = 14.10 km (± 6.7 km)
sigma = 1.24 s gap = 123.27°

Station	Phase	Azimuth (°)	Distance (km)	Residual (s)
Zagreb	Pg	357.5	29.3	–1.03
	Sg	357.5	29.3	–1.28
Rijeka	Pn	257.9	122.6	–0.35
	Sn	257.9	122.6	0.00
Ljubljana	Sg	295.3	127.0	–0.26
Graz	Pn	345.8	173.4	–0.29
	Sg	345.8	173.4	2.33
Trieste	Pn	276.0	176.0	–0.38
	Sg	276.0	176.0	1.14
Pula	Pn	246.1	186.7	–1.17
	Sg	246.1	186.7	–0.36
Vienna	Pg	5.0	299.4	1.99
Padova	Sg	268.4	322.9	1.97
Munich	Pg	312.2	442.1	–1.78
Budapest	Pg	46.1	314.5	0.91
Taranto	Pn	169.4	574.7	1.46
	Pg	169.4	574.7	1.26
Jena	Pn	331.5	694.9	1.41
Heidelberg	Pn	310.5	694.8	–0.74
Moncalieri	Pg	267.4	654.9	–0.19
Göttingen	Pn	328.4	800.7	0.17
Catania	Pn	185.2	897.5	–2.80
Ischia	Pn	198.5	561.9	2.59
	Sn	198.5	561.9	0.87

the earthquake, as well as on the data from Slovenia for 48 localities (kindly provided by Ina Cecić from ARSO, Ljubljana, the Environment Agency of the Republic of Slovenia). Although the government formed a committee to investigate the effects of the earthquake (of which Mohorovičić was a member), and we know he visited the epicentral area on October 12 and 13, no known written report has been filed. Some data could also be collected from local newspapers, and Mohorovičić wrote an article on the earthquake in *Narodne novine* (Mohorovičić 1909) in which he estimated the ground acceleration in the Petrinja cemetery to about 0.1 g. The only photograph of damage we could find (Figure 3) shows the church in Sisak with a collapsed front wall.

The earthquake was felt over a radius greater than 200 km. It caused two deaths (in Lasinja a mason was killed when the church roof collapsed over him, and in Šišinac a roofer died after he fell from the bell tower). Many people were injured. The archive also contains macroseismic data for the strongest aftershock of 28 January 1910 (as a curiosity, many of the questionnaires contain a note that a comet [Halley's] was visible in the skies).

The only macroseismic map published so far was compiled in the framework of the so-called UNESCO Balkan project (Shebalin 1974). The intensities are expressed in the MCS scale, with the epicentral intensity of VIII–IX° MCS (or even IX° MCS based on only one intensity point). In the map, the VIII° isoseismal is nearly circular, whereas the VII° isoseismal is clearly elongated in the NW–SE direction.

For this paper we reanalyzed all available macroseismic data. This revisiting of the dataset is warranted for at least three reasons. First, because today's standards of assigning intensity are different than they were 35 years ago. Second, because assigned intensity values are merely interpretations of the data by a particular analyst and are therefore inherently subjective to some degree. And finally, because the data on damage to buildings often permitted reevaluation of intensity in terms of the EMS-98 scale (Grünthal 1998) that is in common use in Europe today.

Figure 4 shows the estimated intensities for 473 localities. Numerous accounts of earthquake effects on the ground (seismogeological effects)—especially liquefaction, mud-volcanoes and sand-craters—were not used in assigning the degree. Nevertheless, because such effects typically indicate intensity of at least VIII° EMS, we have mapped their reported locations in Figure 4. The isoseismals VI°–VIII° are clearly elongated NW–SE, in the general direction of strike of the main regional faults (Figure 1), indicating pronounced anisotropy of attenuation. The isolated group of locations with intensity VI° EMS to the north of the epicentral area is most probably caused by a topographic effect, as these localities lie on the slopes of Mts. Ivančica, Kalnik, and Bilogora.

FAULT-PLANE SOLUTION

Due to low seismicity of the Kupa Valley area ever since the 1909 earthquake, only four fault-plane solutions (FPS) are available in the FPS database for earthquakes in Croatia (Archives of the Department of Geophysics; see also Herak *et al.* 2009) for this region. All of them correspond to relatively weak events and indicate faulting caused by tectonic pressure directed SSW–NNE.

Since the 1909 event was recorded by seismographs all over Europe, we have inspected available seismograms in hopes of collecting enough data to constrain the FPS for this important event. As seen in the examples in Figure 2, due to low magnification of mechanical seismographs, the *P* waves were in general recorded rather weakly, except for the nearest stations (ZAG, RIY, POL, GRA, SAR). Furthermore, only one vertical seismograph recorded it (GTT), but the *P*-wave polarity is not discernible. This is not a serious shortcoming, as the vertical polarity of the *P* wave can be deduced from the sense of motion of horizontal component(s) when the epicenter is known. Of all seismograms at our disposal, we could identify the *P*-wave onset with reasonable confidence on at least one horizontal component on 11 of them (see Table 2). One of the

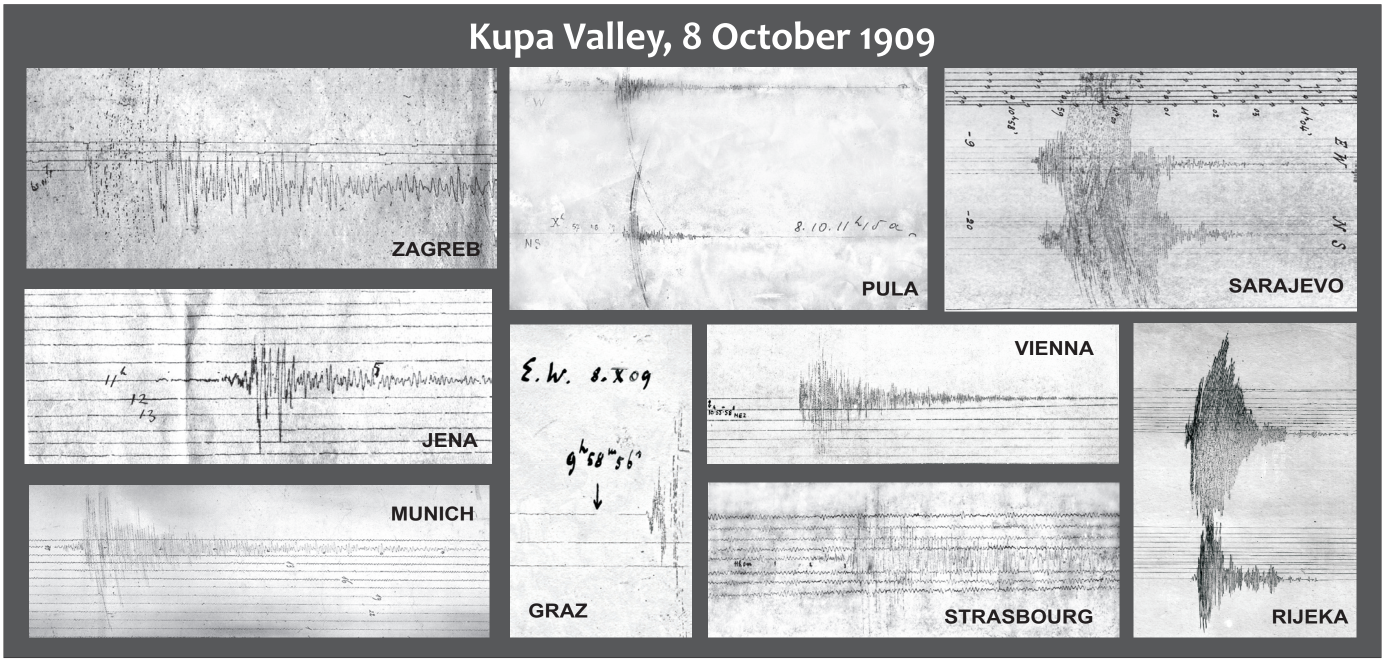
TABLE 2
Overview of Stations Used to Compute the Magnitude and the Fault-Plane Solution

Station	Instrument	Comp.	M_S	Horizontal First Motion Polarity	Deduced vertical first motion polarity	Source[1]
Uppsala (UPP)	Wiechert (1000 kg)	N, E	5.63	—	—	ES
Uccle (UCC)	Wiechert (1000 kg)	N, E	5.78	N (very small, uncertain)	C	ES
Munich (MNH)	Wiechert (1200 kg)	N, E	5.83	— (beginning in the hour mark)	—	DG
Göttingen (GTT)	Wiechert (1200 kg)	N,E	5.83	N, W (doubtful)	C	ES
De Bilt (DBN)	Wiechert (1000 kg)	N, E	6.56[2]	—	—	ES, CM
Strasbourg (STR)	Wiechert (1000 kg)	N	5.88	N (very small, uncertain)	C	DG
Vienna (VIE)	Wiechert (1000 kg)	N	5.74	— (beginning in the hour mark)	—	VI
Jena (JEN)	Wiechert (1000 kg)	N, E	5.63	S (EW-seismogram not available)	D	DG, JE, ES
Rijeka (RIY)	Vicentini (100 kg)	N, E	5.58	S (doubtful), W (doubtful)	C	DG, RK
Ógyalla (OGL)	Bosch (10 kg)	N, E	5.96	—	—	RK
Budapest (BUD)	Wiechert (1000 kg)	N, (E)	>5.82[3]	—	—	RK
Graz (GRA)	Wiechert	N, E	—	N, W (clear)	C	DG
Zagreb (ZAG)	Wiechert (80 kg)	NE, NW	—	NE, NW (clear)	D	DG
Pula (Pola, POL)	Wiechert (80 kg)	N, E	—	N(doubtful), W	C	DG
Kalocsa (KAL)	Wiechert (200 kg)	E	—	E (aftershock, 10 Oct 1909)	D	DG
Sarajevo (SAR)	Vicentini	N, E	—	S, E	C	DG
Sofia (SOF)	Wiechert	N	—	N (doubtful)	D	DG

1. ES – Euroseismos (2009); DG – Archives of the Department of Geophysics, Faculty of Science and Mathematics, Zagreb; CM – Chris Meester, personal communication; VI – Vienna: station book and seismograms (scanned copies, courtesy W. Lenhardt and A. Vogelmann); JE – Monatliche Erdbebenberichte der Seismischen Station zu Jena (1909); RK – R. Kövesligethy (1913) (scanned copy, courtesy P. Monus).

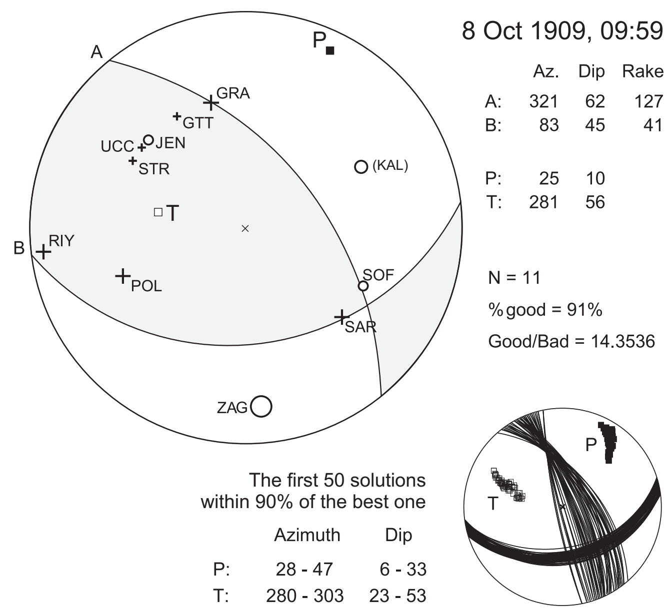
2. Rejected in computations, as the dominant period (T = 12 s) exceeds recommended values for the DBN epicentral distance of 9.6° (see text).

3. The trace on the EW component went off the edge of the recording paper at elongation of 24 mm.

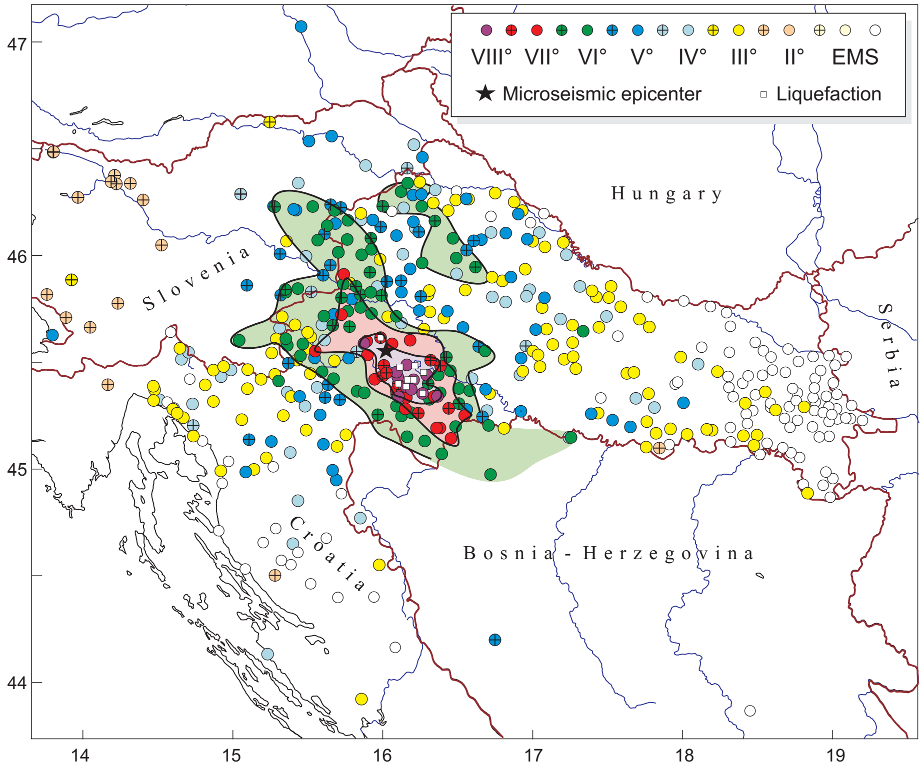


▲ **Figure 2.** Samples of the Kupa Valley earthquake seismograms collected by A. Mohorovičić.

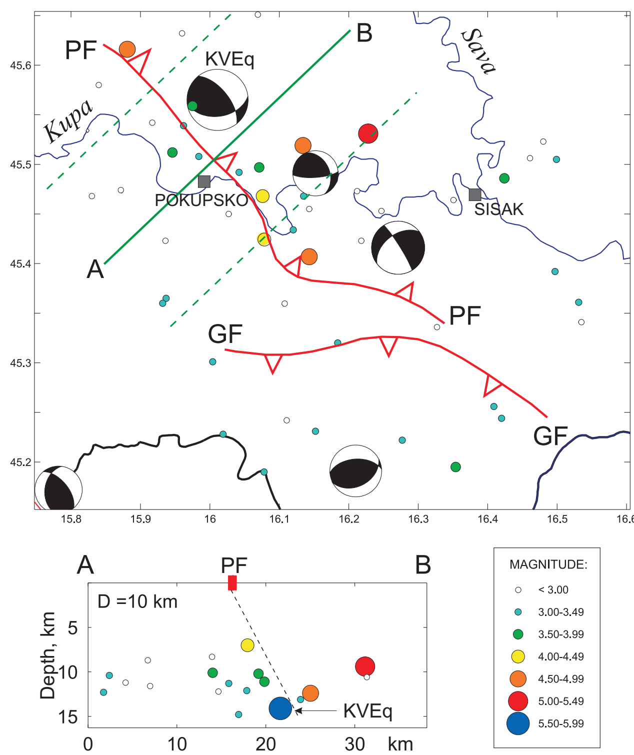
▲ **Figure 3.** The church in Sisak after the Kupa Valley earthquake of 1909, view of the facade (after Cvitanović 1996).



▲ **Figure 5.** Lower hemisphere equal-area projection of the focal sphere for the Kupa Valley earthquake. Compressional quadrants are shaded. The size of symbols scales with subjectively assigned weight between 1 and 5 (see text). Note that dilatation on Kalocsa (KAL) corresponds to the largest aftershock of 28 January 1910. The best 50 solutions with misfits within 90% of the best one in a Monte Carlo search for fault parameters (10 million tries), are shown in the lower right part of the figure, along with the corresponding pressure (*P*) and tension (*T*) axes.



▲ **Figure 4.** Macroseismic map for the Kupa Valley earthquake. The isoseismal areas corresponding to the VIII°, VII°, and VI° EMS are shown in violet, pink, and green, respectively. White squares show locations where liquefaction-related effects were observed.



▲ **Figure 6.** A map of the Pokupsko area (white rectangle in Figure 1), showing all available FPS for this region. Only earthquakes located with 12 onset-times or more are shown. The Kupa Valley earthquake FPS from Figure 5 is marked KVEq. Vertical profile AB showing foci of events between the two dashed lines (10 km from AB) is shown in the bottom part. The cross-section of the profile with the surface trace of the Pokupsko fault (PF) is displayed as a red rectangle. The dashed line shows the dip of the nodal plane A from FPS in Figure 5.

polarities (KAL) is for the largest aftershock of 28 January 1910, so the FPS in Figure 5 is in fact a composite. Further problems stem from the fact that the polarity of components was stated in available sources in only a few cases; in all other cases we assumed that "up" on the NS and EW components means ground movement toward north and east, respectively. It may well be that this guess does not hold in some cases, or that we misinterpreted notes in available documents (*i.e.*, it is not always clear what "positive" or "up" means, because seismograms were often analyzed upside-down, with time increasing to the left). The weight of each polarity was subjectively assigned a value between 1 and 5, depending on the clarity of the first motion(s) and on the reliability of other relevant data.

The resulting fault-plane solution, shown in Figure 5, indicates reverse faulting under tectonic pressure directed SSW–NNE, which is in agreement with contemporary studies (see above). The strike of the fault-plane A in Figure 5 closely corresponds to the strike of the Pokupsko fault (Figures 1 and 6), whereas its dip agrees with the spatial distribution of reliably located hypocenters along the profile AB in Figure 6.

CONCLUSIONS

Our revisit of the Kupa Valley earthquake and analysis of all available data resulted in an improved instrumental location of this important historical event. Considering also the fault-plane solution—the earliest one in our FPS database—we conclude that the earthquake most probably occurred about 10 km north of Pokupsko on the steeply dipping reverse Pokupsko fault at the depth of about 14 km. The fact that the epicenter lies in the northwest part of the meisoseismal area suggests a unilateral rupture toward the southeast. Reanalyzing macroseismic data we found the maximum intensity of VIII° EMS. Pronounced elongation of isoseismals indicates strong anisotropy of attenuation in the Pokupsko epicentral area, which is the largest in the direction perpendicular to the strike of the main geological features. These new data contribute to the overall understanding of the regional tectonics and will thus also improve hazard estimates for the Pokupsko area.

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