The 2008 West Bohemia earthquake swarm in the light of the WEBNET network

Tomáš Fischer, Josef Horálek, Jan Michálek, Alena Boušková

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Corresponding Author: Dr. Tomas Fischer,

Corresponding Author's Institution: Geophysical Institute ASCR

First Author: Tomas Fischer

Order of Authors: Tomas Fischer; Josef Horálek; Jan Michálek; Alena Boušková

Abstract: A swarm of earthquakes of magnitudes up to ML=3.8 stroke the region of West Bohemia/Vogtland (border area between Czechia and Germany) in October 2008. It occurred in the Nový Kostel focal zone, where also all recent earthquake swarms (1985/86, 1997 and 2000) took place, and was striking by a fast sequence of macroseismically observed earthquakes. We present the basic characteristics of this swarm based on the observations of a local network WEBNET, which has been operated in the epicentral area, on the Czech territory. The swarm was recorded by 13 to 23 permanent and mobile WEBNET stations surrounding the swarm epicentres. In addition, a part of the swarm was also recorded by strong-motion accelerometers, which represent the first true accelerograms of the swarm earthquakes in the region. The peak ground acceleration reached 0.65 m/s2. A comparison with previous earthquake swarms indicates that the total seismic moments released during the 1985/86 and 2008 swarms are similar, of about 4E16 Nm, and that they represent the two largest swarms occurred in the West Bohemia/Vogtland region since the ML=5.0 swarm of 1908. Characteristic features of the 2008 swarm are its short duration (four weeks) and rapidity, and consequently the fastest seismic moment release compared to previous swarms. Up to 25 000 events in the magnitude range of 0.5<ML<3.8 were detected using an automatic picker. A total of 9 swarm phases can be distinguished in the swarm, five of them exceeding the magnitude level of 2.5. The magnitude-frequency distribution of the complete 2008 swarm activity shows a b-value close to 1. The swarm hypocenters fall precisely on the same fault portion of the Nový Kostel focal zone that was activated by the 2000 swarm (ML≤3.2) in a depth interval from 6 to 11 km and also by the 1985/86 swarm (ML≤4.6). The steeply dipping fault planes of the 2000 and 2008 swarms seem to be identical considering the location error of about 100 m. Also, focal mechanisms of the 2008 swarm are identical with those of the 2000 swarm, both matching an average strike of 170° and dip of 80° of the activated fault segment. An overall upward migration of activity is observed with first events at the bottom and last events at the top of the of the activated fault patch. Similarities in the activated fault area and in the seismic moments released during the three largest recent swarms enable to estimate the seismic potential of the focal zone. If the whole segment of the fault plane was activated simultaneously it would represent an earthquake of ML~5. This is in good agreement with the estimates of the maximum magnitudes of earthquakes that occurred in the West Bohemia/Vogtland region in the past.

Response to Reviewers: Dear Editor,

Thank you for your final review of our manuscript. We have accepted all your suggestions, namely unified the ML notation and corrected other mistakes. The figures are now submitted in high quality form.

I believe now the MS is in good form to be published. Manythanks for enabling us to publish in JOSE.

Yours sincerely,
Tomáš Fischer

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Tomáš Fischer(1,2), Josef Horálek(1), Jan Michálek(1) and Alena Boušková(1)

(1) Institute of Geophysics, Academy of Science of the Czech Rep.
(2) Charles University in Prague, Faculty of Science

Abstract

A swarm of earthquakes of magnitudes up to M_L=3.8 stroke the region of West Bohemia/Vogtland (border area between Czechia and Germany) in October 2008. It occurred in the Nový Kostel focal zone, where also all recent earthquake swarms (1985/86, 1997 and 2000) took place, and was striking by a fast sequence of macroseismically observed earthquakes. We present the basic characteristics of this swarm based on the observations of a local network WEBNET, which has been operated in the epicentral area, on the Czech territory. The swarm was recorded by 13 to 23 permanent and mobile WEBNET stations surrounding the swarm epicentres. In addition, a part of the swarm was also recorded by strong-motion accelerometers, which represent the first true accelerograms of the swarm earthquakes in the region. The peak ground acceleration reached 0.65 m/s^2. A comparison with previous earthquake swarms indicates that the total seismic moments released during the 1985/86 and 2008 swarms are similar, of about 4E16 Nm, and that they represent the two largest swarms occurred in the West Bohemia/Vogtland region since the M_L=5.0 swarm of 1908. Characteristic features of the 2008 swarm are its short duration (four weeks) and rapidity, and consequently the fastest seismic moment release compared to previous swarms. Up to 25 000 events in the magnitude range of $0.5<M_L<3.8$ were detected using an automatic picker. A total of 9 swarm phases can be distinguished in the swarm, five of them exceeding the magnitude level of 2.5. The magnitude-frequency distribution of the complete 2008 swarm activity shows a *b*-value close to 1. The swarm hypocenters fall precisely on the same fault portion of the Nový Kostel focal zone that was activated by the 2000 swarm ($M_L \leq 3.2$) in a depth interval from 6 to 11 km and also by the 1985/86 swarm ($M_L \leq 4.6$). The steeply dipping fault planes of the 2000 and 2008 swarms seem to be identical considering the location error of about 100 m. Also, focal mechanisms of the 2008 swarm are identical with those of the 2000 swarm, both matching an average strike of 170° and dip of 80° of the activated fault segment. An overall upward migration of activity is observed with first events at the bottom and last events at the top of the of the activated fault patch. Similarities in the activated fault area and in the seismic moments released during the three largest recent swarms enable to estimate the seismic potential of the focal zone. If the whole segment of the fault plane was activated simultaneously it would represent an earthquake of M_L~5. This is in good agreement with the estimates of the maximum magnitudes of earthquakes that occurred in the West Bohemia/Vogtland region in the past.

1. Introduction

The region of West Bohemia (Czech Republic) and Vogtland (Saxony, Germany) is well known for its geodynamic activity (Fig. 1). Periodically recurring intraplate earthquake swarms are the most striking features of the region. High flux of mantle derived CO_2 indicated by more than one hundred CO_2-rich mineral springs and numerous gas vents seem to be a further peculiarity of region. Earthquake swarms are mainly attributed to volcanic areas, geothermal fields, and mid-ocean rifts (e.g. *Wyss et al., 1997; Dreger et al., 2000*), the worldwide most intensive swarms occur apparently in Iceland, which is a part of the mid-Atlantic plate boundary *(e.g. Stefansson et al., 2006, Jakobsdóttir et al., 2008)*. Intraplate earthquake swarms without active volcanism occur mainly in areas of enhanced crustal fluid activity, particularly in regions of Quaternary volcanism (Ibs-von Seht et al., 2008). One of such regions is West Bohemia and Vogtland, where the youngest known volcanic activity occurred at about 0.3-0.5 Ma ago *(Gögen and Wagner, 2000)*. This region belongs to the western part of the Bohemian Massif where three principal tectonic units – the Saxothuringian, Moldanubian, and Teplá-Barrandian – are in contact *(Babuška and Plomerová, 2008)*. It is intersected by an ENE-WSW trending neotectonic structure, the Eger rift, and by the NNW-SSE striking Mariánské Lázně fault. An active fault system trending N-S, the Počátky-Plesná zone, has been detected recently *(Bankwitz et al., 2003).* The area is intruded by several granitic plutons with estimated depth of 10 km *(Blecha et al. 2009).*

In terms of seismicity, the West Bohemia/Vogtland region belongs to the north-south trending Leipzig-Regensburg seismoactive zone (*Bankwitz et al., 2003*; *Korn et al., 2008*) with the largest historical earthquakes reaching macroseismic intensity (on the MSK-64 scale) of VIII in 1346 and VII-VIII in 1366 and 1872 (*Leydecker, 2005*). West Bohemia/Vogtland is typical of a frequent occurrence of weak earthquake swarms, mostly of magnitudes $M_L \leq 3.5$. Extraordinarily strong swarm activity was observed at the turn of the 19th and 20th centuries. Intensive swarms occurred in 1896/97, 1903, 1908/09 with less intensive swarms in between (1900, 1901, 1904, 1906 and 1911). Swarms with macroseismically observed shocks also occurred in 1914, 1929, 1962 and 1973 (*Grünthal, 1989; Kárník et al., 1987*). The swarm in 1985/86, with two shocks reaching the magnitudes of M_L=4.6 and M_L=4.2, represents a new revival of intensive swarm activity in this region.

The two probably strongest earthquakes in this region were those of March 6, 1872 and November 3, 1908, both with magnitudes M_L=5.0. While the magnitude of the former one was estimated on the base of macroseismic observations, the latter was estimated instrumentally. The macroseismic and instrumental observations were first coupled by *Credner (1904)* for the 1903 swarm but the first earthquake swarm being reliably documented by instrumental observations is that of 1908 (*Etzold, 1919*). However, it should be noted that instrumental observations of local swarm events were poor due to low sensitivity and also inappropriate, poorly known frequency responses of seismographs operated at that time nearby the epicentral region. E.g., only 13 events of the 1962-earthquake swarm were recorded at the Cheb station. This, together with the fact that neither seismograms nor bulletins from the early stations Cheb and Hof have been handed down, makes the magnitude comparison of the past and recent West Bohemia/Vogtland swarms rather difficult. Proper observations in the region began only after the 1962 swarm when a network of analogue stations VOGTLAND was established in the border area of Saxony (*Neunhöfer and Güth, 1989*). A new stage of digital seismic observations in West Bohemia was initiated with the strong 1985/86 swarm. The first permanent digital seismic station NKC was established in the main focal zone Nový Kostel in 1989 and became a basis for the present WEBNET network. Further WEBNET stations were set up gradually from 1991 to 2004. Nowadays, West Bohemia and Vogtland are among the best-monitored seismically active areas in Europe. Besides WEBNET, which is jointly operated by the Institute of Geophysics and the Institute of Rock Structure and Mechanics of the ASCR in Prague, the broader seismogenic region is monitored by the Saxonian network SXNET *(Korn et al., 2008*), the Bavarian Seismological Network (http://www.erdbeben-in-bayern.de), and KRASNET operated by the Masaryk University in Brno in the period of 1991-2008 (*Nehybka and Skácelová, 1995*). Two decades of continuous observations from WEBNET form a basis for the majority of studies of the West Bohemia/Vogtland earthquake swarms.

Showing a few tens of thousands events within the last twenty years, the Nový Kostel (NK) focal zone (centre ≈ 50.23ºN, 12.45ºE) was disclosed to dominate the recent seismicity of the whole region. Besides numerous microswarms, the most significant earthquake activities there were the 1985/86 swarm (M_L≤4.6), a weaker swarm in January 1997 (M_L≤3.0), a medium swarm in autumn 2000 (M_L≤3.3), and an intensive swarm in October 2008 (M_L≤3.8) (*Fischer and Horálek, 2003*). In particular, being studied from many aspects, the swarms in 1997 and 2000 represent the milestones in understanding the nature of the West Bohemia/Vogtland earthquake swarms. *Fischer and Horálek (2003)* found that the NK zone displays a pronounced fault plane at the depths between 6 and 11 km. It is oriented almost S-N (strike 169^o N) and steeply dips (dip 80^o) westward, which corresponds well with the presumed Počátky-Plesná tectonic line (see Fig. 1). The source mechanisms of the 2000 swarm, in contrast to the one in 1997, fits well the geometry of the main NK fault plane. This points to a progressive rupturing of one segment of the main fault plane. Triggering mechanisms acting during such rupturing were investigated on the basis of the 2000 swarm data by *Hainzl and Fischer (2002), Parotidis et al. (2003), Hainzl and Ogata (2005), and Fischer and Horálek (2005). Horálek and Fischer (2008)* summarized outcomes of the 1997 and 2000 swarm studies. They inferred that faults in this region are in a subcritical steady state as a result of the regional tectonic stress and their portions can be brought to a critical state due to the increase of pore pressure of crustal fluids After reaching instability, a self-organization of the swarm activity prevails and fluids mainly act in the background, i.e., they keep the fault segments with the swarm activity in a critical state.

Brief information on the 2008 swarm was given by *Horálek et al. (2009)*. The aim of our paper is to provide basic characteristics of the 2008 swarm based on the WEBNET observations and compare them with previous swarms in 1985/86, 1997 and 2000. This involves precise hypocenter locations, space-time distribution, energy release and preliminary focal mechanisms.

2. WEBNET seismic network and 2008-swarm data

At present WEBNET consists of 13 three-component digital seismic stations and covers an area of about 900 km^2 (Fig. 1). Seismometers are installed, on concrete pillars in 5 m deep vaults. Central station NKC is situated in the centre of the main focal zone NK, further six stations (SKC, VAC, LBC, POC, STC, KVC) surround this zone. The remaining six stations (KRC, KOC, LAC, ZHC, KAC, TRC) are located in minor focal zones. The network layout ensures a proper areal and azimuthal coverage of the focal area, particularly with respect to the NK zone.

Eleven stations are equipped with passive seismometers SM-3, two stations with broadband seismometers Güralp 40-T and one station with the LE-3D sensor (Table 1). WEBNET is formed by two subnets (N and L in our notation), which differ in data acquisition systems and telemetry used. Subnet N (stations NKC, SKC, VAC, LBC, POC, STC, KRC, ZHC and KAC) is equipped with the Janus-Trident (Nanometrics) data acquisition system and with WaveLan microwave telemetry enabling internet access to each station. Subnet L consists of four stations (NKC, KVC, KOC, LAC) equipped with the Lennartz 5800 PCM data acquisition system with one-way radio telemetry, which enables data transmission from distant stations KOC and LAC. It also facilitates parallel operation of two different seismograph systems, the Güralp 40-T/Janus-Trident and SM-3/5800 PCM at the central station NKC. Two independent subnets with overlapping stations guarantee uninterrupted observations in case of outage of one of them. The data from both subnets are transmitted to the data centre at the TV tower Zelená Hora near Cheb, which is connected to the internet. Station TRC is operated in an autonomous mode due to problems with a telemetry route to the data centre.

The configuration of WEBNET and the parameters of seismograph systems guarantee high-quality recording of the West Bohemia/Vogtland events of magnitudes $-0.5 \leq M_L \leq 5$ (the dynamic range is 120 dB). All WEBNET stations produce seismograms proportional to the ground velocity in a frequency band of 0.5 - 80 Hz (subnet N) or 0.5 - 60 Hz (subnet L), and 0.033 - 80 Hz at stations equipped with Güralp 40-T seismometers. The sampling rate of all stations is 250 Hz. Subnet N provides both continuous and triggered data while subnet L provides triggered data only.

Additionally, ten seismic vaults consisting of a container with a concrete pillar at about 2 m depth were built to provide the best possible areal and azimuthal coverage of the West Bohemia seismogenic region. During the 2008 swarm they were equipped with LE-3D seismometers and 24-bit Gaia data acquisition systems. The frequency response of these stations is proportional to the ground velocity between 1.0 and 80 Hz and a sampling rate of 250 Hz is used. The basic parameters of the permanent and temporary WEBNET stations are listed in Table 1; further details can be found at *www.ig.cas.cz/en/structure/observatories/west-bohemia-seismic-network-webnet*.

Tab 1. Permanent and temporary stations of WEBNET

Permanent stations	Code	Lat [°N]	Lon [°E]	h [m]	Instrumentation	Subnet	Operated since
Nový Kostel	NKC	50.2331	12.4479	564	SM-3/5800 PCM	L	1986
					Güralp 40-T/Janus-Trident	N	2001
Kopaniny	KOC	50.2652	12.2336	575	SM-3/5800 PCM	L	1994
Kraslice	KRC	50.3316	12.5304	760	SM-3/Janus-Trident	N	1994
Lazy	LAC	50.0508	12.6250	838	SM-3/5800 PCM	L	1995
Skalná	SKC	50.1698	12.3611	455	SM-3/Janus-Trident	N	1994
Trojmezí	TRC	50.3032	12.1448	566	LE-3D/Gaia		1994
Studenec	STC	50.2591	12.5197	666	SM-3/Janus-Trident	N	1997
Luby	LBC	50.2655	12.4123	638	SM-3/Janus-Trident	N	2001
Vackov	VAC	50.2354	12.3772	530	SM-3/Janus-Trident	N	2001
Květná	KVC	50.2049	12.5113	621	SM-3/5800 PCM	L	2001
Kaceřov	KAC	50.144	12.518	502	SM-3/Janus-Trident	N	2001
Počátky	POC	50.322	12.427	795	SM-3/Janus-Trident	N	2004
Zelená Hora	ZHC	50.0706	12.3088	631	Güralp 40-T/Janus-Trident	N	2005
Temporary stations							
Bublava	BUBD	50.383	12.514	700	LE-3D/Gaia		
Horní Paseky	HOPD	50.225	12.266	685	LE-3D/Gaia		
Hrádek	HRAD	50.194	12.537	530	LE-3D/Gaia		
Hřebeny	HRED	50.215	12.566	543	LE-3D/Gaia		
Kopanina	KOPD	50.204	12.475	490	LE-3D/Gaia		
Loučná	LOUD	50.278	12.575	646	LE-3D/Gaia		
Plesná	PLED	50.208	12.338	575	LE-3D/Gaia		
Polná	POLD	50.156	12.236	510	LE-3D/Gaia		
Sněžná	SNED	50.311	12.501	713	LE-3D/Gaia		

The 2008 swarm was recorded in total by 13 to 23 permanent and temporary WEBNET stations without any significant gaps. All seismograms of permanent stations are unclipped, even at the stations located just in the epicentral area. The triggering threshold of permanent and mobile stations was about M_L=-0.5 and 0.5, respectively. Prevailing frequencies of the largest events in the ground velocity seismograms range approximately between 3 and 10 Hz, so that WEBNET seismograms from permanent stations can be regarded as broadband with respect to the frequency band of ground velocity. This is manifested in Fig. 2 showing a very good fit of seismograms of the M_L=3.8 event recorded by the Güralp 40-T/Janus-Trident and SM-3/5800 PCM seismographs at station NKC.

A part of the 2008 swarm was also recorded by strong-motion accelerometers ALTUS K2 (Kinemetrics). The accelerometers were operated in cooperation with GFZ Potsdam from October 22, 2008 until the beginning of February 2009 at the WEBNET stations NKC, KVC, SKC, and VAC. This enabled a comparison of accelerometer recordings with accelerograms obtained by numerical differentiation of WEBNET velocity seismograms. Quite good fit between the ALTUS-K2 accelerograms and those derived from velocigrams at station NKC (Fig. 3) shows that WEBNET seismograms can easily be used for deriving accelerograms. Note that the ALTUS-K2 recordings provide the first proved accelerograms of the West Bohemia earthquakes with macroseismic effects on buildings.

Two types of bulletins of the 2008 swarm are available. First, there are manual readings of the P- and S-wave arrival times and amplitudes from six selected stations (NKC, KVC, LBC, VAC, SKC, KRC), which are suitably distributed to ensure precise hypocentre locations. The seismogram processing is still in progress. These data form the basis for routine FastHypo locations (Hermann, 1979) provided on the interactive map www.ig.cas.cz/en/structure/observatories/webnet/map-of-epicenters and for relative master event locations provided on request. Second, a homogeneous magnitude-time catalogue was generated by the automatic P- and S-wave picker that is based on an algorithm of *Fischer (2003)*. This catalogue contains about 25 000 events in the magnitude range -0.5<M_L<3.8 with a magnitude of completeness of -0.3 (see Fig. 4), which is by 0.5 lower than that for the 2000 swarm (*Hainzl and Fischer, 2002*). This enhancement is on account of applying an automatic event detection to continuous seismograms, which was, however, impossible for the 2000-swarm catalogue because only triggered seismograms were available at that time.

3. Basic characteristics of the 2008 swarm, comparison with previous swarms

The 2008 swarm has been the strongest seismic activity in the West Bohemia/Vogtland region since the severe swarm of 1985/86 and surprised both the public and seismological community by its fast sequence of macroseismically observed earthquakes. It took place, similar like the previous swarms in 1985/86, 1997 and 2000, in the main NK focal zone. It arose quite soon after the previous intensive swarm in 2000 and was preceded by an increased microswarm activity in that area *(Fischer and Michálek, 2008)*. The previous 2000 swarm with five largest events exceeding M_L=3 faded away in 2001 in the form of few microswarms (Fig. 5). The period between 2002 and 2003 was characterized by a relative quiescence followed by a seismic unrest starting in 2004. This activity was manifested in a sequence of microswarms with increasing maximum magnitudes reaching M_L~2.0. The hypocenters followed a steeply dipping fault plane, which was the origin of most of the previous swarms and background activity. Thus, the occurrence of the 2008 swarm, which took place at the same fault plane, can be regarded as a culmination of the previous microswarm activity.

Tab. 2. Focal parameters of the strongest (M_L≥3.0) 2008 swarm events, determined from manual P- and S-wave readings using an absolute locating procedure included in the SeisBase package (*Fischer and Hampl, 1997*).

Date	**Origin time UTC**	**Latitude [°N]**	**Longitude [°E]**	**Depth [km]**	**M_L**

2008-10-09	22:20:37.91	50.215	12.445	9.6	3.5
2008-10-10	03:22:05.26	50.213	12.447	9.5	3.6
2008-10-10	03:22:06.87	50.208	12.443	9.2	3.2
2008-10-10	08:08:46.22	50.213	12.448	9.7	3.7
2008-10-10	11:18:41.62	50.221	12.443	9.6	3.3
2008-10-12	07:44:56.31	50.213	12.447	9.4	3.8
2008-10-14	04:01:36.31	50.217	12.444	9.7	3.0
2008-10-14	19:00:33.10	50.213	12.448	8.9	3.7
2008-10-28	08:30:11.50	50.216	12.446	7.6	3.8

During this swarm, nine $M_L \geq 3.0$ earthquakes (see Table 2) and about 100 $M_L \geq 2.0$ earthquakes occurred; six largest events with magnitudes of $M_L \geq 3.5$ were observed macroseismically in a broader area of West Bohemia (a brief overview of macroseismic observations was given in *Horálek et al., 2009*). The maximum observed ground motions at the WEBNET stations there were 9.5E-3 m/s for ground velocity, 2.6E-4 m for displacement and 0.65 m/s^2 for acceleration, see Table 3. It is very likely that the ground accelerations in some areas were substantially higher. This concerns particularly those located in the Cheb Basin because the given maximum ground accelerations were measured outside the basin on concrete pillars attached to the bedrock. Near-field static displacement in the order of 1E-5 m was observed by *Zahradník and Plešinger (2009)* in the broadband records at NKC. Using an empirical formula log M_o = 1.05 M_L + 11.3 (*Hainzl and Fischer, 2002*), the seismic moments of the largest events are estimated to be between 1.5E15 and 2E15 Nm.

Tab. 3. Maximum observed ground motions

Maximum velocity	Station	**Earthquake origin time**
9.5 mm/s	STC	Oct. 28, 08:30
7 mm/s	KOPD (mobile station)	Oct. 28, 08:30
Maximum displacement	Station	
0.26 mm	STC	Oct. 28, 08:30
0.2 mm	NKC	Oct. 12, 07:44
Maximum acceleration	Station	
0.65 m/s^2	STC	Oct. 28, 08:30
0.5 m/s^2	PLED (mobile station)	Oct. 28, 08:30

A brief scenario of the 2008 swarm was as follows. The 2008 swarm started at midnight from October 5 to 6 by a short burst of $M_L \leq 2$ swarm-like seismicity lasting only few hours (Fig. 6a). In this respect it would rank among the frequent microswarms occurring since 2004 (Fig. 5). This burst of seismicity was followed by a sporadic activity with $M_L<2$ persisting for about 40 hours. Then (in the evening of October 7), a new, more intensive swarm phase occurred, that lasted about 12 hours, succeeded. This phase included M_L=2.5 events, some of them felt by people in a broader area. The trembling was accompanied by the acoustic effects and scared the population. The most intensive phase started in the evening of October 9; it lasted two days and included three M_L>3.5 shocks. After that, a fairly intensive swarm activity, which included M_L=3.8 and 3.7 shocks of October 12 and October 14, persisted till October 15. The period between October 15 and October 27 was characterized by a gradual swarm activity decay, which was broken by its abrupt increase dominated by a M_L=3.8 shock of October 28; this shock exhibited the largest ground motions (see Table 3) and also the strongest macroseismic effects in the epicentral area. In total, 9 swarm phases can be distinguished, five of them exceeding the magnitude level of 2.5 (Fig. 6a); the terminating phase P9 with the biggest M_L=2.8 event lasted till the end of 2008 (Fig. 6b).

A characteristic feature of the 2008 swarm is its rapidity and high rate of energy release. If one compares the approximate duration of the main swarm period being characterized by swarm phases with M_L>2.5 events then one gets about 7 weeks for the 1985/86 swarm, one week for the much weaker 1997 swarm, 10 weeks for the 2000 swarm and only 4 weeks for the 2008 swarm (Fig. 6b). The rapidity of the 2008 swarm is underlined by the total seismic moment released, which is about three times larger than that of the 2000 swarm. In particular, the cumulative seismic moment released during the 1985/86 and 2008 swarms were similar, about 4.3 E16 Nm and 4.0E16 Nm, compared to 1.4E16 Nm for the 2000 swarm and only about 6E14Nm for the 1997 swarm (Fig. 7).

The magnitude-frequency distribution of the complete 2008-swarm (Fig. 4) shows a *b*-value close to 1, which is typical of the West Bohemia/Vogtland earthquake swarm; $b \approx 1.0$ have been observed also for swarms of 1908, 1962, 1985/86 and 1997 by *Neunhöfer and Hemmann (2005)* and for the 2000 swarm by e.g. *Fischer (2003) and Tittel and Wendt (2003)*. Similarly, *Hainzl and Fischer (2002)* report $b \approx 1.0$ for the complete 2000 swarm with a considerable variation during the sequence.

Another noteworthy feature of the 2008 swarm is an abundance of the strongest events (M_L>3.5) and a lack of events in magnitude range from 3.0 to 3.5, which is clearly demonstrated in Figs. 4 and 6a. The magnitude gap between the strongest and medium events resembles the characteristics of the mainshock-aftershock sequences. Contrary to earthquake swarms, the mainshock-aftershock sequences are typical of the occurrence of the mainshock that exceeds the remaining events by 0.5 magnitude unit at minimum. In this respect, the 2008 swarm may confirm the findings of *Hainzl and Fischer (2002)* who showed that the 2000 swarm can be represented by a sequence of overlapping aftershock sequences, each of them dominated by a mainshock.

4. Location of the 2008-swarm events

Similar to our previous studies of activity in the NK zone (*Fischer and Horálek, 2003 and 2005; Fischer and Michálek, 2008*) we obtained the precise locations of the 2008 swarm events by the master-event localization based on the method of *Zollo et al. (1995)* with the use of a 1-D gradient velocity model of *Málek et al. (2000)*. The method is based on finding the minimum of the variance

$V = 1/N\sum\left(\Delta T_0^i - \overline{\Delta T_0}\right)^2$ of the difference ΔT_0 between the origin times of the master event and located events. Here T_0^i is the origin time calculated from the arrival time and travel time of the phase *i* and *N* is the number of phases. Similar to other relative location methods, it is required that the distance of the located events to the master event is much smaller than the hypocentral distance, i.e. the rays are almost identical. Events with P- and S- arrival times from 4 stations at least were relocated. Because the station configuration of WEBNET has changed since 2000, it was not possible to use the same master event for the 2008 swarm hypocenters as it was for the 2000 ones. Hence, we chose a new master event (event of M_L=1.5 from October 14, 2008, 10:44), which was recorded during the full operation of the WEBNET network. Its position 50.2155°N, 12.4481°E and depth 9580 m was determined by the relative localization using the master event from the 2000 swarm.

In the next we will address the relative position of the 2000 and 2008 earthquake swarms. In this context we use the term fault plane in its general sense; fault segment and the smaller patch are areas delimited by hypocenters upon the fault plane. As mentioned above, the hypocenters of the 2008-earthquake swarm occurred in the same NK focal zone as the 1985/86 and 2000 swarms. Furthermore, the 1985/86 and 2000 swarms shared a common fault plane, striking NNW (strike/dip 169°/80°) in a depth range from 6.5 to 10.5 km (see Figs 4 and 5 in *Fischer and Horálek, 2003*). However, the real extent of the fault plane activated by the 1985/86 swarm could not be determined due to missing data from the first swarm period. It was also shown that the 1997 swarm took place in two differently oriented fault plane segments belonging to the main fault. As follows from Fig 5 and 8a, the 2000 and 2008 swarm hypocenters appear to share a common fault plane. i.e. it is hard to discern if the fault planes activated by the 2000 and 2008 swarms are identical or distinct. To quantify the possible separation of the activated fault planes we subdivided the fault patch in a number of cells and determined the average off-plane coordinate for the hypocenters belonging to individual swarms (X_{00} and X_{08}), and its standard deviation (σ_{X00} and σ_{X08}). By comparing the absolute value of the difference X_{00} - X_{08} (i.e. the distance of the 2000 and 2008 fault planes) and the mean value of the standard deviations one can learn if the fault planes activated during the two swarms are discernible with respect to the location error. In particular, the predominance of the difference X_{00} - X_{08} over the uncertainty of the off-plane coordinate ($\sigma_{X00} + \sigma_{X08}$)/2 would indicate distinct fault planes of the two swarms. It turns out that while the difference X_{00} - X_{08} (thin line) oscillates from 0 to 120 m, the uncertainty of the off-plane coordinate ranges between 20 and 90 m (see Fig. 8b). Both opposite and similar trends of the two curves occur. However, in most cells the difference of coordinates is smaller than their standard deviation, which indicates that it is not possible to distinguish the fault planes of the two swarms. Hence, within the attainable location accuracy of about 100 m, the fault planes of the 2000 and 2008 swarms appear to be the same.

Fig 9 shows the comparison of the space-time distribution of the 2000 and 2008 swarm hypocenters (2080 and 2020 M_L>0.5 events, respectively). Both the 2000 and 2008 swarms show a fish-like pattern: oval (2000 swarm) or circular (2008 swarm) main fault patch with an inclined tail pointing to the north. The colour-coded hypocenters suggest a similar hypocenter migration: the first events occurred at the bottom of the fault patch (dark blue) and the latest events in the top-most tail (dark red) of the hypothesized fish. However, in more detail, the space-time pattern of the main fault patch shows a different migration style for the two swarms with a general upward migration of the 2008 swarm compared to the counter-clockwise migration of the 2000 swarm.

5. Focal mechanisms – preliminary results

To get a first idea of faulting during the 2008 swarm, we estimated fault-plane solutions of 70 events throughout the whole swarm, using *Maeda's (1992)* method. We inverted 13 P-wave polarities and amplitudes of the direct P-waves as a minimum, and tested stability of solutions by omitting individual stations or their pairs. Only stable solutions, which are depicted in the form of a composite plot in Fig. 10b, have been taken into account. Resultant focal mechanisms are left-lateral, mostly oblique normal, with a large strike-slip component. Even though they show fair variability implying jagged rupturing along the ruptured fault segment, the general pattern corresponds well to the strike (170°) and dip (80° westward) of the fault segment as well of the whole main focal zone NK. The predominant slip angles of about 30° are consistent with those of previous studies of focal mechanisms acting in the NK zone (e.g., *Antonini, 1988; Plenefisch and Klinge, 2003; Fischer and Horálek, 2005*). Note the striking similarity between focal mechanisms of the 2000 and 2008 swarms demonstrated in Fig. 11. The patterns indicate subhorizontal P-axes in the NW-SE direction and nearly horizontal T-axes in the NE-SW direction. This is consistent with the orientation of the axes of the maximum (σ_1) and minimum (σ_3) regional tectonic stress in the West Bohemia/Vogtland crust (*Švancara et al., 2008*). Such solution confirms our previous idea that the faulting during individual swarms in the region is controlled mainly by the regional tectonic stress (*Horálek and Fischer, 2008*) and that the N-S left-lateral (sinistral) movements with southward subsidence prevail in the NK. However, deeper understanding of the faulting and forces acting during the swarm requires a detailed study of source mechanisms in the full moment tensor description.

6. Size of the 2008 swarm and seismic potential of the area

As mentioned in Section 3, the 2008 swarm was exceptional for its rapidity and its total seismic moment released. It logically raised a question of its size with respect to the earlier West Bohemia/Vogtland swarms. However, such comparison is an intricate problem due to poor data from the historical local seismic stations. To compare roughly the 2008 swarm size with that of the earlier swarms we used studies of *Kárník et al. (1987), Neunhöfer and Stelzner (1989)* and *Neunhöfer and Hemmann (2005)*. They had evaluated the magnitudes of 120 West Bohemia/Vogtland swarms and microswarms from a period between 1908 and 1999 using the Iida formula (designed for the magnitude estimate of local events if observations from homogeneous set of stations are not available). As a measure of size we took the magnitude of the largest swarm earthquake. We could infer that only three swarms of 1903, 1908 and 1985/86 exceeded the magnitude threshold of M_L=4.0 and that other swarms occurring in this period reached or possibly slightly exceeded the magnitude M_L=3.0 (swarms in 1929 and 1962). This implies that the 2008 swarm has ranked among the four strongest swarms in the West Bohemia/Vogtland region since 1903; only the swarms of 1908 (M_L~5.0), and 1985/86 (M_L=4.6) were much more intensive in terms of magnitudes of the largest earthquakes. The size of the 1903 swarm is uncertain; *Neunhöfer and Stelzner (1989)* give the magnitude of the largest earthquakes slightly exceeding M_L=4.0 whereas according to *Kárník et al. (1987)* the 1903-swarm size is similar to that of 1985/86.

Undoubtedly, the accuracy of the magnitude determination and comparability of the magnitudes of the recent and earlier seismicity are of paramount importance and we are aware of great uncertainties of the magnitude estimations due to various factors, e.g. different instrumentations, lack of stations, low quality of records, directivity or different ways of magnitude estimations. Let us give two particular examples: (i) the strongest earthquake of the 1908 swarm, which is generally assumed to be of M_L~5.0, was evaluated by *Neunhöfer and Hemmann (2005)* as M_L=4.4; (ii) the magnitude of the largest event in the 1997 swarm was evaluated by *Neunhöfer and Hemmann (2005)* as M_L=2.3 while WEBNET gives a value of M_L=3.0.

The WEBNET formula $M_L = \log A_{smax} - \log 2\pi + 2.1 \log R + C - 1.7$ (A_{smax} is the maximum absolute value of the total amplitude of the S-wave ground velocity measured in μm/s, R is the hypocentral distance in km, and C is the station correction) is calibrated to the magnitudes estimated by PRU, the primary station of the Czech Regional Seismological Network. Note that the magnitude estimations of the largest 2008 events reported by some international seismological agencies or data centres are higher as compared to our magnitudes M_L. For example, the magnitude of the event on October 8, 2008, 08:08:46 UTC (M_L=3.7 by WEBNET) is estimated by NEIC with M_L=4.1, by LDG with M_L=4.4, by GRF with M_L=4.1; nevertheless station PRU gives a magnitude of M_L=3.7.

A worth noting issue arising from this comparison is the fact that no swarm activity since 1903 has exceeded the magnitude of M_L=5.0. This relates to a question of the seismic potential of the area. Interestingly, the three recent large swarms (1985/86, 2000 and 2008) occurred in a single focal zone of Nový Kostel and further, the hypocenters of 2000 and 2008 swarms occupy almost the same fault area. *Hainzl and Fischer (2002)* estimated the total area of the main cluster of the 2000 swarm to 9 km^2; the area of the 2008 swarm estimated in a similar way amounts to 12 km^2. With respect to the fact that also the known hypocenters of the 1985/86 swarm occurred on the same fault plane segment, one can speculate that the main hypocenter cluster of the 2000 and 2008 swarms represents the largest fault area capable of brittle deformation in the NK zone. Accordingly, if the cumulative seismic moment of the 2008 swarm (4E16 Nm) would be released in a single mainshock, the maximum expected M_L

magnitude would amount to 5.0, which is the same as the maximum magnitude estimates of the activity at the break of 20th century.

However, the precise location of the historical seismicity is uncertain. In particular, the macroseismic data concerning the activity in a period of 1872 – 1908 and the rough locations of the 1962 swarm put the historical epicenters to about 15 km to the north, to the Klingenthal - Kraslice area (e.g. *Neunhöfer and Hemmann, 2005*), see Fig. 1. On the other hand, the agreement between the maximum magnitude estimate of a particular fault segment corresponding to NK zone and the maximum magnitude estimated from historical macroseismic observations in a nearby area could be considered as a prove of the reliability of the estimates.

7. Discussion

The increasing microswarm activity in the period of 2004-2008 (see Fig. 5), which showed a pronounced migration to the south and downwards from a depth of 10 to 13 km, foreshadowed the oncoming of a larger earthquake swarm. In our recent paper, which was accepted one month before the 2008 swarm onset *(Fischer and Michálek, 2008)*, we indicated the probability of its soon occurrence stating that "*the frequent recurrence of microearthquake swarms emerging since 2004 indicates a new activation of the area after the 2000 swarm. Nevertheless, in spite of a relatively large number of events, the seismic energy of this activity is negligible compared to the energy released during a large swarm, similar to that of the year 2000*". And further, "*Thus one could speculate that if the microswarm activity before the 2000 swarm had a causal relationship to a generation of the 2000 swarm, the recent microswarms could be viewed as a precursor to a future swarm in larger depths in the southern part of the focal zone.*" Our assumption that the gradually growing microearthquake swarm activity since 2004 was a precursor to the intensive swarm of October 2008 has been proven, indeed. However, in contrast to the speculation of greater depth of the new swarm deduced from apparent depth-ward migration of the preceding microearthquake swarms, the 2008 swarm occurred surprisingly in the same depth range as the 2000 swarm.

The recurrence interval of 8 years between the 2000 and 2008 swarms appears to be rather short compared to the intervals between the other strongest swarms (1903, 1908, 1962, and 1985/86). This relates to the question of tectonic loading of the activated fault segment. According to *Horálek and Fischer (2008)*, the faulting during individual swarms is mostly controlled by the regional tectonic stress. However, the faults are brought to a critical state by pore pressure increase. The moment tensors of most events show prevailing double-couple component, the volumetric part occurs only exceptionally on unfavourably oriented faults *(Horálek et al., 2002)*. Thus it could be of interest to evaluate the mean slip along the whole activated fault segment to learn the rough rate of tectonic loading. Taking the total seismic moments of the 2000 and 2008 swarms (1.4E16 and 4E16 Nm, see Fig. 8), shear modulus of 30 GPa and the total fault area of the main cluster of the swarms (9 and 12 km^2) one arrives at the average slip of 5 cm and 11 cm for the 2000 and 2008 swarms, respectively. By comparing the average slip (10 cm) with the inter-swarm period of 10 years (1986 – 2000 and 2000 – 2008), one would get a tectonic loading rate of ~1 cm/y if the released slip would equal the cumulative loading. Being aware of a large uncertainty of this guess, such a rate appears rather fast for a small intra-continental fault segment extending to about 10 km^2. Furthermore, aseismic creep of the same rate should be considered in the neighbouring parts of the fault. Creeping parts of faults are commonly observed, e.g. the Parkfield segment of the San Andreas Fault. Such behavior caused by a decreased friction coefficient is even more likely in the case of fluid-permeated faults, which is indeed the case of West-Bohemia/Vogtland due to high CO_2 flux.

The relatively fast recurrence interval and apparent high loading rate may be questioned if taking into account the known activity in the period from 1872 to 1908, whose location is estimated from macroseismic data at about 15 km to the north. If this was true then the fault portion of about 25 km length would experience a stepwise strain release with a burst of activity in the Klingenthal-Kraslice area at the break of 20th century and a recent burst of activity in the Nový Kostel area at the break of 21st century some 100 years later. (Note in Fig. 1, that the Klingenhal-Kraslice area occurs at the prolongation of the NK focal zone to the north; it exhibits a repeated microswarm activity which usually precedes or follows the swarms in the NK focal zone). Because the available records do not allow to estimate reliably the location of the historical seismicity, we are missing the information on the previous activation of the NK focal zone. Hence, the recurrence interval in the NK focal zone would definitely exceed 130 years, which is the period of fairly reliable earthquake swarm observations. In such a case the tectonic loading rate would drop to less than 1 mm/y, which agrees well with the loading rates expected within the continents. It should be noted that further 100 km to the north the seismoactive belt extends along the Leipzig-Regensburg zone with earthquakes reaching the magnitude of 2.8 within the last decade *(Korn et al., 2008)*. Thus we believe that a complex analysis of the recent and historical seismic activity in a broader area of West-Bohemia/Votland, Saxony to the north and Bavaria to the south could improve our understanding of the seismogenic processes, whose effects are recently concentrated in West Bohemia.

The 2008 swarm represents a high quality data set providing the opportunity to deepen our understanding of the triggering and driving forces of the seismic activity in the area. Among others, further studies will probably address the analysis of focal mechanisms in a full moment tensor description, spatio-temporal and seismo-statistical studies, determining the seismic source parameters including finite source models. A paleoseismological study could contribute to revelation of the enigma of a possible high loading rate and creeping parts of the seismoactive fault in the NK focal zone.

8. Conclusions

- The 2008-earthquake swarm occurred in the period from 6th October to the beginning of December 2008 in the Nový Kostel area of West Bohemia /Vogtland. The swarm included 9 events of M_L>3.0

with two largest events of magnitude M_L=3.8, which has made it the most intensive swarm since the M_L≤4.6 swarm in 1985/86.

- The swarm was recorded by 13 to 23 permanent and mobile WEBNET stations without gaps. Additionally, the period from October 22, 2008 until the beginning of February 2009 was also recorded by strong-motion accelerometers ALTUS K2 (Kinemetrics) deployed at four WEBNET stations. The maximum ground motions in the 2008 swarm observed by the WEBNET correspond to the displacement of 0.25 mm, velocity of 9.5 mm/s and acceleration of 0.65 m/s^2. By comparing the accelerograms with the differentiated WEBNET velocigrams we have shown that WEBNET seismograms can be easily used for deriving accelerograms.
- Up to 25 000 events in the magnitude range -0.5<M_L<3.8 were detected using an automatic picker A total of 9 swarm phases can be distinguished in the swarm, five of them exceeding the magnitude level of 2.5. The magnitude-frequency distribution of the complete 2008-swarm shows a *b*-value close to 1.
- The 2008 swarm showed an excess of the strongest events (M_L>3.5) in contrast to the lack of events in the magnitude range from 3.0 to 3.5. This feature is in accord with our previous finding based on the 2000 swarm analysis which indicates that the West-Bohemia swarms can be regarded as a set of multiple mainshock-aftershock sequences
- Comparison with the previous earthquake swarms in the NK area has shown that the 1985/86 and 2008 swarms were similar in terms of the seismic moment (4E16 Nm) released, compared to 1.4E16 Nm for the 2000 swarm and only 6E14 Nm during the 1997 swarm.
- The 2008 swarm has shown the fastest seismic moment release due to its short duration. The main part of the swarm lasted only 4 weeks, compared to 8 weeks during the 1985/86 swarm and 10 weeks during the 2000 swarm.
- The hypocenters fall precisely on the same fault portion of the NK focal zone that was activated by the 2000 swarm and most probably also by the 1985/86 swarm in a depth interval from 6 to 11 km. The steeply dipping fault planes of the 2000 and 2008 swarms appear identical within the bounds of the location error of about 100 m.
- Also, the focal mechanisms of the 2008 swarm are identical with the focal mechanisms of the 2000 swarm, both matching the average strike 170° and dip 80° of the activated fault segment.
- The hypocenters of the first swarm phase occurred (similar to the 2000 swarm) at the bottom of the activated fault patch. In general, an upward migration took place in comparison with the 2000 swarm, which exhibited a counter-clockwise migration of hypocenters.
- Considering the magnitude of the largest earthquake as a measure of the swarm size, the 2008 swarm has ranked among four strongest swarms in the West Bohemia/Vogtland region since 1903 (the beginning of the instrumental observations). Only the swarms in 1908 (M_L~5.0), and 1985/86 (M_L=4.6) were more intensive in terms of magnitudes of the largest earthquakes.

- The similarities in the activated fault areas and in the seismic moment released during the three recent largest swarms point to a limited seismic potential of the focal zone, which would amount to an earthquake of M_L~5 if the whole fault plane segment was activated simultaneously.

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Figure captions

Fig. 1. West Bohemia/Vogtland region with the earthquake epicentres (Horálek and Fischer, 2008), WEBNET seismic stations and principal faults (EG - Eger rift, MLF - Mariánské Lázně fault). The maximum compression striking 160° (*Švancara et al., 2008*) is indicated in the lower right corner. The solid line indicates the Czech-German border, squares mark towns in West Bohemia, SE Saxony and NE Bavaria. The German KTB superdeep borehole is indicated in the lower left corner. The Nový Kostel and Kraslice-Klingenthal focal zones are indicated by dashed rectangle and ellipse, respectively. A gray rectangle indicates the Počátky-Plesná fault zone.

Fig. 2. Seismograms of the M_L = 3.8 event recorded by the Güralp 40-T/Janus-Trident and SM-3/5800 PCM seismographs at station NKC of a M_L=3.8 event; the time is measured relative to 28-10-2008 8:30:12.5 UTC. Both seismograms are sampled at 250 Hz and band-pass filtered in the range of 0.2 – 40 Hz. Amplitude is normalized to the maximum value recorded at this station.

Fig. 3. WEBNET CMG-40T (fs=250 Hz) and ALTUS-K2 (fs=200 Hz) accelerograms from station NKC of a M_L=3.8 event; the time is measured relative to 28-10-2008 8:30:12.5 UTC. Accelerogram for CMG-40T is derived from the original velocigram. Both are band-pass filtered between 0.1-25 Hz. Amplitude is normalized to the maximum value recorded at this station.

Fig. 4. Cumulative magnitude frequency distribution for the swarms of 1985/86 (blue), 1997 (light blue), 2000 (green) and 2008 (red).

Fig. 5. Top: Magnitude-time distribution of seismicity in the focal zone NK from 1991 to 2008. Note the dominance of the 2000 (green) and 2008 swarms (dark red). Bottom: Depth cross-section of focal zone NK along the main fault plane NK (right) and perpendicular to it (left). Color coding is proportional to the origin time. The rectangle indicates the fault area shown in Fig. 8.

Fig. 6. a) Magnitude-time course of the main part of the 2008 swarm with phase numbers indicated on top. Note that phases P3, P4, P5 and P7 are dominated by strong mainshocks (at least one). b) Magnitude-time course of the 1985/86, 1997, 2000 and 2008 swarms using the same time scale. Main part of the swarms is indicated by bold line .

Fig. 7. Cumulative seismic moment released during the earthquake swarms of 1985/86 (blue), 1997 (light blue), 2000 (green) and 2008 (red). The vertical scale for the 1997 swarm (right axis) is 10 times magnified compared to the other swarms (left axis).

Fig. 8. The 2000 (a) and 2008 (b) swarm activity in the magnitude-time plot (top) and fault plane view (bottom) (same projection as in Fig. 5). The color-coding is proportional to event order. Note that both the swarms have initiated at the bottom of the fault patch (dark-blue colors) and terminated at the top-most tail on the right. A similar time period of 128 days is displayed for both swarms.

Fig. 9. a) Cross section of the fault segment of the 2000 (circles) and 2008 (crosses) swarms; the horizontal coordinates are rotated 13° clockwise. b) Difference of the mean off-plane coordinate of the 2000 and 2008 swarm events (solid line) compared to the mean standard deviation of the off-plane coordinate of the 2000 and 2008 swarm events (dashed line). The mean and standard deviation are measured in rectangular cells of 150 m size along the fault plane.

Fig. 10. Focal mechanisms for swarm in years 2000 (left) and 2008 (right), lower hemisphere projection is used. The 2000 swarm mechanisms are taken from Fischer and Horálek (2005) and correspond to all 133 events with M_L >= 1.7. For the 2008 swarm the preliminary mechanisms of 29 selected events with M_L >= 2.0 were determined. All mechanisms are left-lateral with a NS oriented fault plane.

Fig 1

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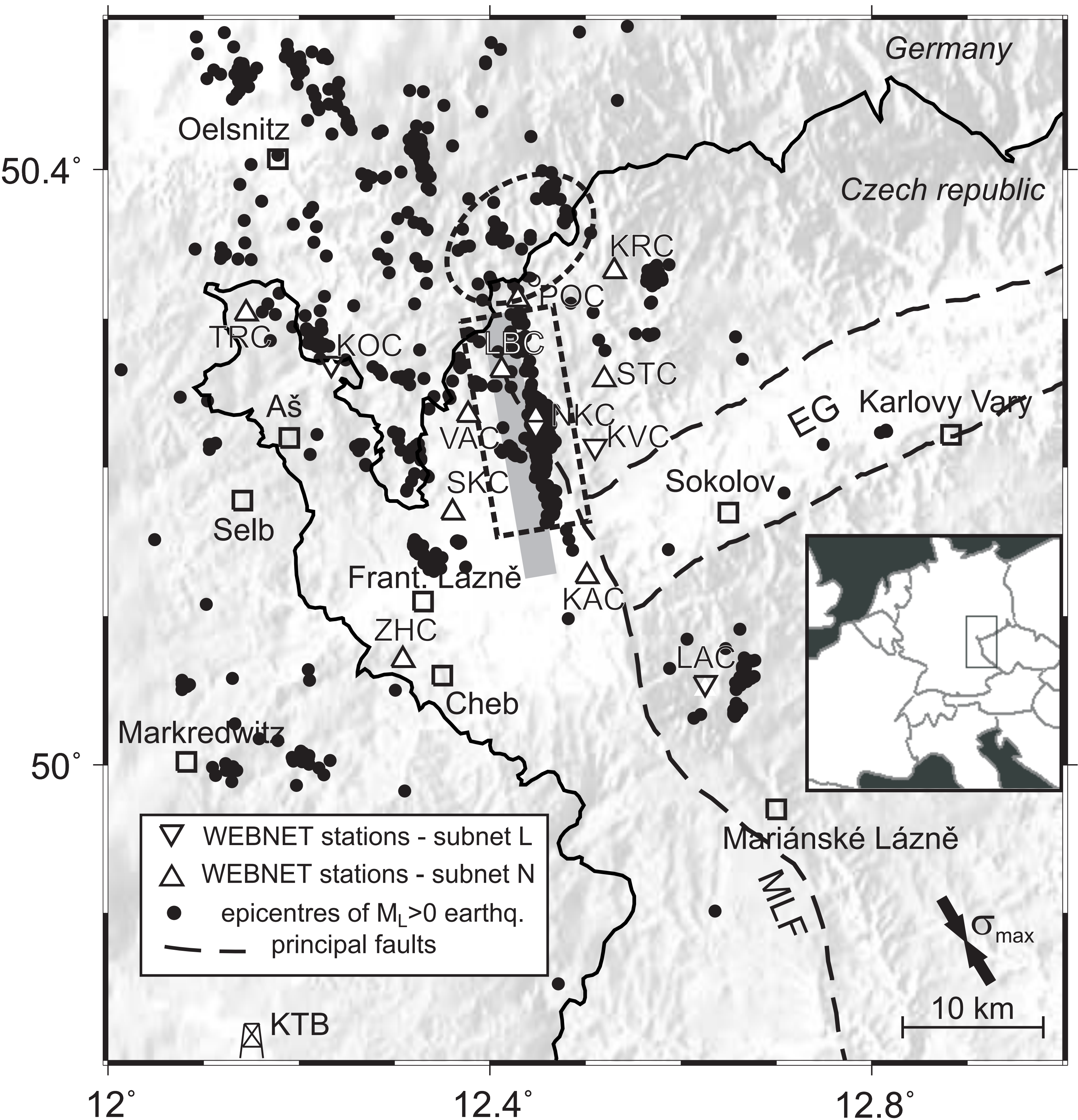

Fig 2
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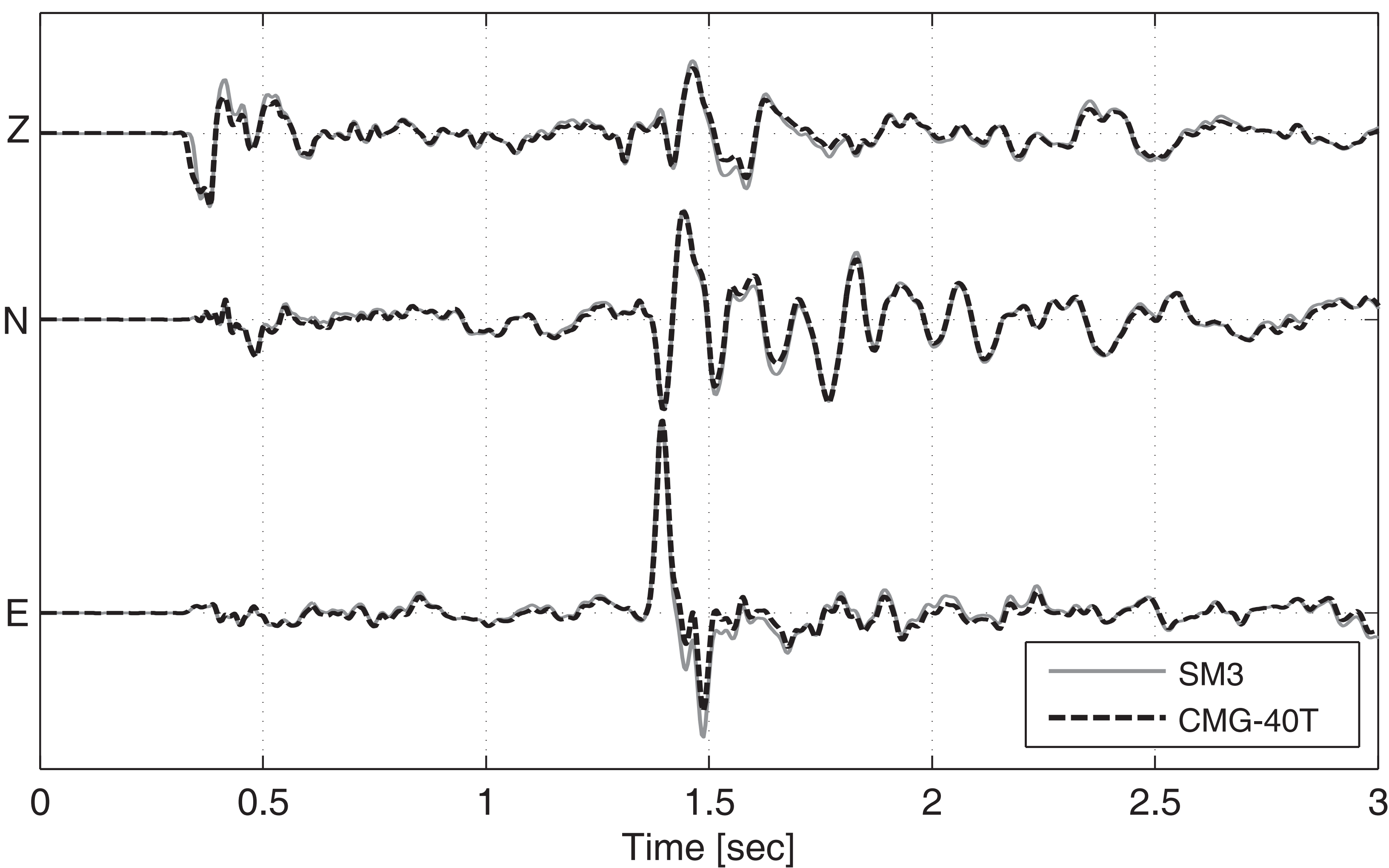

Fig 3

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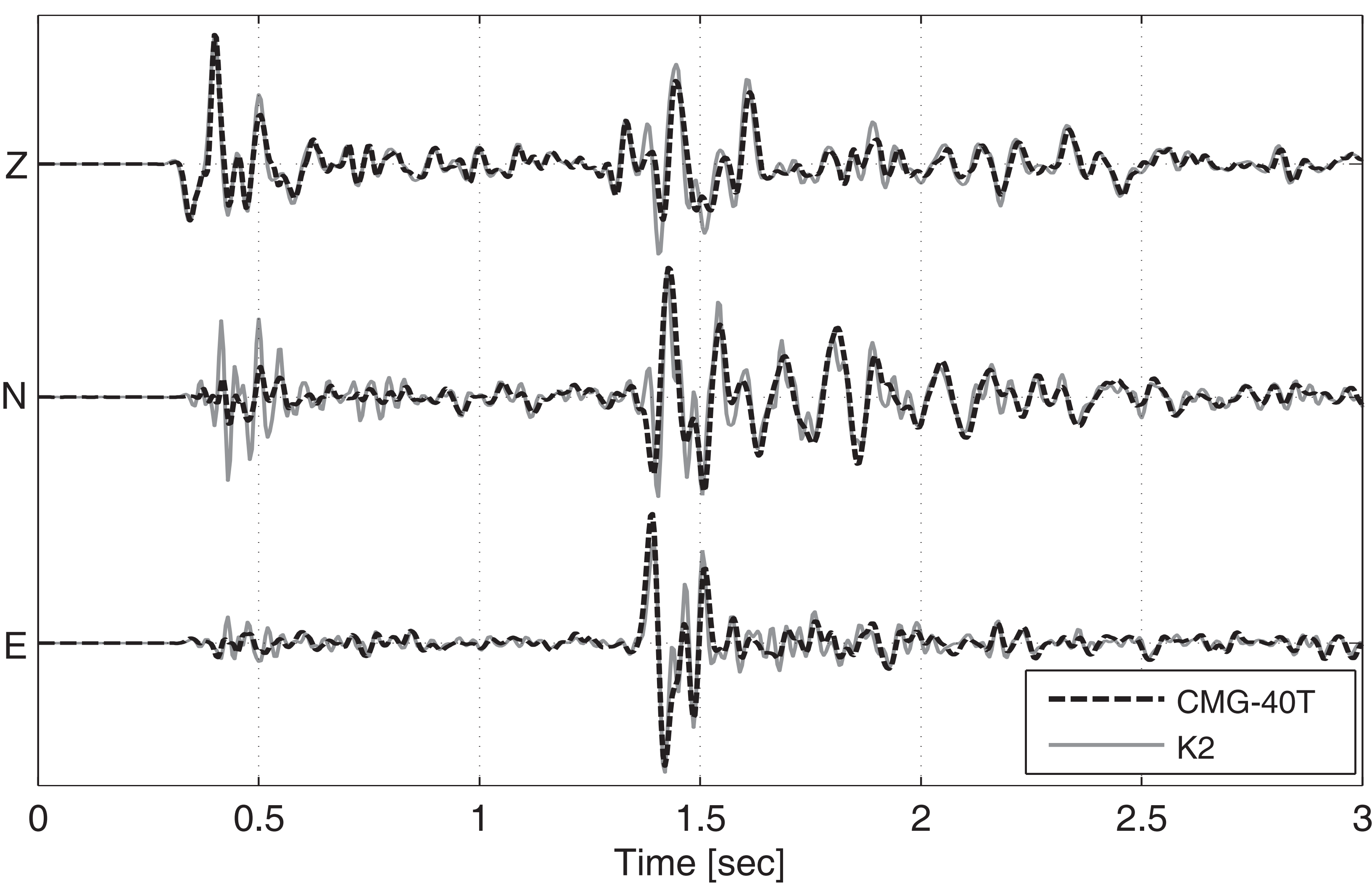

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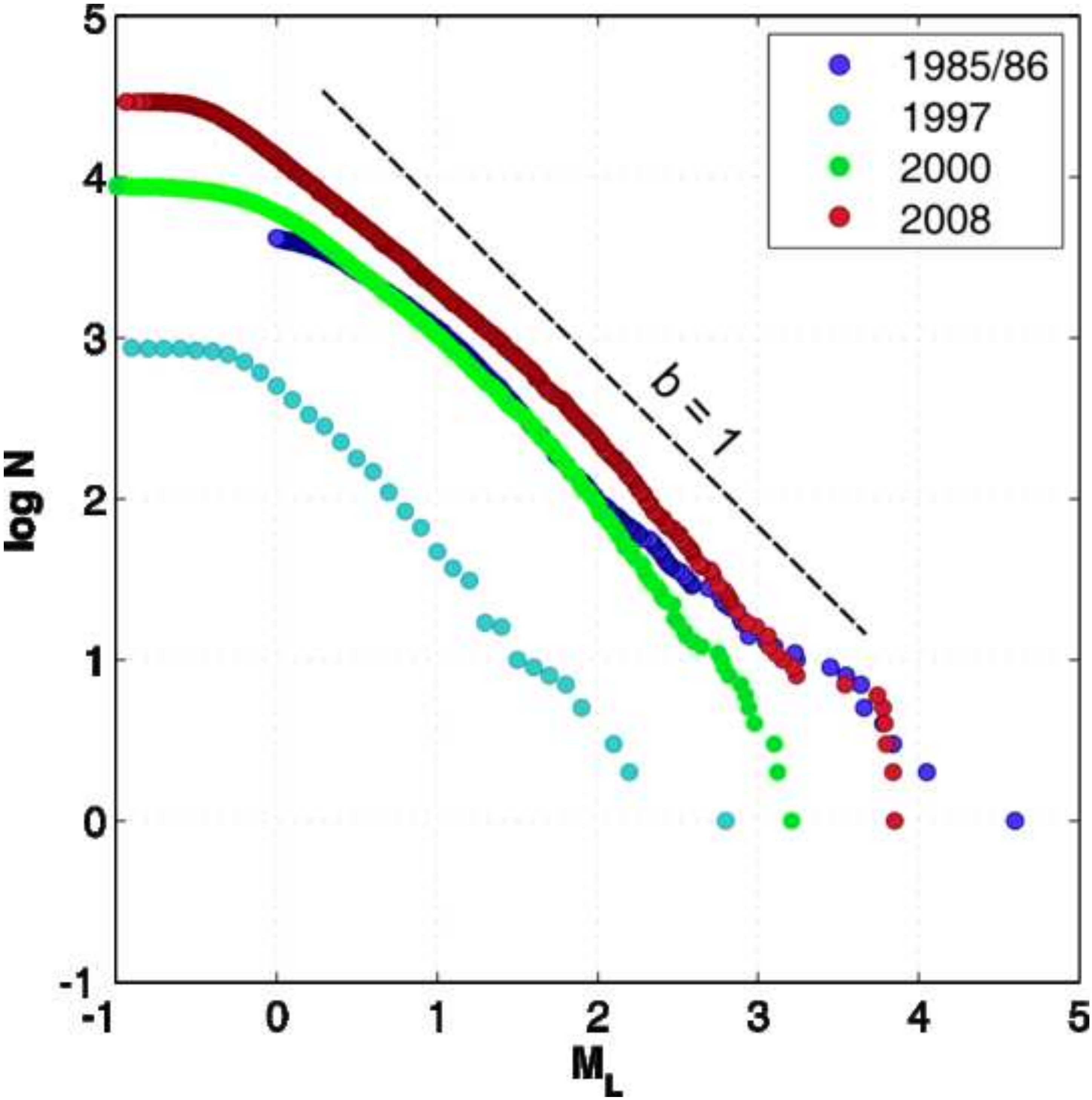

Fig 5a
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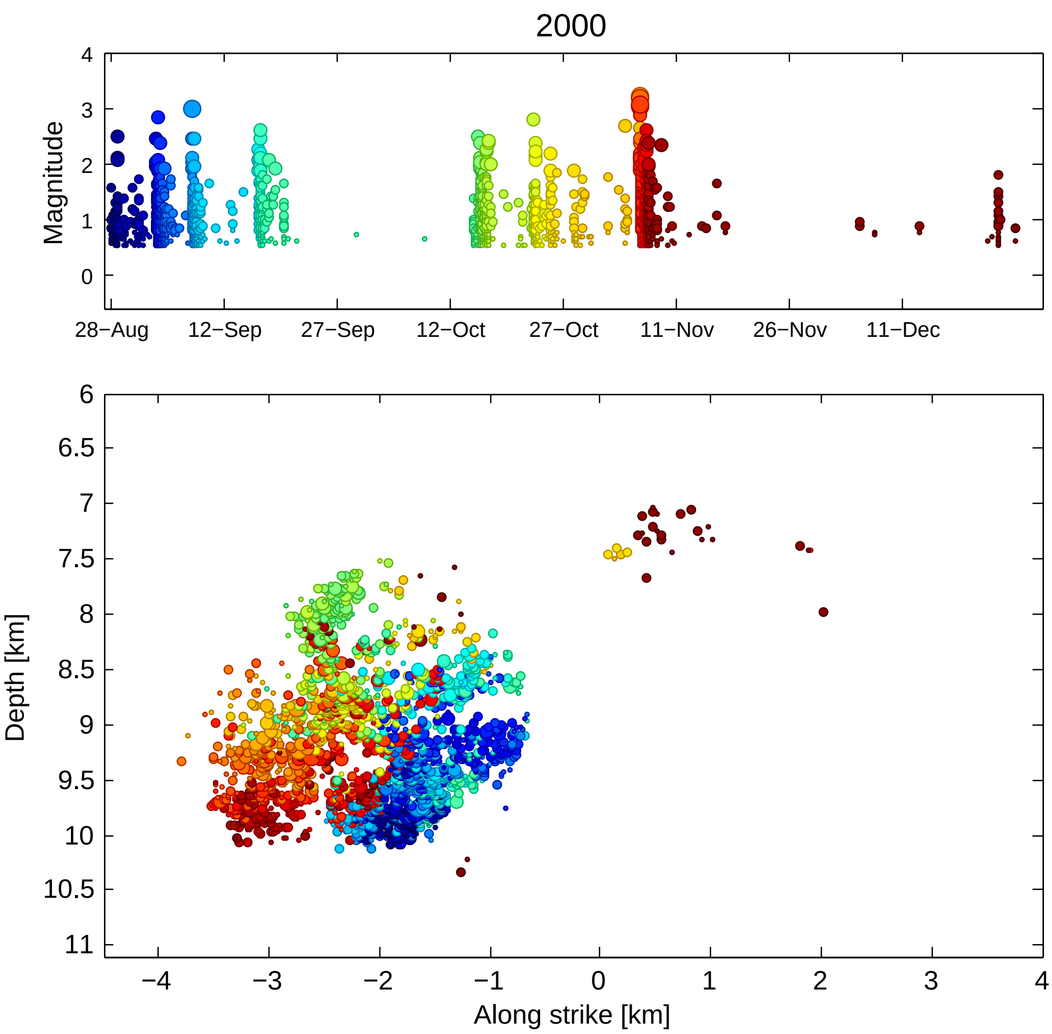

Fig 5b

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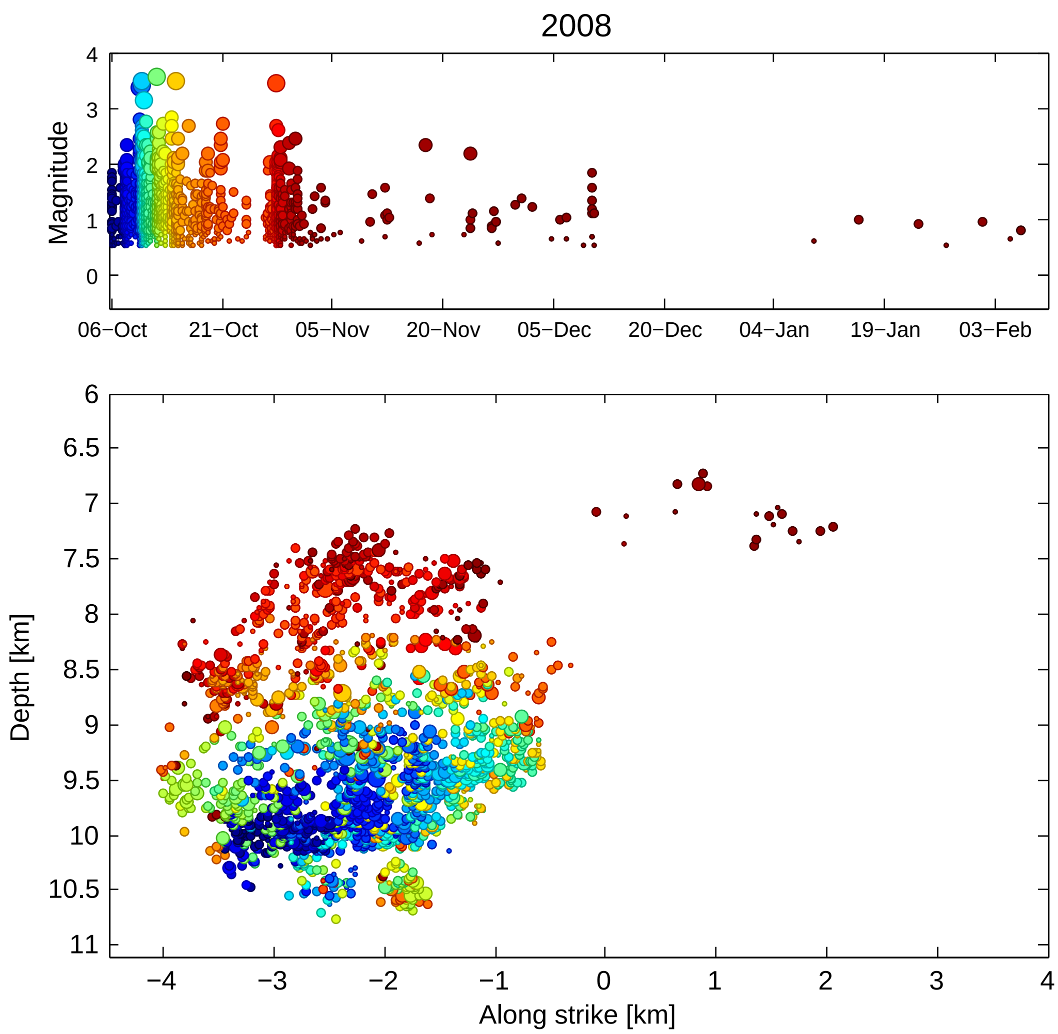

Fig 6

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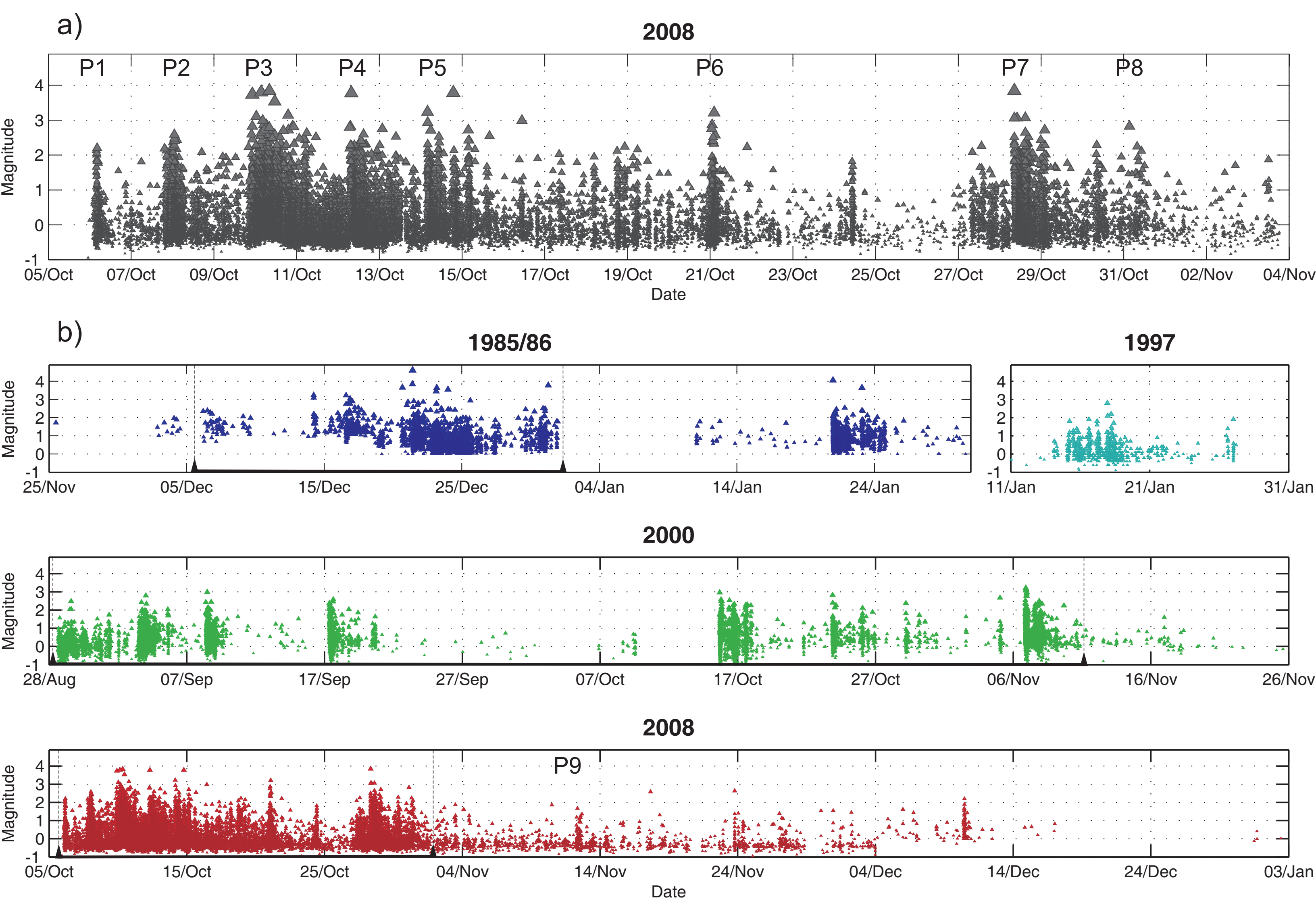

Fig 7
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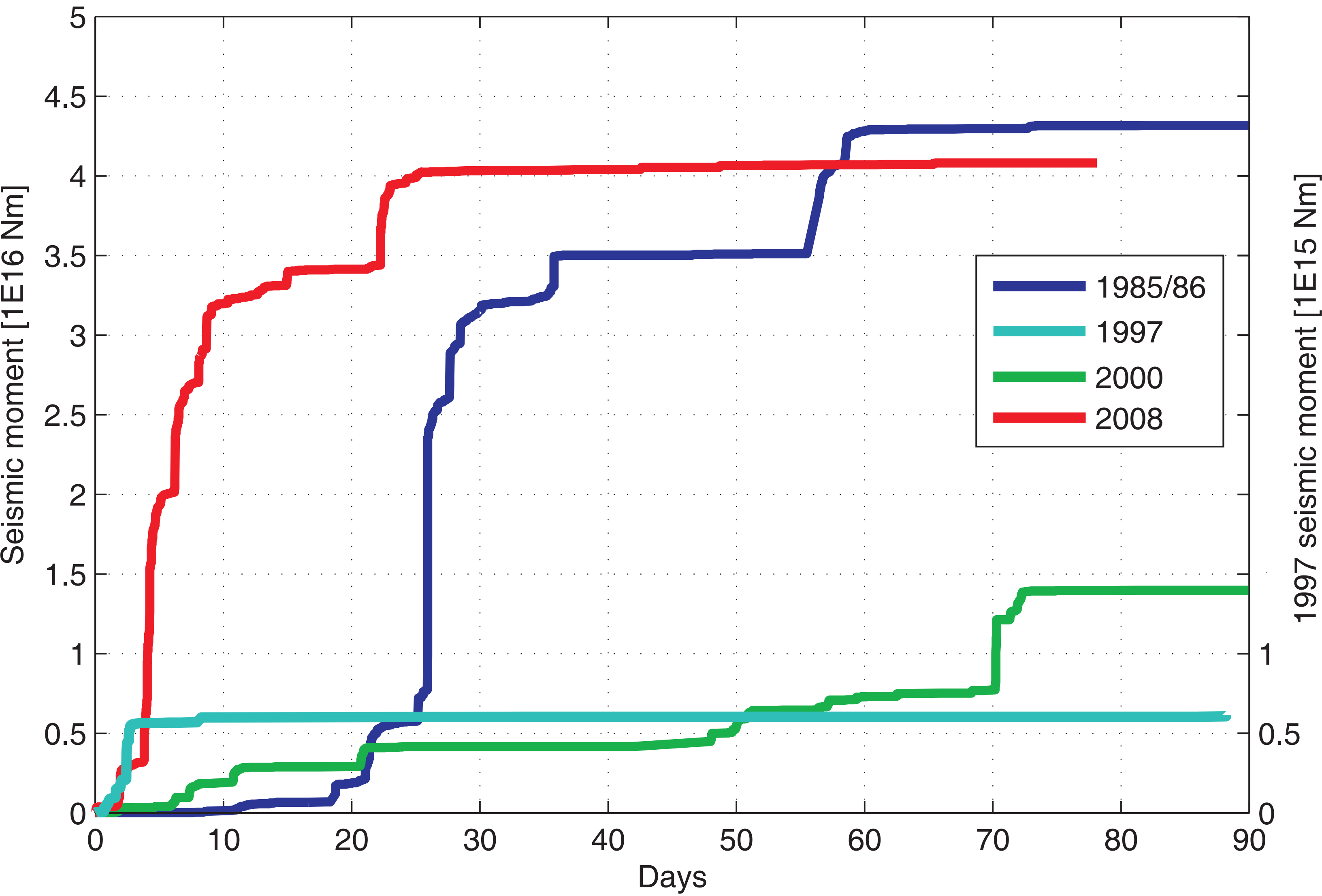

Fig 8
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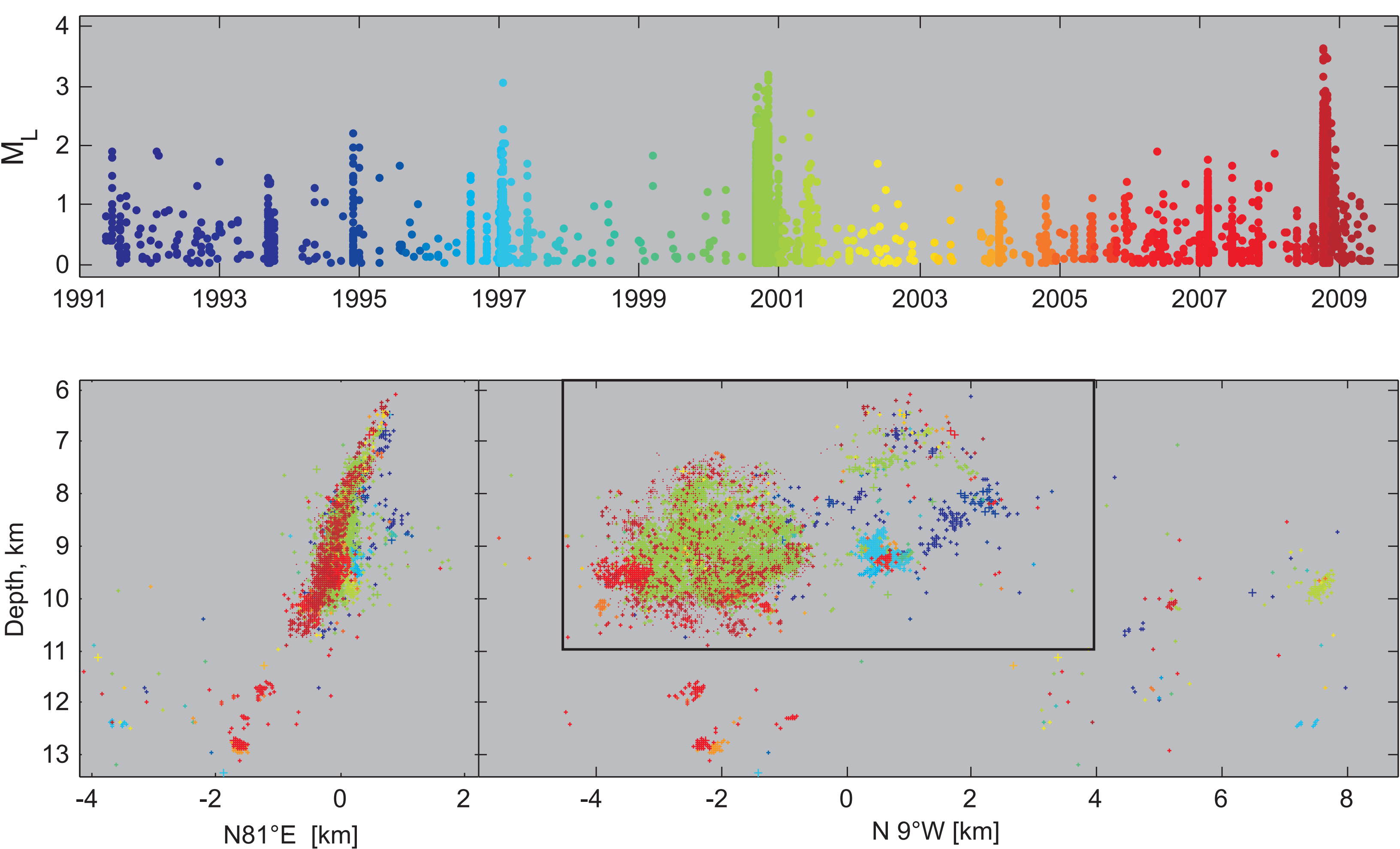

Fig 9

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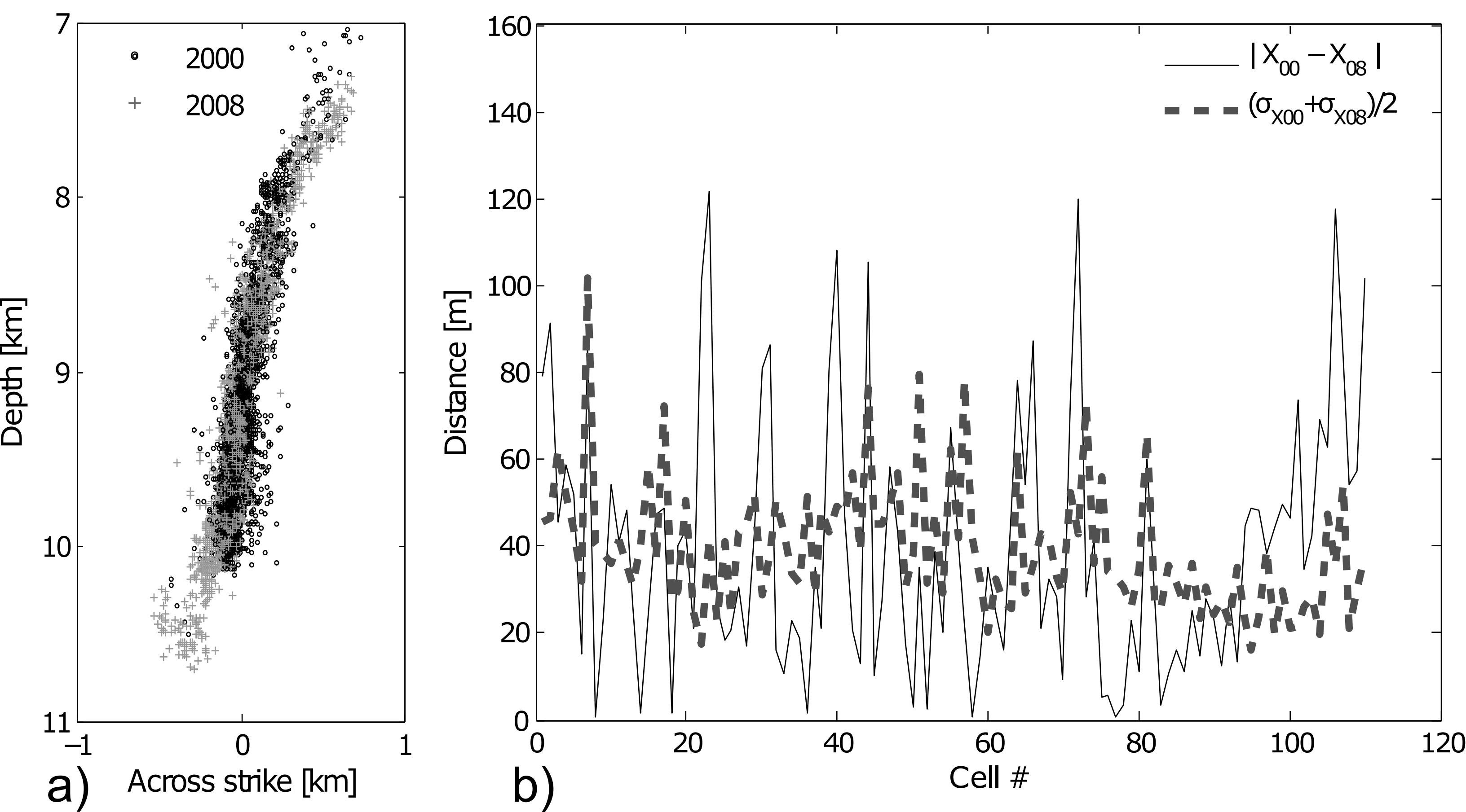

Fig 10
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