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Analysis of the local lithospheric magnetic activity before and after Panzhihua $M_w = 6.0$ earthquake (30 August 2008, China)

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Abstract. Lithospheric ultra low frequency (ULF) magnetic activity is recently considered as a very promising candidate for application to short-time earthquake forecasting. However the intensity of the ULF lithospheric magnetic field is very weak and often masked by much stronger ionospheric and magnetospheric signals. The study of pre-earthquake magnetic activity before the occurrence of a strong earthquake is a very hard problem which consists of the identification and localization of the weak signal sources in earthquake hazardous areas of the Earth's crust.

For the separation and localization of such sources, we used a new polarization ellipse technique (Dudkin et al., 2010) to process data acquired from fluxgate magnetometers installed in the Sichuan province, China. Sichuan is the region of the strongest seismic activity on the territory of China. During the last century, about 40 earthquakes with magnitude $M \geq 6.5$ happened here in close proximity to heavy populated zones.

The Panzhihua earthquake $M_w = 6.0$ happened in the southern part of Sichuan province on 30 August 2008 at 8:30:52 UT. The earthquake hypocentre was located at 10 km depth. During the period 30–31 August – the beginning of September 2008, many clustered aftershocks with magnitudes of up to 5.6 occurred near the earthquake epicentre.

The data from three fluxgate magnetometers (belonged to China magnetometer network and placed near to the clustered earthquakes at a distance of 10–55 km from main shock epicenter) have been processed. The separation between the magnetometers was in the range of 40–65 km.

The analysis of a local lithospheric magnetic activity during the period of January–December 2008 and a possible source structure have been presented in this paper.

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1 Introduction

Up to the present days, earthquake (EQ) still remains one of the most dangerous natural hazards in seismoactive areas. Hence, short-time EQ prediction is very important, not only for Developing countries but also for highly developed industrial states, which may suffer a significant loss after great seismic shocks. In spite of more than fifty years of intensive study in this field, the achievements are rather modest; this is confirmed by the unexpected occurrence of the Wenchuan $M_w = 7.9$ (China, 2008) and L'Aquila $M_w = 6.3$ (Italy, 2009) EQs.

During the two last decades the ultra low frequency (ULF) magnetic precursors (frequency range is about 0.001–10 Hz) have been considered as the most prominent for short-time EQ forecasting (Hattori and Hayakawa, 2007; Hayakawa et al., 2007; Bleier et al., 2009). (Here are only a few examples of the recent articles). However, the magnetic field of pre-EQ crustal activity is very weak (usually below 1 nT) and completely overlaps with Pc1-Pc5 pulsations of ionospheric/magnetospheric origin. These difficulties are principal for reliable crustal signal separation from Pc or man-made interference and sometimes lead to controversial results (Campbell, 2009; Thomas et al., 2009a, b) or wishful thinking.

In order to avoid these obstacles a new method of pre-EQ lithospheric magnetic field signal detection has been proposed (Dudkin et al., 2010, see also a recent review of related problems therein). This methodology is based on space selection of these signals with the use of two or more 3-component magnetometers placed at distance 50–100 km from EQ hypocentre and on the calculation of ULF magnetic field polarization ellipse (PE) parameters.

It is known that a magnetic dipole moment vector and its magnetic field PE at any time are in the same plane (Fig. 1). Each measuring point with 3-component magnetometer allows calculation of PE parameters and its plane

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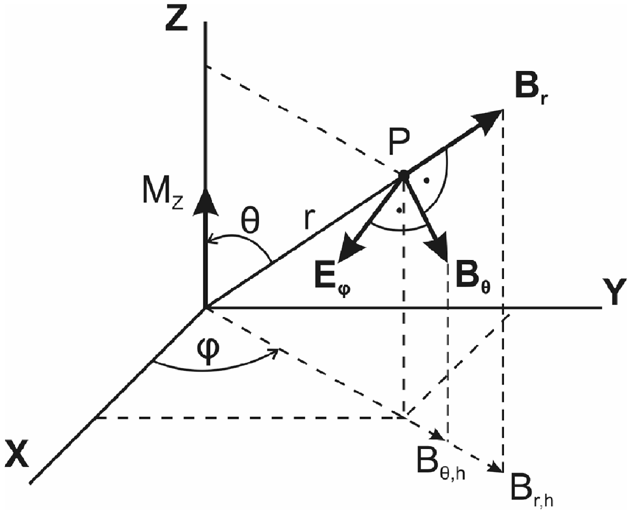


Fig. 1. Magnetic dipole source and components of EM field.

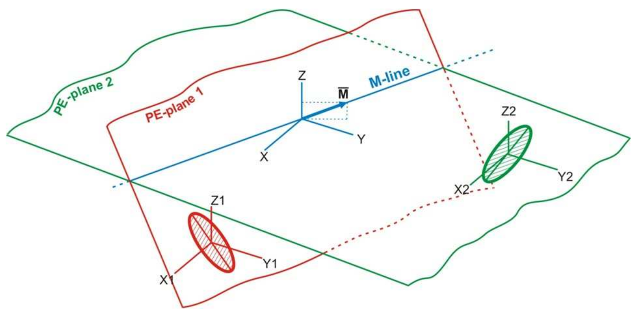


Fig. 2. M-line formation at two PE planes intersection.

position. Two spaced magnetometers give the possibility to find a line of two PE planes intersection, which contains a magnetic dipole moment aligned along it and which is named as M-line (Fig. 2). It is clear that for far sources (both ionospheric and magnetospheric) the PE major axes ratio is close to unity. For lithospheric source, if its distance to the measuring points is less than 50–100 km, this ratio usually differs from 1 (in detail about selection criteria see Dudkin et al., 2010). The calculation of M-lines' intersection with chosen crustal block for each elementary time-frequency window of dynamical Fourier spectra and the use of selection criteria allow the discrimination of lithospheric sources from ionospheric/magnetospheric ones. This means that if an M-line intersects, chosen crustal block and PE major axes ratio for this line exceeds a given threshold; then, such a block is considered as magnetically active. We name it M-block. Such an event relates to elementary lithospheric signal. (Non-lithospheric signals are considered as ionospheric|magnetospheric). This method was introduced by Dudkin et al. (2010) and applied to the Koyna-Warna (India) region.

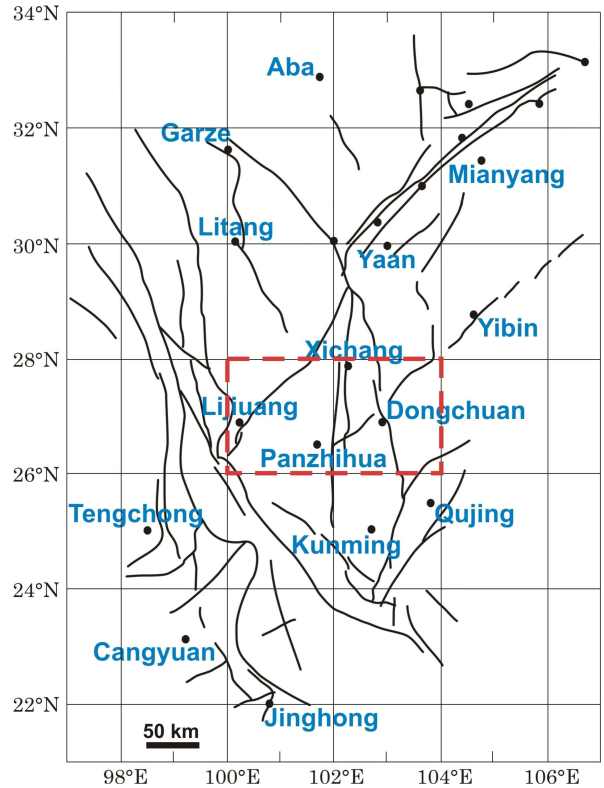


Fig. 3. Faults map of the Sichuan-Yunnan seismoactive area.

In this article, we demonstrate an application of the proposed method for the study of crustal magnetic activity before and after Panzhihua $M_w = 6.0$ EQ which occurred on 30 August 2008 at 8:30:52 UT in the southern part of Sichuan province, China. The EQ hypocentre was located in point 26.28° N, 101.92° E at depth 10 km. This EQ was not an aftershock of $M_w = 7.9$, 2008 Wenchuan EQ because it was triggered along another fault.

The paper structure is as follows: the Sect. 2 gives a short description of some peculiarities and seismic activity in Western Sichuan region. The measuring sites' configuration, the results of data processing from three flux-gate magnetometers during 2008 and selected ULF EQ magnetic precursors of lithosperic origin are described in Sect. 3. The discussion of the results obtained with comparison of the Koyna-Warna experiment' peculiarities are given in Sect. 4 and followed by Sect. 5 with conclusions.

2 A short description of Western Sichuan region seismotectonics

Mainland China is a region of a very high level of seismotectonic activity. The most seismically active intraplate area of China is located between 100°–105° E. The EQs in this region are caused by the resistance to the extension of the Tibetan plateau from the Tienshan mountain range to the north as well as the rotation of the rhombic shape block of Sichuan – Yunnan area (Cole et al., 2006; Li et al., 2006). The tectonic stress field in this region is characterized by clear zoning, particularly in the Sichuan-Yunnan region where the spatial heterogeneous features of tectonic stress field are significant (Cui et al., 2006).

The Sichuan and Yunnan provinces belong to a so-called rhombic-shaped subplate under the influence of the highest intraplate seismicity in the territory of China. These provinces are densely populated (a total population of approximately 180 millions) and industrially developed. Because of the active and complex tectonic background, during the 20th century about 40 EQs with magnitude $M \geq 6.5$ happened in close proximity to heavily populated areas causing significant casualties and material losses (Huang et al., 2002; Gkarlaouni et al., 2008).

The Western Sichuan region belongs to the Sichuan-Yunnan rhombic block, or more exactly to the middle Yunnan sub-block. This sub-block has the form of a triangular tectonic domain, which is confined by the NE-trending Lijiang-Xiaojinhe fault, NS-trending Anninghe fault, NW-trending Zemuhe fault, NS-trending Xiaojiang fault, and NW-trending Red River fault (Xiwei et al., 2003). The focal depths of strong EQs vary mainly between 3 km and 15 km within the crust, indicating in this way that the width of the brittle seismogenic layer in this region is less than 20 km. The crust thickness is about 40–45 km (Huang et al., 2002; Yang et al., 2005; Gkarlaouni et al., 2008). The Panzhihua region consists of basic rocks, mainly basalt and granite (Jiren et al., 1988; Shellnutt and Jahn, 2010). Tectonic faults in this region relate to the strike-slip type with slip rate about 6 mm a^{-1} (Gkarlaouni et al., 2008). A faults map of Sichuan-Yunnan seismoactive area is shown in Fig. 3.

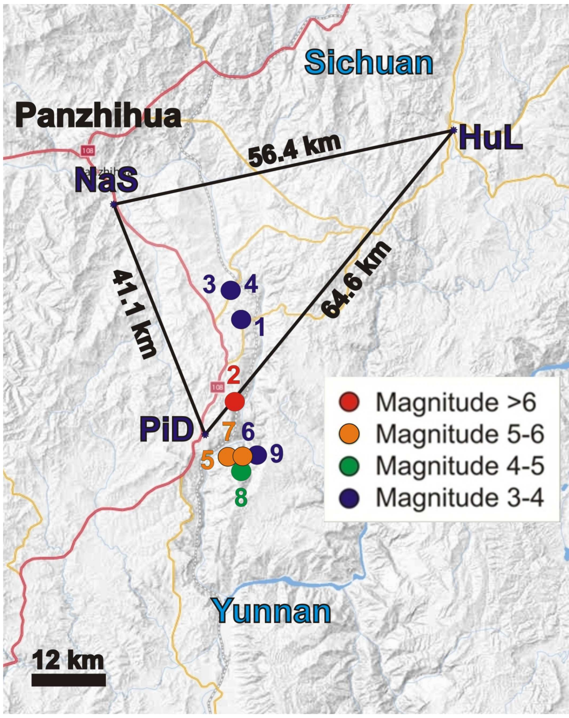
3 Description of data processing methodology and experimental results

For further development and test of the proposed method we used the synchronous data processing from three spaced fluxgate magnetometers placed near the epicentre of Panzhihua $M_w = 6.0$ EQ at distances of 10–55 km and near the populated area HuiLi (point HuL or 1), NanShan (point NaS or 2) and PingDi (point PiD or 3). The magnetometer sampling rate was 1 Hz. The distance between magnetometers was in the range of 40–65 km (Fig. 4). The relationship between local seismic and lithosperic ULF magnetic activity was studied in area 55×55 km, in depth range of 0–30 km and at volume about 90 000 km^3 (Fig. 5). Data about seismicity in the monitored area during the year 2008 were obtained from the local seismometer network and processed for EQs of magnitude $4 \geq M \geq 2$ in the Institute of Geophysics, Beijing. Information considering the major seismic events on 30–31 August is also shown in Fig. 4, where data about EQ with $M > 4$ are taken from USGS catalogue. We can see only a small foreshock activity about 2 h before main strike and 8 aftershocks (three of them have a significant value) during the next day.

For lithospheric magnetic activity detection, the procedure of so-called "blind search" has been used. This means that the monitored area was partitioned by blocks $5 \times 5 \times 5$ km (1st decomposition) and $2 \times 2 \times 2$ km (2nd decomposition) up to the depth of 30 km (Fig. 5). Then the intersection of M-lines with each block and for each elementary time-frequency window of the dynamical Fourier spectra in the frequency range of 0.001–0.5 Hz at application of selection criterion was investigated. This procedure is close to the real system operation at detection of the ULF lithospheric pre-EQ magnetic activity.

The results of detected crustal magnetic activity over the year 2008 are shown in Figs. 6, 7. For a pair of magnetometers in points PiD-Hul (points 3-1), the increased crustal magnetic activity on 29 August 2008 is clearly seen, one day before Panzhihua $M_w = 6.0$ EQ. The quantity of the ionospheric/magnetospheric signals is in good correlation with the diurnal value index of global geomagnetic activity Kp (Fig. 7). Other pairs of magnetometers did not show essential growth of magnetic activity because of problems with the magnetometer in measuring point NaS. The seismic events over the year 2008 show the absence of significant seismic activity in the monitored area before the main shock on 30 August (Fig. 8).

The depth distribution of magnetically active crustal blocks in the monitored area coincides well with EQ focal depth (Fig. 9). Azimuthal and ascent angles for M-lines of the crustal sources are distributed mainly in a narrow zone about 20–40 and 10–15 degrees, respectively (Fig. 10). Time and frequency distribution of crustal-related M-lines on 29 August shows a significant growth of pre-EQ crustal magnetic activity about 30–32 h before the main shock in the frequency range 0.002–0.016 Hz (Fig. 11). The values of PE major axes in points PiD and HuL on 29 August are shown in Fig. 12. Blue and black points mark the signals of lithospheric or ionospheric/magnetospheric origin, respectively. The compactness in time of lithosperic signals as opposed to the uniform appearance of the ionospheric/magnetospheric signals should be noted. Wavelets and dynamical Fourier spectra of PE major axes in three measuring points at 0–5 h UT on 29 August do not allow the separation of crustal signals from the ionospheric/magnetospheric ones. In the same way, during August-September beginning in 2008, the S_Z/S_H-ratio (i.e. polarization ratio) behavior for point PingDi, that is closest to EQ epicenter, does not show appropriate increase up to value 1.5–2 in frequency band 0.01–0.03 Hz (see for comparison Dudkin et al., 2010).



	Data	Magnitude	H (km)
1	30.08.08 06:14:31	3.5	28
2	30.08.08 08:30:52	**6.0**	**10**
3	30.08.08 08:49:33	3.7	23
4	30.08.08 09:41:02	3.7	10
5	31.08.08 08:31:09	**5.6**	**10**
6	31.08.08 08:40:51	3.6	16
7	31.08.08 09:34:05	**5.2**	10
8	31.08.08 11:00:29	**4.7**	10
9	31.08.08 17:56:44	3.6	18

Fig. 4. Magnetometers position and major seismic events during 30–31 August 2008.

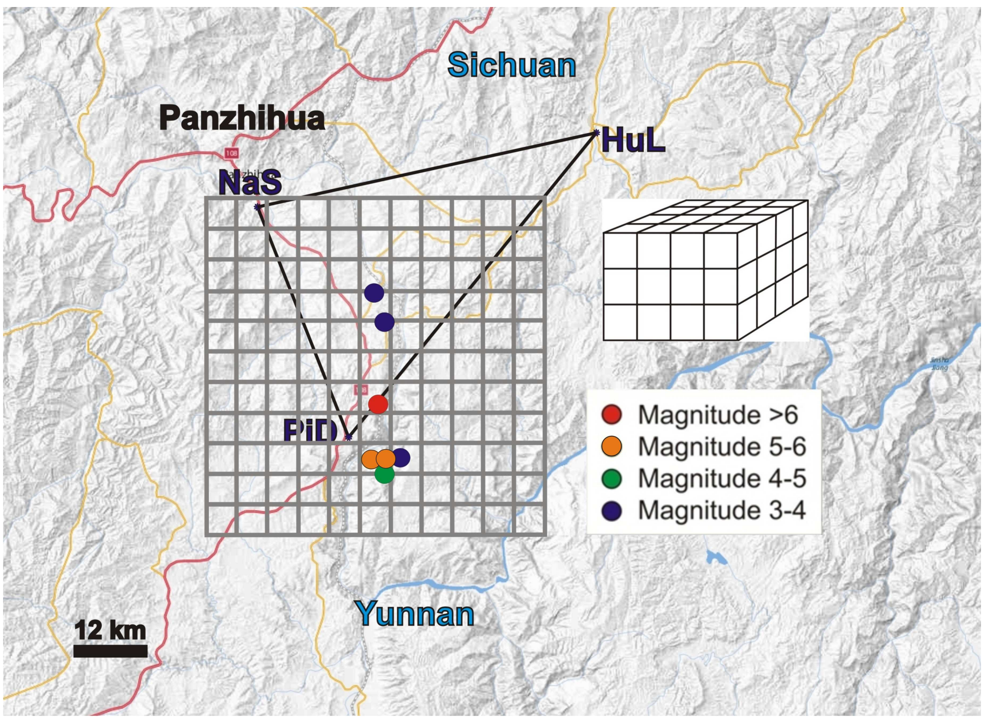


Fig. 5. Decomposition of Panzhihua seismoactive area on elementary blocks.

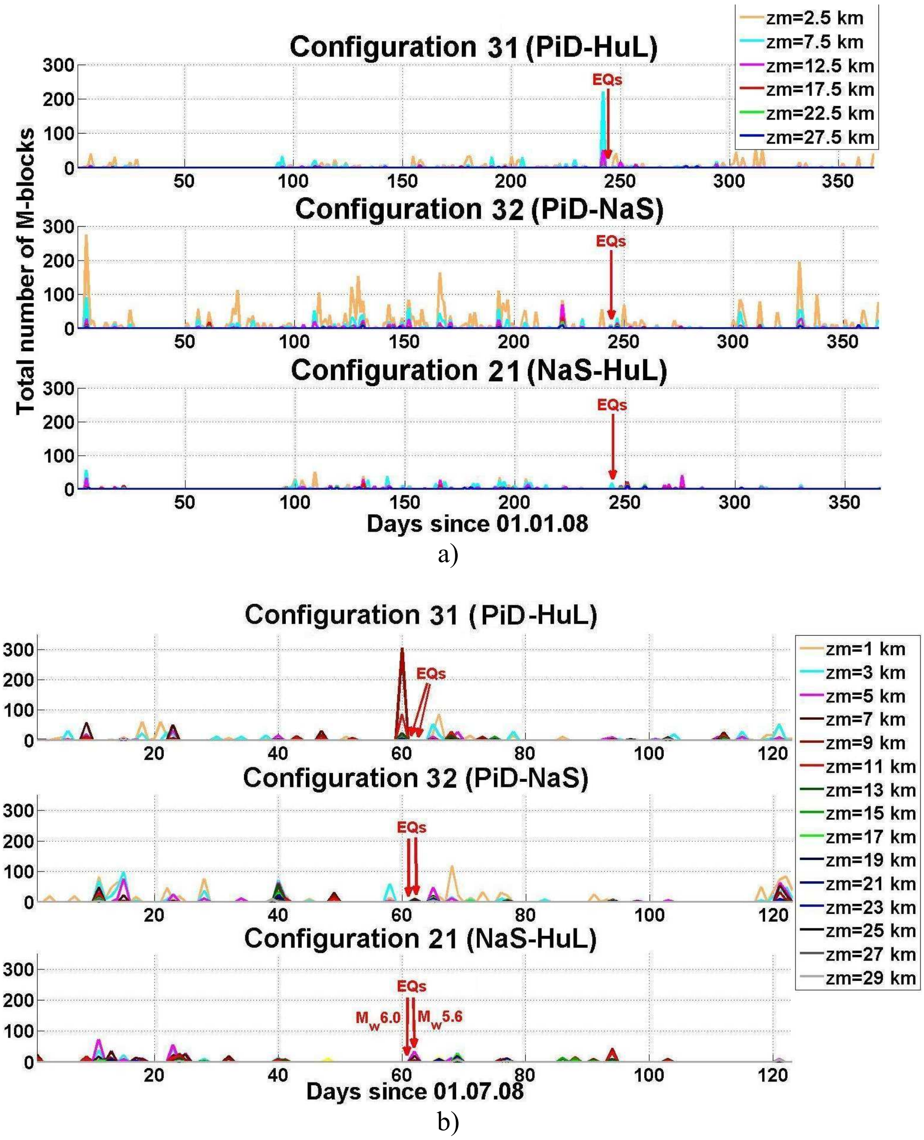


Fig. 6. The distribution of active crustal blocks number over the year 2008 for each pair of magnetometers: **(a)** general view; **(b)** detailed picture during two months before and after Panzhihua EQ. Here the studied area was decomposed on subblocks 5 × 5 × 5 km (Fig. 6a) and 2 × 2 × 2 km (Fig. 6b). A depth of horizontal slab is denoted by zm. The strongest aftershock $M_w = 5.6$ is also shown.

The spatial distribution of the crustal magnetically active blocks in the slab at depths 6–8 km on 29 August shows their almost compact localization at a distance of about 20 km from the EQ epicentre (Fig. 13). This slab corresponds to a maximum of the depth distribution of the magnetically active crustal blocks in Fig. 9. A faults map of Sichuan seismoactive area is shown in Fig. 14. The red line represents the maximum of M-lines azimuth angle distribution in the crust on 29 August 2008. The area of pre-EQ magnetic activity maximum is marked with a green star and the EQ $M_w = 6.0$ epicentre is marked by a red star. We can see that the maximum of pre-EQ crustal magnetic activity was observed in the area about 10 km^3 with a length of 10 km in the depth range of 6–8 km at the distance of about 20 km from the main shock epicentre (see Fig. 13). The maximum of the azimuth angle distribution for the magnetic moments of crustal origin is in good agreement with the direction of a local fault near HuiLi and fault plane solution for the main shock $M_w = 6.0$ and the aftershock $M_w = 5.6$ (calculated at the Institute of Geophysics, Beijing).

4 Discussions of obtained results

The applied technique for the detection of pre-EQ lithospheric magnetic activity is new and the Sichuan region is the

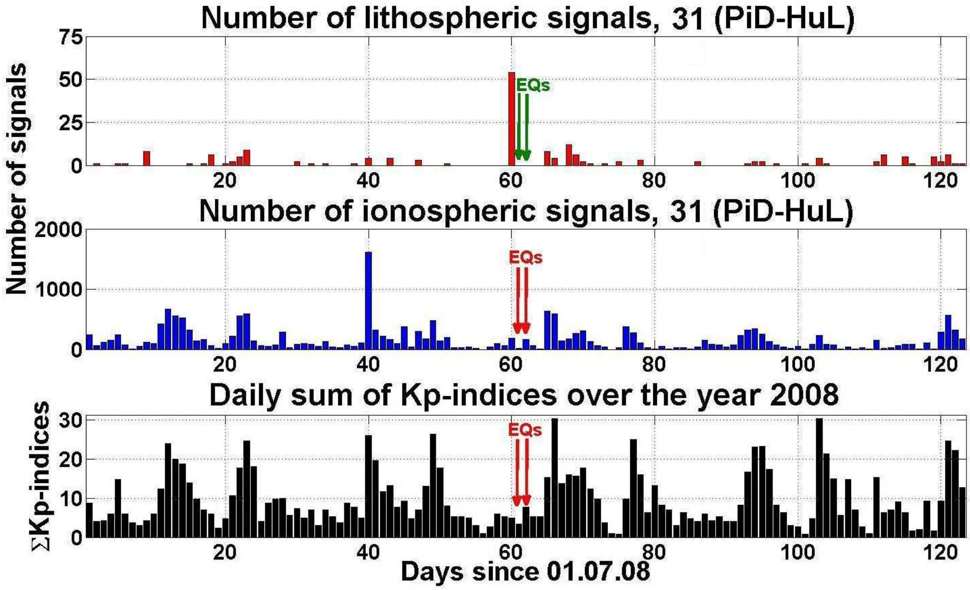
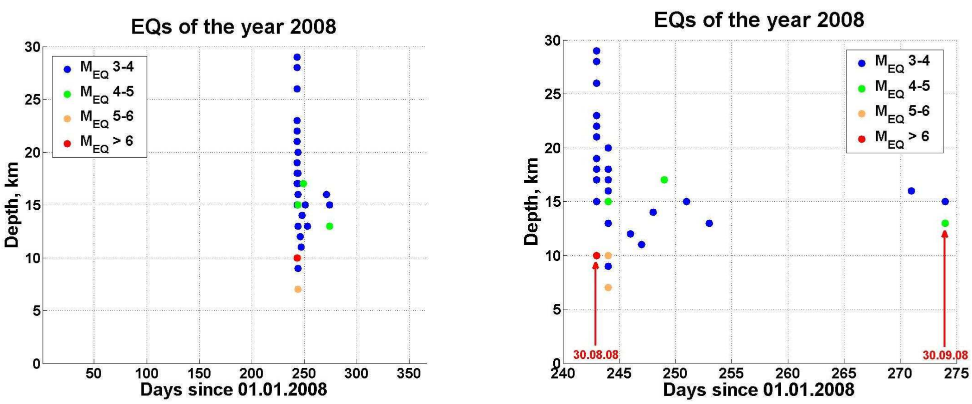


Fig. 7. Number of detected lithospheric (red) and ionospheric (blue) signals (M-lines) and diurnal Kp index value (black) during the time two months before and after Panzhihua EQ.



a) b)

Fig. 8. Seismic events in the monitored area over the year 2008: **(a)** general distribution; **(b)** detailed view.

second application of this method. Here we discuss the main peculiarities of magnetic field measurements, data processing and the results obtained in Panzhihua and Koyna-Warna regions (Dudkin et al., 2010). Their comparison shows some essential differences.

1. Differences in conditions:

a. The Panzhihua region is in the seismoactive area under the influence of high intraplate seismicity as opposed to the Koyna-Warna region with reservoir-induced seismicity of modest value;

b. the magnitudes of studied EQs vary: $M_w = 6$ and $M_w \approx 4$ in Panzhihua and Koyna-Warna regions respectively;

c. in the measuring sites of the Panzhihua region, the typical fluxgate magnetometers were used as opposed to very sensitive induction ones in Koyna-Warna area.

d. the sampling rate of fluxgate magnetometers was 1 Hz and induction magnetometers 64 Hz;

e. the maximum distance between the EQ epicentre and a magnetometer was about 55 km and 90 km in the Panzhihua and Koyna-Warna regions, respectively.

f. the observational period in the Panzhihua region was presented by almost continuous data over the year 2008 as contrasted to frequent noncontiguous data from the Koyna-Warna region (because of power line cutoff).

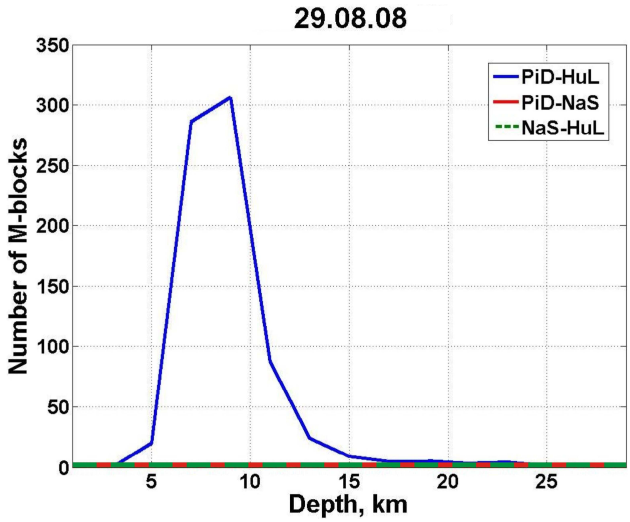


Fig. 9. The depth distribution of magnetically active crustal blocks in the monitored area one day before EQ.

2. Difference in data processing:

a. data from induction magnetometers were resampled to 1 Hz by averaging;

b. the monitored crustal area in Panzhihua region was decomposed on elementary blocks that gives a possibility of localization and rough estimation of magnetically active structures in crust. Additionally, the procedure of "blind search" was applied for simulation of the magnetometer system work in regime of pre-EQ activity search. In Koyna-Warna experiment the crustal area was considered as monoblock.

3. Differences in obtained results:

a. in Panzhihua region the strong lithospheric magnetic activity was revealed only one day before the main shock, i.e. two bursts 32 and 30 h before the main shock. After it any essential activity was not found. In Koyna-Warna region the increased lithospheric magnetic activity was found few days before EQs and just once about few days after the main shock.

b. the frequency range of the lithospheric signals which were classified as ULF magnetic precursors was about 0.002–0.016 Hz and 0.01–0.07 Hz in the Panzhihua and Koyna-Warna regions, respectively;

c. the values of PE major axes for ULF magnetic precursors were in the limits of 100–1000 pT and 2–80 pT in the Panzhihua and Koyna-Warna regions, respectively.

At analysis of obtained results some common features of the experiments in both seismoactive regions were found.

1. The increased pre-EQ ULF lithospheric magnetic activity appeared very compact in time as opposed to almost uniform distribution in time of the ionospheric/magnetospheric signals.

2. The frequency range of the lithospheric signals completely overlaps with the frequency range of Pc3-Pc5 ionospheric/magnetospheric signals.

3. The quantity of the ionospheric/magnetospheric signals is in good correlation with the diurnal Kp index value.

4. The criterion of M-line selection was chosen the same way as for the Koyna-Warna data processing: i.e. if PE major axes ratio from two measuring points exceeded threshold 2, then the magnetic dipole source considered as crustal.

Some remarks on proposed method selectivity.

1. From crustal M-lines, azimuthal and ascending angles distribution (Fig. 10) and location of magnetically active blocks (Fig. 13): it is clearly seen that for any M-line point in upper half-space a distance to PiD measuring site is smaller than to HuL one. This means that for all sources in air (or on ground surface) signals in point, HuL should be less than in point PiD. However, for all signals indicated as precursors, we got the opposite result (see Fig. 12). Thus, the ULF magnetic activity about 30–32 h before main shock really had the lithospheric origin.

2. Besides this, for the given distance between sites HuL-PiD (∼65 km), and for any source at h ≥ 85 km, the maximum of PE major axes ratio n should be less than 2 (because of magnetic dipole field intensity decreases as inverse cube of distance). Thus, any of the ionospheric/magnetospheric dipole-like sources are discriminated by condition $n \geq 2$.

3. In addition, a good correlation between the number of signals related to ionospheric/magnetospheric origin and the value of Kp-index is the evidence of the correct sources' discrimination (see Fig. 7).

We should emphasize that M-line's azimuth and ascend angles define not only the direction to the crustal magnetic source but also the direction of its magnetic moment vector. The data analysis of two experiments shows that for the crustal sources, the preferred direction of their magnetic moment vectors follows the local seismogenic faults.

It seems that the crustal ULF magnetic source mechanism for both regions should be similar, too. Magnetotelluric study of the eastern Tibetan plateau discovered two major high conductive slabs (with conductivity up to 1 S m^{-1}) at depths of 20–40 km, which extend horizontally more than 800 km from the Tibetan plateau into southwest China (Bai

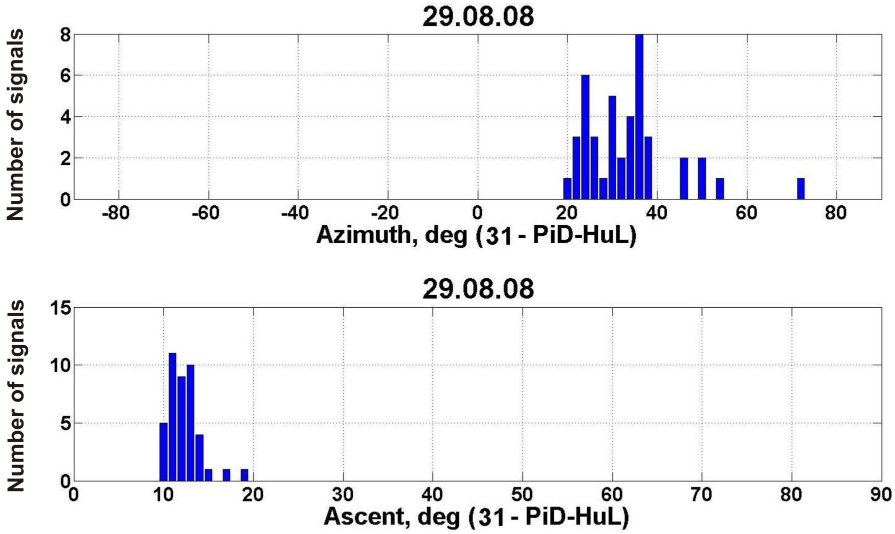


Fig. 10. Azimuthal and ascent angles distribution for crustal M-lines.

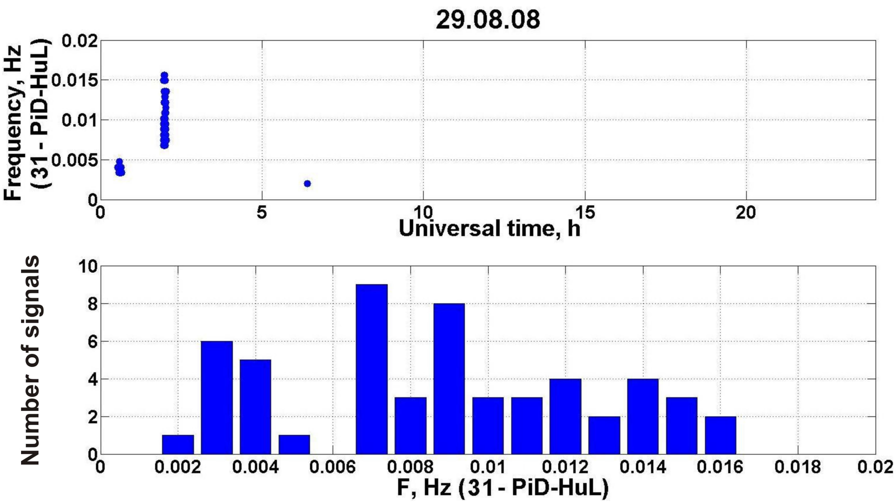


Fig. 11. Time and frequency distribution of pre-EQ crustal magnetic activity on 29 August.

et al., 2010). Under these slabs, the lithospheric conductivity becomes lower. Apparently, the appearance of such a high conductivity in this region is a presence both aqueous fluids and/or partial melt.

The upper parts of two high conductive slabs are in good coincidence with the major strike-slip faults and regions with geothermal phenomena. These slabs could form the shear zones for relative motion of lithospheric blocks (Bai et al., 2010). The shearing processes in mid and lower crustal rocks could lead to formation of a network with aligned, interconnected fluid-filled cracks (Tullis et al., 1996).

Thus, the mechanism of crustal ULF magnetic activity in the presence of high pressure fluids could also be invoked by an electrokinetic effect similarly to the Koyna-Warna region (Dudkin et al., 2010). However, the alternative source mechanisms, for example inductive or piezomagnetic effects, should also be taken into account.

5 Conclusions

A new direction-finding method for the study of ULF lithospheric magnetic activity using two or more spaced 3-component magnetometers was successfully tested for the procedure of so-called “blind search” in lack of a priori information about space-time coordinates of magnetic sources. This provides the possibility for separation of the lithospheric and the ionospheric/magnetospheric sources and the localization of areas with maximum magnetic activity. Such an approach can be used at operation conditions close to a real-time detection of pre-EQ lithospheric magnetic activity.

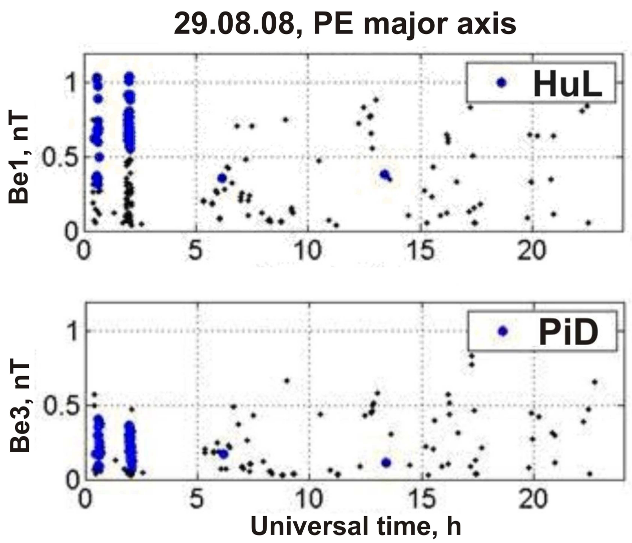


Fig. 12. PE major axis values in point HuL (Be1) and PiD (Be3) on August 29. Blue points are the signals of lithospheric and black points are those of ionospheric/magnetospheric origin. The compactness of lithosperic signals and almost uniform appearance in time of the ionospheric/magnetospheric signals should be noted.

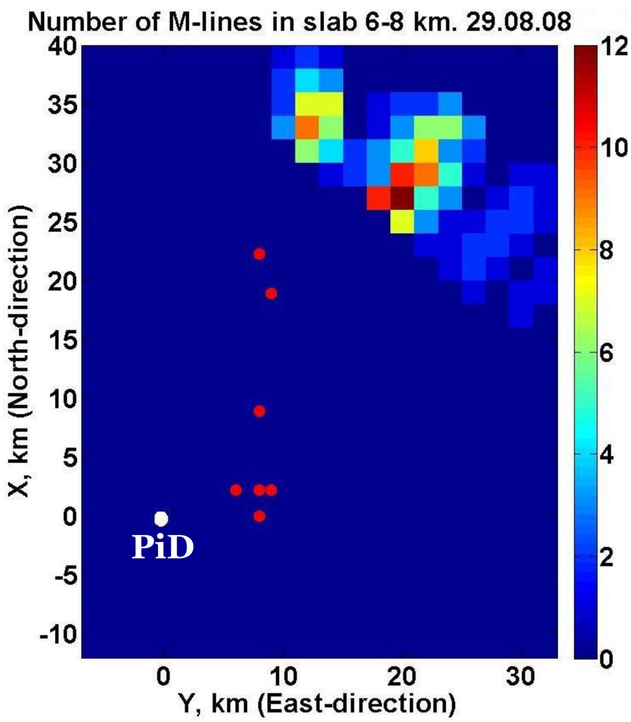


Fig. 13. Spatial distribution of crustal magnetically active blocks in the depth range of 6–8 km on 29 August. Red dots relate to the EQ epicentres on 30–31 August.

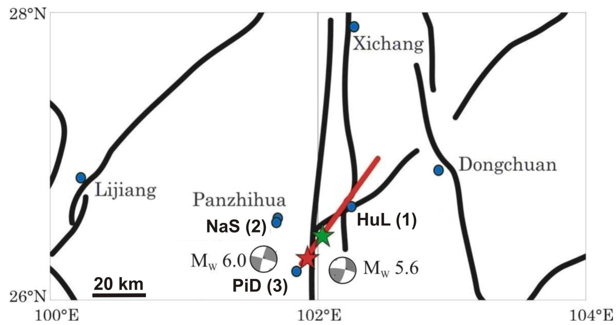


Fig. 14. Faults map of Sichuan seismoactive region and detailed view of the monitored area. The red line represents the maximum of M-lines azimuth angle distribution in the crust on 29 August 2008. The area of pre-EQ magnetic activity maximum is marked by a green star and the EQ $M_W = 6.0$ epicentre is marked by a red star. Populated places are denoted by blue circles. The fault plane solutions for $M_W = 6.0$ EQ and main $M_W = 5.6$ aftershock are also shown.

The method was applied to magnetic field data in the ULF range obtained from fluxgate magnetometers located in three spaced measuring sites in a region of active tectonics (Sichuan province, China).

Using this method, the ULF pre-EQ crustal magnetic activity before $M_W = 6.0$ EQ on 30 August 2008 (8:30:52 UT, 26.28 N, 101.92 E, h = 10 km, Sichuan, China) was reliably detected and localized.

Magnetic precursors were detected about 30–32 h before the main shock in frequency band of 0.002–0.016 Hz. The maximum of pre-EQ magnetic activity was found in the area of about 10 km^3 with a length of 10 km and in the depth range of 6–8 km at a distance about 20 km from the main shock epicentre. The M-lines orientation, i.e. the magnetic dipoles moment direction, is in close agreement with the local fault direction and the fault plane solution for the main shock $M_W = 6.0$ and the strongest aftershock $M_W = 5.6$.

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