Earthquake electromagnetic precursor anomalies detected by a new ground−based observation network

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Abstract: It is a debated topic if there is any observable precursor anomalies prior to earthquake (EQ hereafter) and if the stronger EQ can be successfully predicted. During the last decades quite a lot of observable electromagnetic (EM) precursors were published by using a techniques equipped in either satellites or on ground-based stations. But there are only a few cases that the short-term precursor anomalies of EM field before earthquakes were observed by using alternate EM fields on ground. This paper will present a new EM observation network built in recent years and show a new finding of EM field with the variation of a one-year cycle observed using the network. As an example, the short-term precursor anomalies of apparent resistivity before the Yangbi EQ (Ms=5.1) occurred on March 17, 2017 in Yunnan province will be studied. The observed anomalous phenomena indicate that the anomaly before the EQ can be captured only if a reasonably effective method is used, and it is believed that continuously observed data on the fixed observation network for long time is a effective means for studying anomalies that appeared before earthquakes. This network can also play an important role in studying the EM environment from space.

Key words: Electromagnetic observation network; natural EM phenomena; precursor anomaly; apparent resistivity; space EM environment

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1 INTRODUCTION

Earthquake is one of most severe natural disasters. More than half of lives lost are caused by earthquakes among natural disasters in the world. EQ also causes huge economic losses, e.g., about 800 billion RMB were lost during the Wenchuan EQ (Mw=7.8, 2008) [1]. Therefore, the governments and scientists of many countries especially those countries with frequent earthquake have paid great attention on the study of EQ prediction. It was in the 1960s that the study on the EQ prediction was started and national projects for EQ prediction were designed in several countries e.g., China, Japan, USSR and USA [2-3].

As well known, the EQ prediction is an extremely difficult scientific problem in the world [4]. Nevertheless, some progress on the EQ prediction has been made especially when the EM methods are used [5-19]. Earthquake prediction could be classified into the three categories: long-term, intermediate-term (a few years to hundred years prior to EQ for both above) and short-term prediction (hours, days and weeks or months prior to EQ) [6]. Both the long-term and intermediate-term EQ predictions are mainly based on the geological studies of faults, historical records of seismicity and recent observed data of seismology and geodesy [20].The short-term prediction is the most effective for reduction of economic losses and saving lives, but it is much more difficult due to that it needs to estimate the occurrence time, place and magnitude of an EQ in advance. Unfortunately, except few EQ, e.g., the Haicheng Ms=7.3 earthquake on February 4 of 1975, most strong earthquakes have not been predicted [2]. Therefore some governments and scientists regarded EQs unpredictable.

Fortunately, a large number of scientists still persist in studying the short-term prediction and have observed quite a lot of anomalous phenomena before EQ by using EM methods. For instance, the anomalous increase of the crustal conductivity was up to 60% before San Fernando EQ (Ms=6.4) on February 9, 1971 [5] by magnetotelluric observation. Anomalous current changes were observed before EQs with magnitude bigger than Ms3.0 occurred in Kozu-shima Island from May 14, 1997 to June 25, 2000 [11]. The anomalous increases of magnetic field in ULF frequency band were observed a few days before Spitak EQ (Ms=6.9) in Armenia on December 8, 1988 and before Loma Prieta EQ (Ms=7.1) in south California on October 17, 1989, respectively, and the abrupt increase appeared in a few hours before two EQs [21]. The epicenter distances of these two earthquakes are 128km and 7km from the observation sites. Many anomalies of EM field of various fre-

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quency bands as HF/VHF and VLF/LF, plasma density, TEC, powerful particle and the particle temperature etc. caused by the EQs were observed using the devices in satellite and on ground-based sites [6].

More and more scientists recognize that there indeed exist the short-term precursors before EQs [22], which could be observed especially when the EM method is used. To accumulate sufficient number of reliable observed cases about precursors prior to EQs is the only and important way for study on modeling the generation mechanism of precursors and on the probability of EQ occurrence using observed precursors. This study is an effort in this direction and uses a new EM observation network to detect the short-term anomaly precursor before EQs in order to collecting more examples. The network can be used in detecting either resistivity anomalies of the crust or EM field anomalies of earthquakes and used in observation of either natural EM source or artificial EM source [19]. The following will mainly be on the observation using natural signals.

2 THE NEW BUILT OBSERVATION NETWORK

The first EM observation network, consisting of 30 stations, has been built recently under the support of the National Development and Reform Commission of China, the network covers the Beijing Capital Area (BCA) and southern section of North South Seismic Belt (NSSB) in China as illustrated in Fig.1.

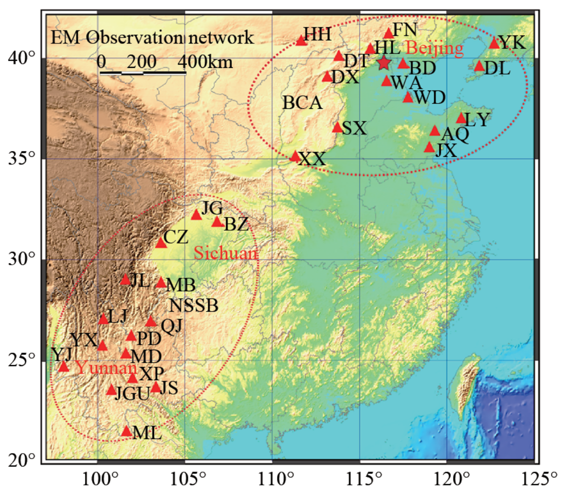

Fig. 1 The station distribution of EM observation network. Red triangles indicates stations. The 15 stations are located in BCA and other 15 stations are distributed over NSSB. Abbreviation symbols nearby stations show station names, e.g. Dali station is named as YX (Yuexi, a small town).

The network is designed to record the natural electromagnetic signal from 1000 Hz to 1000s. The five electromagnetic components Ex (NS electric field), Ey (EW electric field), Hx (NS magnetic field), Hy (EW magnetic field) , and Hz(vertical magnetic field) are measured at each station of the network.

The measurement device is the improved ADU-07 produced by Metronix in Germany. The induction coil - sensor - is used in measuring the magnetic field. The sensor is put in an underground cellar 2 m deep with guarantying their precision of the azimuth and horizon. Two orthogonal horizontal electric fields are measured using electrodes connected to the device. The space of two electrodes in each direction (NS, EW) is in between 50—100 m. Each electrode is served by both of un-polarized Pb-PbCl and lead plate. In the first few years, un-polarized Pb-PbCl electrodes were used and then the leads plates are used. The electrodes are buried at more than 2 m depth, some at the depth of about 10m in order to keep same level of two electrodes in one azimuth.

The artificial EM signals are recorded in every morning and evening, respectively by each station of the network. The natural EM signals are recorded with three samples. The lower sample rate (16 Hz) is used for recording data of all time. The recorded data are amounted up to 200 MB per day and stored in the server equipped at each station. The data are transmitted to the servers in each corresponding Province Bureau Center and then to the China Earthquake Network Center (CENC) in Beijing in real time or quasi-real time.

A special Computing Center that is built in the Institute of Geology, China Earthquake Administration (IGCEA) in Beijing has 6 servers, which serves for monitoring, transmission and storage, processing and anomaly analysis for all recorded data by all stations (Fig.2).

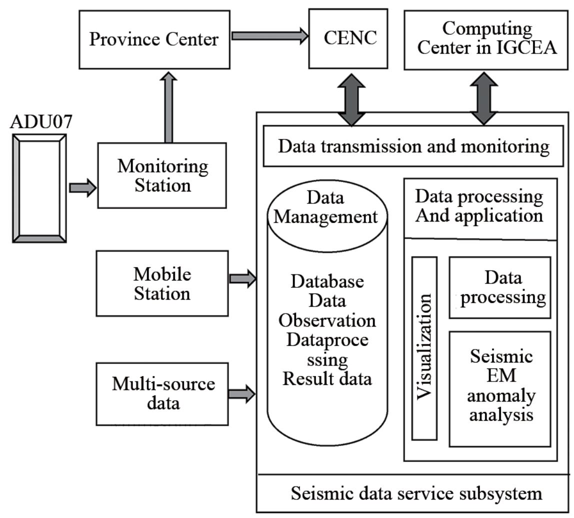

Fig.2 The architecture of the network in Institute of Geology, CEA (IGCEA), which is composed of data monitoring, data transmition/storage and anomaly processing / analysis

3 Typical electromagnetic phenomena

The original time series and spectrum of each of the five EM components, impedance tensor, apparent resistivity and impedance phase etc. will be used for the detection of EM field anomalies related to EQs and also used for studying EM environment in space. The impedance tensor elements, Zxx,Zxy,ZyxandZyy are estimated by using the spectra of horizontal electromagnetic field components (Ex, Ey, Hx and Hy) according to following formulas.

$$Ex = ZxxHx + ZxyHy \tag{1}$$

$$Ey = ZyxHx + ZyyHy \tag{2}$$

The apparent resistivity ρ_{ij} and impedance phase $\phi ij$are calculated by using impedance tensor elements Zij.

$$\rho_{ij} = \frac{1}{\omega\mu}\left|Z_{ij}\right|^2 \tag{3}$$

$$\phi_{xy} = \mathrm{Arctan}(Z_{ij}) \tag{4}$$

where subscript ij indicates NS (xy) and EW (yx) polarization for the apparent resistivity and phase, respectively, additionally ω indicates angular frequency and μ indicates permeability.

The data pre-processing is firstly conducted in the station and further processing and analysis are performed in the Computing Center. Some typical natural EM phenomena are recorded at stations during the last years since the network was built. Fig.3 shows a characterized periodical variation of spectra of EM components in frequency domain at Fengning (FN) station. The spectra with period of one year were firstly found and are different from traditional cognition on basic geomagnetic field with period of half year [23]. The maximum value appears in the summer solstice and minimum in the winter solstice.

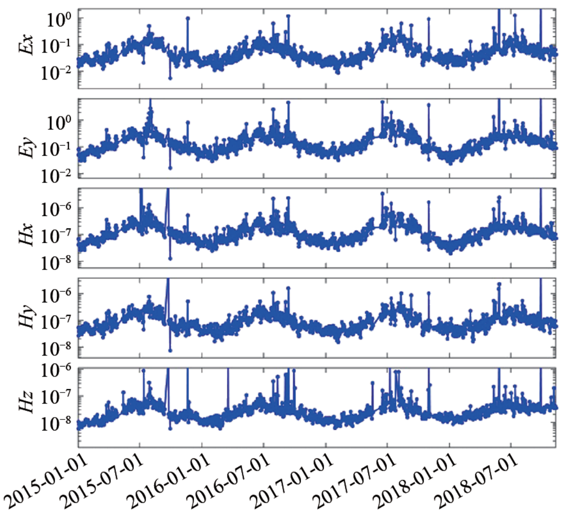

Fig.3 The spectra of five electromagnetic field components (*Ex*, *Ey*, *Hx*, *Hy* and *Hz* from top to bottom) at Fengning (FN) station. The horizontal axis shows recording time from July 1, 2014 to January 1, 2018

In addition, the magnetic storm, Schumann resonance and co-seismic wave EM field are well recorded at network stations, which are not only used in the study on the back-ground EM field and but also can be used in the study of anomalies related to earthquakes.

4 EXAMPLES OF ANOMALOUS RESISTIVITY BEFORE THE YANGBI EARTHQUAKES

The anomalies in the original time series, spectra of recorded electromagnetic fields and/or apparent resistivity before EQ are weak in general. To detect the anomalies in the data needs understanding the characteristical back-ground field of each EM component and evaluating the quality of the recoded data for long time e.g. several years. In addition, the observed data often contains noise caused by the culture disturbance. Recognizing the anomalies possibly related to earthquake must understand the character of the normal background of data and noise, and then be able to differentiate between them. Therefore it is necessary to examine huge amount data recorded for long time. The advantage of the observation network is that it can provide us with an opportunity to analyze a great amount of data. The most important work in recognizing and catching the anomalies related to earthquake is to select the normal data observed without being influenced by culture noise. That is, the recognized anomalies must be discovered from the normal observed data without noise. Then we further analyze the EQ events occurring within the corresponding period and finally examine if there is any relationship between the anomalies and the events.

Fig. 4 shows four steps for studying anomalies before EQs. The first step is to use and analyze huge amount of the observed data, then the second step is to carefully choose the quality data (reflecting normal background field data) from huge amount of the data with rejecting the data that has been interfered. After that a top-down level analysis is carried out for identifying and capturing anomalies in the data for time domain and frequency domains. The last step is to investigate the relationship between anomalies and earthquake events. With this analysis approach, the real examples about the precursor anomalies before several stronger EQs (>Ms 4.4) occurred near the network stations during last several years using continuously observed data are obtained.

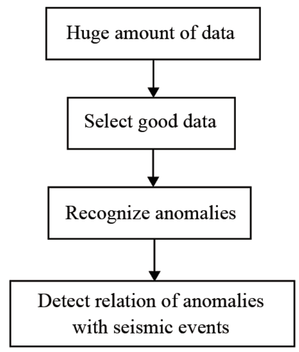

Fig.4 The strategy used in analysis of EM anomaly precursor before shock

As an example, we present the precursor of apparent resistivity prior to Yangbi EQ (M=5.1). This earthquake occurred on March 27, 2017 near Dali city in Yunnan province. The epicentre depth is about 12 km, which was located in the west of Nanjianweishan fault in big Honghe fault belt and the earthquake mechanism solution is dextral strike-slip [24]. Dali station (YX) is the nearest station to the epicenter with 32 km distance and locates to the east of the Nanjianweishan fault (Fig.5).

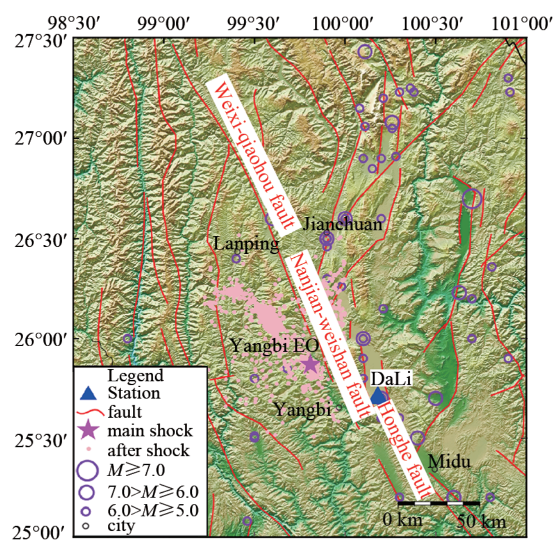

Fig.5 The location of Yangbi EQ (pentagram) and Dali station (YX, triangle)

Based on the apparent resistivity and phase curves of every day of a few years before and after the Yangbi earthquake, it is found that the quality data appear in between frequencies of 100Hz and

1 Hz. Thus only those data within this frequency band are used for anomaly analysis. On the other hand, the temporal variation of apparent resistivity and phase from July of 2015 to July of 2017 are stable without stronger noise caused by disturbance. The error of apparent resistivity during this period of time is generally less than 5% which is belonging to excellent data for MT measurement. It can be seen from the data that anomalies appeared before the Yangbi earthquake at Dali station (*YX*) (Fig. 6(a)).

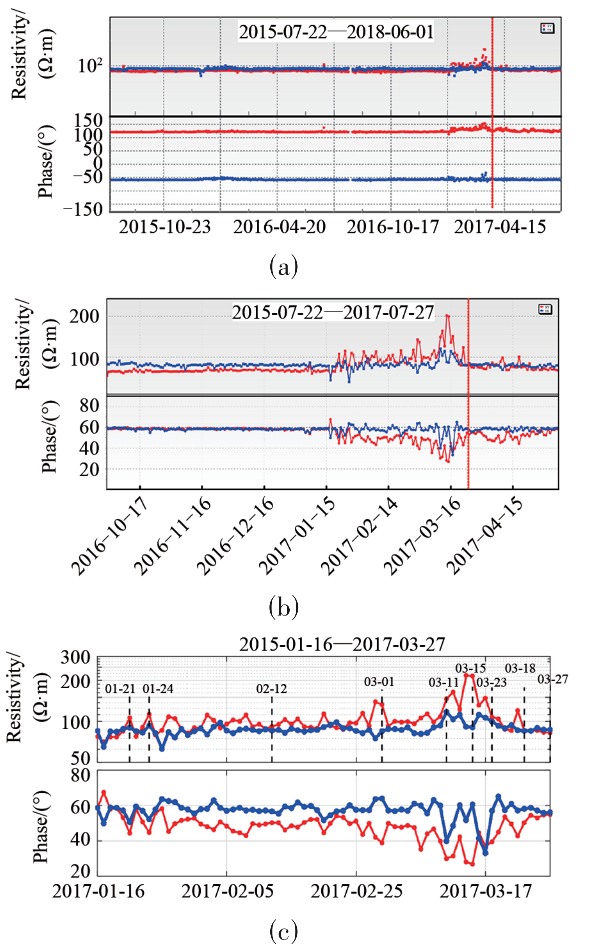

Fig.6 (a) The temporal variation of both polarizations of apparent resistivity ρ_{xy} (red) and ρ_{yx} (blue) in upper panel and phase φ_{xy} (red) and φ_{yx} (blue) in bottom panel from July 30 of 2015 to June 1 of 2017 for 74Hz (about 2 years) at Dali (YX) station. (b) The temporal variation of them from October 1 of 2016 to April 30 of 2017. (c) The temporal variation of them from January 16, to March 27of 2017 (shock day). The dashed lines show onset of anomalous variation of the resistivity and phase before Yangbi EQ. The red vertical lines in (a) and (b) indicate the shock day.

By enlarging the amplitude of the apparent resistivity and phase curves in Fig. 6(a) the anomalies in the curves are clearly seen (Fig.6(b)). Both polarizations of apparent resistivity ρ_{xy}(red) and ρ_{yx} (blue) started to gradually increase in pulse type from January 16 of 2017 (about 10 weeks before EQ). They reached the maximum and then rapidly decreased to the back-ground values. In order to see the details of apparent resistivity variation the section of time axes covering the time period of anomaly occurrence is amplified (Fig. 6(c)).

Both of polarizations of apparent resistivity ρ_{xy}(red) and ρ_{yx} (blue) reached the maximum is on March 15 of 2017 (12 days before the EQ). They returnd to the back-ground value on March 23—24 of 2017 (3-4 days before EQ). From the pictures it can be seen that the variation amplitude of anomalous ρ_{xy} is bigger than that for ρ_{yx}. For the ρ_{xy} the values of single pulses of anomalous resistivity are generally 30—80% bigger than the back-ground value. The maximum value is about 130% larger than the back-ground value. Correspondingly, both impedance phase φ_{xy} and φ_{yx} firstly gradually decreased and recovered to the back-ground value after they reached the minimum value. The variation amplitude of anomalous impedance phase φ_{xy} is larger than that for φ_{yx}.

There are similar anomalous changes in apparent resistivity before some other earthquakes, for instance the Jinggu earthquake (Ms=5.9) occurred in Jinggu county in Yunnan province on December 6, 2014. According to the variation features of apparent resistivity before the earthquakes we made an experimental forecasting for Pingyi earthquake (M=3.1) occurred in Shandong province on April 11, 2018, which is near the big seismically active fault belt, Tanlu fault belt. Before this earthquake both of polarizations of apparent resistivity synchronously changed at two stations Anqiu (AQ) and Juxian (JX) located near Tanlu fault belt in Shandong province. On March 29, 2018 the formal forecasting for this earthquake was made in a meeting of CEA. The epicenter distances from these two stations are about 150 km and 100km, respectively. The apparent resistivity started increase on December 15, 2017 and reached to the maximum on March 10, 2018 and then decreased. The Pingyi earthquake occurred in the decreasing process of the apparent resistivity.

5 DISCUSSION ON GENERATION MECHANISM OF THE ANOMALIES

In addition to the apparent resistivity anomaly some other anomaly phenomena, e.g., electrical current, the original time series and spectrum of electromagnetic field and so on before earthquakes are found [6—8, 14, 19—20]. The anomalies from both resistivity and current are representative of the change of electric conductivity of earth crust under surface in the earthquake generation process. The anomaly in time series and spectrum is considered as EM anomaly emitted from the foci and can be measured on surface or in the atmosphere during the earthquake generation process.

Regarding the generation mechanism of electromagnetic anomalies there are the some assumptions proposed. A popular idea is that the earthquakes often occur in the region near or along existing fault or hidden fault [5]. The rock porosity could be changed in the earthquake generation process and as a consequence the fluid or water existed in the crack or pore space could be also changed. Therefore the rock conductivity could be changed. The conductivity increased when the fluid was getting rich and connectivity enhanced. On the contrary the conductivity decreased [25-26]. Due to most of faults are bending fault[22], the relative movement between two plates of fault is not stable leading the instable change of porosity and thus the unstable change of fluid in the crack. Therefore the rock resistivity or conductivity varies unstably, i.e., it sometime increased and sometime decreased like as change in pulse type. Besides, electro-kinematic effect can also be used in interpretation on the conductivity change [27]. Friction electricity, piezoelectric [26] and earthquake-ionosphere coupling effect [2] may also lead the variation of electromagnetic field.

The Yangbi EQ occurred near the big Honghe fault belt where many faults with different sizes are developed [28]. The foci of the Yangbi earthquake located near the faults which is a conductive boundary between high and low resistivity blocks in the crust according to MT observation [29]. The fluid or water are assumed to exist in the crack or pore space in the faults. During the earthquake generation process the unsmooth relative movement between two plates in both sides of the bending faults may produce the electrokinematic effect, friction and/or squeezing movement of the faults etc. This kind of unsmooth deformation of the faults could cause the unstable movement of the fluids in the crack. Thus the crustal resistivity may unstably change like as change of resistivity in pulse type appeared before the Yangbi earthquake.

6 CONCLUSION

The study on the space electromagnetic environment and resistivity anomalies before the earthquake using new built EM observation network has revealed that the network is an important means and has potential wide application value.

The network has the continuous measurement of five components of EM fields at each station in alternate frequency band. It is different from previous stations only used in measuring DC resistivity or basic geomagnetic field for study either on monitoring seismic anomalies or on the EM environment.

An analysis method for detection of the anomaly is proposed. The quality long-term observation data is an essential condition for confirmation of the anomalies related to earthquake or to other natural disasters. Detection of the credible anomalies from the huge amount of the data is a key step.

It is found that the electromagnetic field in alternate frequency band has a period of one year which is different from traditional cognition on basic geomagnetic field with the period of half year. It is postulated that the former represents the regulation of variation of alternate EM field and the latter represents the active degree of the basic geomagnetic field.

The anomalous resistivity before the Yangbi EQ (Ms=5.1) is detected which started to gradually increase in pulse type on about 10 weeks and reached to the maximum on about 10 days and then recovered to the background value in a few days before earthquake. This anomalous phenomena has a typical meaning for study on the resistivity anomaly before the stronger earthquake using the data observed at station with dozens km distance to the epicenter.

To study the regularity of the anomaly appeared prior to the earthquake and the generation mechanism of anomaly needs to obtain more practical examples. To make a breakthrough in the earthquake prediction the stereoscopic monitoring on earth surface and in the space and comprehensive analysis on the EM data with other geophysical data is necessary. The authors are working towards this direction.

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