Fracture Electric Field: A Synthetic Model for Seismogenic Process and its Relationship with Preseismic Electric Anomalies and Earthquakes

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Abstract

Unobservability of the seismogenic process in a causative fault that makes earthquake (EQ) prediction difficult. Although the relationship between the preseismic electric anomaly (PSEA) and the mainshock indicates that both the PSEA and EQ may originate from same course proceeding in the seismogenic zone, as evidenced by experiments on stressed granite, geological interpretation of those observations, and experiments was limited by the traditional granite formation theory. Based on new information from studies of granite genesis and geotransects, we present a synthetic model, the fracture electric field (FEF), to elucidate the seismogenic process on a causative fault and its logical linkage with the PSEA and EQ. The model is constrained with various data from the 1975 Haicheng EQ and verified by survey data from an FEF monitor station constructed in 2012 in Guangzhou, China. The main conclusions are as follows:

(1) An uneven or undulant fault-plane is the prerequisite for stress-accumulation in the locality of the plane to form a seismogenic zone;

(2) The position of the continental seismic layer corresponds to that of the crustal granite layer, suggesting that the seismogenic process of any causative fault in continents may produce the PSEA;

(3) A normal FEF exists in a causative fault and can be measured beyond the preseismic situation. Thus, it is possible to detect the seismogenic process of a fracture through monitoring the variation of its FEF when the fracture enters a preseismic situation.

Introduction

A structural earthquake (EQ) involves the sudden release of energy stored in fractures in the seismogenic zone that is unknowable prior to the EQ. Some seismic precursors may carry information on the processes occurring in the seismogenic zone (Watts and Burov 2003; Hayakawa 2012; Petraki et al. 2015; Ouzounov et al. 2018), and among them, the preseismic electric anomaly (PSEA) has attracted the attention of geoscientists because it suggests a link between the EQ occurrence and the observed electromagnetic (EM) signals (Gaffet et al. 2003; Varotsos et al. 2003; Vallianatos et al. 2004; Freund et al. 2006; Haines and Pride 2006; Konstantaras et al. 2008; Ren et al. 2012; Sevgi 2014; Gao et al. 2015; Petraki et al. 2015; Hayakawa 2018; Shebalin 2018; Wang et al. 2018). The formation mechanism of the PSEA was illustrated by 1) the streaming potential (Morrison et al. 1979; Merzer and Klemperer 1997; Bernabé 1998; Jouniaux et al. 2000), 2) piezoelectricity (Bishop 1981; Sadovskii 1986; Chen et al. 1999; Ogawa and Utada 2000; Gershenzon and Bambakidis 2001), and 3) the combination of electrons and holes acting as a battery when certain rocks are under stress (Freund 2000; 2007a; b). Those physical explanations were well constrained by experiments or simulations but weakly supported by geology. For example, both the piezoelectricity and electron-hole battery mechanisms are mainly based on experiments of granite producing electric charges when stressed (Bishop 1981; Sadovskii 1986; Chen et al. 1999; Ogawa and Utada 2000; Gershenzon and Bambakidis 2001; Freund 2000; 2007a; b). In geology, granite is an intrusive igneous rock, and granite bodies are distributed irregularly within the crust.
This means that a causative fault is not necessary to cut the granite to produce the PSEA current. This also prevents the concordance of the geologic models with PSEA observations.

By re-examining published PSEA data of some well-studied EQs in China and Japan and by combining studies on ‘rock-battery’ (Freund 2000; 2007a; b), the crustal granite layer (Chen et al. 2003; Chen and Grapes 2007; Chen et al. 2017c), geotransects (Kuznetsov et al. 2008; Migursky et al. 2008; Yefimov et al. 2008; Ma 2009), and focal mechanism solutions (e.g. Sandu and Zaicenco 2009), we developed a synthetic model referred to as fracture electric field (FEF) to explain the seismogenic process in a geological fault and the correlation between the process and both the PSEA and the following EQ.

Observation And Experimental Investigation Of PSEAs

PSEAs of some known EQs

PSEAs are characterised by a dramatic increase in the ground current prior to the EQ, which can be detected by instruments on the ground. Telluric current surveys in China began in the 1960–1970s. The survey lines were usually aligned in the N–S and E–W directions, or perpendicular/parallel to the local structural trend (each line with two electrodes buried in soil or sediments), and the potential difference (PD) of the two electrodes in each line was measured (Chou et al. 2008). PSEAs related to some known EQs in China have been well documented: 1976 Yanyuan EQ (27.48°N,101.08°E; Ms 6.7), 1976 Tangshan EQ (39.6°N, 118.2°E; Ms 7.8), 1975 Haicheng EQ (40.39°N, 122.48°E; Ms 7.3), 1976 Longling EQ (98.6°E, 22.35°N; Ms 7.4), 2000 Xinghai EQ (35.4°N, 99.53°E; Ms 6.6), 2001 Western Kunlun Pass (WKP) EQ (36.2°N, 90.9°E; Ms 8.1), 2008 Wenchuan EQ (31.01°N, 103.42°E; Ms 8.0), and 2010 Yushu EQ (33.1°N; 96.7°E; Ms 7.1) (Zhu and Wu 1982; Chou et al. 2008; Fan et al. 2014). The PSEA diagrams in Fig. 1a–f corresponding to different EQs in China indicate that PSEAs appear several weeks or even months before the mainshocks, and rapidly decrease or disappear with the mainshocks.

Figure 1g shows the PSEA of the Ms 6.6 EQ that took place in Japan on 7 February 1993 (Uyeda et al. 2000). The PSEA starts in the middle of December 1992, is maintained for nearly two months, and returns to normal on 7 February 1993 with the onset of the Ms 6.6 mainshock. Although there are some transient fluctuations with an unclear cause, the PSEA diagram displays similar features to those in Fig. 1a–f.

Formation mechanism of PSEA— experimental investigation

Due to the long-lived (i.e., several weeks or months) characteristics of PSEAs, it is difficult for the rock-rupturing mechanism, which may be responsible for the co-seismic EM phenomena (Wu et al. 2007), to explain the formation of PSEAs. It is also difficult for the streaming potential mechanism to explain the formation of PSEAs because in this mechanism, the moving fluid is commonly considered to be driven by fracturing or EQ waves (Chou et al. 2008; Ren et al. 2015). Considering that the energy released by a structural EQ is accumulated before the EQ, the PSEA may correspond to the process of stress-
accumulation in a causative fault. Such an inference has been experimentally demonstrated by many authors (Finkelstein and Powell 1970; Finkelstein et al. 1973; Scholz et al. 1973; Nitsan 1977; Bishop 1981; Sobolev et al. 1982; Wang and Wang 1985; Wu et al. 1990; Sasaoka et al. 1998; Teisseyre 2002; Hadjicontis et al. 2004; Yoshida and Ogawa 2004). Figure 2a shows the experiment by Freund and colleagues who applied stress to one side of a 120 cm × 15 cm × 10 cm granite slab and measured the generated currents using the electric circuit (Freund et al. 2006; Freund 2007a; b). The experimental result indicates that the electrons (e\(^-\)) flow out of the stressed side while the positive holes (h\(^+\)) flow through the rock to another side by functioning as a semiconductor. The electrons and the holes meet at the unstressed side through the outer circuit, constituting a ‘rock-battery’.

The mechanical-electrical relationship revealed by the experiment indicates that the current increases with increasing stress and decreases rapidly in the absence of stress, as shown in Fig. 2b.

To apply the experimental results for explaining the EM precursors of EQs, Freund (2007b) designed a model in which the lithosphere is divided into two parts: The upper part is the sialic (the upper-middle) crust with a thickness of 30 km and the lower is the mafic crust and upper mantle. Electrically, the sialic upper part is assumed as p-type conductive while the mafic lower part as n-type, and the contact of the two parts is presumed as the p-n junction where the temperature is around 600 °C. When the structural force acts on the upper part, it activates the holes in the ‘source’ area and the holes flow within the rocks. Meanwhile, the electrons are activated in the lower part due to the loading and expanding of the upper part. The electrons and p-holes meet at the p-n junction to close the battery circuit (Fig. 2c). This model has been broadly used to account for the preseismic EM phenomena (Freund et al. 2006; Uyeda 2013; Helman 2014; Sevgi 2014), however, it can be questioned as follows:

1. In the rocks consisting of the sialic upper-middle crust, only granite (sensu lato) produces an electric current (electrons and holes) when stressed. If there is no granite (which is considered intrusive) in the source (S) area, no hole current can be activated to flow in the sialic crust (Fig. 2c).

2. The model in Fig. 2c only describes the possible cause of the observed EM signals, without concerning the EQ. Therefore, even though a strong EM disturbance is detected, we cannot use it to predict EQs because there is no logical linkage between the EM and the EQ in the model.

Model of FEF and its relationship to PSEA and EQ

By integrating the geophysical observations on the PSEAs (Fig. 1), experimental investigations on the stressed granite (Fig. 2), geological studies on granite formation and distribution (Fig. 3), and seismological studies on the focal mechanism solutions (Gu et al. 1976; Ekström and England 1989; Sipkin 1994; Sandu and Zaicenco 2009; Zeng et al. 2013; Dologlou 2014; Mohamed et al. 2015), we present a synthetic model to explain the seismogenic process of a causative fault and the correlation
between the process and the geophysical phenomena observed on the ground surface, i.e., the PSEAs and the EQs.

**Geological support from studies on granite genesis and geotransects**

Though Freund and his colleagues have experimentally revealed the mechanical–electrical relationship within stressed granite and conspicuously elucidated its physical basis from electrochemistry (Freund et al. 2006; Freund 2007a; b)(Fig. 2, applying these understandings to the natural process—i.e., to explain the relationship between the PSEA and the EQ as shown in Fig. 1—is complicated by the traditional geological theory that supposes the sialic upper-middle crust to be made up of metasedimentary rocks with intrusive granite (sensu lato). Compared to other rocks, granite possesses numerous quartz crystals and, thus, can produces electrons and holes when stressed, as proved by Freund’s experiments (Fig. 2). Other rock types, either without quartz (such as carbonatite), or with a random arrangement of quartz grains (such as quartz-bearing sedimentary rocks and some metamorphic rocks) typically show weak electric effects (Nitsan 1977; Sobolev et al. 1982; Wang and Wang 1985; Sasaoka et al. 1998; Teisseyre 2002; Hadjicontis et al. 2004; Yoshida and Ogawa 2004; Freund et al. 2006). This means that if the generation of a PSEA is due to stress on rock in the seismogenic zone, the rock should be granite (Finkelstein et al. 1973; Sadovskii 1986; Wu et al. 1990; Sasaoka et al. 1998). However, granite bodies are distributed separately within the upper-middle crust (Wickham 1987; Brown et al. 1995; Vanderhaeghe 2001; Sawyer et al. 2011; Clemens 2012). We have no reason to believe that an intrusive granite body existed in the seismogenic zone and was cut through by the causative fault, thus generating the PSEA. Even where an EQ and its causative fault occur in a granitic basement, the assumption that the PSEA is caused by stressed granite at the seismogenic fracture zone cannot be established because the granite batholith is commonly estimated as being only several kilometres thick (Petford et al. 2000; Clemens 2012); however, the majority of continental EQs occur at depths between 5 km and 25 km (Ito 1990; 1999) where the existence of granitic rocks has not been investigated.

In the last two decades, advances in the theoretical study of granite genesis (Chen et al. 2003; Chen and Grapes 2007; Chen et al. 2017a; Chen et al. 2017c), and geophysical–geological investigations of geotransects in some terranes (Kuznetsov et al. 2008; Migursky et al. 2008; Yefimov et al. 2008; Ma 2009), have revealed that granite within the crust is layered and situated between the metasedimentary roof and the mafic lower crust (Fig. 3). This means that causative faults in the continents, at least in some crustal terranes as revealed by the geotransect in Fig. 3, cut though the granite layer and that stress-accumulation in the fracture seismogenic zone may produce the PSEAs observed on the Earth’s surface.

**Accumulation and release of stress on a causative fault**

A structural EQ involves the release of energy accumulated in the seismogenic fracture zone that is known as the seismic source when the EQ occurs, as indicated by focal mechanism solutions (e.g. Gu et al. 1976; Sandu and Zaicenco 2009; Zeng et al. 2013; Dologlou 2014; Mohamed et al. 2015). If a fault-
plane is flat and smooth, it should be difficult to accumulate stress in a local place of the plane. This means that a rough or undulant fault-plane should be responsible for generation of a seismogenic zone when slipping occurs along the fault-plane. Apart from the strike-slip fault, the hanging wall of a fault moves either downwards or upwards in a 2D section (Fig. 4). Figure 4a1 and b1 show the undulant fault-planes where the \( m \) point is located at the upwarp of the footwall, and the \( n \) points at the different downwarps of the hanging wall, respectively. When a fault is in a stable state, stress should be homogenously distributed on the fault-plane (Fig. 4a1, b1). If the hanging fault-block slips over the fault-plane as a normal fault (Fig. 4a2) or as a reverse fault (Fig. 4b2), point \( n \) gradually moves from position \( n_0 \) to \( n_1 \) to approach point \( m \) in the footwall. Meanwhile, stress around the obstruction node progressively increases with the reducing contact area between two walls due to \( n \) and \( m \) bulging in opposite directions (Fig. 4a2, b2). While the slipping fault-block is held up by the obstruction node, stress increases to the maximum value and the major pressure stress axis is perpendicular to the contact of the two bulges (Fig. 4a2, b2). As soon as point \( n \) slips over the obstruction node, the accumulated stress is quickly released, triggering the EQ (Fig. 4a3, b3). Currently, we can use the information from the seismograms to calculate the stress-field orientation and the slip direction in the EQ source (Ekström and England 1989; Sipkin 1994; Sandu and Zaicenco 2009; Mohamed et al. 2015).

The structural model in Fig. 4 illustrates the course from accumulation to release of localised stress on an undulant fault-plane during slipping of the hanging fault-block. The model is consistent with the geophysical observations shown in Fig. 1, i.e. the EQ denotes the release of stress, and the PSEA should be associated with the stress-accumulation in the EQ source (seismogenic zone).

The rapid dislocation on the fault-plane along with point \( n \) slipping over the obstruction node will likely produce a series of feather ruptures in the wall rocks (Fig. 4a3, b3), and those ruptures may be observed on the ground surface, i.e., seismic fissures or cracks (Fig. 6).

**Model of FEF and its relationship to PSEA and EQ**

In 3D space, the situation of a stress-field that governs the slipping direction of fault-block is much more complicated than that in the 2D section (Fig. 4), as indicated by studies on the focal mechanism (e.g. Gu et al. 1976; Sandu and Zaicenco 2009; Zeng et al. 2013; Dologlou 2014; Mohamed et al. 2015). Yet, the prerequisite of localised stress-accumulation on a fault-plane is the roughness or undulant shape of the plane, which determines the existence of the seismogenic zone. The slipping direction of the fault is mainly related with the stress-field orientation in the seismogenic region. Any causative fault with recorded EQ, regardless of the direction of the slip, must be with a rough or undulant fault-plane. As soon as the slipping fault-block is held by the obstruction node, a seismogenic zone around the node is formed. In order to highlight the correlation between the seismogenic zone and the PSEA, we ignored the quantitative details of stress-field and simply assumed that the slipping hanging wall has been held and at the moment the major pressure stress axis in the seismogenic zone is as that shown in Fig. 5a.

During the formation of the seismogenic zone, the increasing stress acted on the granitic wall rocks on two sides of the fault-plane in the zone activates electronic charge carriers, both electrons and holes (Freund 2000; 2007a). For the hanging wall, the holes activated by stress can flow through the granitic
rock along the stress gradient, and most likely concentrate on the top surface of the hanging fault-block opposite to the stressed region (seismogenic zone), producing the EM emissions as suggested by Freund (2007b). On account of the granitic rock rejecting electrons and allowing only the holes to pass, the electrons generated from the stressed granitic wall rocks in the seismogenic zone have to flow out of the stressed granite. Yet, as pointed out by Freund: *for electrons to also flow out, both the source and the unstressed rocks need to be in contact with an n-type material. In the laboratory, this contact is easily established ...by placing a Cu tape on the stressed rock.... In Nature, in a pre-earthquake situation where stresses build up deep in the crust, this closure of the battery circuit is not easily established* (Freund, 2007b, p. 3).

In our model (Fig. 5a), electrons from the stressed granitic wall rocks on two sides of fault-plane in the stressed region flow to the fracture zone that typically provides storage space for water. The water-bearing fracture zone acts as a wire, allowing the electrons to flow in the zone. Since action and reaction are equal and opposite, a pair of rock-batteries with poles oriented in opposite directions should simultaneously occur in the two walls of the fracture zone (Fig. 5a).

Electrons from the stressed region flow to the water-bearing fracture zone, and the wall rock of the fault-plane beyond the stressed region are presumed as intact granite with poor electrical conductivity, thus the electric charge from the seismogenic zone are trapped in the water-bearing fracture zone to form the FEF. The FEF acts as a wire with its upper part connecting the underground water layer of near-surface, so that the electric charges flow along the layer by the shortest way to meet the p-hole concentration on the top of granite in the hanging fault-block, closing the circuit of the upper battery (Fig. 5a). At the same time, the lower part of the FEF may connect the intra-crustal lower velocity (or high conductivity) zone that is widely distributed in the continental seismic belts such as the circumpacific and the tethyan belts (as summarised by Chen and Grapes 2007), or the p-n junction (around the 600 °C isotherm) suggested by Freund (2007b) (Fig. 2c), to close the circuit of the lower battery. The pair of rock-batteries and the outer circuit mentioned above can be demonstrated in principle by integrating two experimental circuits, as shown in Fig. 5b.

In the two rock-batteries, the lower battery and its outer circuit is unobservable and was not considered to be a concern. The current flow along the outer circuit of the battery in the hanging wall, however, can be observed on the ground surface during the pre-earthquake, i.e., the PSEA measured from soil or sediments (Figs. 1, 5a). Figure 5c schematically shows the relationship between the direction of P-axis and the shape of FEF with its outer circus.

When point \( n \) slips over the max resistance point, the accumulated stress around the obstruction node (seismogenic zone) will be quickly released, as evidenced by the EQ, and thus the PSEA rapidly decreases or disappears with the onset of the mainshock as indicated by the geophysical observations shown in Fig. 1 and the experimental investigations shown in Fig. 2b.
Geological, geo-electrical, and seismological constraints of FEF from the 1975 Haicheng EQ in NE China

Notwithstanding that the FEF model reasonably illustrates the seismogenic process of a causative fault in the deep crust and its logical linkage to both PSEA and EQ, it is necessary for the model to be constrained by the geological, geo-electrical, and seismological data related to a known EQ. The 1975 Haicheng EQ, in the Liaoning Province, NE China (Gu et al. 1976), was successfully forecasted 9 hours prior to the mainshock based on various seismic precursors (Adams 1976; Wang et al. 2006). This success, however, received insufficient appreciation from the scientific community because the formation mechanism of those precursors remained unclear.

The Haicheng EQ (Ms7.3) occurred on 4 Feb. 1975. The epicentre of the EQ was located at 122°48'E and 40°39'N with the focus depth around 16 km. The EQ was caused by a rupturing of the NW—NWW trending fracture, called the Xiuyan- Haicheng Fault (XHF). The southeast part of the XHF strikes NW 320° and the northwest part at around NWW 285°, and the fault dips to the southwest at 65°–80° (Fig. 6a) (Zhu and Wu 1982; Wan 2000; Wang et al. 2006).

Preseismic phenomena

Data from the telluric current survey in different positions record the variation of local geo-electric field, indicating that occurrence of the PSEA associated to the Haicheng EQ was more than one month prior to the mainshock. At position P1 (Fig. 6a), for instance, strong geo-electric variation was documented as beginning in Dec, 1974 (Zhu and Wu 1982). Figures 6b and 6c show the observation diagrams of the PSEA at position P102 where two sets of survey lines were aligned in the N–S and E–W directions by the geophysicists of the No.102 geological team, and observation in the position initiates on Jan. 8, 1975, i.e., four weeks prior to the mainshock. Diagrams of the N–S survey lines possess the typical feature of the PSEAs shown in Fig. 1, i.e., appearing weeks prior to the mainshock and disappearing or rapidly decreasing with the mainshock (Fig. 6b), whereas those of the E–W lines appear to not possess such features (Fig. 6c) (Chou et al. 2008). However, if exchanging the two electrodes of an E–W line, i.e. subtrahend and minuend to calculate the PD values, the PD diagrams of the E–W lines will turn over, showing similar characteristics to those in Fig. 6b.

All the survey positions with observable PSEA are distributed on the southern side (hanging wall) of the XHF. The long axis of western part of the PSEA region strikes around NW285° and the eastern part at around NW320°, totally parallel to the XHF (Fig. 6a). This means that the electric current of the PSEA was derived from the fracture zone (XHF), and that the p-hole concentration of the upper battery should be situated on the top of the hanging fault-block, as illustrated in Fig. 5a.

Co-seismic phenomena

Rapid dislocation of the causative fault during EQ commonly causes deformation of the ground, producing co-seismic cracks as shown in Fig. 4a3 and 4b3. In the Haicheng EQ, a series of co-seismic
fissures (with lengths < 100 m) and cracks (≥ 100 m) commonly with extensional characteristics were produced during the mainshock (Zhu and Wu 1982). The majority of the fissures and all the cracks are distributed on the hanging wall in the southern side of XHF. The cracks are predominantly around E–W (including NWW and NNE) trending, obliquely crossing the XHF (Fig. 6a). The characteristics of the EQ fissures and cracks, including the geometric shape, assembly feature, trending, and spatial distribution, indicate that dislocation of the XHF in the mainshock should be a normal fault as illustrated in Fig. 4a3 with left- lateral strike slip (Wang et al. 1976; Wang et al. 2006).

Post-seismic phenomena

From the mainshock to the end of 1975, 699 aftershocks (Ms ≥ 2) were recorded, in which, > 95% were with a foci-depth of < 15 km (Zhu and Wu 1982). Epicentres of the mainshock and most aftershocks are located on the hanging wall in the southern side of the XHF with a cluster orientation along the XHF. The I – I’ section in Fig. 6a, which is almost parallel to the XHF, displays the locations of the EQ focus projecting to the section (Fig. 6a). In consideration of the steep angle of the XHF (65°–80°), the I – I’ section can be regarded as the fault-plane where the location of the mainshock represents the preseismic stress-accumulation segment on the fault-plane, i.e., the seismogenic zone. In contrast, the aftershocks can be explained as originating from the hysteretic slipping of the hanging fault-block on the fault-plane after it passed the main obstruction node (seismogenic zone).

To summarise, the various geological, geo-electrical and seismological phenomena generated in the pre-, co-, and post-mainshock stages of the 1975 Haicheng EQ display a clear logical linkage in the FEF framework.

Survey And Verification Of FEF

As shown in Fig. 5a, the long axis of the rock-battery is parallel to the P-axis of the stress-field that is mainly associated with the slipping orientation of the fault-block (Fig. 4a2, 4b2), and the PSEA current mainly occurs in the area between the causative fault and the concentration of p-holes on the top of the granitic fault-block (Fig. 5a, 5c). When the telluric current survey points are arranged beyond the area, those survey points are unable to find the PSEA. Yet, if we directly measure the variation of FEF of the causative fault through a borehole, reliable information concerning the stress-accumulation in the fault can likely be obtained.

The FEF illustrated in Fig. 5a is in a preseismic situation, which is related to the PSEA, and characterised by the fracture zone as a ‘wire’ and the seismogenic zone as the ‘electric source’. Beyond the preseismic situation, the FEF is a normal field which is generated due to the pressure of the hanging fault-block. The characteristics of a normal FEF is without an evident ‘electric source’; in other words, the whole fault-plane with granitic rock on the two walls can be regarded as a ‘source’. Obviously, the PSEAs (Fig. 1) measured by burying the electrodes in soil or sediment cannot be used to track the ‘electric source’ for there is no logical linkage between the PSEA and the seismogenic zone. We suggest putting a public electrode (A)
into the FEF through the borehole as shown in Fig. 6, and the others (electrodes B and C) into the soil on the ground in different planar distances from the borehole, and then measuring the PD between the public electrode and the other electrodes (Fig. 7). In this way, the following monitor results can be expected:

1. PD graphs of the two channels should vary synchronously for both with a public pole (A) in the fault and an electric current from the same source;
2. The PD of channel A-B should be greater than that of channel A-C because the former has a longer distance than the latter.

Financially supported by the Guangzhou government in 2012, we designed and constructed an FEF monitor station on the Guang–Cong regional fault that extends through the Guangzhou City to test the FEF model. The monitor borehole was drilled into the fracture zone to a depth of 203 m, and electrode A was placed in the borehole at a depth of 200 m. Electrodes B and C were buried in soil at a depth of 2.5 m, and the planar distances from the borehole were 50 m for pole B and 6 m for pole C. Operation of the monitoring device commenced in December 2012 and recorded the PD values of the two channels every 10 seconds. To limit the length, Fig. 8 shows only the results for January of each of the first three years since 2013, which are in good agreement with the theoretical expectation described above: the PD value of the A-B channel is larger than that of A-C, and both change synchronously (Fig. 8).

The data shown in Fig. 8 demonstrate the existence of a normal FEF in the regional fault. This is significant for the EQ prediction because it implies a possibility of detecting the seismogenic process of the fault through monitoring the variation of the FEF if the fault enters the preseismic situation.

**Discussion And Conclusion**

Unknowability of the seismogenic zone prior to EQ and unobservability of stress-accumulation in the zone challenge EQ prediction. The PSEA, characterised by its appearance before the mainshock and disappearance or rapid decrease with the mainshock, indicates that the PSEA and its corresponding EQ may originate from same geological process proceeding in the seismogenic zone, as demonstrated by experiments on the mechanical-electrical relationship of stressed granite. Applying these observations and experimental results to reconstruct the geological process that produced the PSEA and the EQ, however, was complicated by the traditional theory of granite formation. Establishing a logical framework that is able to accommodate the various geological, geo-electrical, seismological, and experimental observations related to EQs should be the initial step towards understanding the seismogenic process. The presented FEF model illustrates the entire developing process of a causative fault from stable to preseismic, and finally to a seismic situation, preliminarily revealing the logical linkage between the process and both the PSEA and the EQ. A variety of geological, geo-electrical, and seismological data of the 1975 Haicheng EQ was used to constrain the FEF model, and the survey data from a monitor station in Guangzhou, China was applied to test and verify the model. It is concluded:
1. An undulant fault-plane is the prerequisite for the stress-accumulation in locality of the fault-plane;
2. The position of the continental seismic layer (Ito 1990; 1999) is corresponding to that of the continental granitic layer (Chen and Grapes 2007; Migursky et al. 2008; Yefimov et al. 2008; Chen et al. 2017b; Chen et al. 2017c). Thus, the seismogenic process of any causative fault that cuts through the granitic layer may produce the PSEA;
3. A normal FEF exists in a causative fault beyond preseismic situation, which can be measured;
4. It is possible to detect the seismogenic process of a fracture through monitoring the variation of its FEF when the fracture is in a preseismic situation.

**Abbreviations**

structural earthquake (EQ)

preseismic electric anomaly (PSEA)

electromagnetic (EM)

fracture electric field (FEF)

potential difference (PD)

Western Kunlun Pass (WKP)

Xiuyan - Haicheng Fault (XHF)

**Declarations**

Competing interests

There are no conflicts of interest to declare.

Availability of data and materials

The monitor data of figure 8 shown as supplementary material.

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Authors' contributions

Zhen Chen contributed to manuscript preparation and wrote the manuscript.
Guo-Neng Chen contributed to the conception of the study and manuscript revision.

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Figures
Daily averaged diagrams of the preseismic electric anomalies (PSEAs) of some earthquakes (EQs) in China and Japan. $I/\mu A$ represents the potential difference between two electrodes of a survey line. a–f are redrawn from Chou et al. (2008), and g recompiled after Uyeda et al. (2000).
Figure 2

(a) Experimental setup with a slab of granite that has one end in a press, Cu contacts attached to the front and back, an electric circuit with ammeters to measure currents (one between each Cu contact and ground), and a capacitive sensor to measure the surface charge. The results indicate that the electrons flow out of the stressed side and the holes flow through rock acting as a battery, and both electrons and holes meet at the unstressed side through the outer circuit. (b) Relationship between strength of the electrons and p-hole currents and the stress (dotted line) acting on the stressed side. (c) Idealized model to transpose the set-up from the experiment depicted in (a) onto the Earth's crust. S represents the source of holes (redrawn after Freund et al. 2007a, b).

Figure 3

Geotransect 2-DV in northeastern Russia (simplified after Migursky et al. 2008). The supra layer in green is metasedimentary rock with seismic wave velocities of 3.0–5.8 km/s; the red layer (6.0–6.8 km/s) is a granitic layer, and the basement in green is the mafic lower crust (6.8–7.6 km/s); black dashed lines represents fractures.
Figure 4

Relationship between the shape of fault-plane and development of a seismogenic zone in a cross section; (a1)–(a3) for normal fault (red line), (b1)–(b3) for reverse fault; G for gravity; F for tectonic force; solid red line for fault; dashed red line for the induced structure; red shadow for the stress-accumulation area; yellow arrow for the major pressure stress axis when the slipping is held; pink dashed line for the earthquake (EQ) waves.
Figure 5

(a) Synthetic model for the accumulation-release process of stress in the fracture seismogenic zone and correlation between the process and both the preseismic electric anomaly (PSEA) and earthquake (EQ); the yellow arrows represent the direction of stress; the half oval-shape with blue-red gradation represents the rock-batteries where the holes flow in opposite direction to the yellow arrows; the white arrows represent the flow of electrons with the Z-shaped blue zone as the outer circuit of the rock-batteries; (b)
combination of two experimental circuits in Fig. 2a for comparison with the synthetic model, where F corresponds to the fault in (a), and (c) schematic diagrams for relationship between the P-axis direction and both the fracture electric field (FEF) and its outer circus, with PSEA denoting the area where the surface current may be detected in a preseismic situation.

Figure 6

a. Map showing the distribution of causative fault, the preseismic electric anomaly (PSEA) observation positions, epicentres, and earthquake (EQ) fissures related to the Haicheng Ms 7.3 EQ. 1. Positions without observed PSEA; 2. Positions with observed PSEA; 3. Epicentre of mainshock; 4. Causative fault (Xiuyan-Haicheng Fault; XHF), 5. I–I’ section line; 6 EQ fissure distribution area; 7-9 EQ cracks with...
lengths of 100–500 m, 500–1000 m, and ≥ 1000 m, respectively; (b) potential difference (PD) diagrams of the N–S survey lines, and; (c) PD diagrams of the E–W survey lines variations (see A for location).

Figure 7

Ideal model for monitoring the fracture electric field (FPF). Dots denoted by A, B, and C for different electrodes.
Figure 8

Fracture electric field (FEF) patterns from January 2013–2015 for the Guang–Cong fault at the Guangzhou monitoring station (original data are optimised by slip averaging of 30 minutes). Blue = A-B channel potential difference (PD) variation; red = A-C channel PD variation. Divergence of the curves with time is most likely related to changing soil humidity, and the jumps in the curves within the first twenty days of January 2013 are explained as disturbances of charged material suspended in water or particles falling from the borehole wall.

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