Anisotropic change in apparent resistivity before earthquakes of $M_S \geq 7.0$ in China mainland

Tao Xie, Yan Xue, Qing Ye and Jun Lu

China Earthquake Networks Center, Beijing, China

ABSTRACT
Since 1967 when DC apparent resistivity observation was carried out in China, there have been 16 times or groups of earthquake of $M_S \geq 7.0$ occurred within about 400 km from the monitoring stations. The apparent resistivity showed medium-short term continuous changes before 13 times or groups of these earthquakes. The medium-term changes usually lasted for several months to about two years. Apparent resistivity of monitoring arrays placed in different directions at the same station showed anisotropic change related to the maximum principal compressive stress orientation (i.e. P axis). The larger the angle between a monitoring array and the P axis is, the greater the magnitude of change in apparent resistivity is. According to the results from rock physics experiments, resistivity model of cracked rock-soil medium, and fault virtual dislocation model, the changes in apparent resistivity before earthquakes may be related to the seismogenic process through a way of resistivity change caused by medium deformation.

1. Introduction
Electrical resistivity is an important physical property for sedimentary rock-soil, which is highly variable and primarily governed by a wide range of properties including matrix mineral composition, crack ratio, crack structure, fluid saturation, fluid salinity, temperature. The continuous load of compressive stress, by causing crack growth and directional alignment, would tend to increase connectivity of these crack films. Thus, resistivity would decrease with the accumulation of stress and strain. There might be a high degree of stress-strain accumulation at the locked fault segment and its vicinity area before an earthquake. Build-up of strain ought to be accompanied by change in resistivity. So resistivity is widely used in dynamic monitoring of the late stage of seismogenic process.

During the 1950s to 1980s, Japan, the Soviet Union and the United States carried out experimental observations of apparent resistivity for earthquake prediction. Literatures have reported some prominent changes in apparent resistivity before
moderate earthquakes, and the quasi-coseismic step changes before and after the main shocks (Barsukov and Sorokin 1973; Mazzella and Morrison 1974; Morrison et al. 1977, 1979; Nerseov et al. 1979; Park 1991; Madden et al. 1993). The monitoring arrays placed in seaside caves recorded diurnal variations in synchronized with the tides (Rikitake and Yamazaki 1967, 1969, 1976; Yamazaki 1974, 1975).

In China, apparent resistivity has been monitored continuously at fixed stations since 1967, using Schlumberger arrays. So far, there are more than 90 stations being placed in the main active seismic areas. Related literatures have also reported medium-short term anomalous changes which appeared before more than 100 cases of $M_s \geq 5.0$ occurred in or near the monitoring network, impending accelerating changes before some strong earthquakes, quasi-coseismic step changes near the rupture zones, and opposite recovery changes after earthquakes (Qian et al. 1982, 1985, 1998; Wang et al. 2002; Du 2011; Xie et al. 2022). The medium-short term anomalous changes are often successive declines or rises with magnitudes exceeding 1%, deviating from the previous years’ steady background range. These abnormal changes usually lasted for a few months to about two years (Qian et al. 1982; Wang et al. 2002). For some great earthquakes, around which the stations are placed relatively dense, the magnitude of change attenuates and the starting time delays from the epicenter to the peripheral area (Qian et al. 1982). Monitoring arrays in different directions at the same station usually have different magnitudes of change. The array perpendicular to or near perpendicular to the P axis has the maximum magnitude of change, while the magnitude of change is the minimum or even unnoticeable when the array is parallel to or sub-parallel to the P axis (Du 2011; Xie et al. 2018).

Many studies have been carried out in an attempt to find the relation between changes in apparent resistivity and earthquakes. Laboratory measurements of resistivity on rock specimens under deformation to failure in uniaxial and triaxial compress show that resistivity of water-bearing rocks declines as the stress exceeding about half of the fracture stress. The decline rate increases considerably near the stage of final fracture (e.g. Brace et al. 1965; Brace and Orange 1968; Morrow and Brace 1981; Jouniaux et al. 1994, 2006; Heikamp and Nover 2003). The magnitude of resistivity change in axial direction is usually greater than that in the transverse direction (Brace 1975; Zhang and Lu 1983; Glover and Vine 1992). In-situ experiments taken on field soil using Schlumberger arrays also showed decline change in apparent resistivity under compress stress loading, and recovery change as stress unloading (Zhao et al. 1983). Apparent resistivity measured at three common midpoint arrays, i.e. parallel to, perpendicular to, and oblique (at a 45° angle) to the compress stress in the in-situ experiments, displayed the same characteristics of anisotropic change as the abnormal changes before earthquakes. These experimental results reveal the complicated relation between resistivity change and rock-soil medium deformation at the meso-scale. Micro-cracks play important roles in resistivity change for geomaterial as stress is taken into account (Scholz et al. 1973; Mjahckin et al. 1975).

Archie’s equation is often used to discuss the relation between resistivity and the properties of the constituent parts of sediment. The differential form of resistivity versus parameters in Archie’s equation could reveal the influence of each parameter on resistivity change. The variation of water content, salinity, and crack structure (described by the cementation and tortuosity constants) are the primary factors on
resistivity change under the assumption of invariability of mineral composition, while the effect from pure elastic deformation on resistivity change is negligible (Qian 2010). An approximately effective resistivity tensor was derived for three-phase cracked rock-soil medium based on the parallel-serial connection approximation, so as well the differential form between the resistivity change and crack change. The resistivity behaves the same characteristics of anisotropic change as results from experiments above, as crack growing or closing (Xie et al. 2020). On the other hand, though lateral heterogeneity of substratum will cause apparent resistivity anisotropy (Singh 1985), it has little effect on anisotropic change (Xie and Lu 2020). Therefore, the phenomenon of anisotropic change in apparent resistivity in the vicinity area of the epicenter before an earthquake can be regarded as a possible sign that resistivity anomalies are related to the late stage of seismogenic process.

In this paper, we present the anisotropic changes in apparent resistivity before 13 times or groups of earthquake of $M_S \geq 7.0$ occurred in China mainland. Then, preliminary discussion is taken on the possible mechanism of these anisotropic changes from the meso-scale to the macroscopic scale, based on results from experiments, resistivity model, and fault virtual dislocation model.

2. Apparent resistivity measurement

After the 1966 Xingtai $M_S 7.2$ earthquake in Hebei province, China began to build fixed apparent resistivity stations for earthquake monitoring and prediction. Several
monitoring stations were initially set up for experimental observation in the Xingtai seismic area. In April 1967, the first station went into operation. Apparent resistivity observation has been gradually extended to the main active seismic areas in China since 1970. Fixed Schlumberger array was used at these stations to take continuously measurement. The current electrodes spacing is from 500 m to 2.4 km for different stations or arrays. In general, each station has two or three common midpoint horizontal arrays on ground surface (electrodes are often buried at a depth of about three meters), and two of them are often orthogonal (Figure 1). Parts of these stations have vertical arrays, i.e. the four electrodes are placed at different depths in a borehole which is filled with clay after electrodes are installed. The position of each electrode is fixed, so the detection volume underground is also fixed. Therefore, the measured value of apparent resistivity is a kind of comprehensive reflection of the medium resistivity within the detection range. The resistivity change underground with time can be continuously monitored in this way.

Analogue resistivity meter was used at the stations prior to 1990s. Measurement was taken at an interval of three hours during the daytime and six hours during the nighttime. Automatic digital resistivity meter has been used since 1990s, and measurement is taken once an hour. Direct current is applied through the two current electrodes, and potential difference is measured between the two potential electrodes. Applied current is often from 1 A to 3 A at these stations. Current intensity in each measurement is fixed for a station, if there is no special reason. Five to ten sets of

Figure 2. The 16 times or groups of earthquake of $M_s \geq 7.0$ occurred within about 400 km of the monitoring stations since 1969 and their focal mechanisms. The mechanisms of the 13 times or groups of earthquake with apparent resistivity anomalies are denoted by red focal spheres. The black focal spheres are the three earthquakes with no obvious anomalies before the main shocks.
potential difference data and current intensity data are recorded for each measurement. After eliminating error data, mean value of the remaining data is taken as apparent resistivity value of this measurement. The potential difference resolution of currently used resistivity meter is 0.01 mV. Relative change in resistivity lower than 1% can be detected without considering background noise. Regular verification is carried out every three months on the resistivity meter, using standard resistance or standard power supply, to ensure authenticity of the measured data. The measurement system has a merit of long-term stability. Mean square deviation of daily measurement is less than 1% at the stations with low background electromagnetic noise.

3. Anisotropic changes in apparent resistivity

There have been 16 times or groups of earthquake of $M_S \geq 7.0$ occurred since 1969 within about 400 km from the station network (Figure 2). The focal mechanism solutions of these earthquakes are displayed in Table 1. Parts of these focal mechanisms are from U. S. Geological Survey catalog (https://www.usgs.gov/programs/earthquake-hazards/lists-maps-and-statistics). Table 2 shows the information of apparent resistivity changes before the 13 times or groups of earthquake of $M_S \geq 7.0$, recorded in literatures or analyzed from the observed data. Majority of these changes showed medium-short term continuous declines or rises, lasting from several months to about two years before the main shocks. Figure 3 shows some of these apparent resistivity changes. Two exceptions are the change in Qingxian station before the Tangshan earthquake in 1976, and the changes in Tianshui station before the Jiuzhaigou earthquake in 2017. Apparent resistivity in Qingxian station showed decline change with magnitude of about 2% since only two days before the main shock. Tianshui station showed disturbance changes rather than the common type of continuous decline or rise.

| Num. | Date      | Location | Lon.$^\circ$ | Lat.$^\circ$ | $M_S$ | Strike$^\circ$ | Dip.$^\circ$ | Slip.$^\circ$ | Strike$^\circ$ | Dip.$^\circ$ | Slip.$^\circ$ | $P$ axis$^\circ$ | Source                |
|------|-----------|----------|-------------|-------------|-------|---------------|--------------|--------------|---------------|--------------|--------------|----------------------|------------------------|
| 1    | 1969/07/18| Bohai    | 119.40      | 38.20       | 7.4   | 199           | 80           | 164          | 292           | 75           | 10           | 246                  | Zhang et al. 1988      |
| 2    | 1973/02/06| Luhuo    | 100.70      | 31.30       | 7.6   | 125           | 87           | 0            | 35            | 90           | 177          | 80                   |                        |
| 3    | 1974/05/11| Daguan   | 104.10      | 28.20       | 7.1   | 137           | 86           | 5            | 47            | 85           | 176          | 272                  |                        |
| 4    | 1975/02/04| Haicheng | 122.72      | 40.73       | 7.3   | 110           | 81           | -15          | 203           | 75           | -170         | 66                   |                        |
| 5    | 1976/05/29| Longling | 98.70       | 24.60       | 7.4   | 194           | 46           | 34           | 79            | 66           | 130          | 141                  | Zhang et al. 1990      |
|      |           |          | 99.00       | 24.50       | 7.3   | 101           | 78           | 163          | 194           | 73           | 13           | 148                  |                        |
| 6    | 1976/07/28| Tangshan | 118.18      | 39.63       | 7.8   | 217           | 85           | -159         | 125           | 69           | -6           | 78                   | USGS                   |
|      |           |          | 118.65      | 39.83       | 7.1   | 72            | 44           | -110         | 279           | 49           | -72          | 75                   |                        |
| 7    | 1976/08/16| Songpan  | 104.09      | 32.72       | 7.2   | 166           | 51           | 60           | 29            | 48           | 122          | 63                   |                        |
|      |           |          | 104.10      | 32.48       | 7.2   | 172           | 45           | 72           | 17            | 48           | 107          | 95                   |                        |
| 8    | 1988/11/06| Lancang  | 99.72       | 22.83       | 7.6   | 313           | 71           | 164          | 48            | 75           | 20           | 190                  | Mozaffari et al. 1999  |
|      |           |          | 99.60       | 23.38       | 7.2   | 330           | 59           | 155          | 74            | 69           | 34           | 200                  | Jiang 1993             |
| 9    | 1990/04/26| Gonghe   | 100.08      | 36.08       | 7.0   | 123           | 35           | 61           | 337           | 60           | 109          | 54                   | Zhang et al. 2000      |
| 10   | 1995/07/12| Menglian | 99.30       | 22.00       | 7.3   | 320           | 72           | 165          | 55            | 76           | 19           | 187                  | Chen et al. 2002       |
| 11   | 1996/02/03| Lijiang  | 100.30      | 27.20       | 7.0   | 157           | 50           | -109         | 5             | 43           | -68          | 3                    |                        |
| 12   | 2008/05/12| Wenchuan | 103.40      | 30.95       | 8.0   | 222           | 37           | 107          | 21            | 55           | 77           | 119                  | Zhang et al. 2009      |
| 13   | 2010/04/14| Yushu     | 96.60       | 33.20       | 7.1   | 119           | 83           | -2           | 209           | 88           | -173         | 74                   | Jiang et al. 2018      |
| 14   | 2013/04/20| Lushan   | 103.00      | 30.30       | 7.0   | 205           | 39           | 89           | 26            | 51           | 91           | 116                  | Wang et al. 2013       |
| 15   | 2017/08/08| Jiuzhaigou| 103.80      | 33.20       | 7.0   | 153           | 84           | -33          | 246           | 57           | -173         | 105                  | USGS                   |
| 16   | 2021/05/22| Maduo    | 98.34       | 34.59       | 7.4   | 281           | 88           | 1            | 191           | 89           | 178          | 236                  | Zhang and Xu 2021      |
Table 2. The apparent resistivity changes before the 13 times or groups of earthquakes of $M_S \geq 7.0$.

| Num. | Date       | Location   | $M_S$ | Num. | Date       | Location   | $M_S$ | $D$/km | Arrays  | $RC/%$ | $T$/Month | $\Theta$/ | Source                  |
|------|------------|------------|-------|------|------------|------------|-------|--------|---------|---------|------------|-----------|-------------------------|
| 1    | 1969/07/18 | Bohai      | 7.4   | 418  | NS         | Dabaish    |       | -3.2   | 10      | 10      | 66         |            | Wang et al. 2002         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Niujiaqiao | 405   | -1.5   | 8       | 66      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Dacaozhuang| 400   | -1.5   | 6       | 66      |            |           |                         |
| 2    | 1973/02/06 | Luhuo      | 7.6   | 45   | N30°E      | Garze      |       | -7.0   | 3       | 50      |            |           | Qian and Zhao 1980        |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Yaan       | 300   | -4.5   | 3       | 40      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Songpan    | 320   | -2.0   | 7       | 80      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Kangding   | 220   | +2.0   | 6       | 60      |            |           |                         |
| 3    | 1974/05/11 | Daguan     | 7.1   | 180  | NS         | Xichang    |       | -5.2   | 11      | 88      |            |           | Wang et al. 2002         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Miyi       | 245   | -3.5   | 11      | 88      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Huili      | 240   | +1.5   | 15      | 88      |            |           |                         |
| 4    | 1975/02/04 | Haicheng   | 7.3   | 90   | N51°W      | Taian      |       | +9.0   | 10      | 73      |            |           | Wang et al. 2002         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Changli    | 310   | -2.0   | 9       | 66      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | EW        | -2.0   | 9       | 24      |         |            |           |                         |
| 5    | 1976/05/29 | Longling   | 7.4   | 54   | N73°E      | Tengchong  |       | -10.5  | 25      | 68      |            |           | Qian et al. 1985         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | N17°W      | Chuxiong | -3.7   | 25      | 34      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | N75°E      |        | +7.5   | 12      | 54      |            |           | Wang et al. 2002         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | N60°W      |        | -      |         |         |            |           |                         |
| 6    | 1976/07/28 | Tangshan   | 7.8   | 5    | NS         | Tangshan   |       | -5.5   | 18      | 78      |            |           | Qian et al. 1998         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Changli    | 35    | -6.4   | 13      | 75      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Baodi      | 80    | -3.0   | 16      | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Qingguang  | 110   | -3.1   | 12      | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Zhongxinhuang | 150 | -4.5   | 19      | 38      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Majiagou   | 10    | -17.6  | 2       | 77      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | N69°E      |        | -15.0  | 2       | 9       |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Baliliao   | 140   | -4.7   | 17      | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Xiji       | 120   | -3.3   | 17      | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Xuzhuangzi | 140   | +2.6   | 9       | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Qingxian   | 160   | -2.0   | 2 Days  | 78      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
| 7    | 1976/08/16 | Songpan    | 7.2   | 100  | N85°E      | Wudu       |       | -2.0   | 19      | 22      |            |           | Qian and Zhao 1980        |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | Songpan    | 70    | -2.0   | 14      | 85      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
| 8    | 1976/08/23 | Pingwu     | 7.2   | 215  | EW         | Tengchong  |       | -5.0   | 20      | 80      |            |           | Wang and Yu 1989          |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | NS         | 282   | +7.1   | 8       | 36      |            |           | Zhang et al. 2000         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
| 9    | 1990/04/26 | Gonghe     | 7.0   | 335  | EW         | Wuwei      |       | +7.1   | 8       | 36      |            |           |                         |
|      |            |            |       |      |            |            |       |        |         |         |            |           |                         |
|      |            |            |       |      |            | NS         | 237   | -2.3   | 11      | 2       |            |           |                         |

(continued)
As counted by stations, there are 38 changes before the 13 times or groups of earthquake. 32 of these changes show the same pattern of anisotropic change. For a single station, the array with larger angle versus the P axis has larger magnitude of change, while the array with smaller angle versus the P axis has smaller magnitude of change or even unnoticeable change. The 6 exceptions are Huili station before the Daguan earthquake in 1974, Changli station before the Haicheng earthquake in 1975, Wuwei station before the Gonghe earthquake in 1990, Mianning station before the Lijiang earthquake in 1996, Tianshui and Wudu station before the Jiuzhaigou earthquake in 2017, respectively. Huili station showed an opposite pattern of anisotropic change. The arrays of EW and NS direction showed 2.9% and 1.5% of rise, respectively. But the array of EW direction was approximately parallel to the P axis, and array of NS direction was approximately perpendicular to the P axis. The two arrays at Changli station showed the same magnitudes of change before the Haicheng earthquake though the array of NS direction had larger angle versus the P axis than the array of EW direction. However, Changli station was more likely affected by the Tangshan earthquake in 1976, with a distance of only 35 km away from the epicenter of the Luanxian earthquake which was the max aftershock of Tangshan earthquake. Changli station showed expected anisotropic change before the Tangshan earthquake. The array of NS direction at Wuwei station encountered malfunctions before the Gonghe earthquake, making us unable to discuss its anisotropic change. The arrays of N5°E and N45°W direction at Mianning station showed expected anisotropic change before the Lijiang earthquake. But the array of N85°W direction, which had the largest angle versus the P axis, did not show any noticeable change. Wudu station was remodeled in 2014. The original three horizontal arrays were replaced with two vertical arrays. Disturbance changes in apparent resistivity before earthquakes are usually caused by the instability of the spontaneous electric field (Du 2011). Consequently,

| Num. | Date       | Location | M  | Source              |
|------|------------|----------|----|---------------------|
| 11   | 2008/05/12 | Wenchuan | 8.0| Du 2011             |
| 12   | 2013/04/20 | Lushan   | 7.0| Du et al. 2015      |
| 13   | 2017/08/08 | Jiuzhaigou | 7.0 | Gao 2020 |

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changes recorded at both stations of Wudu and Tianshui before the Jiuzhaigou earthquake are not suitable to the discussion of anisotropic change.

The angles between the arrays and the P axes of the 13 times or groups of earthquake are also shown in Table 2. The Luanxian earthquake was occurred in the eastern area of the Tangshan earthquake. Changli station was more close to the Luanxian earthquake. And P axis of $75^\circ/C_{14}$ is used to character the angles between arrays and the P axis. The rest stations were located in the western area of the Tangshan earthquake, so P axis of $78^\circ/C_{14}$ is used for these stations. The Pingwu earthquake was occurred in the southern area of the Songpan earthquake. Wudu station was located in the

Figure 3. Apparent resistivity changes before some $M_S \geq 7.0$ earthquakes. The red line is the variation trend predicted from data before the anomaly appeared. The shaded green denotes the abnormal change. (a) The Luhuo $M_S 7.6$ earthquake in 1973. (b) The Daguan $M_S 7.1$ earthquake in 1974. (c) The Tangshan $M_S 7.8$ and Luanxian $M_S 7.1$ earthquakes in 1976. (d) The Songpan $M_S 7.2$ and Pingwu $M_S 7.2$ earthquakes in 1976. (e) The Lancang $M_S 7.6$ and Gengma $M_S 7.2$ earthquakes in 1976. (f) The Gonghe $M_S 7.0$ earthquake in 1990. (g) The Lijiang $M_S 7.0$ earthquake in 1996. (h) The Wenchuan $M_S 8.0$ earthquake in 2008. (i) The Lushan $M_S 7.0$ earthquake in 2013. (j) The Jiuzhaigou $M_S 7.0$ earthquake in 2017.
northeastern area of the Songpan earthquake and was more close to this earthquake. Songpan station was located in the southwestern area of the Pingwu earthquake and was more close to it. P axis of 63° and 95° are used for Wudu station and Songpan station, respectively. Tengchong station was located in the northwestern area of the Lancang earthquake in 1988, and was more close to it compared with the Gengma earthquake occurred on the same date. P axis of 190° is used for Tengchong station.

The distances from stations of Chengdu, Jiangyou, and Wudu to the Wenchuan earthquake are measured by the distances from the stations to the rupture zone, because the Wenchuan earthquake had a rupture zone of about 330 km. According to the different rupture features, the main rupture zone can be roughly divided into four sections. The piecewise focal mechanisms of the main shock show that the directions of the P axis near Chengdu, Jiangyou, and Wudu station are 119°, 355°, and 85°, respectively (Zhang et al. 2009). Garze station was located in the direction roughly perpendicular to the fault and 330 km far from the rupture zone. The whole direction of 113° (Zhang et al. 2009) is used to character the angles between arrays at Garze station and the P axis.

4. Discussion

The interpretation of such apparent resistivity anisotropic change relies on the knowledge on the relationship between the resistivity change and seismogenic process. If change in apparent resistivity before an earthquake is caused by the stress-strain change, the background of stress-strain variation is needed as a reference when we discuss the possible mechanism between apparent resistivity change and the earthquake. Several aspects should be taken into account, including (1) meso-scale relationship between resistivity change and deformation in experiment; (2) theoretic explanation for the experiment result; (3) background of deformation variation before an earthquake; (4) agreement of anomalies with the mechanism.

4.1. Results of rock physics experiments

Shallow sedimentary rocks contain various degrees of pores or cracks. The structure of geomaterial can be roughly divided into two parts: one is the matrix composed of minerals, and the other is the pores or cracks containing fluid or gas. In general circumstance, conductivity of rock matrix is poor, while cracks often have low resistance due to dissolved conductive ions when they contain water. Conductivity of the sedimentary medium mainly depends on the conductivity of the fluid contained in the cracks and on the crack structure. Experiment results show that the resistivity of water-bearing medium is closely related to the porosity, saturation, ion concentration in aqueous solution, temperature, and crack structure (Nover 2005). Resistivity decreases with increasing porosity for water-bearing medium, and also decreases with increasing saturation at a constant porosity. Concentration and migration rate of conductive ions in the crack water increase with rising of temperature. Resistivity increases with declining temperature, especially below the freezing point of crack water (Glover et al. 1994; Roberts 2002).
In general, during the period of apparent resistivity anomaly ranging from a few months to about two years, temperature of underground medium within a depth from tens of meters to kilometers in non-geothermal areas can be regarded as unchanged. The main detection range of apparent resistivity is below underground water level. Water has enough time to flow into or out of the cracks. Water saturation can also be regarded as relatively stable. Therefore, it is considered that changes in crack volume and in crack structure under stress are the main reason for the change in apparent resistivity before an earthquake (Scholz et al. 1973; Mjachkin et al. 1975; Du 2011).

Resistivity of rock samples has been measured under deformation to failure in uniaxial and triaxial compress (Brace et al. 1965; Yamazaki 1966; Morrow and Brace 1981; Zhang and Lu 1983; An et al. 1996; Glover et al. 1997; Jouniaux et al. 2006). The results show that resistivity of water-bearing rock decreases in the middle and late stage of compressive stress loading process, while it increases or recovers in the process of stress unloading. Most of the samples show accelerating declines in resistivity when they are approaching failure (Figure 4). The resistivity decreases by more than 1%, even by more than 50% in some experiments. Anhydrous rocks show slight upward change under compressive stress. A few sets of arrays were placed on rock samples, and each set had three common midpoint Schlumberger arrays which were parallel to, perpendicular to and oblique (at a 45° angle) to the orientation of compressive stress, respectively (Chen et al. 1983, 2013; Samouelian et al. 2004). Apparent resistivity measured by the perpendicular array has the maximum decrease magnitude, while the parallel array has the minimum magnitude. The decline magnitude of the oblique array falls within the up and low bounds of the other two arrays. Obvious anisotropic change appears at the arrays with new cracks cross through, while the other arrays do not show such significant anisotropic change. There is an approximate correlation of $\Delta \rho_a/\rho_a = K\Delta L/L$ between relative change in resistivity and the axial strain, where $K$ is termed the amplification factor of the medium. $K$ is larger for small strain than that for large strain (Figure 5). And there is also a tendency that $K$ increases with increasing saturation to a peak value then falls off (Yamazaki 1966; Morrow and Brace 1981; Zhao et al. 1983).
In order to display the resistivity change of geomaterial under compressive stress in natural state, in-situ experiments have also been carried out (Zhao et al. 1983). Several sets of Schlumberger arrays with different distances away from the stress source were placed. Each set has three common midpoint arrays placed in a way as above. The compressive stress was simulated by a jack placed in an excavated groove. Apparent resistivity shows the same pattern of anisotropic change as laboratory experiments (Figure 6). Furthermore, the magnitude of apparent

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**Figure 5.** Magnitude of relative change in resistivity with axial deformation under compressive stress. The slope of the curves is the amplification factor of $K$. (a) The relation of resistivity change vs. axial strain for a lapilli tuff specimen at a water content of 18% (Yamazaki 1966). (b) Relative change in resistivity with strain for a Silverado tuff sample as function of water saturation (Morrow and Brace 1981).

**Figure 6.** Anisotropic change of apparent resistivity in an in-situ experiment (Zhao et al. 1983). Compressive stress was applied by a jack placed in an excavated groove. Apparent resistivity decreases as stress loading and increases as stress unloading. The perpendicular array has the maximum change, while the parallel array has the minimum change. The magnitude of the oblique array falls within the upper and lower bounds of the other two arrays.
resistivity change decreases with the increasing distance from the array to the stress source.

In some experiments, volume of rock sample was measured synchronously (Hallbauer et al. 1973; Tapponnier and Brace 1976; Bobet and Einstein 1998). The total volume of the rock sample decreases at the early stage of stress loading, while it increases as further loading of stress (Figure 7), under conditions of low confining stress and low temperature. The non-linear stress-strain behavior is believed to be attributed to the growth, interaction and coalescence of micro-cracks. Volume dilatation reflects continuous generation of new cracks, accompanied by the phenomenon of sound emission (Brace et al. 1966; Brace 1975; Scholz et al. 1973; Mjachkin et al. 1975; Ashby and Hallam 1986). New crack growth under compressive stress occurs at the onset of dilatancy by several mechanisms, such as shear along pre-existing cracks, stress concentration along intergranular boundaries, and grain-to-grain contact (Brace and Bombolakis 1963; Kemeny 1991; Amann et al. 2014; Liu et al. 2019). One similarity of these mechanisms is that the crack growth is extensile and approximate in the direction of the maximum principal stress (Figure 8).

Figure 7. Stress–strain diagram showing different stages of crack development during a uniaxial compression test (Xue et al. 2014).
4.2. Resistivity model

Qian (2010) discussed the relationship between resistivity change and the various factors based on the extended Archie’s equation of \( \rho_t = \alpha \rho_w \varphi^{-m} S_w^n \). It is considered that the variation of water content, temperature, salinity of water solution, and crack structure are the main controlling factors of resistivity change under the condition that the components of geomaterial matrix remain unchanged. The influence of pure elastic deformation on resistivity can be ignored. In order to further explain the anisotropic change in apparent resistivity from experiments and field observations, an approximately effective resistivity tensor was proposed for three-phase cracked rock-soil medium as follow (Xie et al. 2020)

\[
\rho = \frac{\phi}{A} \frac{\rho_t \rho_m}{\rho_t (I - A)} + \rho_m A \psi + (I - \frac{\phi}{A}) \rho_m \tag{1}
\]

where \( \rho \) is the effective resistivity tensor, \( \rho_t \) is resistivity of crack fluid. \( \rho_m \) is resistivity of matrix. \( \phi \) is crack ratio. \( \psi \) is fluid saturation. \( A \) is a crack shape tensor describing the shape of thin cracks. \( I \) is the second order unit matrix. The differential form between the resistivity change and crack change is

\[
\begin{bmatrix}
d\rho_1/\rho_1 \\
d\rho_2/\rho_2 \\
d\rho_3/\rho_3 
\end{bmatrix} = \eta d\psi + BA_0 r d\zeta \tag{2}
\]
where $\rho_1$, $\rho_2$, $\rho_3$ is resistivity of the three electrical axes, respectively. $\eta = (\eta_1, \eta_2, \eta_3)^T$ is saturation sensitivity. $A_0$ is the crack shape tensor when coordinate system is along the three electrical axis. $r$ is the direction vector of crack growth. $d \xi$ is the change element of cracks. $B$ is an amplification matrix which describes the effects of crack change on resistivity change

$$
B = \begin{bmatrix}
B_{11} & B_{12} & B_{13} \\
B_{21} & B_{22} & B_{23} \\
B_{31} & B_{32} & B_{33}
\end{bmatrix} = \begin{bmatrix}
k_1 & k_1 \xi_1 & k_1 \xi_1 \\
k_2 \xi_2 & k_2 & k_2 \xi_2 \\
k_3 \xi_3 & k_3 \xi_3 & k_3
\end{bmatrix}

(3)
$$

where

$$
k_i = \frac{\rho_i - \rho_m \psi}{\rho_i(1 - a_i + \phi) + \rho_m(a_i - \phi)\psi}, \xi_i = \frac{\rho_i}{\rho_i(1 - a_i) + \rho_m a_i \psi}
$$

(4)

$\xi_i$ is the transverse weight and its value is generally $0 < \xi_i \ll 1$. The anisotropic change of resistivity is controlled by the matrix of $B$ when saturation remains stable or its variation magnitude is small enough to be negligible. According to Eq. (1), the electrical axis along the alignment direction of the cracks has the lowest resistivity, denoted by $\rho_1$ here. In addition, electrical axis of $\rho_1$ has the largest amplification factor of $k_1$ (absolute value). $k_1$ is usually several times or even orders of magnitude larger than $k_2$ and $k_3$. In consequence, electrical axis of $\rho_1$ has the largest magnitude of resistivity change when cracks grow along the direction of $\rho_1$, resulting in resistivity anisotropic change. In addition, the absolute value of $k_1$ decreases with crack growth before the stage of approaching to be totally fractured. However, $k_1$ increases rapidly as the rock tends to be completely fractured (Xie et al. 2020). The early evolution stage of $k_1$ would provide an explanation for the larger amplification factor of $K$ at small strain than that at large strain (Yamazaki 1966; Morrow and Brace 1981), and latter evolution stage for the rapid decrease in resistivity near the rupture (Brace and Orange 1968; Zhang and Lu 1983).

Shallow crustal medium often contains pre-existing cracks, and the alignment and orientation of these cracks are controlled by tectonic stress. Two principal stress components in the shallow surface are usually along the horizontal direction and the third one is along the vertical direction. Cracks are usually aligned approximately in the direction of the maximum principal compressive stress in compressional tectonic regions (Crampin et al. 1984). Under this simplification, two electrical axes are in horizontal direction and the third one is in vertical direction. In a homogeneous half-space medium, the apparent resistivity observed on the surface using the Schlumberger array is (Краев 1951)

$$
\rho_a = \frac{\sqrt{\rho_1 \rho_2 \rho_3}}{\sqrt{\rho_1 \cos^2 \theta + \rho_3 \sin^2 \theta}}
$$

(5)

where $\rho_1$, $\rho_2$ is resistivity of the two horizontal directions, respectively. $\rho_1$ represents the minimum electrical axis. $\rho_3$ is resistivity of the vertical electrical axis. $\theta \in [0, \pi/2]$ is the angle between array and the direction of $\rho_1$. The differential form between relative change in apparent resistivity $d\rho_a/\rho_a$ and $\theta$ is
\[
\frac{d(d\rho_a/\rho_a)}{d\theta} = \frac{1}{2} \left( \frac{d\rho_1}{\rho_1} - \frac{d\rho_2}{\rho_2} \right)^2 \sin 2\theta
\]  

Equation (6) means that vertical electrical axis of \( \rho_3 \) takes no effects on the anisotropic change in apparent resistivity when carrying out measurement on ground surface. Schlumberger array perpendicular to \( \rho_1 \) (i.e. both the directions of crack growth and the maximum horizontal compressive stress) has the maximum change in apparent resistivity, while the array parallel to \( \rho_1 \) has the minimum change. The variation magnitudes of the oblique arrays are between them. There is an angle difference of \( 90^\circ \) between the apparent resistivity change and the resistivity change as the Schlumberger array is used. Figure 9 shows anisotropic change in resistivity and in apparent resistivity based on Eq. (2) as cracks grow along the direction of \( \rho_1 \). The anisotropic change in apparent resistivity from Eq. (2) or Eq. (7) is in good agreement with the results from laboratory experiments and in-situ experiments.

Figure 9. Anisotropic changes in resistivity \( \rho_1 \) of the three electrical axes and in apparent resistivity when the cracks grow along the minimum electrical axis (i.e. \( \rho_1 \) here). (a) Schematic diagram of crack growing along \( \rho_1 \). (b, c) Dry rock with no water supply; (d, e) Partially saturated rock with no water supply; (f, g) Partially saturated rock with water supply, and the supply rate keeps the saturation invariable.
4.3. Fault virtual dislocation model

The studies from experiments and theoretical resistivity model above have basically clarified the relationship between resistivity change and micro-crack variation at meso-scale. However, there is still lacking a connection of ‘medium deformation and resistivity change’ between the meso-scale mechanism and the macroscopic phenomenon of abnormal resistivity change before an earthquake. That is whether or how the areas, where the monitoring stations with abnormal change before an earthquake are located, are affected by the build-up of high stress-strain level.

It can be expected from the above experiment results that absolute stress level is often needed to discuss the relationship between crack variation and stress. However, it is difficult to obtain successive absolute stress-strain measurement at present for a large tectonic region. On the other hand, the general quantitative mathematic relationship between the stress level and micro-crack activity is not clear. One alternative compromise way is to obtain the qualitative spatial distribution characteristic of the stress-strain accumulation required to produce the coseismic slip using the fault virtual dislocation model. The coseismic slip displacement is loaded in a way of equal in magnitude but opposite in direction in the model. The areas of compression enhancement or relative expansion before an earthquake can be displayed (Zhao et al. 1996; Xie et al. 2022). Then we can discuss the relationship between the decline or rise change in apparent resistivity and the regional deformation state of compression enhancement or relative release. The schematic diagrams of coseismic slip and virtual dislocation model of thrust, normal fault, and strike-slip earthquakes are shown in the figure below.

Figure 10. Schematic diagram of coseismic dislocation and fault virtual dislocation model of the three types of faults. (a) Strike-slip fault. (b) Thrust fault. (c) Normal fault.
For an earthquake contains both thrust and strike-slip components, or both normal and strike-slip components, the virtual displacement can be decomposed into two directions of parallel to and perpendicular to the strike of the fault on the fault plane. It should be noted that results from the virtual dislocation model are the changes of stress or deformation, not the absolute state of stress-strain. China mainland is in compressive tectonics as a whole. The compression areas from the virtual dislocation model can be seen as areas with compression enhancement before the earthquake. However, for the extension areas from the model, we cannot distinguish them between true extension areas and compressive areas. They can be regarded as relative extension areas where the original tensile effect is strengthened or the original compressive effect is released to some extent.

The fault virtual dislocation model can be calculated using the Deformation and Stress-Change Software of Coulomb 3.3 (Lin and Stein 2004; Toda et al. 2005). The
empirical relationship between magnitude and fault rupture parameters (Wells and Coppersmith 1994) is applied if fine coseismic fault rupture model is not available. Xie et al. (2022) has completed the analysis on the 13 times or groups of earthquake of $M_S \geq 7.0$. All stations with decline changes, except the change in Mianning station before the Lijiang earthquake, were located at areas of compression enhancement, and all stations with rise changes were located at areas of relative extension. It is in good agreement with the experiment results that the resistivity decreases during compressive stress loading and increases during unloading. Two examples of the Tangshan $M_S 7.8$ and the Wenchuan $M_S 8.0$ earthquakes are shown in Figure 11. There were 11 stations showed anomalous changes before the Tangshan earthquake (Table 2). Only the station of Xuzhuangzi showed rise change, and it was in the area of relative extension before the mainshock. The other 10 stations with decline changes were in the areas of compression enhancement (Figure 11a). The three stations of Chengdu, Jiangyou, and Garze showed decline changes were in the areas of compression enhancement before the Wenchuan Earthquake. While the station of Wudu was in the area of relative extension, and it showed rise change (Figure 11b).

The build-up of stress-strain on the locked fault applied extra deformation on the original tectonic background, which becomes a bridge linking the meso-scale mechanism to the change in apparent resistivity around the epicenter. The deformation characteristic controls the shape of decline or rise change in apparent resistivity. The magnitudes of change recorded by arrays in different directions at a station are controlled by the direction of maximum principal compressive stress.

5. Conclusions

There have been 16 times or groups of earthquake of $M_S \geq 7.0$ occurred within about 400 km from the fixed stations during the more than 50 years of continuous apparent resistivity monitoring in China mainland. Middle-term to short-term anomalous changes in apparent resistivity appeared before 13 times or groups of these earthquakes. There were 38 anomalous changes in terms of stations, and 32 of which showed the same pattern of anisotropic change. For a station with two or more Schlumberger arrays placed on ground surface, the array has larger magnitude of change when it has larger angle from the maximum principal stress direction. The accumulation of tectonic stress on a locked fault adds additional deformation on the areas around the epicenter. The original compressive deformation in some areas is enhanced, and the apparent resistivity in these areas behaves decline change. While some other areas suffer release on the original compression, and stations in these areas show rise change in apparent resistivity. The enhancement of compressive stress might cause slight growth of micro-cracks along direction of the maximum principal compressive stress, leading to anisotropic change in resistivity of shallow stratum as well as the anisotropic change in apparent resistivity monitored on ground surface. For a single station, the greater the angle between the array and the direction of maximum principal compressive stress, the greater the magnitude of change is. Therefore, there might be a relationship of ‘resistivity change caused by medium
deformation’ between the anisotropic change in apparent resistivity and the late stage of seismogenic process.

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**Data availability statement**

Focal mechanism solutions are from USGS catalog and references cited in Table 1. Parts of the apparent resistivity data are from the database of China Earthquake Networks Center. Majority of information in apparent resistivity anomalies is from references cited in Table 2.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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