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Changes in Apparent Resistivity in the Late Preparation Stages of Strong Earthquakes

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1. Introduction

In China, a large-scale observation network that is comprised of a number of apparent resistivity (for short, AR) stations has been established for the purpose of earthquake (EQ) monitoring and prediction since the 1966 Ms7.2 Xingtai EQ in Hebei Province. Presently, over 70 AR stations are in observation in seismically active belts in densely populated areas and nearby some of large, medium-sized cities. The 2008 Ms8.0 Wenchuan great EQ in Sichuan province occurred in the AR station network that was located in the border area of both Sichuan and Gansu provinces. In the 1970s-1980s, more than 110 AR stations had been in observation, and in those years, several great earthquakes (EQs) occurred nearby AR stations, such as the 1976 Ms7.8 Tangshan EQ in Hebei province, the 1976 Ms7.2 Songpan-Pingwu EQ in Sichuan province, the 1976 Ms7.4 Longling EQ in Yunnan province, and the 1988 Ms7.6 Lancang-Gengma EQ in Yunnan Province. At an AR station, two horizontally perpendicular observation channels or three channels, more one horizontally skewed channel (a NE or NW channel, as illustrated in Fig.1a), are employed, and for each channel, an AR observation configuration with a symmetry four-electrode array is installed (Fig.1b). For most stations, the current electrode spacing $\overline{AB} = 1000 \sim 2000\text{m}$.

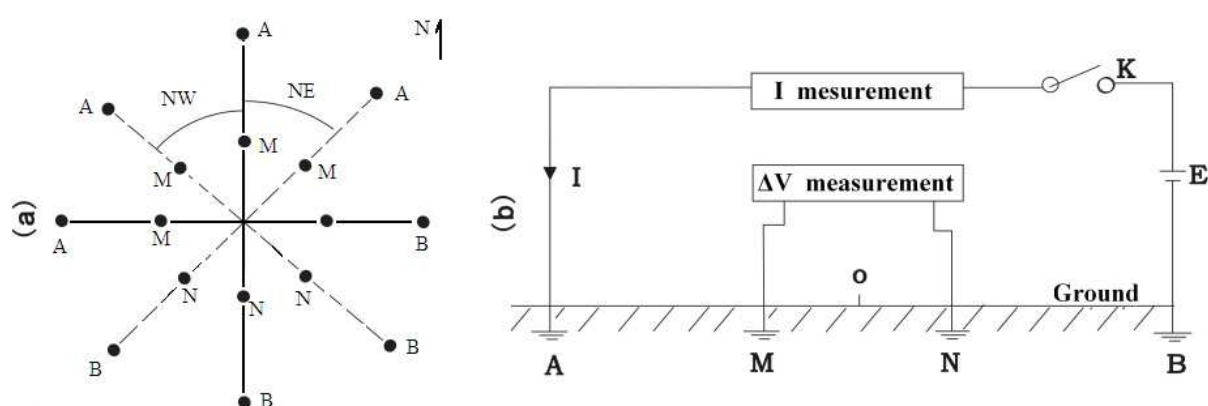


Fig. 1. The observation channels (a) and symmetric four-electrode resistivity array for a channel (b) at a geo-electrical station

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Some of the AR stations have continuously observed for more than 40 years, and a lot of AR data are observed. Using these data we can understand whether the earthquake-related AR changes are recorded or not, which is an issue that should be seriously discussed because the precursory anomalies before EQs have been strongly debated. In this chapter we try to study the issue from two respects: (1) the EQ case research on AR changes recorded before EQs, and (2) the theoretical analysis on anisotropic AR changes related to the maximum principal compression stress (P – axis) azimuth of focal mechanism solution, nearby an EQ focal region in the late preparation stages of a strong EQ. This chapter will help objectively evaluate and comprehend the AR precursory changes related to EQs.

2. EQ case research

Before several great EQs with magnitude of $M_s \geq 7.0$ and some moderate EQs, obvious AR anomalies, which include the medium-term anomalies that start to appear about 2-3 years to several months before EQs and the imminent anomalies that start to appear about 3 months to several days preceding EQs, are recorded at geo-electrical stations nearby the epicentral areas, in China. Some of the anomalies are ascertained after EQs, whereas some are discerned before EQs. More interestingly, two groups of EQs with magnitude of M_s 6 nearby AR stations are actually forecasted on a one-year time scale using medium-term AR anomalies, for which the expected EQ magnitudes and forecasted locations are all right.

2.1 AR changes ascertained after EQs

2.1.1 Reappearing AR anomalies before two great EQs

In 1976, three great EQs with magnitude of $M_s \geq 7.2$ occurred in the mainland Chinese, such as the July 28 $M_s 7.8$ Tangshan EQ in Hebei province, the Aug. 16 $M_s 7.2$ Songpan-Pingwu EQs in Sichuan province, and the May 29 $M_s 7.4/7.3$ Longling EQ in Yunnan province. Of the EQs, the Tangshan EQ and Songpan-Pingwu EQ occurred in a local AR station network, and significant AR changes were ascertained after the EQs. As shown in figure 2^[1], obviously drop AR changes were recorded at station Changli-Houtuqiao (CLH) in Hebei province, before the $M_s 7.8$ Tangshan EQ (80 km from CLH station) and at station Wudu-Hanwang(WDH) in Gansu province, before the Songpan-Pingwu $M_s 7.2$ EQ (105 km from WDH station), respectively. On those days, the two stations were in normal operation. It can be seen from raw AR daily mean curves of the two stations that AR changes fell all during about 40 days before the occurrence of the two great EQs, which were notable short-term anomalies proceeding the two EQs. Especially, during about 20 days before the two EQs AR changes started to fall by a larger margin, which were imminent anomalies before the impending EQs. Then, immediately after the occurrence of the two EQs, the drop changes started to rise. Based on the two AR anomalies corresponding to the two EQs, we can discuss two problems as follows:

The first problem is on the repeatability of AR anomalies before the two EQs. The $M_s 7.8$ Tangshan EQ occurred in Hebei Province, in east China, and the $M 7.2$ Songpan-Pingwu EQ occurred in north Sichuan province, in western China. The distance between the two EQ epicenters were beyond 1500 km; and the two stations were located in different tectonic units (station CLH was nearby the Cangdong fault belt in the Beijing-Tianjin-Tangshan area, in east China, and station WDH was nearby the Bailong river fault belt in South Gansu province, in western China). The underground geo-electrical structure of the two stations was very different. Nevertheless, the drop AR changes of the two stations before the two

great EQs and their recovery AR changes immediately after the two events had a similar changeable pattern in appearance. Therefore, the anomalous AR changes were believed to be the anomalies related to the two great EQs.

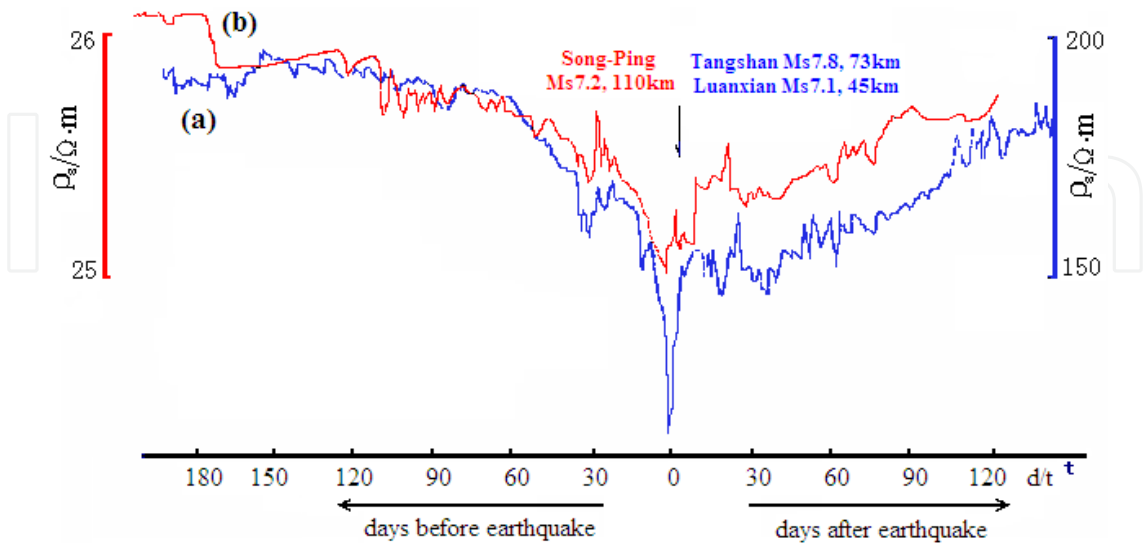


Fig. 2. AR changes observed at CLH station before the 1976, Ms7.8 Tangshan EQ (a), and at WDH station before the 1976, Ms7.2 Songpan-Pingwu EQ (b)

The second problem is on the drop pattern of the two AR anomalies. It is obvious from figure 2 that the AR changes have a notable drop pattern during the imminent stage of the two impending great EQs. In general, the underground medium is abundant with water and the medium resistivity is susceptible to water, therefore, we believed that the changes of underground water resulted in these drop AR changes before the two impending EQs. Figure 3 are the raw AR daily-mean curve at CLH station and the raw curve of water level

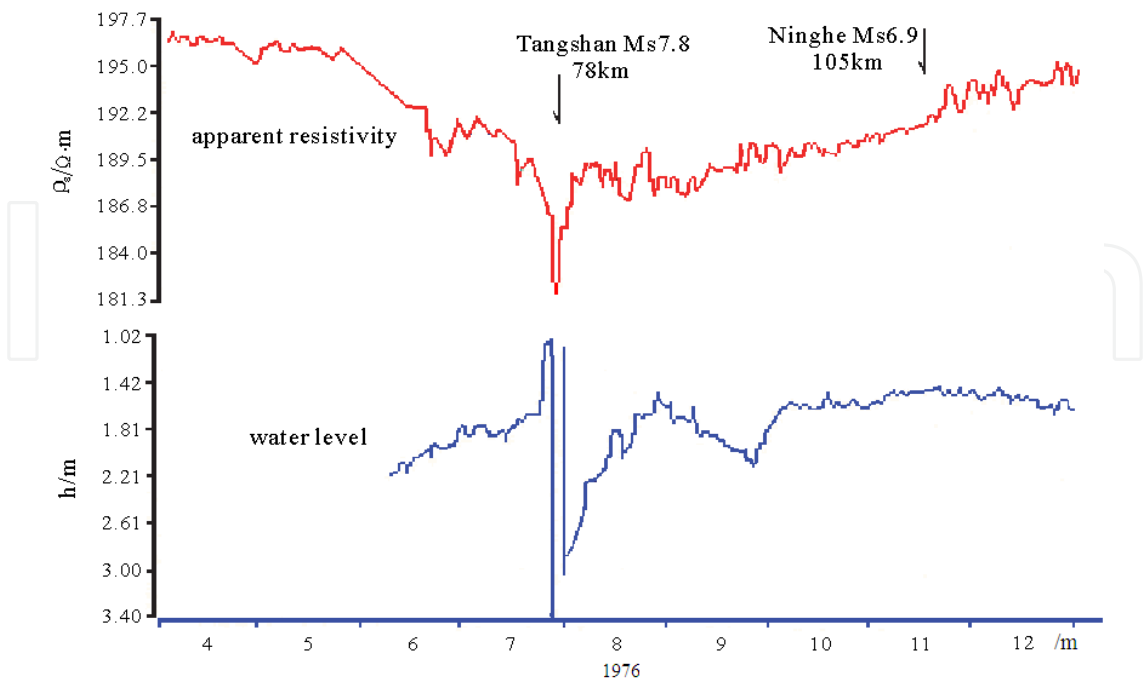


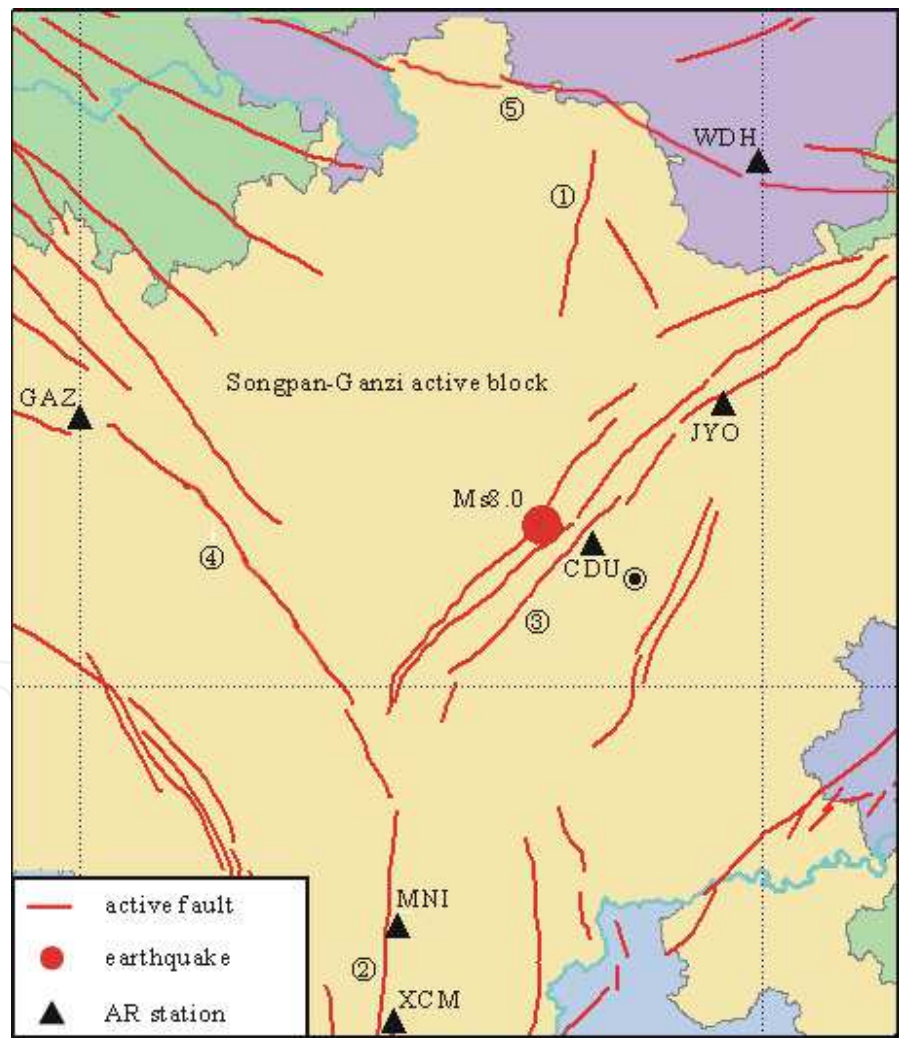
Fig. 3. The AR change observed at CLH station and the water level change observed at Longjiadian station

observed at underground water station^[2], Longjiadian station which was about 20 km from station CLH and nearby the Cangdong rupture zone. We can notice from figure 3 that immediately before and after the occurrence date of the EQ, the drop AR change at station CLH was well corresponding to the rise change in water level at station Longjiadian. The opposite changeable patterns between electric and water are quite significant, which indicated that the water in the underground medium nearby the focal region played an important role in AR changes.

It can be seen from figure 3 that nothing was recorded before the Ms6.9 Ninghe aftershock (Nov. 15, 1976) at the geo-electrical and water stations, a possible reason for which was explained by associating with the mainly active faults in/nearby the focal region and the focal mechanism of the aftershock by Du *et al.*^[3-4].

2.1.2 AR anomalies corresponding to the Ms8.0 Wenchuan EQ

On May 12, 2008, a great EQ of Ms8.0 struck the Wenchuan county and its adjacent area in Sichuan province of China, and within one month following it, more than thirty Ms5.0~6.4



①Minjiang river fault, ②Anning river fault, ③Doujiang Weir-An county fault, ④Xianshui river fault, ⑤White Dragon River fault

Fig. 4. Distributions of station, epicenter and fault.

aftershocks occurred along the NE-strike fault belt beyond 300 km long, from the Wenchuan county to the Ningqiang county in Shaanxi province. There were six AR stations within 400 around the main epicenter, which were Chengdu station (CDU, 35km), Jiangyou station (JYO, 150 km), Ganzi station (GAZ, 331 km), Mianning station (MNI, 260) and Xichang station (XCM, 360 km) in Sichuan province, and WDH station (300 km) in Gansu province (Fig.4).

2.1.2.1 Medium-term AR anomalies before the EQ

Significant AR anomalies were recorded at four stations in the medium-term stage before the Ms 8.0 Wenchuan EQ as follows.

1. Locally concentrated anomalies

The anomalies were recorded at CDU, JYO, GAZ and WDH during the medium-term stage before the EQ, which were in the range of 400km from the main epicenter (Fig.5, Fig.6).

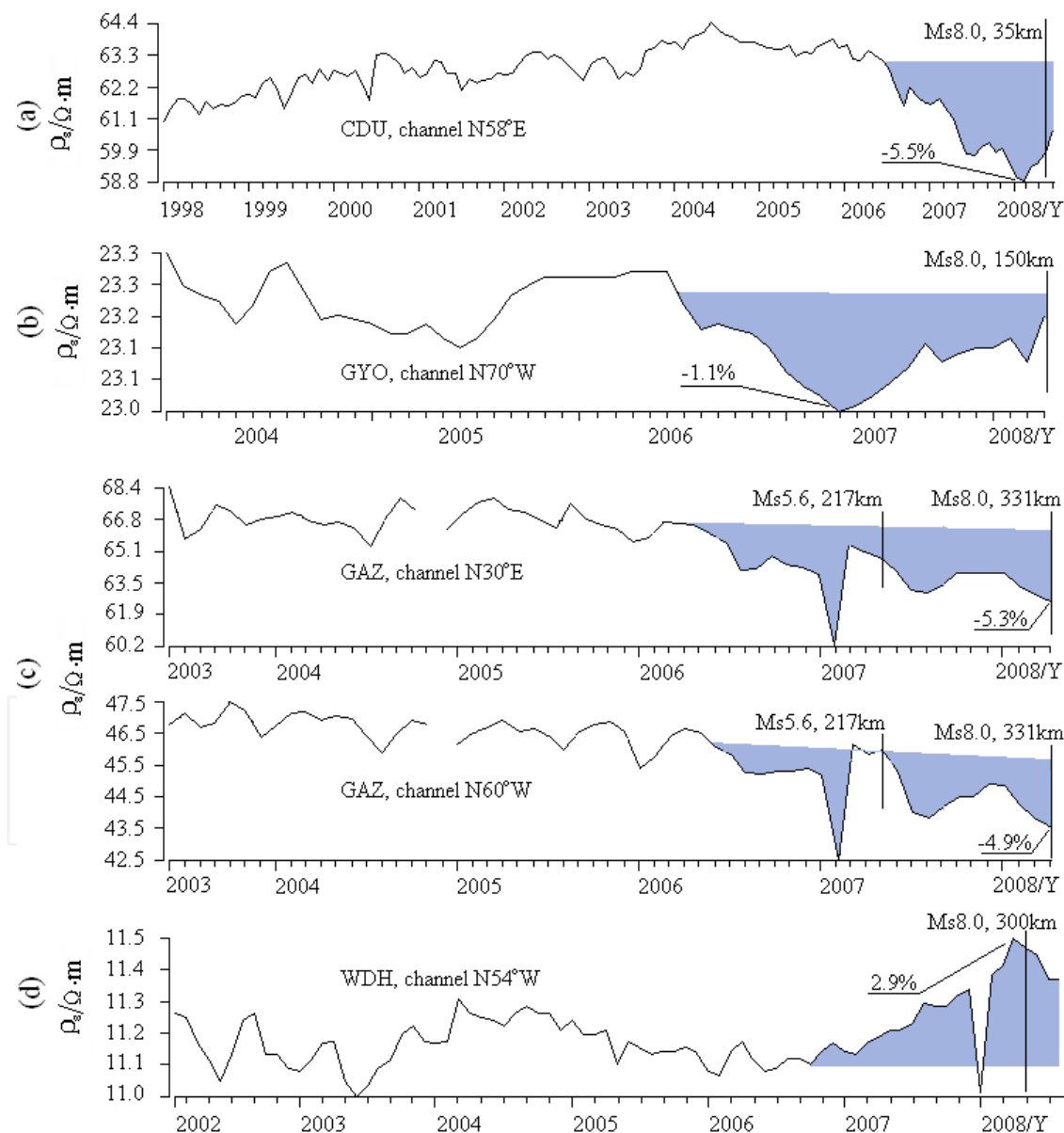


Fig. 5. AR monthly mean changes observed at four stations that were located along the Songpan-Ganzi active block before the M8.0 Wenchuan EQ

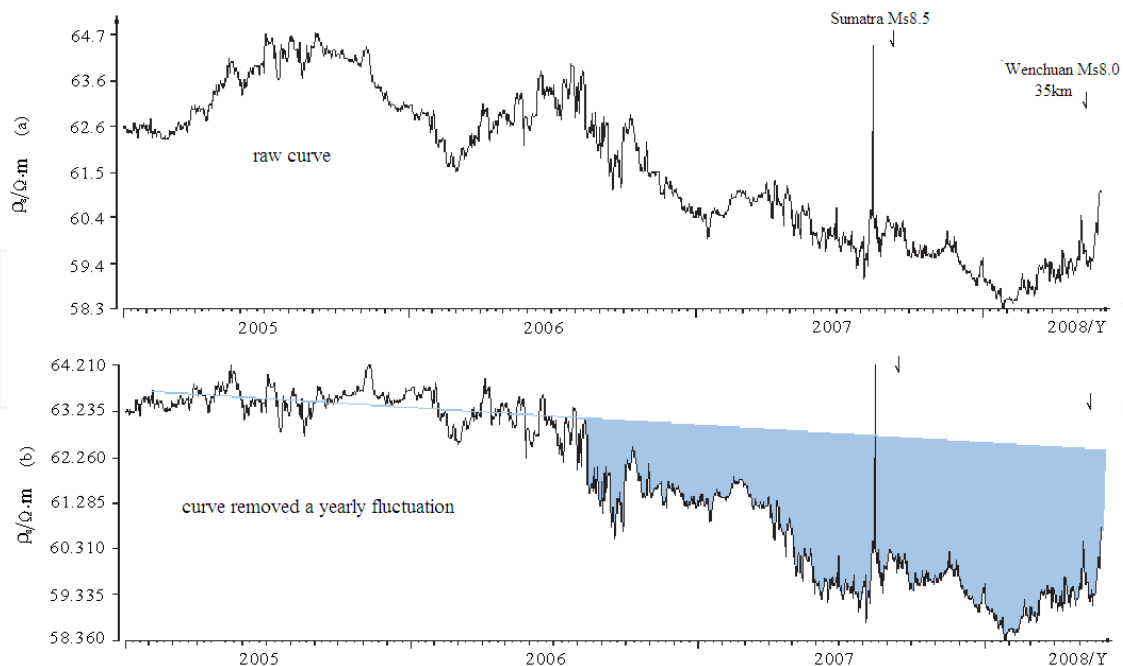


Fig. 6. AR daily mean changes observed at CDU station before the M8.0 Wenchuan EQ

Furthermore, the spatial distribution of the anomalies was tectonically relevant to the Songpan-Ganzi active block. The main shock and its aftershocks occurred along the Longmen mountain nappe structure of the block. Accordingly, the anomalies were recorded at the four stations along the bordering faults around the block (Fig.4), whereas such anomalies were not recorded at the two stations MNI and XCM, which were located along the Anning river fault, beyond the block. This situation is similar to that which was observed before the 1976 Ms7.8 Tangshan EQ when anomalies appeared mostly at the stations along NE- and NW-striking conjugate faults in the Beijing-Tianjin-Tangshan areas.

According to previous statistical studies on numerous EQ cases^[5-6] by other Chinese scholars, the spatially distribution of medium-term AR anomalies is about 300~400 km before an EQ with magnitude of $M_s \geq 7.0$. According to paper^[7], for $M_s > 6.0$ EQs most AR anomalies distribute in the range of 400 km from epicenters and there is commonly no obvious difference between the ranges for $M_s > 6.0$ EQs and $M_s \geq 7.0$ EQs. The results show that an epicentral distance of 400km can be used as a reference for identifying medium-term AR anomalies related to $M_s > 6.0$ EQs. Du *et al.*^[8] studied the relationship between the spatial distribution of medium-term anomalies of other precursor observations in China, such as AR, groundwater chemical components and water level, geo-stress and geo-deformation, and the mainly active fault around the epicentral region, as a result, it was believed that the anomalies usually appeared nearby the faults around EQ focal areas.

The spatial distribution of the medium-term AR anomalies before the Wenchuan great EQ, which were concentrated in the range of 400 km from the main epicenter and along the bordering faults around the Songpan-Ganzi active block, was in accordance with the foregoing research results.

2. Synchronous medium-term AR anomalies

These AR anomalies started to appear from about Aug. 2006 at CDU, JYO, GAZ and WDH. In other words, they appeared synchronously before the main shock at the four stations which were located along the bordering faults of the Songpan-Ganzi active block. The

behavior was similar to previous research results. According to Du et al.^[8], the medium-term AR anomalies along a actively geological structure around an EQ focal area usually started to appear synchronously or quasi-synchronously. In fact, the medium-term anomalies in observation of groundwater chemical components and water level, geo-stress and geo-deformation along a same structure also have such behavior as seen in AR observation^[8].

3. Mostly drop-type AR anomalies

The drop-type anomalies were recorded at stations CDU, GAZ and JYO. Only at station WDH, was a rise-type anomaly recorded, yet this was not isolated. Stations WDH and Tianshui (TSE), in Gansu province, were all located to the north of the main epicenter, and station TSE was to the north of station WDH, which was nearby the NWW-striking western Qinling rupture belt and was 452 km from the main epicenter. At station TSE, a rise anomaly beyond 1% appeared during two months period preceding the main shock, which was the most prominent AR change in the last ten years at the station. The phenomenon of mostly drop-type AR anomalies coincided with previous researches, and the spatial distribution of the medium-term anomalies at the four stations well tallied, in the range of -400 km, with that before EQs with magnitude $M_s > 7.0$.

For change of patterns, a drop-type or rise-type change, of the medium-term AR anomalies which were processed by using the normalized variation rate method (NVRM)^[9,7], Du et al.^[10,7] got the following statistic results: for $M_s \geq 7.0$ EQs, about 100% of the anomalies in the range of 150 km from epicentral areas are negative (a drop-type pattern) and about 71% of the anomalies in the range of 400 km are still negative. The reasons on the change patterns of the anomalies was theoretically explained by papers^[10, 7].

4. Large-amplitude anomalies

At station CDU, which was the nearest station to the EQ epicenter, the anomaly amplitude reached up to -5.5%. At stations GAZ and WDH, which were farther away from the EQ epicenter than station CDU, the anomaly amplitudes reached up to -5.3% – -4.9% and 2.9%, respectively. The mean of the anomaly amplitudes was larger than that before the 1976 M7.8 Tangshan EQ, and the anomaly amplitudes of the three stations decreased with the increase of epicentral distance. The anomaly recorded at JYO was small in amplitude, only -1.1%, although it was nearby the main EQ epicenter area (according to an investigation after the EQ, the measuring instrument at the station was not in good operation at that time, with a fixed error).

The relationship between AR anomaly amplitude and EQ magnitude has been studied by numerous scholars^[5-7]. The anomaly amplitude before the Wenchuan great EQ was in accordance with the previous researches.

5. Anisotropic AR changes

Two observation channels, along N58°E and N49°W directions, are employed at station CDU. The anomaly amplitude recorded through the N58°E channel was -5.5%, whereas no anomaly was recorded through the N49°W channel. According to previous works^[2,11], this anisotropic AR changes roughly indicated that the underground media here had been under the action of the maximum compressive stress in the NW-SE direction during the period from about Aug. 2006 to the occurrence of the main shock. At station GAZ, two channels, along N30°E and N60°W directions, are employed. The anomaly amplitude recorded

through the N30°E channel was -5.3%, and that recorded through the N60°W channel was -4.9%. This indicated that the media here had been under the maximum compressive stress in the NWW-SEE direction during the period. The maximum compressive stress directions that were revealed by the AR changes at the two stations basically corresponded to the P-axis azimuth of the main shock^[12]. Station JYO was near the northern aftershock area of the great EQ, and two channels, along the N70°W and N10°E directions, are employed at the station. The comparison between anomaly amplitudes recorded through the two channels was still credible as the measuring instrument at the station had just a fixed error. The anomaly amplitude recorded through the N70°W channel was -1.1% and no anomaly was recorded through the N10°E channel. This indicated that the media here had been under the maximum compressive stress close to the NS direction during the period, which well corresponded to the P-axis azimuths of most strong aftershocks in the northern aftershock area.

In summary, the behaviors of these medium-term AR anomalies, such as their spatial distribution within 400 km, their tectonic relevance to the Songpan-Gazi active block, and their amplitude attenuation with increasing distance, as well as their synchronous, mostly descending, large-amplitude and anisotropic changes, strongly support that these anomalies are indeed related to the focal processes of the main shock and strong aftershocks. Such locally concentrative AR anomalies as recorded at the four stations have not been succeeded in identifying in areas beyond 400 km from the EQ epicenter.

2.1.2.2 Short-term AR anomalies before the EQ

During the short-term period before the occurrence date of the great EQ, no obvious anomaly, like these recorded at station CLH (72km) in Hebei province before the 1976 M7.8 Tangshan EQ and at station WDH (110 km) before the 1976 M7.2 Songpan-Pingwu EQs (Fig.2), was recorded at the six stations within 400 km from the EQ epicenter. Upward AR changes commenced at station CDU from March 2008 and at station JYO from April 2008 (Fig.5a-b and Fig.6). The patterns consisting of an initial medium-term drop change followed by a short-term rise change before the EQ are consistent with these of the electrical resistivity change within an EQ focal area that are forecasted by DD model^[13-14]. In fact, such patterns appeared often nearby epicentral areas of previous strong EQs^[9, 27]. However, the rise change, upon which the main shock occurred, did not satisfy the anomaly criterion in amplitude, so no sufficient precursory information could be confidently detected in the period when approaching the EQ.

Du *et al*^[3, 15] studied the spatial distribution characteristics of imminent AR anomalies before the moderate, strong EQs that occurred in the continent of China. As a result, it was got that the spatial distribution of the anomalies was influenced by mainly active faults around EQ focal areas and focal mechanisms. The influences include: (1) the anomalies appear mostly along or nearby the faults; (2) most anomalies are distributed in the two areas that are symmetrical about an epicenter and that azimuthally tie to the P- or T-axis areas that correspond to the focal fault movement; (3) If there is an active fault between a station and an epicentral area, and the fault strike is along or close to the azimuth of the foregoing P- or T-axis, then, no imminent anomaly is usually recorded at the station in the period when approaching the EQ, or an anomaly is generally weak in amplitude.

For example, in the Songpan-Pingwu area in Sichuan Province, three EQs with magnitude of Ms7.2, Ms6.7 and Ms7.2 occurred successively within 8 days in August 1976 at almost the same location (Fig.7), under the action of the compressive stresses in the NE direction (for the previous Ms7.2 EQ) and near to the EW direction (for the following Ms6.7/7.2 EQs)^[16].

And the P-axis azimuths of the three EQs were 63° , 101° and 95° , respectively, resulting in an right-lateral movement of the NNW-striking Huya fault (i.e., the focal fault) when the previous Ms7.2 EQ occurred, and then an left-lateral movements of the fault when the following Ms6.7 and Ms7.2 EQs occurred^[16]. At that time, three stations were in observation within a range of ~ 190 km from the three epicenters: station Songpan (SPN, 45km, and it was abandoned shortly afterwards) in Sichuan Province and station Lixian (LXN, 190 km, and abandoned in the 1990s) and station WDH (110 km), in Gansu Province. There were obvious differences between AR changes recorded at station SPN and those recorded at station LXN (Fig. 8). Station SPN was located on the west side of the Minjiang River fault (MRF) with the NNE strike, whereas the epicenters were to the east of the fault. As a result, no imminent AR anomaly was recorded at station SPN when approaching the occurrence date of the first Ms7.2 EQ, though the station was only 45 km from the epicenter, whereas at LXN station, a drop anomaly with amplitude of -0.8% was recorded during 4 days before the EQ in despite of being 190 km away. Contrarily, for the subsequent Ms6.7 and Ms7.2 EQs, a drop anomaly with amplitude of -3.5% was clearly captured at station SPN during 3–4 days before them. This anomaly amplitude was much greater than that recorded at station LXN before the first Ms7.2 EQ. No imminent anomaly appeared at station LXN for the latter EQs. At station WDH, which was located between station LXN and the three epicenters and was near to the north side of the White Dragon River fault (WDRF) with the EW strike, the AR changes recorded before the three events were similar to those seen at station LXN.

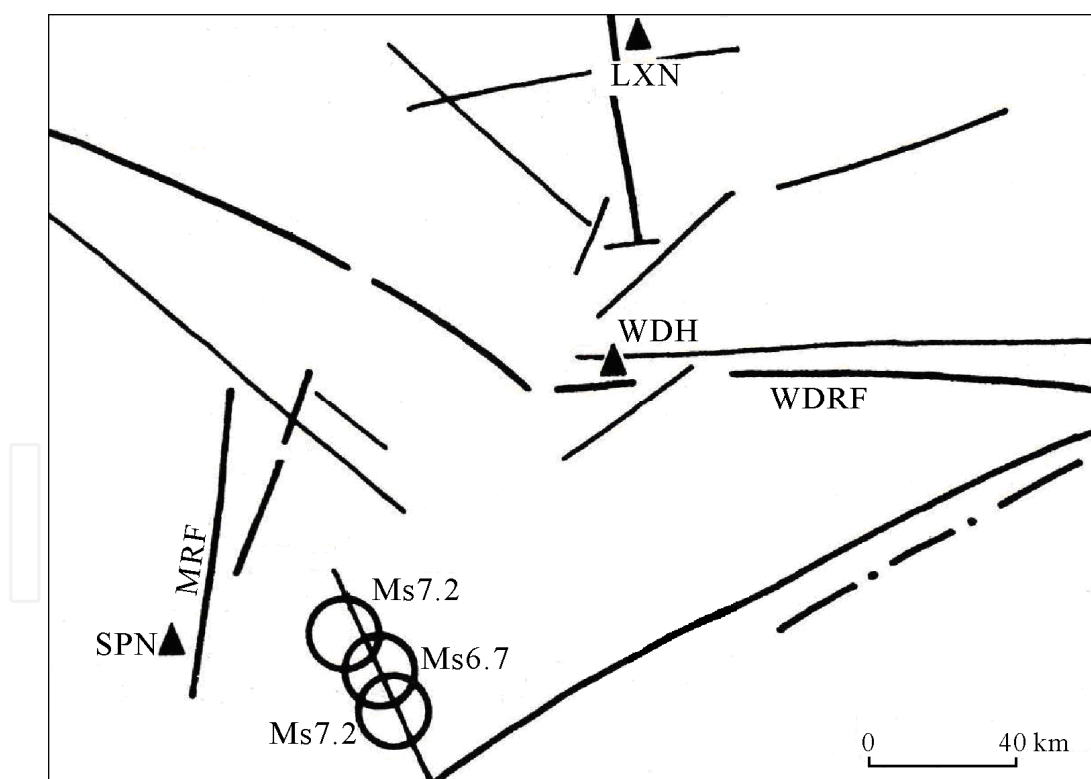


Fig. 7. Distribution of epicenters, active faults and AR stations

According to papers[4, 17], imminent anomalies recorded at underground water level and water chemistry stations before the moderate, strong EQs which occurred in the continent of China also demonstrated such spatial distribution as AR imminent anomalies, which was related to mainly active faults of epicentral areas and EQ focal mechanisms. From loading

experiments of rock sample^[18], the crust medium nearby active faults are susceptible to stress disturbances during the loading processes, therefore, the AR and underground-water anomalies which is related to the geo-stress changes are easy recorded nearby the faults. Paper [19] calculated the strain distribution in a geologic body model with a fault using the elasto-plastic 2-D finite element method, and then the calculated strain values are converted into relative AR changes. It can be seen from the spatially non-uniform distribution of these calculated AR changes that the spatial distribution of AR changes which are related mainly active faults around epicentral areas and EQ focal mechanisms, as described in papers [3,15,7], can be well explained. In fact, the spatially non-uniform distribution of imminent anomalies in observation of underground water level and water chemistry, as described in papers [4, 17], can be well explained based on the calculated strain distribution by paper [19] also.

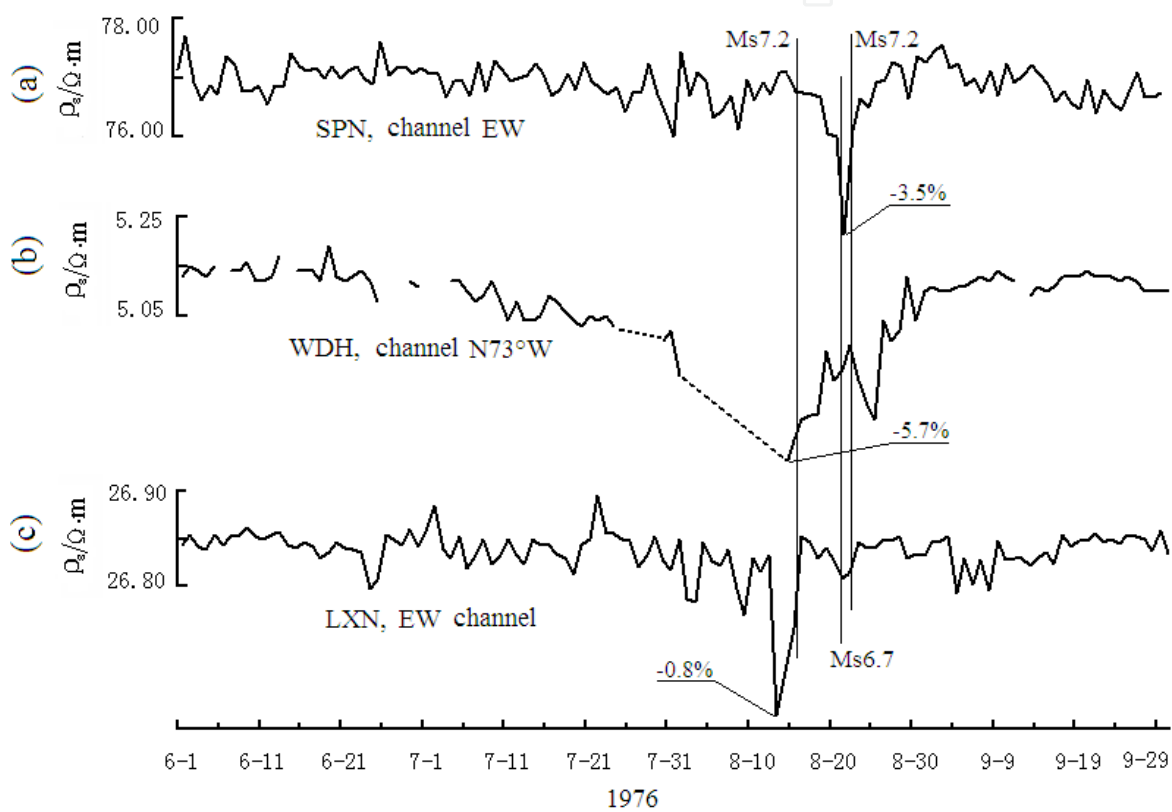


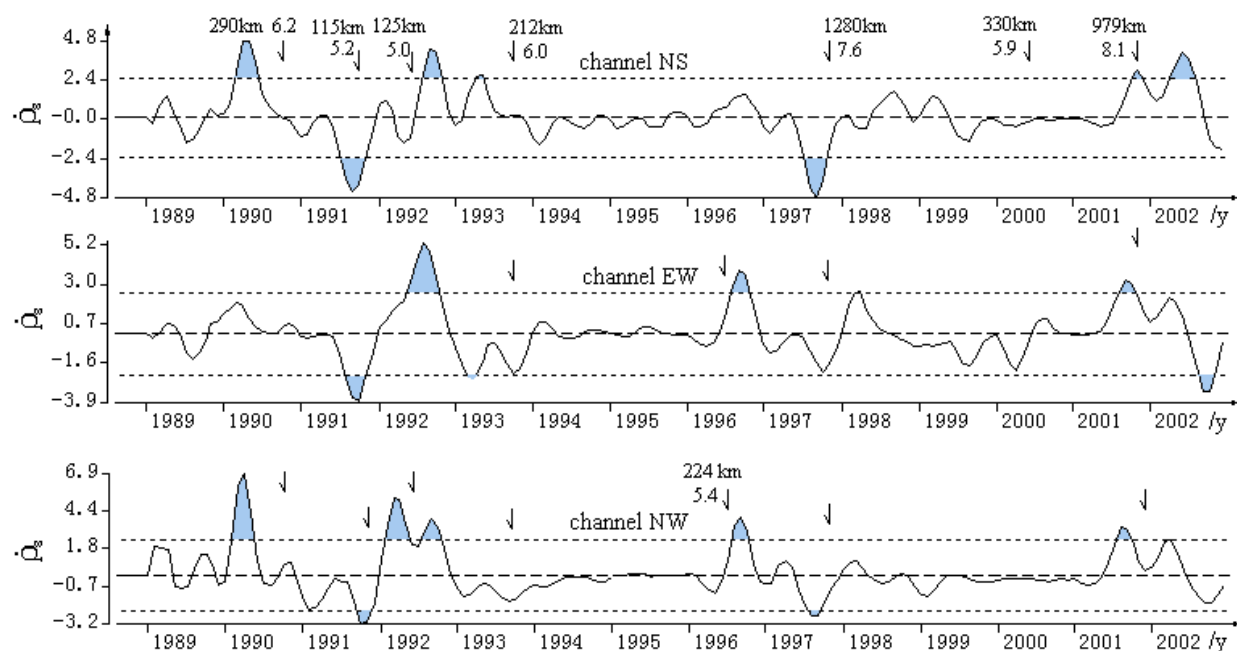
Fig. 8. AR daily-mean curves of SPN (a), WDH (b) and LXN (c) stations

Based on the above-mentioned research works, the lack of imminent AR anomalies before the Wenchuan great EQ can be roughly explained. The main shock and strong aftershocks occurred to the west of the NE-striking Doujiang Weir-An county fault; station GAZ was located on the southwestern side of the NW-striking Xianshui River fault, and station WDH was located on the northern side of the NWW-striking WDRF (Fig.4 and Fig.7). Hence, the reason why no anomaly was recorded at stations GAZ and WDH during the period when approaching the great EQ can be explained. The reason why no anomaly was seen at stations MINI and XCM can be explained also. Stations CDU and JYO were located to the east of the Doujiang-Weir-An county fault, near the main epicenter and in the area liable to record the anomaly related to the main shock, but at the two stations only weak upward changes were recorded during the period. The reason for this remains to be explained and requires additional research.-A possible reason is affected by secondary faults nearby the two stations.

2.2 Medium-term AR anomalies discerned before EQs

On Oct. 25, 2003, two EQs with magnitude of Ms6.1 and Ms5.8 occurred in Minle-Shandan area in Gansu province of China. This year, on Jul. 21, one Ms 6.2 EQ occurred in the Dayao area in Yunnan province, and on Oct. 6, a Ms6.1 EQ occurred also in Dayao area. In fact, the medium-term AR anomalies were well discerned before the two groups of strong EQs, and the EQ locations and magnitudes were successfully forecasted on a one-year time scale, in Nov. of 2002.

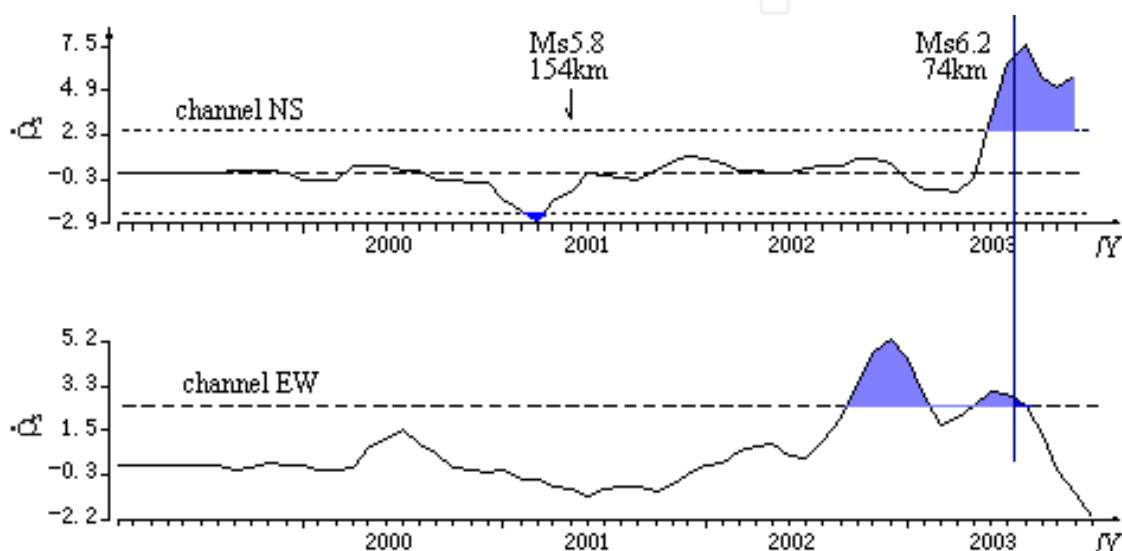
Within the range of ~400 km from the epicenters of the Ms 6.1/5.8 Minle- Shandan EQs, there were 6 AR stations, such as Shandan (SHD), Wuwei (WWE), Jayuguan (JYG), Lanzhou (LZL), Linxia (LNX) and Dingxi (DGX) stations, which are all set by China Earthquake Administration (CEA). Of 6 stations, the previous 5 stations, not including DGX station, were in good observation at that time. Of the 5 stations, reliable medium-term AR anomalies, drop-type AR changes, appeared at station SHD during the end of 2002. This station has always kept an observational environment which is up to the technical requirement of seismic geo-electrical station in the long-term observation. Figure 9 shows AR normalized variation rate curves of three channels of this station from Aug. of 1988 to Oct. of 2002, based on monthly AR averages, which are processed by the normalized variation rate method (NVRM)^[9,7] in Nov. of 2002. It can be seen from the curves that notable medium-term or short-term AR anomalies which were up to the identification criterion for NVRM anomaly, beyond the threshold value of ± 2.4 , appeared before several EQs with magnitude of Ms ≥ 5.0 around the station from 1990 to 2001. In 2002, two drop-type AR anomalies appeared again through channels EW and NW of the station, and a rise-type anomaly did through channel NS. These anomalies were new, following the rise-type anomalies of three channels in the end of 2001 which corresponded to the Nov. 2011 Kunlunshan mountain Ms8.1 EQ far—one type of anomalies which had nothing with the focal process of the great EQ^[20, 7-8]. According to the past EQ cases of the station where AR anomalies corresponded to EQs around and the research results in papers [8,10], Du *et al.* forecasted in Nov. 2002 that one strong EQ will occur nearby the station in 2003 year.



Note: these curves were drawn in Nov. of 2002

Fig. 9. NVRM curves of AR changes of SHD station (from Aug. of 1988 to Oct. of 2002)

In Nov. of 2002, Du *et al.* also detected that AR anomalies appeared at Panzhihua (PAH) and Yuanmou (YNM) in Yunnan province. The AR data, monthly mean data, observed by the two stations were processed using NVRM. Figure 10 gives the NVRM curves of PAH station which were reprocessed in 2004. This station was settled in 1970s, around which many EQs with magnitude of $M_s \geq 5.0$ have occurred since then, accordingly, at this station AR anomalies have been recorded before the EQs. According to the previous EQ monitoring efficiency of the station, Du *et al.* forecasted in Nov. of 2002 that the AR upward anomaly of 2002 at this station, as seen in figure 10 (the lower curve in the figure), possibly indicated an future strong EQ nearby the station. Besides, at YNM station which was close to the PAH station, AR upward anomalies appeared in the end of 2002 also. Thus, the credibility for the expected EQ was increased.

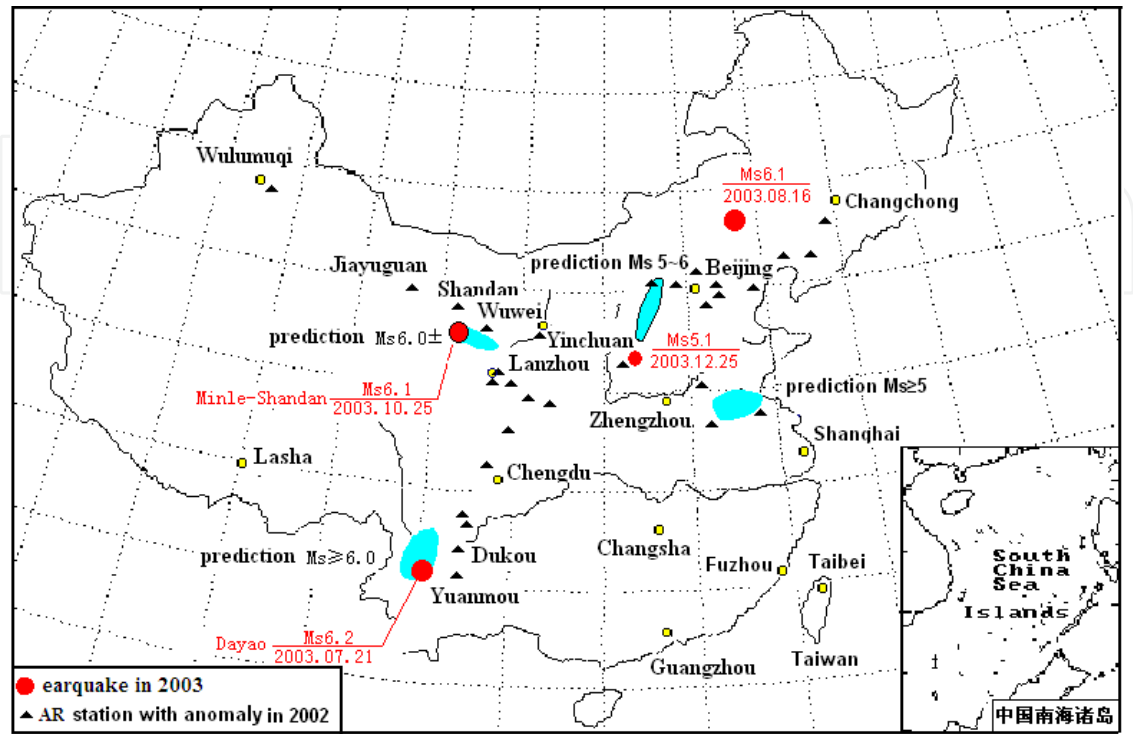


Note: these curves were drawn in Nov. of 2004

Fig. 10. NVRM curves of AR changes of PAH station (from Jan. of 199 to Dec. of 2003)

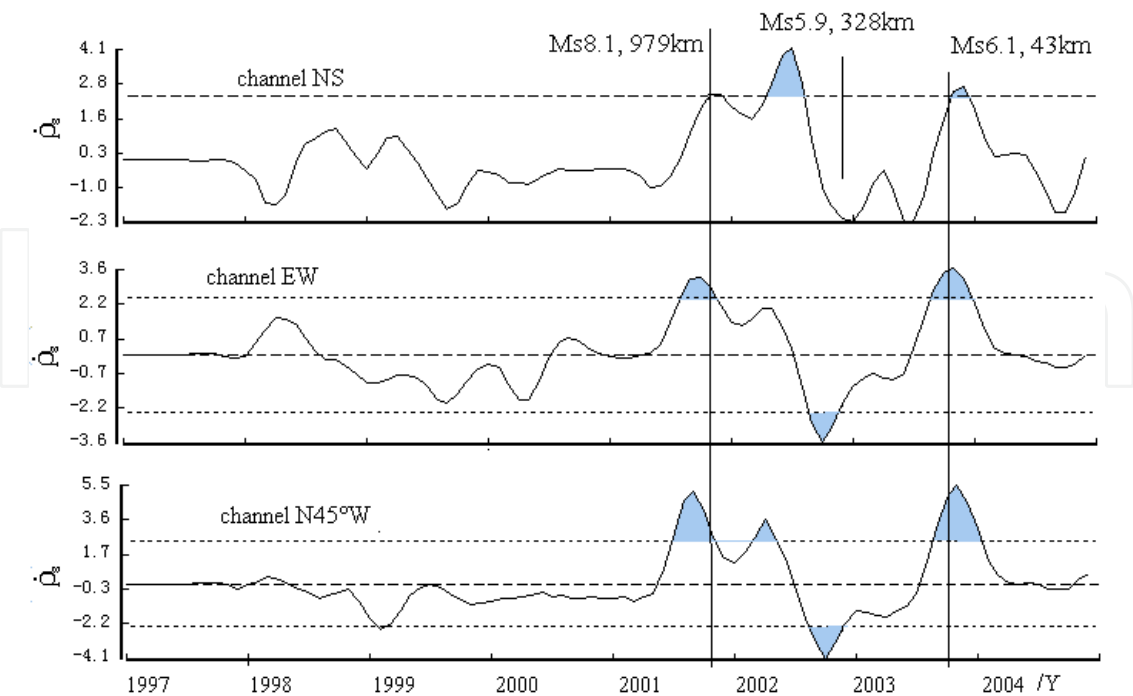
Apart from these above-mentioned, Du *et al.* processed the observation data of other AR stations in the continent of China in Nov. of 2002, as a result, in other places some AR anomalies appeared in 2002 also. Thus, Du *et al.* submitted an EQ forecast view to CEA, a formal written report in Nov. of 2002. In the report, Du *et al.* believed that several EQs probably occurred in 2003 year within 4 regions with the maximal radius being less than 100 km and the minimal radius being less than 60 km, and expected EQ magnitudes were $M_s 6.0 \pm$, $M_s \geq 6.0$, $M_s 5 \sim 6$ and $M_s \geq 5$ (Fig.11), respectively. As a result, the EQs as expected in this report indeed occurred in the former two regions in 2003. It is the case that the Oct. 25, 2003, $M_s 6.1$ and 5.8 Minle~Shandan EQs just occurred in the forecast region with magnitude of $M_s 6.0 \pm$, in Gansu province; and the Jul. 21 $M_s 6.2$ and Oct. 10 $M_s 6.1$, 2003, Dayao EQs just occurred in the forecast region with magnitude of $M_s \geq 6.0$, in Yunnan province (Fig.11). In figure 11, the two forecast regions were marked in green color, painted in Nov. 2002, and the two solid circles in red are the locations of occurrence of the two groups of EQs. In other two forecast regions with magnitude of $M_s 5 \sim 6$ and $M_s \geq 5$, the expected EQs did not occur, and still nearby the forecast region with magnitude of $M_s 5 \sim 6$, in Shanxi province, one $M_s 5.1$ EQ happened in Nov. 2003. The former two strong EQs are successfully predicted, which locations and magnitudes are properly estimated and which occurred in 2003 year, a one-year time scale prediction, therefore, it is reasonable to believe that the AR changes

related to the two strong EQs were truly recorded before the occurrence of the two EQs. In 2005, the case for forecasting the two strong EQs was in public reported in paper [21].



Note: (1) Red solid circles are EQ epicenters that occurred in 2003; (2) Green areas are forecast areas where EQ will occur in 2003; (3) Black solid triangles are AR stations where AR anomaly appeared in 2002

Fig. 11. Distributions of epicenters, AR stations and forecast areas



Note: these curves were drawn in 2004

Fig. 12. NVRM curves of AR changes of SHD station (from 1997 to 2004)

After the Ms6.1 and 5.8 Shandan-Minle EQs, Du *et al* again processed the AR data observed at SHD station (43 km) from the two epicentral areas 1997 to 2004 using NVRM, as a result, it can be seen from figure 12 that the medium-term drop-type to short-term rise-type AR changes are similar to the AR changes in the focal area as foretold by the DD model (Dilatancy-Diffusion Model)^[13-14] in appearance, a pattern consisting of an initial medium-term fall followed by a short-term rise.

People may ask why the May 12, 2008, Ms8.0 EQ was not forecasted in the medium-term period before the great EQ, which just occurred around/nearby 6 AR stations in this area? In fact, authors had no time to process and analyze the AR data observed at the 6 AR stations in those days, and the AR changes of the stations were analyzed and studied only after the great EQ^[7].

3. Anisotropic AR changes related to strong EQ

Kraev studied the calculating method of AR in a homogeneous anisotropy medium^[22]. Later, Brace *et al.*^[23], Chen *et al.*^[24] and Lu *et al.*^[25] reported that during the loading process of most rock (soil) samples, AR changes showed the directional changes which were associated with the maximum loading direction. In recent years, people try to explore related-earthquake anisotropic AR changes, which would have an important significance to understand the stress status in/nearby the EQ focal region, to explain the reason of related-earthquake AR changes and to forecast an EQ. However, it is very difficult to detect the anisotropic changes from actual EQ cases. Such researches were reported only in China because China has long made a lot of fixed-site AR observations. Qian *et al.*^[26] and Du *et al.*^[9, 11] reported that the anisotropic AR changes that were associated with the maximum compressional stress (P-axis) azimuths of EQ focal mechanism solutions, and Du *et al.*^[2, 27] try to explain the anisotropic AR changes in theory.

3.1 Analysis of EQ cases on anisotropic AR changes

The studied EQ cases are picked out according to the following three principles: ①strong EQs with magnitude of $M_s \geq 5.5$, ②EQs nearby AR stations, and ③AR changes in the later stages of EQ preparation. From the formula to estimate the focal body radius L ^[29], $M_s = 3.3 + 2.1 \log L$, for Ms5.5 EQ L is no more than 15 km, for Ms 6~7 EQ L is no more than 60 km and for Ms7.8 EQ L is about 140 km. According to Du *et al.*^[7, 10], AR anomalies within tens km for Ms 6~6.9 EQs and within 150 km for $M_s \geq 7.0$ EQs are mostly characterized by drop-type changes in the medium-term stages of EQ preparation. The underground medium commonly contains rich water, so the concentrative range of the drop-type AR changes is well coincident with the focal body radius L . This indicates how we pick out the EQs nearby stations.

It is very important in study of anisotropic AR changes to distinguish the precursory AR anomaly related to strong EQs from observational AR data. Therefore, NVRM is usually used to process data. Du *et al.*^[11] have studied anisotropic AR changes, using NVRM, recorded at 41 stations before 27 $M_s \geq 5.5$ EQs that occurred in the Chinese mainland. The results show that for over 95% of the stations, the anisotropic AR changes appeared during the later stages of EQ preparation, which were obviously related to the P-axis azimuth of EQ focal mechanism solution. The behaviors of these anisotropic changes are that the AR change recorded through the channel perpendicular (or almost perpendicular) to the azimuth is a maximum in amplitude, whereas that recorded through the channel along (or close to) the azimuth is a minimum.

For example, the two observation channels, N20°E and N70°W channels, are installed at station PGU that had epicentral distances of 111 and 140 km for the 1976 Ms7.8 Tangshan EQ and Ms7.1 Luanxian aftershock; the P-axis azimuths of the two events were 75° and 297°, respectively, roughly in the EW direction. As a result, the medium-term drop-type and short-term rise-type AR changes recorded through N20°E channel (with a near NS direction) prior to the EQs were greater in amplitude than those through N70°W channel (with a near EW direction) (Fig.13). As another example, three channels, NS, EW and N45°W channels, are installed at station SHD that had an epicentral distance of 43 km for the 2003 Ms6.1 Minle- Shandan EQ; the P-axis azimuth of this EQ was 65°. As a result, the medium-term drop-type and short-term rise-type AR changes recorded through N45°W channel prior to the EQ were greater in amplitude than those through EW channel (Fig. 12).

It is obvious that the relationship between the anisotropic AR changes and the P-axis azimuth from actual EQ cases agrees well with the relationship between the directional AR changes and the maximum loading direction in most experiments of water-bearing rock (or soil) samples. This proves that such AR changes are just related to the EQ preparation process.

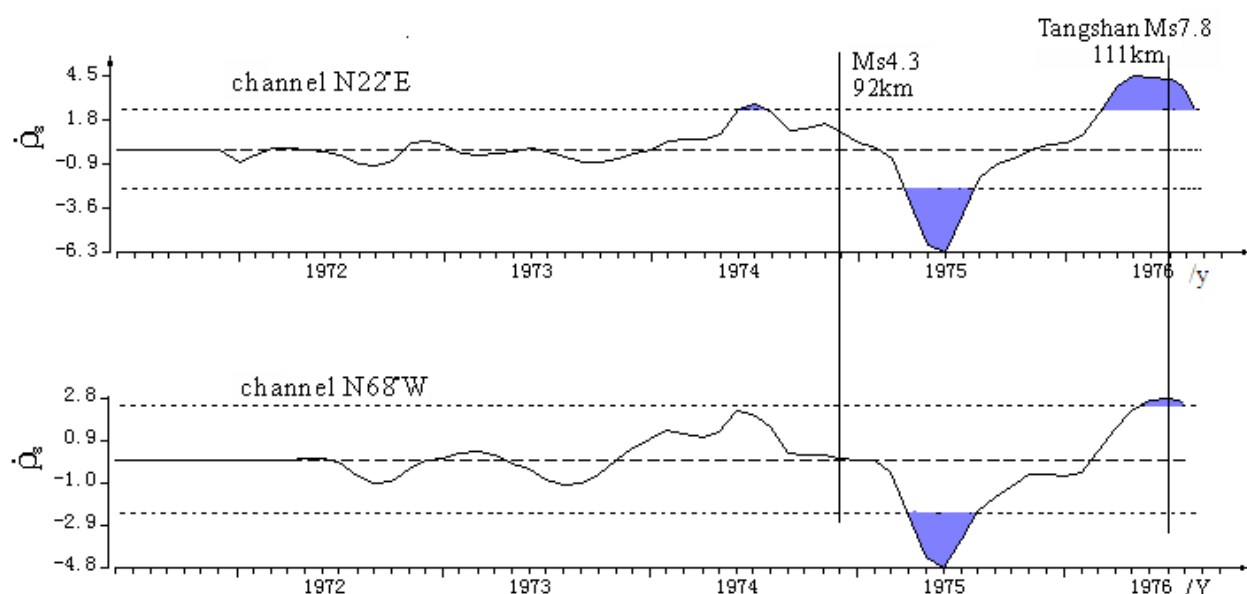


Fig. 13. NVRM curves of AR changes of station PGU for the 1976 Ms 7.8 Tangshan EQ

3.2 Theoretical analysis on anisotropic AR changes

According to DD model, the micro cracks inside the underground medium fast and nonlinearly develop immediately before the main rupture within an EQ focal area, their strikes align predominately in a certain direction and underground water fast come in them. Barsukov^[29] interpreted a larger amplitude change in resistivity on the assumption that the micro cracks are tortuously linked each other, and underground water comes in them, as a result, the conductive aisles inside the medium are formed. Mei *et al.*^[30] deduced that in the later preparation stages of strong EQs a number of micro-cracks inside the medium of an EQ focal region is increased sharply. The fact that in the medium-term stages before moderate, strong EQs of the Chinese mainland, for larger-magnitude EQs the AR anomaly amplitude increases fast, whereas the anomaly duration increases more slowly^[10] supports Mei's deduction. According to Crampin *et al.*^[31], the maximum compressional stress inside the

near-surface crust is commonly horizontal, and because of hydrostatic pressure of rock the horizontal cracks are closed and the erect cracks are developed, with the normal of the erect cracks being usually mostly horizontal and the strikes of the cracks being predominantly along in the direction of the maximum compressional stress axis. As a result, this forms an EDA medium with conductive fluid. According to the above-mentioned discussions, we presume that in the later preparation stages of strong EQs there probably exist two physical behaviors inside the medium in and nearby the focal area: (a) the erect micro-cracks is well developed, their number is non-linearly increased, and their strikes are predominantly along the direction of the maximum compressional stress axis. (b) in above-mentioned processes, the macro-cracks are linked each other and the underground water with low resistance comes fast in them. This forms the conductive aisles in the medium. As the result of its sensitivity to water, the electrical resistivity of the medium, therefore, undergoes significant changes.

Based on the two physical behaviors, we approximately regard the medium in/nearby the EQ focal region as a homogeneous azimuthal anisotropic medium. We establish a Descartes coordinate system $o-x_1x_2x_3$ on the ground where x_1 , x_2 and x_3 are three electrical principal axes, respectively, which x_2 is along the horizontal loading direction (this means the P-axis direction of EQ focal mechanism solution in study of EQ cases), x_1 is horizontal and perpendicular to the direction and x_3 is downwards vertical to the ground surface. ρ_1 , ρ_2 and ρ_3 are true resistivity (TR) along the three axes, respectively, and $\rho_1 > \rho_2 = \rho_3$. φ is the angle between ground observation channel X and the axis x_1 . Another ground observation channel Y is perpendicular to channel X. Based on the calculating formula for the relative AR changes ($\Delta\rho_s/\rho_s$) in the anisotropic medium by Du *et al.*^[2] (after referring to paper [22]), we can get the relation of relative AR changes ($\Delta\rho_{sx}/\rho_{sx}$ and $\Delta\rho_{sy}/\rho_{sy}$) of observational channels X and Y to relative TR changes ($\Delta\rho_1/\rho_1$ and $\Delta\rho_2/\rho_2$) in two horizontal principal axes directions. When $\varphi = 0^\circ$ (here, channel X is perpendicular to the loading direction and channel Y is along the direction) the relation is as follows:

In x_1 direction (perpendicular to the maximum loading direction)

$$\frac{\Delta\rho_{sx}}{\rho_{sx}} = \frac{\Delta\rho_2}{\rho_2} \quad . \quad (1)$$

In x_2 direction (along the loading direction)

$$\frac{\Delta\rho_{sy}}{\rho_{sy}} = \frac{1}{2} \left(\frac{\Delta\rho_1}{\rho_1} + \frac{\Delta\rho_2}{\rho_2} \right) . \quad (2)$$

According to most loading experiments of rock (soil) samples, following two inequalities are generally true:

$$\text{When } \frac{\Delta\rho_s}{\rho_s} < 0, \quad \frac{\Delta\rho_{sx}}{\rho_{sx}} < \frac{\Delta\rho_{sy}}{\rho_{sy}}; \quad (3)$$

$$\text{When } \frac{\Delta\rho_s}{\rho_s} > 0, \quad \frac{\Delta\rho_{sx}}{\rho_{sx}} > \frac{\Delta\rho_{sy}}{\rho_{sy}}. \quad (4)$$

From formulas (1) ~ (3), we can get that the TR changes along the two principal axes satisfy the following inequality:

$$\frac{\Delta\rho_2}{\rho_2} < \frac{\Delta\rho_1}{\rho_1}. \quad (5)$$

Let the AR variation rate $\dot{\rho}_s = \Delta\rho_s / \Delta t$ (Δt is a time interval). When the underground medium change from homogeneous ($\rho_{sx} = \rho_{sy}$) into anisotropic ($\rho_{sx} \neq \rho_{sy}$), we can obtain the inequality of $\dot{\rho}_{sx} < \dot{\rho}_{sy}$ from inequality (3), in which $\dot{\rho}_{sx}$ is the AR variation rate of channel X and $\dot{\rho}_{sy}$ is that of channel Y. From the inequality and formulae (1) and (2) as well as the calculating formula for ρ_s in the anisotropic medium, the following inequality is obtained^[11]:

$$\dot{\rho}_2 < \frac{\lambda^2}{2\lambda - 1} \dot{\rho}_1. \quad (6)$$

Where $\dot{\rho}_1$ and $\dot{\rho}_2$ are TR variation rates along two electrical principle axes, and a true anisotropic coefficient $\lambda = \sqrt{\rho_2 / \rho_1}$ ($0 < \lambda < 1$). In the case of $0.5 < \lambda < 1.0$ (viz., $1 < \rho_1 / \rho_2 < 4$), we get the following inequality:

$$\dot{\rho}_2 < \dot{\rho}_1. \quad (7)$$

If the AR changes along the loading direction and perpendicular to the direction are all increased the sign ">" will replace "<" in inequalities (5) and (7), from inequality (4). According to inequalities (5) and (7) and their derivation conditions, we can have the following understandings: anisotropic TR changes in which the change along the loading direction is more prominent than that perpendicular to the direction cause anisotropic AR changes in which the change perpendicular to the direction is more prominent than that in the direction. It is obviously that there are a difference of 90° between the directions of both the most prominent AR change (perpendicular to the loading direction) and the most prominent TR change (along the loading direction). This result distinctly explained the relationship between the most loading direction and the anisotropic AR changes when approaching the main rupture of most rock (or soil) samples and theoretically supported the research results from actual EQ cases.

3.3 A Reason for anisotropic AR changes

From the TR relationship among three principal axes in the anisotropic medium, $\rho_1 > \rho_2 = \rho_3$, we assume the shape of a single micro crack as a schistose ellipsoid that takes ρ_1 axis as its rotation axis, and whose radius is a in x_2 direction, b in x_3 direction and c in x_1 direction and $a=b>c$ (an erect crack). And then, we assume that the resistivity in saturated-water cracks (water is rich within the underground medium) is ρ_f , that of framework is ρ_o and the crack ratio is v . Using Kraev's result^[22] we have the approximate formulae of $\Delta\rho/\rho$ versus $\Delta v/v$:

$$\left. \begin{aligned} \frac{\Delta\rho_1}{\rho_1} &\approx \frac{\rho_f - \rho_o}{\rho_o/v + \rho_f} \cdot \frac{\Delta v}{v} \\ \frac{\Delta\rho_2}{\rho_2} &\approx \frac{\rho_f - \rho_o}{\rho_f/v + \rho_o} \cdot \frac{\Delta v}{v} \end{aligned} \right\} \quad (8)$$

In generally, $\rho_o \gg \rho_f$. From formulae (8), $\Delta\rho_1/\rho_1 < 0$ and $\Delta\rho_2/\rho_2 < 0$ when $\Delta v/v > 0$, and they will decrease with $\Delta v/v$ going bigger, which could be why most AR anomalies in/nearby the epicenter region in the late preparation stages of strong EQs are commonly a drop-type pattern; And $\Delta\rho_1/\rho_1 > 0$ and $\Delta\rho_2/\rho_2 > 0$ when $\Delta v/v < 0$, and they increase with $\Delta v/v$ decreasing. This is coincident with the physical analysis. Because $v \ll 1$, in formulae

$$(8) \quad \left| \frac{\rho_f - \rho_o}{\rho_o/v + \rho_f} \right| < \left| \frac{\rho_f - \rho_o}{\rho_f/v + \rho_o} \right|, \text{ so for } \Delta v/v > 0 \text{ and } \Delta v/v < 0 \text{ cases } \frac{\Delta\rho_2}{\rho_2} / \frac{\Delta\rho_1}{\rho_1} > 1 \text{ all the time}$$

when the AR changes of channels X and Y, $\Delta\rho_{sx}/\rho_{sx}$ and $\Delta\rho_{sy}/\rho_{sy}$, are all increased or decreased. This is coincident with the physical meaning of inequality (5). Let $\dot{\rho}_i = \Delta\rho_i/\Delta t$

($i = 1, 2$), the equation, $\frac{\dot{\rho}_2}{\dot{\rho}_1} \approx \frac{\rho_o\rho_f}{(\rho_o v + \rho_f)^2}$, can be deduced. Thus we get that $\dot{\rho}_2/\dot{\rho}_1 > 1$ all the

time. This is coincident with the physical meaning of inequality (7).

In general, it can be seen that anisotropic TR changes is obviously associated with ρ_f , ρ_o and v , which is clear in theory, and anisotropic AR changes arise from anisotropic TR changes. Therefore, the reason for AR changes and their anisotropic changes as well as their pattern (drop-type or rise-type) are clear in theory also.

4. Conclusions

1. The AR changes related to the late preparation process of strong EQs are indeed recorded in china. The two proofs are as follows: (a) Reappearing AR changes are observed before two great EQs. (b) Two strong EQs are successfully predicted using AR changes observed at stations nearby on an one-year time scale, which three elements, such as locations, magnitudes and year 2003, are all right.
2. Of 41 stations in or nearby the epicentral areas of 27 strong EQs, for over 95% stations the anisotropic AR changes are related to the maximum compressional stress directions of the EQ focal mechanism solutions. Their behaviors are: the most prominent AR change appears perpendicular or nearly perpendicular to the direction. The relationship between the anisotropic changes and the direction is well coincident with the directional AR changes in the loading process of most rock (soil) samples. And the relationship can be explained in theory. Therefore, we can confirm that the anisotropic AR changes which are directly associated with the later preparation processes of strong EQs are truly recorded nearby epicentral regions.
3. The reasons for AR changes and their anisotropic changes as well as their pattern (drop-type or rise-type) are clear. The compressional action along the maximum compressional stress direction plays an important role in/nearby the EQ focal region in the later preparation stages of strong EQs. This caused that the micro cracks in the underground medium develop fast in number, and their strikes are predominant along the direction, as a result, conductive aisles in the medium are linked each other and

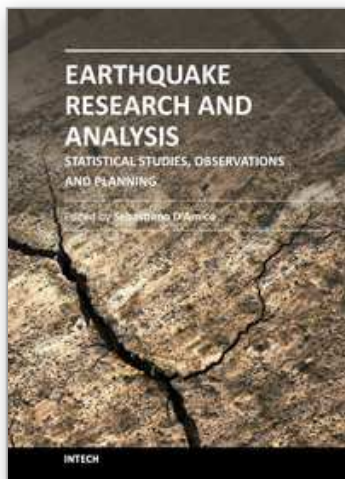
underground water comes fast in. The physical processes induce the TR changes which drop-type pattern occurs in a medium dilatancy stage and rise-type pattern does in a closure stage of micro cracks, and also induce the anisotropic TR changes in which the most prominent change appears along the maximum compressional stress direction.

4. In a homogeneous anisotropic medium, the AR change is in agreement with the TR change in drop-type or rise-type pattern, hence, a drop-type pattern of AR change appears in a medium dilatancy stage and a rise-type pattern appears in a closure stage of micro cracks. Because of the directional discrepancy with 90° angle between the most prominent TR change and the most prominent AR change, the anisotropic AR changes, in which the most prominent change appears perpendicular or nearly perpendicular to the maximum loading direction, just appear.

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Earthquake Research and Analysis - Statistical Studies, Observations and Planning

Edited by Dr Sebastiano D'Amico

ISBN 978-953-51-0134-5

Hard cover, 460 pages

Publisher InTech

Published online 02, March, 2012

Published in print edition March, 2012

The study of earthquakes plays a key role in order to minimize human and material losses when they inevitably occur. Chapters in this book will be devoted to various aspects of earthquake research and analysis. The different sections present in the book span from statistical seismology studies, the latest techniques and advances on earthquake precursors and forecasting, as well as, new methods for early detection, data acquisition and interpretation. The topics are tackled from theoretical advances to practical applications.

How to reference

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Du Xuebin, An Zhanghui, Yan Rui, Ye Qing, Fan Yingying, Liu Jun, Chen Junying and Tan Dacheng (2012). Changes in Apparent Resistivity in the Late Preparation Stages of Strong Earthquakes, Earthquake Research and Analysis - Statistical Studies, Observations and Planning, Dr Sebastiano D'Amico (Ed.), ISBN: 978-953-51-0134-5, InTech, Available from: <http://www.intechopen.com/books/earthquake-research-and-analysis-statistical-studies-observations-and-planning/changes-in-apparent-resistivity-in-the-late-preparation-stages-of-strong-earthquakes>

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