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Georesistivity precursors to the Tangshan earthquake of 1976

Fu-Ye Qian, Yu-Lin Zhao and Jun Lu
Institute of Geophysics, State Seismological Bureau, Beijing, P.R. China

Abstract

Georesistivity precursors and corresponding coseismic effects to the Tangshan earthquake of 1976 are given as follows: 1) resistivity measurements with accuracies of 0.5% or better for over 20 years show that resistivity decreases of several percent, which began approximately 3 years prior to the Tangshan earthquake, were larger than the background fluctuations and hence statistically significant. An outstanding example of an intermediate-term resistivity precursor is given. 2) Georesistivity decreases of several percent observed simultaneously at 9 stations beginning 2-3 years prior to the 1976 Tangshan earthquake are such a pervasive phenomenon that the mean decrease, in percent, can be contoured on a map of the Beijing-Tianjin-Tangshan region. This shows the maximum decrease centered over the epicenter. 3) Corresponding coseismic resistivity changes, $\Delta\rho_c/\rho_c$, during the M 7.8 Tangshan earthquake were observed at all 16 stations within 240 km from the epicentre. These observed $\Delta\rho_c/\rho_c$ are opposite in sense but similar in spatial distribution to corresponding georesistivity precursors. This observation suggests that the Tangshan earthquake is a rebound process. Calculation indicates that these georesistivity precursors could be represented by a virtual dislocation, of opposite sign to the real dislocation produced at the time of the Tangshan earthquake. These reported $\Delta\rho_c/\rho_c$ offer very convincing evidence for accepting corresponding anomalies prior to the earthquake as its precursors. 4) It is inferred from observed anisotropic decreases in georesistivity that before the Tangshan earthquake the crust was compressed and that the angle between the maximum principal stress σ_1 and the earthquake fault was about 80° before the earthquake *i.e.*, the fault was locked by the σ_1 which is almost normal to the fault.

Key words *georesistivity precursors – coseismic effects – virtual dislocation model – anisotropic resistivity change – maximum principal stress direction*

1. Introduction

The prediction of earthquakes is a fascinating subject but also a world-wide problem of great difficulty in modern geosciences. The key to making a successful forecast is to understand fully and hence to identify the earthquake precursors correctly. The case of the georesistivity observed before the great M 7.8 Tangshan earthquake of 1976 is thus reported in the present study in order to discuss the mechanisms of earthquake precursors.

Geoelectric resistivity measurements were started in 1967 in the meizosismal zone at Hejian and Xingtai, Hebei Province, China. which was at about the same time as Japanese, Russian and American scientists (Rikitake and Yamazaki, 1969; Barsukov, 1970; Mazzella and Morrison, 1974; Fitterman and Madden, 1977; Yukutake *et al.*, 1978; Zhao and Qian, 1969). Schlumberger arrays, with fixed electrodes and separation between current electrodes equaling 1-3 km are used and these measurements are sensitive to shallow crust (upper 300-1000 m). Currents, I, of 1-5 A are

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Mailing address: Dr. Fu-Ye Qian, Institute of Geophysics, State Seismological Bureau, No. 5 Minzuxueyuan Nanlu, Haidian District, Beijing 100081, P.R. China; e-mail: ZYL@cdsndmc.css.gov

used to generate a potential difference (ΔV) across potential electrodes 100 times larger than the noise level. Six to twelve measurements are made daily, and each measurement consists of several readings. The ratio $\Delta V/I$ is used for calculating the geoelectric resistivity ρ_x. Precisions are better than 0.3-0.5% are obtained by averaging the readings into monthly means. Calibration of the instruments are carried out regularly and the stability of the instruments was satisfactory. The cables used are well insulated so that interference due to leakage are practically non-existent the data of the few instances troubled by leakage interference are discarded and not used in the averaging for those data affected by seasonal variations, the periodic components are filtered out. After such a reduction, if many points show a tendency of change that exceeds three times the standard deviation, an anomaly is supposed to exist because we have recorded that resistivity retains a constant value for years at some stations on strong earthquakes nearby and without seasonal variations (Qian *et.al.*, 1987).

Within the past 29 years, anomalous variations of geoelectric resistivity were observed before the occurrence of large earthquakes in China (Zhao and Qian, 1993). Among these, the case history for the Tangshan earthquake of 1976 with regard to resistivity anomaly is the most interesting.

2. The intermediate-term precursors of georesistivity

Figure 1 shows the distribution of geoelectric stations in Northern China. Figure 2 shows the continuous twenty-year resistivity record at Baodi (BD) station, which is 80 km from the

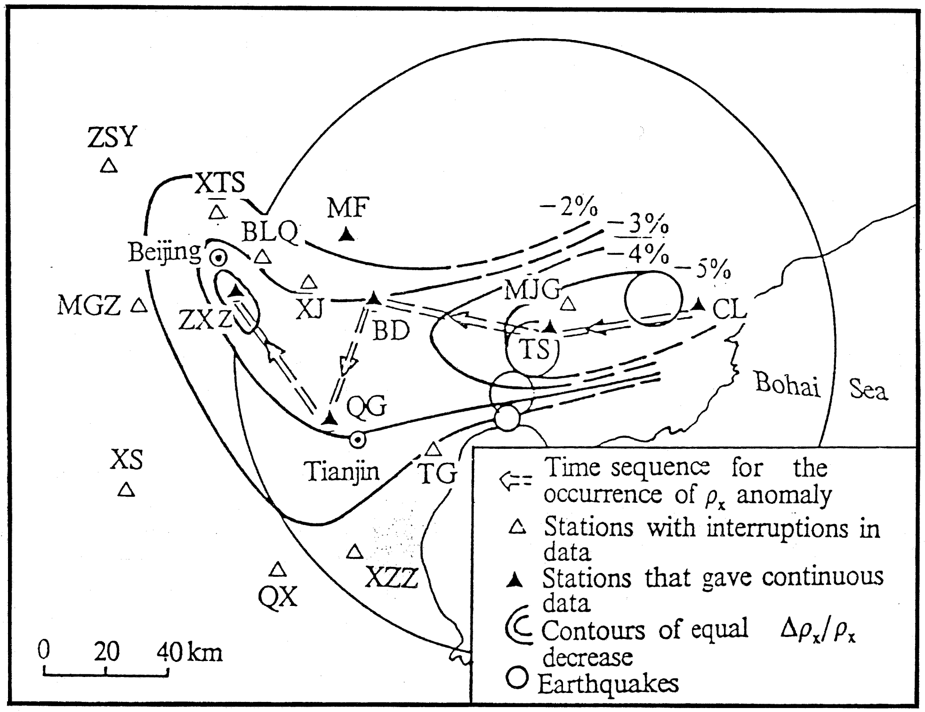

Fig. 1. The distribution of geoelectric stations and contour map of resistivity decreases in Northern China prior to the 1976 Tangshan earthquake.

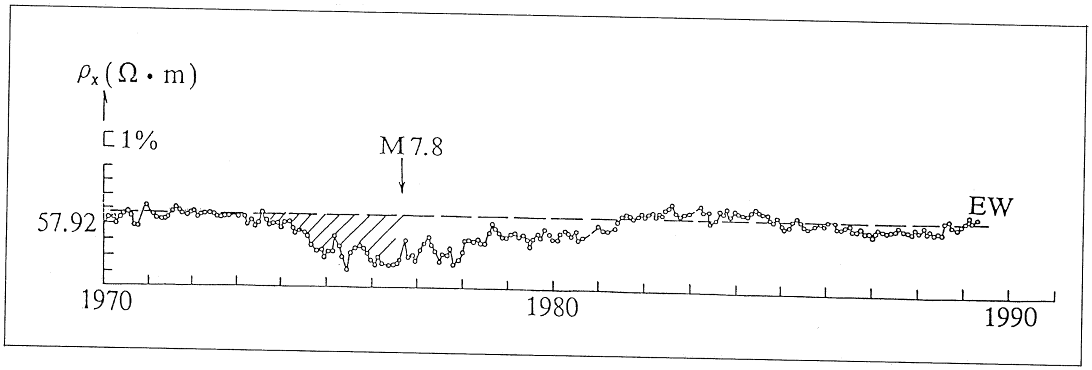

Fig. 2. Resistivity anomaly before the Tangshan earthquake observed at Baodi (BD) station (Δ = 80 km).

Tangshan epicenter. An intermediate-term precursor, shown in fig. 2 as a persistent decrease in resistivity, began about 3 years prior to the Tangshan earthquake. The amplitude (3.1%) of the overall decrease in resistivity was over twenty times the standard deviation (0.15%) and the main shock occurred at the time when the resistivity anomaly had reached its lowest value. After the earthquake the resistivity increased gradually to the «normal» value before the earthquake in about 4 years. Before 1973 and after 1980 the annual rate of change in resistivity was much smaller and no anomaly occurred. Data records for over 20 years show that the decrease prior to the Tangshan earthquake was the only major variation larger than the background fluctuations and, hence, was statistically significant. The Tangshan earthquake was the only strong earthquake within 250 km of the station. Therefore, the recorded decrease in resistivity is apparently associated with the Tangshan earthquake.

Within a radius of 150 km from the epicenter of the Tangshan earthquake, there are 11 geoelectric stations (fig. 1). Resistivity decreases beginning approximately 2-3 years prior to the Tangshan earthquake were observed at 9 stations. The general decrease is such a pervasive phenomenon that the mean decrease (as a percentage) can be contoured on a map of the Beijing-Tianjin-Tangshan region. This shows that the maximum decrease centered over the epicenter and coherent changes occurred over a large region (fig. 1). Drops in water levels were recorded in wells during this same period of time (Wang, 1985), so the resistivity change cannot simply be the result of changing saturation. In fact, a decrease in the water level should lead to an increase in resistivity and not the observed decrease.

Both *in situ* and in laboratory measurements indicate that the resistivity of a partially saturated rock-soil layer is extremely sensitive to a small strain change (Zhao *et al.*, 1990). The ratio of the relative change in resistivity ($\Delta\rho/\rho$) to the relative change in volume ($\Delta\varepsilon$); that is, the amplification factor $K = |(\Delta\rho/\rho)/\Delta\varepsilon|$ shows non-linear behavior at low strain levels. Zhao *et al.* (1990) report that the smaller the strain is, the higher the amplification factor. The amplitude of this georesisitivity precursor varies slowly with distance and hence coherent decreases in resistivity prior to the Tangshan earthquake can be seen over a large region (fig. 1); these correspond to variations in strain.

In order to remove seasonal variations, the monthly anomalies in georesistivity observed at stations around the Tangshan *M* 7.8 event are shown in fig. 3. The curves for two mutually perpendicular arrays at each station are given, and the curves for the stations are arranged according to distance from the Tangshan epicenter. It can be seen from fig. 3 that, except for the Mafang (MF) station, a continuous decrease in resistivity appeared at all the other 5 stations 2-3 years before the *M* 7.8

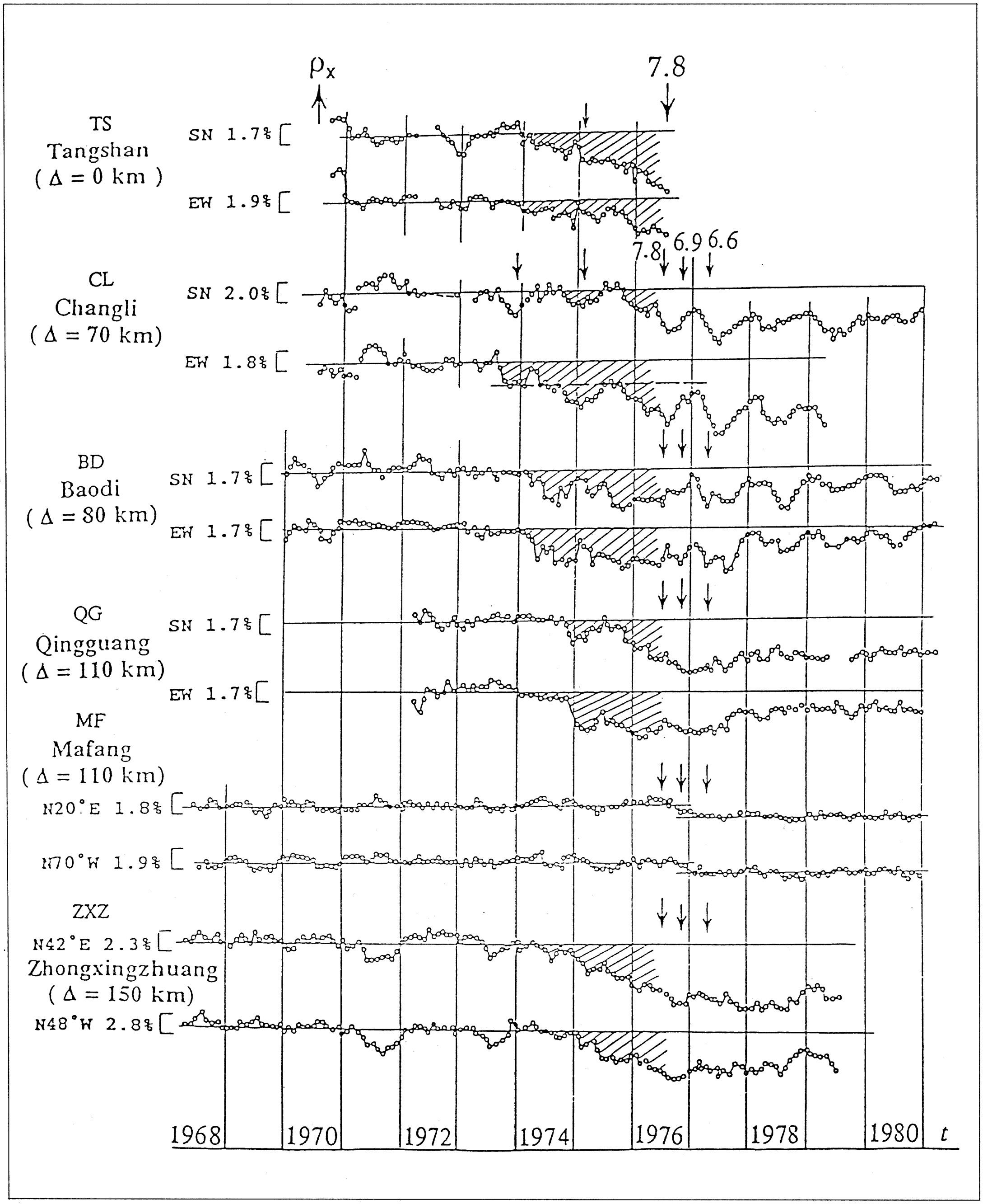

Fig. 3. Graph of the monthly anomalies in resistivity recorded continuously at 6 stations around the *M* 7.8 Tangshan earthquake epicenter.

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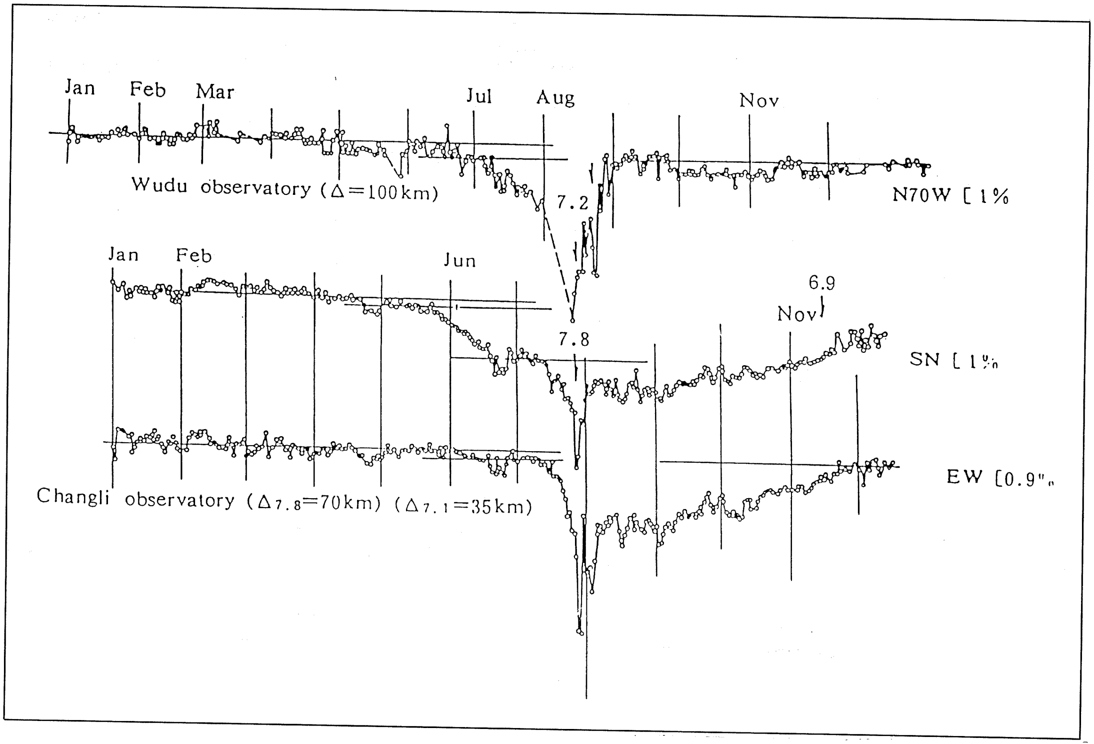

Fig. 4. The accelerated anomalies in resistivity before the Tangshan earthquake at the Changli (CL) station (Δ = 70 km) and before the Songpan earthquake observed at Wudu station (Δ = 100 km).

Tangshan earthquake. The cumulative decrease was over 5-30 times the usual standard deviation. The decrease in resistivity was seen first at stations close to the epicenter and later at more distant stations (fig. 1). The Tangshan (TS) and Changli (CL) stations showed a decrease by the end of 1973, and were within 70 km of the epicenter. The Qingguang (QG) and Zhongxingzhuang (ZXZ) stations exhibited no decrease until the beginning of 1975. The front of the resistivity precursors migrated outward from the epicenter at an apparent rate of approximately 100 km/yr.

Accelerated anomalies can be seen at the Changli (CL) station two months before the Tangshan earthquake. The lower curve in fig. 4 is the record at Changli station before the Tangshan event. The upper curve shows the record observed at Wudu station (33.3°N, 105.0°E) before the 1976 Sungpan earthquake (32.6°N, 104.1°E). The fact that a very similar pattern of the accelerated anomalies in georesistivity occurred just prior to these two earthquakes may be essential to understanding the mechanical process at the source.

3. Coseismic effects and a virtual dislocation model of the intermediate-term precursors in georesistivity

Resistivity offsets in association with the occurrence of the Tangshan earthquake were observed at all 16 stations within 240 km of the epicentre. However, these coseismic changes were not very rapid but were time-dependent, about ten days being required for their completion. Coseismic georesistivity risings (according to experimental results, resistivity rising corresponds to dilatation or releasing of compressional stress) were recorded at 13 stations, including all 9 stations where precursory decrease in resistivity occurred. Figure 5 shows coseismic effects in georesitivity recorded at 7 of them. Coseismic georesistivity falling (corresponding to compression) were recorded at the Xuzhuangzi (XZZ) station, where precursory increase in resistivity had been recorded, and at the 2 other stations which were all situated on the nodal lines. The co-seismic offsets were opposite in sense but similar in spatial distribution to the intermediate-term precursors.

The magnitudes of these coseismic resistivity changes is largest (4-10%) at the epicentral stations, TS, MJG, CL and the coseismic changes is 2% at a distance of 80 km from the epicentre (the BD station). For stations with an epicentral distance exceeding 200 km, the coseismic resistivity changes is no more than 1%. Figure 6 shows the amplitudes of the coseismic resistivity changes, $\frac{\Delta\rho_c}{\rho_c}$, as a function of distance, R, away from the epicentre as:

$$\log\left(\frac{\Delta\rho_c}{\rho_c}\right) = -0.58 - 0.58 \log R.$$

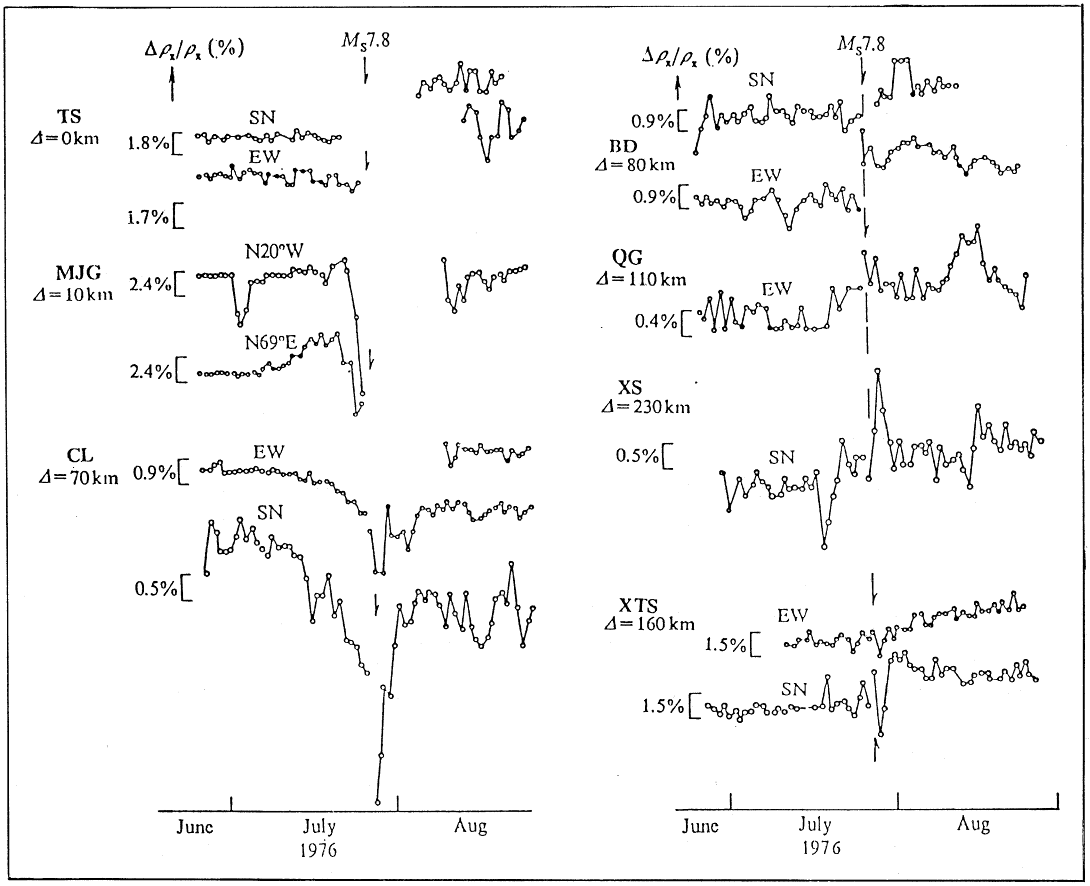

Fig. 5. Coseismic effects in georesistivity during the Tangshan earthquake.

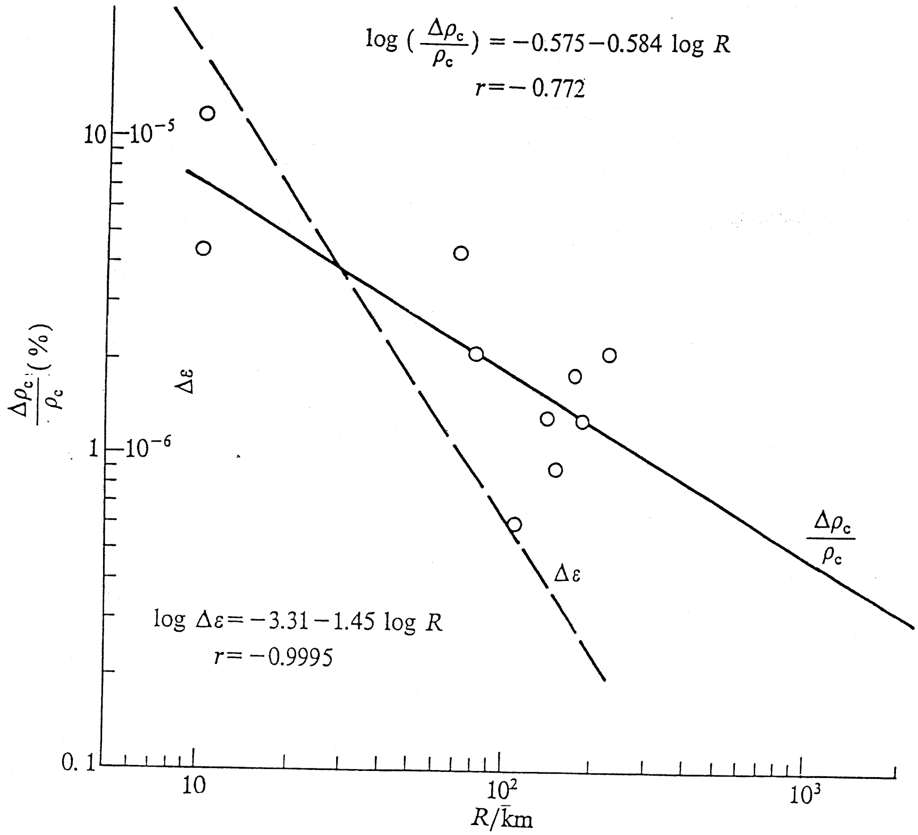

Fig. 6. Resistivity and strain step amplitude as a function of epicentral distance for the *M* 7.8 earthquake.

Included in the figure is the curve in the coseismic strain steps as well, which was obtained by taking a cross section of fig. 6 from Wideman and Major (1967) for a magnitude 7.8 earthquake. Wideman and Major (1967) discovered that coseismic strain steps depend on distance away from the epicentre as $R^{-3/2}$. This discrepancy, which has not yet been resolved, shows that the attenuation in resistivity is much slower than that in strain. The amplification factor $K = \left|\frac{\Delta\rho_c}{\rho_c}\right| / \Delta\varepsilon$ estimated from the comparison between coseismic resistivity steps and coseismic strain steps for the same distance amounts to orders of 10^4-10^5 for a very small strain of about 10^{-6}. Zhao *et al.* (1990) report that the smaller the strain is, the higher the amplification factor. The factor that the amplification factor, *K*, shows non-linear behavior at low strain levels indicates that the property, *K*, of rocks depend on the pore space.

The intermediate-term precursor in georesistivity is considered to be due to the accumulation of strain preceding the Tangshan earthquake. The coseismic changes in georesistivity are considered to be due to strain release when sudden slippage occurs. As mentioned above, the strain accumulations are opposite in sense but similar in spatial distribution to the strain release at the time of occurrence in the Tangshan earthquake. According to the amplification factor estimated from coseismic data both in resistivity and in strain, the theoretical intermediate-term precursor in georesistivity is represented by a virtual dislocation of opposite sign to the real dislocation produced at the time of the Tangshan earthquake. The mainshock occurred on a nearly vertical right-lateral strike-slip fault, striking N30°E, with an asymmetric bilateral fracture which propagated 70 km northeastward and 45 km south westward, the average dislocation of 136 cm, seismic moment of 1.24×10^{27} dyne · cm and stress-drop of 12 bars (Zhang *et al.*, 1980).

Figure 7 shows the calculated resistivity results. It can be seen from this figure that the theoretical distribution of the calculated resistivity precursors is in good agreement with the observed intermediate-term precursors in georesistivity. The calculation indicates that these coseismic resistivity changes offer very convincing evidence for accepting corresponding anomalies prior to the earthquake as its precursors and that the resistivity observation suggests that the Tangshan earthquake is a rebound process.

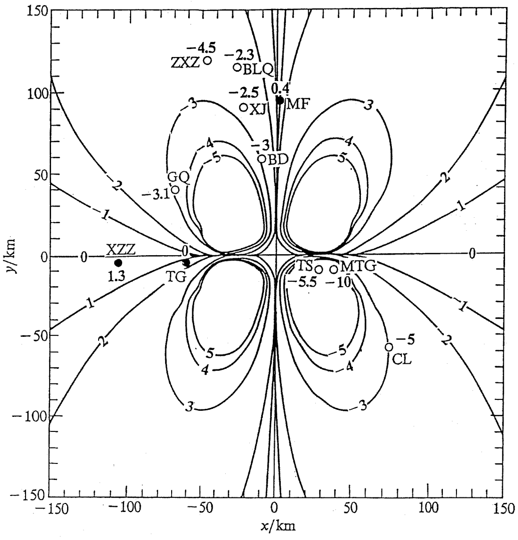

Fig. 7. The theoretical and observed distribution of resistivity precursor to the Tangshan earthquake. Unit: %; the directon of X: N36°E; parameters: $\nu = 0.25$; $E = 8\times10^5$ b; $\tau_c = -236$; $a = 35$ km.

4. The maximum principal stress direction inferred from the anisotropic resistivity change data prior to the Tangshan earthquake

The Tangshan resistivity anomalies are probably related to distributed strike-slip systems which consist of dense sets of parallel or sub-parallel NNE-, NE- or NW-trending faults in North China (Mei *et al.*, 1982; Nur and Ron, 1987; Wang *et al.*, 1978). If the Tangshan earthquake occurring on a previous fault may be explained by a stick-slip mechanism, the reason the fault could be locked requires clarification.

In situ experiments show that changes in georesistivity due to stress variation exhibit anisotropy. The resistivity drops when rock or soil layers are compressed and resistivity $\rho_\perp$, measured along the profile perpendicular to the maximum principal stress σ_1, usually has a larger drop (fig. 8a). However, when rock or soil layers are sheared the $\rho_\perp$ also decreases, but the $\rho_{//}$, parallel to the σ_1, usually increases (fig. 8b). According to these, stress state and the maximum principal stress directions of the crust can be determined.

It can be seen from fig. 3 that ρ_{NS}, for example, at the TS station, or ρ_{NE} at the ZXZ station had larger drop. These observations show that before the Tangshan earthquake the crust was compressed with the σ_1 of about N70°W and that the angle between the maximum principal stress σ_1 and the earthquake fault (N30°E) was about 80°; *i.e.*, the maximum principal stress was almost normal to the fault and the earthquake fault was locked by the σ_1. It is very difficult for a normal compression fault to slip suddenly in terms of our conventional understanding of faulting and earthquake. However, the evidence that sudden movements of high-pressure fluid triggered the Tangshan earthquake will be presented in another paper of ours (Zhao *et al.*, 1997).

5. Concluding remarks

In contrast with the fact that field experiments with the hope of detecting resistivity precursors to earthquake have had much less

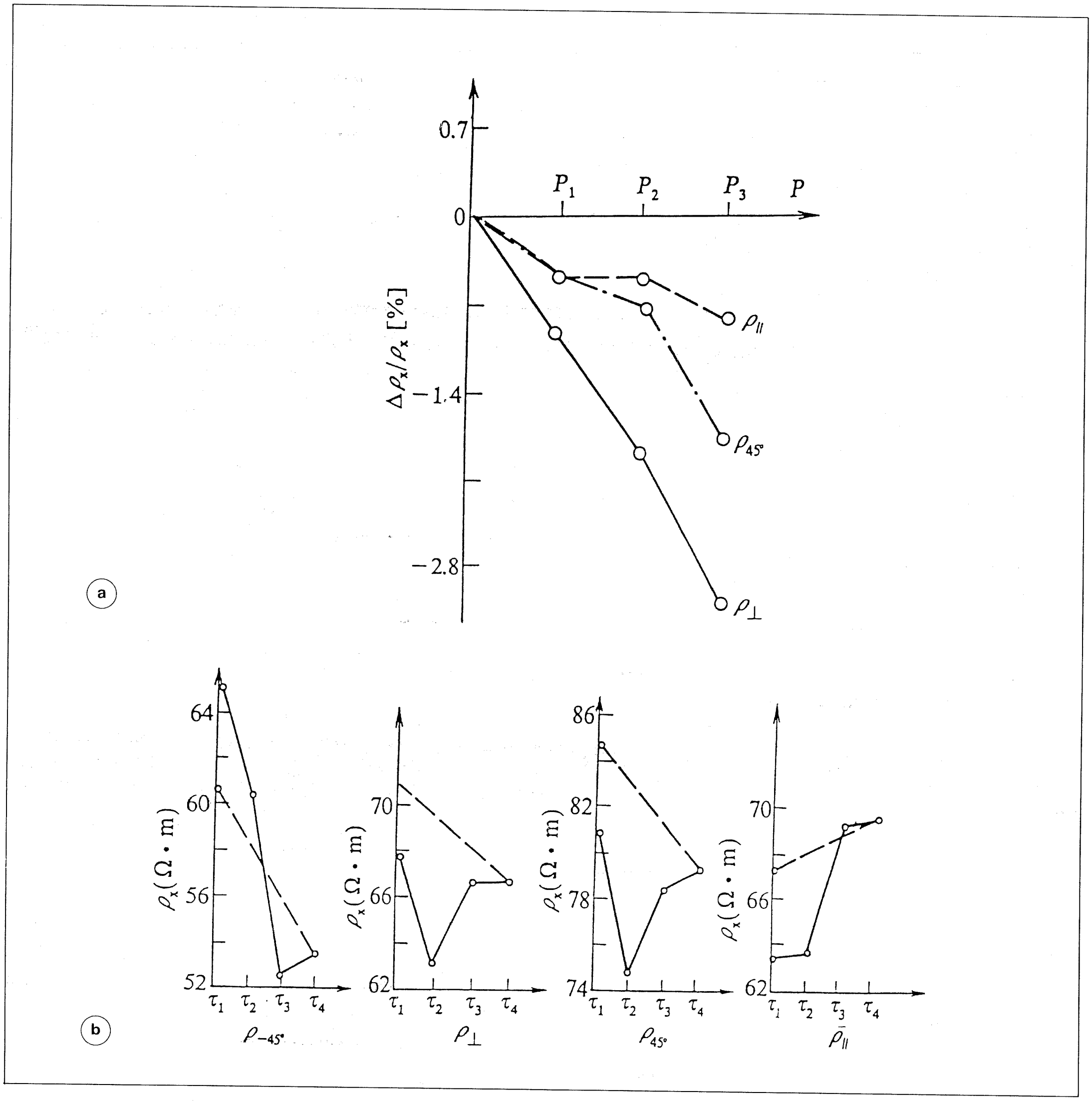

Fig. 8a,b. *In situ* experimental results of the anisotropic resistivity changes as the rock or soil layers are subject to pressure (a), or are sheared (b).

success abroad (Park, 1993), an outstanding example of a resistivity precursor was observed before the Tangshan earthquake in China. The reasons are as follows:

1) Resistivity measurements with accuracies of 0.3-0.5% or better for over 20 years, show that these resistivity precursors of several percent observed simultaneously at more than 9 stations were larger than the background fluctuations and hence statistically significant.

2) Observed maximum resistivity changes of a few percent are in approximate agreement with laboratory measurements.

3) Coseismic resistivity steps were clearly recognized at all 16 stations within 240 km from the epicentre, which were opposite in sense but similar in spatial distribution to corresponding georesistivity precursors.

4) The theoretical distribution of calculated resistivity precursors, in which a virtual dislocation model and a nonlinear amplification factor estimated from coseismic data both in resistivity and in strain were used, is in good agreement with the observed intermediate-term precursor in georesistivity and hence semiquantitative calculation demonstrates that the mechanism causing those precursors is the accumulated preseismic strain and that the coseismic resistivity change is due to strain release when the earthquake occurs.

5) Before the occurrence of the earthquake, the earthquake fault was locked by the maximum principal stress σ_1 itself, which is almost normal to the fault inferred from observed anisotropic decreases in georesistivity.

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