In Situ Stress State in Mainland China

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Abstract—*In situ* stress measurements are one of the important methods for studying the recent tectonic stress field and stress state. In this paper, the stress state and variation of stresses with depth in Mainland China are presented and analyzed on the basis of *in situ* stress data measured by both hydrofracturing and overcoring techniques.

Key words: Stress state, variation of stresses with depth, *in situ* stress measurements.

1. Introduction

In situ stress measurements provide important data for the study of the recent tectonic stress field and stress state of the crust. Stress measurements are of considerable interest in terms of geodynamics as well as in earthquake studies. In addition, they have become increasingly important in such fields as the design of mine tunnels and other underground structures, nuclear waste isolation, development of oil-gas fields, geothermal energy extraction and stability of hydroelectric facilities.

The stress state and the variation of stresses with depth in Mainland China are discussed on the basis of *in situ* stress data obtained by both hydrofracturing and overcoring techniques.

2. Data of the *in situ* Stress Measurements in China

During the past twenty years we have carried out a series *in situ* stress measurements using both overcoring and hydrofracturing methods in various regions of Mainland China (Table 1) (LI *et al.*, 1979, 1986). As a result, we obtained a preliminary result concerning the stress state and the variation of stresses with depth in the upper crust of Mainland China.

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Table 1
The data of *in situ* stress measurements

Site	Data	Depth (m)	Rock age and rock type	S_H (MPa)	S_h (MPa)	Direction of S_H	Method and source
Shunyi Beijing	Nov. 1973	17-19	Ordovician limestone	2.6 ± 0.2	0.4 ± 0.2	$N73^\circ \pm 3^\circ W$	Overcoring Li and Liu (1986)
Wenguan Beijing	Aug. 1974	13-22	Ordovician limestone	3.6 ± 0.8	2.2 ± 0.3	$M65^\circ \pm 5^\circ W$	Ditto
Changping Beijing	Oct. 1974	4-15	Sinina limestone	1.2 ± 0.5	0.8 ± 0.5	$N75^\circ \pm 12^\circ W$	Ditto
Datuichang Beijing	Nov. 1974	4-12	limestone	2.1 ± 0.2	0.9 ± 0.1	$N35^\circ \pm 7^\circ W$	Ditto
Haicheng Liaoning	July 1975	4-16	Presinian magnesite	9.3 ± 0.5	5.9 ± 0.6	$N87^\circ \pm 6^\circ W$	Ditto
Yingkou Liaoning	Oct. 1975	4-14	Presinian dolostone	16.6 ± 0.8	10.4 ± 0.9	$N84^\circ \pm 5^\circ W$	Ditto
Longyao Hebei	June 1976	8-15	Cambrian limestone	3.2 ± 0.2	2.1 ± 0.3	$N87^\circ \pm 9^\circ E$	Ditto
Luanxian 1 Hebei	Aug. 1976	5-22	Ordovician limestone	5.8 ± 0.4	3.0 ± 0.4	$N84^\circ \pm 9^\circ E$	Ditto
Luanxian 2 Hebei	Sep. 1976	6-16	Ordovician limestone	6.6 ± 1.1	3.2 ± 1.1	$N89^\circ \pm 10^\circ W$	Ditto
Shunyi Beijing	Sep. 1976	6-20	Ordovician limestone	3.6 ± 0.2	1.7 ± 0.2	$N83^\circ \pm 4^\circ W$	Ditto
Wenquan Beijing	Oct. 1976	9-21	Ordovician limestone	5.4 ± 0.5	3.1 ± 0.3	$N67^\circ \pm 7^\circ W$	Ditto
Tangshan Hebei	Oct. 1976	6-15	Ordovician limestone	2.5 ± 0.3	1.7 ± 0.1	$N47^\circ \pm 16^\circ W$	Ditto
Sanhe Hebei	Oct. 1976	6-13	Ordovician limestone	2.1 ± 0.2	0.5 ± 0.2	$N69^\circ \pm 5^\circ W$	Ditto
Huairou Beijing	Nov. 1976	9-17	Cambrian limestone	4.1 ± 0.5	1.1 ± 0.6	$N83^\circ \pm 5^\circ W$	Ditto
Farshan Beijing	May 1977	11-19	Yanshan period granite	8.7 ± 0.4	4.5 ± 0.3	$N50^\circ \pm 5^\circ E$	Ditto

Chicheng Hebei	July 1977	6-18	Periodotite	3.3 ± 0.3	2.1 ± 0.4	N82° ± 10°E	Ditto
Fangshan Beijing	Sep. 1977	10-22	Yanshan period granite	5.9 ± 0.4	4.3 ± 0.3	N59° ± 9°E	Ditto
Tangshan Hebei	Apr. 1978	6-11	Ordovician limestone	2.3 ± 0.3	1.1 ± 0.3	N77° ± 8°E	Ditto
Tangshan Hebei	May 1978	5-15	Ordovician limestone	1.6 ± 0.1	1.0 ± 0.1	N71° ± 7°W	Ditto
Luanxian Hebei	July 1978	19-22	Ordovician limestone	5.0 ± 0.5	3.5 ± 0.4	N82° ± 9°W	Ditto
Jinan Shandong	July 1979	6.17-13.29	Ordovician limestone	3.2 ± 0.5	0.6 ± 0.5	N5° ± 6°W	Ditto
Anqiu Shandong	July 1979	13.63-19.0	Ordovician limestone	3.1 ± 0.4	2.0 ± 0.3	N84° ± 11°W	Ditto
Qingdao Shandong	Sep. 1979	3.62-7.95	Yanshan period granite	2.6 ± 0.4	1.4 ± 0.2	N74° ± 7°E	Ditto
Xinyi Jiangsu	Oct. 1979	5.21-10.27	Cretaceous sandstone	1.7 ± 0.1	1.4 ± 0.1	N25° ± 10°W	Ditto
Dingyuan Anhui	Oct. 1979	7.06 ± 14.97	Cambrian limestone	4.1 ± 0.3	2.0 ± 0.2	N50° ± 8°E	Ditto
Suxian Anhui	Oct. 1979	4.36-10.35	Cambrian limestone	4.7 ± 0.4	2.7 ± 0.3	N86° ± 6°E	Ditto
Wuwei Anhui	Dec. 1979	9.74 ± 15	Triassic limestone	1.1 ± 0.1	0.0 ± 0.0	N63° ± 5°W	Ditto
Daye Hubei	Aug. 1965	150	marble	23.0	13.0	N51°W	Ditto (gallery)*
Yichang Hubei	Dec. 1978	31.68	Presinian quartz diorite	11.5 ± 0.7	5.7 ± 0.6	N73° ± 5°W	Ditto
Xiangnan Yunnan	1976	16-18	Ordovician limestone	1.17 ± 0.05	0.83 ± 0.06	N11° ± 6°W	Ditto
Baoshan Yunnan	1976	6-12	Devonian limestone	4.1 ± 0.6	1.5 ± 0.9	N3° ± 9°W	Ditto
Luxi Yunnan	1976	10-16	Jurassic marl	2.4 ± 0.4	1.4 ± 0.3	N82° ± 11°E	Ditto
Panjiakou I Hebei	1980	5-27.69	Archean gneiss	4.8 ± 0.8	2.8 ± 0.6	N15° ± 11°E	Ditto

Table 1 (Contd.)

Site	Data	Depth (m)	Rock age and rock type	S_H (MPa)	S_h (MPa)	Direction of S_H	Method and source
Panjiakou 2 Hebei	1980	5-24	Anchean gneiss	8.0 ± 0.3	4.9 ± 0.2	$N19^\circ \pm 4^\circ E$	Ditto
Anyang Henan	May 1980	8-15	Ordovician limestone	2.4 ± 0.2	1.4 ± 0.2	$N62^\circ \pm 9^\circ W$	Ditto
Jiaozuo Henan	May 1980	13-17	Ordovician limestone	1.3 ± 0.1	0.7 ± 0.1	$N18^\circ \pm 7^\circ E$	Ditto
Jiangxian Shanxi	1980	5-15	Ordovician limestone	4.4 ± 0.4	2.4 ± 0.3	$N22^\circ \pm 7^\circ W$	Ditto
Pingding Shanxi	1980	7.5-10	Ordovician limestone	2.2 ± 0.1	1.1 ± 0.1	$N3^\circ \pm 4^\circ E$	Ditto
Hunyuan Shanxi	Aug. 1980	6-9.3	Ordovician limestone	1.5 ± 0.1	1.0 ± 0.1	$N32^\circ \pm 3^\circ W$	Ditto
Ertan Sichuan	1981	250	basalt	24.9	13.2	$N18^\circ E$	Ditto (gallery)
Pingkouxia Gansu		14.7	granite	2.9	2.2	$N59^\circ E$	Ditto
Jingchuan Gansu	1978	11-44	Presinian marble	4.2	3.5	$N20^\circ E$	Ditto
Jingchuan Gansu	1975	375	Presinian marble	19.8	10.8	$N3^\circ E$	Ditto (gallery)
Jingchuan Gansu	1980	480	granite	24.5	15.4	$N25^\circ W$	Ditto (gallery)
Jingchuan Gansu	1976	460	Presinian marble	50.0	33.4	$N13^\circ W$	Ditto (gallery)
Jingchuan Gansu	1978	480	Ore body	32.0	20.8	$N32^\circ E$	Ditto (gallery)
Puge Sichuan	Aug. 1977	7.42-9.20	Ordovician marl	6.2	4.7	$N54^\circ W$	Ditto
Mianning Sichuan	Sep. 1977	15-25	Yanshan period granite	4.1	-3.6	$N59^\circ W$	Ditto

Danba Sichuan	July 1981	5.23-9.08	Hercynian amphibolite	5.35 ± 0.44	3.45 ± 0.34	N24° ± 9°W	Ditto
Yajing Sichuan	Oct. 1981	6.92-15.59	Triassic sandstone	6.48 ± 0.31	4.84 ± 0.26	N56° ± 9°E	Ditto
Baoxing Sichuan	July 1982	10.43-18.68	Ordovician marble	8.75 ± 0.28	6.13 ± 0.13	N61° ± 4°W	Ditto
Kangding Sichuan	Aug. 1982	2.93-7.09	Triassic sandstone	6.55 ± 0.48	5.15 ± 0.43	N86° ± 10°E	Ditto
Kangding Sichuan	Sep. 1982	5.27-15.02	Jinling period granite	6.15 ± 0.46	3.06 ± 0.47	N82° ± 5°W	Ditto
Tianquan Sichuan	Oct. 1982	5.42-11.79	Triassic sandstone	4.69 ± 0.20	3.29 ± 0.26	N69° ± 7°W	Ditto
Ya'an Sichuan	Nov. 1982	10.19-13.62	Triassic sandstone	4.13 ± 0.27	2.50 ± 0.11	N45° ± 7°W	Ditto
Huize Yunnan	9-13		Paleozoic limestone	12.2 ± 0.3	9.6 ± 0.3	N81° ± 1°W	Ditto
Songming Yunnan	20-30		Carboniferous limestone	9.0 ± 0.5	5.1 ± 0.4	N88° ± 5°W	Ditto
Huaning Yunnan	16-40			6.3 ± 0.6	3.9 ± 0.2	N65° ± 8°W	Ditto
Midu Yunnan	8.0-15.2		Permian limestone	4.3 ± 0.8	2.8 ± 0.5	N78° ± 2°W	Ditto
Xinping Yunnan	16.8-23.3		Jurassic sandstone	10.6 ± 0.2	4.5 ± 0.2	N31° ± 2°W	Ditto
Jianshui Yunnan	13-23		Devonian limestone	11.9 ± 0.2	4.9 ± 0.2	N21° ± 2°E	Ditto
Mojiang Yunnan	7.5-15		Permian limestone	12.3 ± 0.5	7.3 ± 0.2	N44° ± 4°W	Ditto
Jinggu Yunnan	8.1-13.2		Cretaceous sandstone	12.3 ± 0.2	8.5 ± 0.2	N13° ± 4°E	Ditto
Yixian Hebei	Aug. 1980	59-65	Yanshan period quartz diorite	5.4	4.3	N66°W	Ditto
Xinyi Jiangsu	Oct. 1981	39.14-46.21	Cretaceous red sandstone	1.6	1.5	N26°E	Ditto

Table 1 (Contd.)

Site	Data	Depth (m)	Rock age and rock type	S_H (MPa)	S_h (MPa)	Direction of S_H	Method and source
Yinyi	Oct. 1981	65.69–74.55	Cretaceous red sandstone	2.0	1.7	N3°W	Ditto
Jiangsu							
Yixian	Oct. 1980	70.98–73.29	Yanshan period quartz diorite	11.1 ± 0.9	5.9 ± 0.2	N65° ± 6°W	Hydr.* Li <i>et al.</i> (1986)
Hebei							
Yixian	Oct. 1980	82.00–84.45	Yanshan period quartz diorite	7.2 ± 0.9	4.1 ± 0.2	N54° ± 5°E	Ditto
Hebei							
Xinyi	Nov. 1981	196.66–199.00	Cretaceous red sandstone	8.9 ± 0.9	5.5 ± 0.2	N20° ± 2°E	Ditto
Jiangsu							
Xinyi	Nov. 1981	251.66–254.00	Cretaceous red sandstone	10.7 ± 0.9	8.0 ± 0.2	N30° ± 2°E	Ditto
Jiangsu							
Tangshan							
Hebei	Oct. 1982	65.31–67.65	Permian sandstone	4.8 ± 0.9	2.5 ± 0.2	N72° ± 2°W	Hydr. Li <i>et al.</i> (1985)
Tangshan	Oct. 1982	208.98–211.32	Permian sandstone	5.0 ± 0.9	3.4 ± 0.2	N81° ± 2°W	Ditto
Hebei							
Tangshan	Oct. 1982	268.79–271.39	Permian sandstone	6.1 ± 0.9	4.7 ± 0.2	N83° ± 3°W	Ditto
Hebei							
Tangshan	Oct. 1982	293.70–296.30	Permian sandstone	7.8 ± 0.9	5.8 ± 0.2	N86° ± 2°W	Ditto
Hebei							
Zigong	Jan. 1988	624	Triassic sandstone	34.6 ± 1.7	17.3 ± 0.5	N15.5° ± 2°W	Hydr. Qi <i>et al.</i> (1989)
Sichuan							

Zigong Sichuan	Jan. 1988	717	Triassic sandstone	47.1 ± 1.7	21.5 ± 0.6	N25° ± 2°E	Ditto
Zigong Sichuan	Jan. 1988	818	Triassic sandstone	44.8 ± 2.2	20.6 ± 0.7	N31° ± 2°E	Ditto
Xiaguan Yunnan	Oct. 1983	198	Devonian sandstone	15.5 ± 1.7	8.2 ± 0.4	N34° ± 2°E	Hydr. L1 <i>et al.</i> (1992)
Xiaguan Yunnan	Oct. 1983	214	Devonian sandstone	13.2 ± 2.4	8.1 ± 0.5	N25° ± 2°E	Ditto
Xiaguan Yunnan	Oct. 1983	233	Devonian sandstone	14.1 ± 1.8	5.6 ± 0.4	N21° ± 2°E	Ditto
Xiaguan Yunnan	Oct. 1983	419	Devonian gabbro	20.9 ± 1.7	11.7 ± 0.2	N2° ± 2°E	Ditto
Xiaguan Yunnan	Oct. 1983	451	Devonian olivine pyroxenolite	25.5 ± 3.6	15.4 ± 1.0	N7° ± 2°E	Ditto
Jianchuan Yunnan	Sep. 1985	152	Tertiary sandstone	9.8 ± 2.1	7.4 ± 0.1	N32° ± 2°E	Ditto
Jianchuan Yunnan	Sep. 1985	218	Tertiary sandstone	9.1 ± 0.7	6.2 ± 0.2	N35° ± 2°E	Ditto
Jianchuan Yunnan	Sep. 1985	437	Tertiary sandstone	21.2 ± 1.7	12.9 ± 0.5	N53° ± 2°E	Ditto
Jianchuan Yunnan	Oct. 1986	668	Tertiary sandstone	19.1 ± 1.1	13.0 ± 0.3	N3° ± 2°W	Ditto

*Hydr. Hydrofracturing method
gallery. Measured in mine tunnel

3. The Stress State in Mainland China

3.1 The Variation of Horizontal Principal Stresses with Depth

The rate of increase of the horizontal principal stresses with depth in China is generally greater than that of the vertical stresses.

All of these results are summarized in Figure 1. For these data except for Tangshan, we have

$$S_H = (4.5 \pm 2.5) + 0.049 H \quad (\text{MPa})$$

$$S_h = (1.5 \pm 1.0) + 0.030 H \quad (\text{MPa})$$

where S_H and S_h are the maximum and minimum horizontal compressive stresses, respectively, H is the depth in meters, and errors correspond to the shaded area in Figure 1.

3.2 The Variations of the Major Horizontal Shear Stresses with Depth

The variations of the major horizontal shear stresses, $\tau = (S_H - S_h)/2$, with depth are shown in Figure 2, which are characterized by regional variation.

Figure 1

The horizontal stresses as a function of depth (open circles and triangles obtained from the Tangshan region).

Figure 2
Variation of maximum horizontal shear stresses with depth.

According to observations, the major horizontal shear stress as a function of depth in Southwest and Northwest China can be represented by

$$\tau = 0.8 + 0.012 H \quad (\text{MPa}).$$

In North China,

$$\tau = 0.3 + 0.007 H \quad (\text{MPa})$$

and in Tangshan region we have

$$\tau = 0.003 H \quad (\text{MPa})$$

where H is the depth in meters.

3.3 Depth Variation of the Ratio of the Maximum Horizontal Stress to Vertical Stress, and that of the Minimum Horizontal Stress to Vertical Stress

According to the data obtained from *in situ* stress measurements in China, the ratio of the maximum horizontal stress over the vertical stress, $K_H = S_H/S_v$ varies with depth as follows (Fig. 3a)

$$60/H + 0.8 \leq K_H \leq 240/H + 2.0.$$

The average variation is

$$K_H = 150/H + 1.4.$$

Figure 3

Variation of ratios of the horizontal stress to the vertical stress with depth. (a) S_H/S_v ; (b) S_h/S_v .

The ratio of the minimum horizontal stress over the vertical stress, $K_h = S_h/S_v$, varies as follows (Fig. 3b)

$$60/H + 0.4 \leq K_h \leq 196/H + 0.6.$$

The average variation is

$$K_h = 128/H + 0.5.$$

If we consider the lower limitation, we have $S_H \approx S_v$ and $S_h \approx 0.5S_v$. It can be observed from available data that generally the two horizontal stresses are larger than the vertical one, which is a condition favorable to thrusting, though this may be just a shallow phenomenon. In the deeper part, we have $S_H \geq S_v > S_h$, meaning that the stress state favors strike-slip faulting or even normal faulting.

3.4 The Directions of the Horizontal Principal Stresses and the Stress Provinces in China

The stress state in North China has been described in more detail due to the availability of more data. Mt. Taihangshan separates North China into two distinct parts (as shown in Figure 4). East of Mt. Taihangshan, the plain of North China including its surrounding mountainous districts is a broad region with maximum horizontal compressive stress oriented about E–W. This is consistent with the results from other studies (YAN *et al.*, 1979; XU *et al.*, 1992), and similar to the results of S_H from the Japan Islands (TANAKA and OKA, 1979). However, in Shanxi Graben, west of Mt. Taihangshan, there is a sharp change in the direction of S_H (Fig. 4).

In South China, south of the EW oriented Qinling-Dabieshan tectonic zone (see Fig. 4), the direction of the principal stress is rather uniform at WNW–NW and consistent with the directions of the P axis obtained from the fault plane solutions (YAN *et al.*, 1979; XU *et al.*, 1992). The boundary is well defined, coinciding with the alignment of Qinling-Dabieshan Mountain.

There are a few *in situ* stress data in Northeast China. From these data, together with fault plane solutions, we can see that the compressive principal stresses lie predominantly in the ENE direction.

The data coverage in West China is quite sparse. The obtained directions of S_H were predominantly NNE, while some trend nearly NS.

The stress states within Southwest China might be related to the lateral spreading of the Qinghai-Tibet Plateau, however, the stress state is rather complicated there.

According to the geomechanics initiated by Lee in 1946 (LEE, 1984), the tectonic traces of the crust always reflect upon the behavior of the crustal stress. However, the tectonic traces on the crust occurred in groups, and each group of the tectonic traces shows a certain manner of tectonic movement and tectonic stress

Figure 4

The distribution of the maximum horizontal stress direction in the Mainland China and Japan. The data of *in situ* stress measurements in Japan are from TANAKA *et al.* (1979). The data are classified into two groups: shallow (those measured at a depth less than 100 m), and deep. 1—Yinshan tectonic zone; 2—Taihangshan tectonic zone; 3—Qinling-Dabieshan tectonic zone; 4—Longmenshan fault zone; 5—Xianshuihe-Xiaojiang fault zone; 6—Langcangjiang fault zone.

field. Studying the activity of the faults in the Great Britain Islands, ANDERSON (1942) considered that the stress which caused the fault to be active was not local, and in a given time, what influenced most regions of the country belonged to the same general stress system. The results of *in situ* stress measurements reveal that there exist relatively uniform stress distributions in different regions of the continent which can be characterized by principal stresses.

4. Conclusion

On Mainland China the rate of increase of the horizontal principal stress with depth is greater than that of the vertical stress. The depth gradients of the major shear stress vary from region to region. The depth gradient of the major shear stress in Western China is almost twice that of Eastern China. Similarly, a more rapid increase of the horizontal stress with depth has been found in Western China than in Eastern China. These observations may reflect the regional differences in tectonic environments.

It may be observed from the available data that generally the two horizontal principal stresses are larger than the vertical one, a condition favorable to thrusting, although this may be just a shallow phenomenon. In the deeper part, $S_H \geq S_v > S_h$ it seems likely that the stress state favors strike slip faulting or normal faulting.

In Mainland China the horizontal stresses are characterized by strong directionality; the directions of the major horizontal principal stresses are stable and uniform within certain broad areas. These stress directions appear to be associated with geological structure as well as current crustal deformation.

The results described here are mainly based on the analyses of the data obtained from *in situ* stress measurements at shallow depths of 500 m. Whether these results could be extrapolated to the depths of tens of kilometers is at present questionable. For earthquake prediction and geodynamics study, it is essential to carry out *in situ* stress measurements at deeper levels in the crust.

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