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Quantitative analysis of the shallow crustal tectonic stress field in China mainland based on in situ stress data

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ABSTRACT

The latest hydraulic fracturing and stress relief measurement data in the Chinese mainland were collected. The total of 3856 data entries are measured at 1474 locations. The measured area covers 75–130°E and 18–47°N, and the depth range varies from surface to 4000 meters depth, which generally includes each active tectonic block of China and each segment of North–South seismic belt. We investigated the tectonic stress field by removing the effect of gravity. For this, we assume lateral constraints and Heim's rule. The gravity contribution is removed by using the assumption of lateral constraint and Heim's rule. Our results show: (1) the maximum and the minimum horizontal principal stress σ_H, σ_h and the vertical stress σ_V in the shallow crust of China all increase linearly with depth: $\sigma_H = 0.0229D + 4.738$, $\sigma_h = 0.0171D + 1.829$, $\sigma_V = 0.0272D$. Maximum and minimum horizontal tectonic stress varies as a function of depth D linearly $4.738 < \sigma_T < 0.0139D + 4.738$ and $1.829 < \sigma_t < 0.0162D + 1.829$. The horizontal tectonic differential stress is $\sigma_T - \sigma_t = 0.0058D + 2.912$. (2) The intermediate value of σ_{T1} (regression value of tectonic stress inferred from the assumption of lateral constraint at 2000 m depth) changes in different areas, the maximum value of which is 45.6 MPa, while the minimum value of which is 26.8 MPa. Horizontal tectonic differential stress $\sigma_T - \sigma_t$ increases linearly with depth and the maximum and minimum of $\sigma_T - \sigma_t$ is 25.3 MPa and 13.0 MPa, respectively. In general, the stress magnitude is much higher in western than in eastern China. This indicates that the strong Indo-Eurasian collision dominates the present tectonic stress field in Chinese mainland. (3) Compared with other study regions, the northward crustal compression to the Qinghai-Tibet block is relatively lower in magnitude in the shallow subsurface and higher at deeper depth. (4) The orientations of σ_T in China mainland generally form a radial scattering pattern centered in Tibetan Plateau. From western to eastern China, they rotate gradually clockwise from NS to NNE, NE, NEE, and SE, which is consistent with the result of focal mechanism solutions.

1. Introduction

A variety of sources and processes contributes to the stress field in the lithosphere. Among these are dynamics of the lithosphere, heterogeneities in density structure and thickness of the crust and associated topography, plate bending processes and thermal stresses (McNutt, 1987; Zoback et al., 1989). Various types of observations including earthquake focal mechanisms, in situ measurements and geological deformations give information about the large scale lithospheric stress field (Fleitout and Froidevaux, 1983). In situ stress measurement is a direct way to study stress field, thereby the orientation of principal stress and magnitudes of the components of the stress tensor at a point in the earth's crust can be determined. Investigations have been carried out to better understand the stress field based on in situ measurements over the past decades. Voight et al. (1968) pointed out that near-surface stress magnitudes and trajectories can help to establish the type of large-scale stress fields acting on lithospheric plates. Ranalli and Chandler (1975) analyzed reliable in situ stress and discussed their relationship to tectonic movements. Hast (1969) reported that the sum of the horizontal principal stresses in the Fennoscandian block increases linearly with depth. Worotnicki and Denham (1976) discussed the ratio of maximum horizontal to minimum horizontal stress variation with depth in Australia. Brown and Hoek (1978) established the relationship between lateral coefficient and depth according to the measured stress data worldwide and available. Stacey and Wesseloo (1998) calculated regression lines for the ratios of the major and minor horizontal stress to the vertical stress in South Africa. Zoback et al. (1980) estimated the magnitude of

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Table 1
The data used in this paper.

Data type/amount	Depth m	Longitude (°)	Latitude (°)	A quality data	B quality data	C quality data	D quality data	Unknown or E quality data
HF[a]/2985	4–3984	82–128	22–46	127	1717	773	159	209
OC[b]/601	3–1271	75–130	18–47	99	71	241	52	138

[a] HF: hydraulic fracturing measurement.
[b] OC: stress relief measurement.

shear stress on the San Andreas Fault by measuring the variation of shear stress with distance from the fault at comparatively shallow depths. According to Scotti and Cornet (1994), in situ stress measurements deeper than 400 m in central France can be linearly extrapolated to seismogenic depth. Stephansson et al. (1986) displayed a profile of mean stress magnitudes versus depth in Fennoscandia. Li (1988) discussed the stress variation with depth in shallow crust of China and the results were extrapolated to the deep crust. Xie et al. (2004) summarized the basic characteristics and regional division of recent tectonic stress field in China and adjacent areas. Furthermore, most recent studies (Zeng, 1990; Cai, 2000; Zhu and Tao, 1994; Jing et al., 2008; Zhao et al., 2007; Shi, 2004) summarized stress observations in China mainland.

Tectonic stresses are those generated by the forces that drive plate movement (Middleton and Wilcock, 1994). There are a variety of methods for inferring the state of tectonic stress in the crust, including the mechanisms of earthquake, geological features, geodetic observations, and direct in situ measurements. Richardson et al. (1979) established a finite element model to investigate the contribution of forces acting along the plate boundaries to tectonic stresses. Scotti and Cornet (1994) clarified the relationship between lateral density variations in the lithosphere and observed topography and tectonic stress field with the help of simple physical models of a stratified viscous Newtonian lithosphere. In the study by Kirby (1980), the tectonic stress is constrained by the result from experimental deformation of rocks.

In this paper, the latest hydraulic fracturing and stress relief measurement data from the Chinese mainland were collected and sorted. From these data, we analyze the tectonic stress field by removing the contribution of gravity from in situ stresses. The present study was undertaken to investigate the magnitudes and orientations of shallow crustal stress in the active blocks and North–South seismic belt of China mainland.

2. Data

2.1. Data sources

The hydraulic fracturing and stress relief measurement data in the current study are mainly from "Fundamental database of crustal stress environment in continental China" (Xie et al., 2003) and partly from literatures published since 2002. In addition, in situ stress data in working reports of the Institute of Crustal Dynamics, CEA and the Institute of Geo-mechanics, CAGS are included. Stephansson and Zang (2012) introduced the full description of stress data at a given site, according to their introduction Table 1 gives a detailed description of data in this paper.

2.2. Data distribution and study regions

Zhang et al. (2003) defined and delineated the active tectonic blocks to investigate the mechanism of strong earthquake generation in China mainland. Chinese seismologists use late Quaternary tectonic activity as a principle to delineate the blocks. The Chinese continent and its surrounding area is divided into two grades of active tectonic blocks, the 6 first grade blocks are: the Qinghai-Tibet block (QT for short), the Yunnan-Burma block (YB), Northwestern China block (NWC), the South China (SC), the North China (NC), and the Northeast China block (NEC). These active tectonic blocks are important parts of study regions in this paper. Since the onset of earthquake records, almost half of all strong earthquakes ($M > 8$) occurred in the North–South seismic belt. The North–South seismic belt is not only the boundary between the western and eastern active tectonic blocks but also the boundary of the first order tectonic stress districts (Xie et al., 2004). According to the latest division of the North–South seismic belt based on seismological activity proposed by Wen (personal communication, November 8, 2011), it is sub-divided into 3 parts: North segment of N–S seismic belt (NSB), Middle segment of N–S seismic belt (MSB), and South segment of N–S seismic belt (SSB). The Yunnan–Burma block and the South section of N–S seismic belt are almost overlapping so they are treated as a single study region denoted as SSB. The distribution of in situ stress data and study regions are shown in Fig. 1.

2.3. Data selection

A considerable amount of in situ stress data are collected from engineering projects, some of them are inevitably strongly influenced by the local geological conditions or measurement conditions. To ensure the validity and reliability in this study, the following strategies are adopted: (1) incomplete data points lacking the value of a given attribute (depth or magnitudes of horizontal stress) or missing information about principal stresses are excluded. (2) Only those data points of which the intersection angle of principal stresses is between 85° and 95° are adopted. (3) To ensure that our results better reflect the regional state of stress, a simple filtration method is adopted. The procedure is as follows: the linear regression is performed on all data points, and then the corresponding regression line (the red[1] line in Fig. 2) is taken as a central line. We draw two bilaterally symmetric lines (the green lines in Fig. 2) parallel to the central line, which capture 95% of total amount of data points. The data points outside the area are considered to depart from normality and not adopted in this study (Fig. 1). After these selection processes, the number of the hydrofracturing data is 2904 and their depth varies from 4 m to 3984 m. The amount of data points from stress relief methods is 461 and data depth varies from 3 m to 1271 m.

3. Variation of principle stresses with depth in China mainland

Previous statistic analyses of in situ stress in China mainland did not mention the non-uniform distribution of stress data with depth. The amount of the stress data at shallow depth is substantially larger than at deeper levels, therefore the statistical result mainly reflects the stress provinces at shallow depth. To solve this problem, in this study, an equal-interval grouping method is adopted: (1) data are grouped into a series of sets by equal depth

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.