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Geothermal study at the Wenchuan earthquake Fault Scientific Drilling project-hole 1 (WFSD-1): Borehole temperature, thermal conductivity, and well log data

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ABSTRACT

The Wenchuan earthquake Fault Scientific Drilling project-hole 1 (WFSD-1) offers a unique opportunity for studying the faulting behavior and the thermal regime of the Longmen Shan fault zone (LMFZ), east margin of Tibetan Plateau. Thermal conductivity of fault rocks within main fault zone shows strong negative interrelations with the porosity, the gamma ray and the P-wave slowness, as well as a positive interrelation with the density. Here we attribute these correlations to the fractures and the rock-fluid reaction generated from the earthquake, which will increase the porosity, the radioactivity and the P-wave slowness as well as decrease the density and the thermal conductivity, synchronously. 15 continuous temperature profiles were summarized in this paper. Based on integrated studies of temperature variations and thermal gradients, local temperature anomalies were detected at three depth ranges of 480–510 m, 580–610 m and 625–755 m, respectively. These anomalies seem to correspond to different fracture zones and may be attributed to fluid flow in the fractures. In addition, the non-uniform vertical distribution of these temperature anomalies was observed across the co-seismic slip surface at 589.2 m. In the below ~200 m borehole depth, a prominent thermal anomaly zone was developed, implying more factures were generated in the footwall than the hanging wall during the Wenchuan earthquake. The heat flow ranges from 69 mW/m^2 to 72 mW/m^2 for different logs. The persistence of elevated heat flow in the LMFZ appears to rule out frictional heating on the Yingxiu-Beichuan fault (YBF) as the source of the WFSD-1 value, but is probably related to the regional tectonic evolution.

1. Introduction

The May 2008, Mw 7.9 Wenchuan earthquake produced two co-seismic surface ruptures of 270 km and 80 km along the Yingxiu-Beichuan fault (YBF) and Guanxian-Anxian fault (GAF) respectively, with up to ~11 m of offset on the northern part of the YBF (Li et al., 2008, 2009; Xu et al., 2009; Fu et al., 2011). This large earthquake caused disastrous damages in the cities along the Longmen Shan fault zone (LMFZ). In order to investigate the seismic fault features, including its geophysical characteristics and rock physical/chemical variation as well as the thermal history the fault underwent, the Wenchuan earthquake Fault Scientific Drilling project (WFSD) was sponsored by the Ministry of Science and Technology of China and the International Continental Drilling Program.

The WFSD includes five boreholes distributed along the YBF and the GAF, ranging from 550 m to 3400 m depth. The first borehole (WFSD-1) is located at N31.149°, E103.691°, 385 m west of the Wenchuan earthquake surface rupture (Fig. 1b). The drilling of the WFSD-1 was started on 6 November 2008, only 178 days after the earthquake, and was completed on 12 July 2009, with a total depth of 1201.15 m, and 95.4% of core recovery (Li et al., 2013). It was the most rapid drilling response project after the earthquake.

Up to now, using continuous coring and downhole wireline logging from the WFSD-1, the LMFZ has been extensively studied, such as studies of Principal Slip Zone (PSZ), thermal structure, shear stress, drilling mud gas, clay mineral and permeability (Xue et al., 2013; Li et al., 2013, 2014, 2015; Si et al., 2014; Wang et al., 2014; Gong et al., 2015). Studies of downhole thermal physical properties of fault rocks is also one of great importance to understand the rupture process, identify the geological weak and fluid flow zones, as well as constrain on the subsurface thermal

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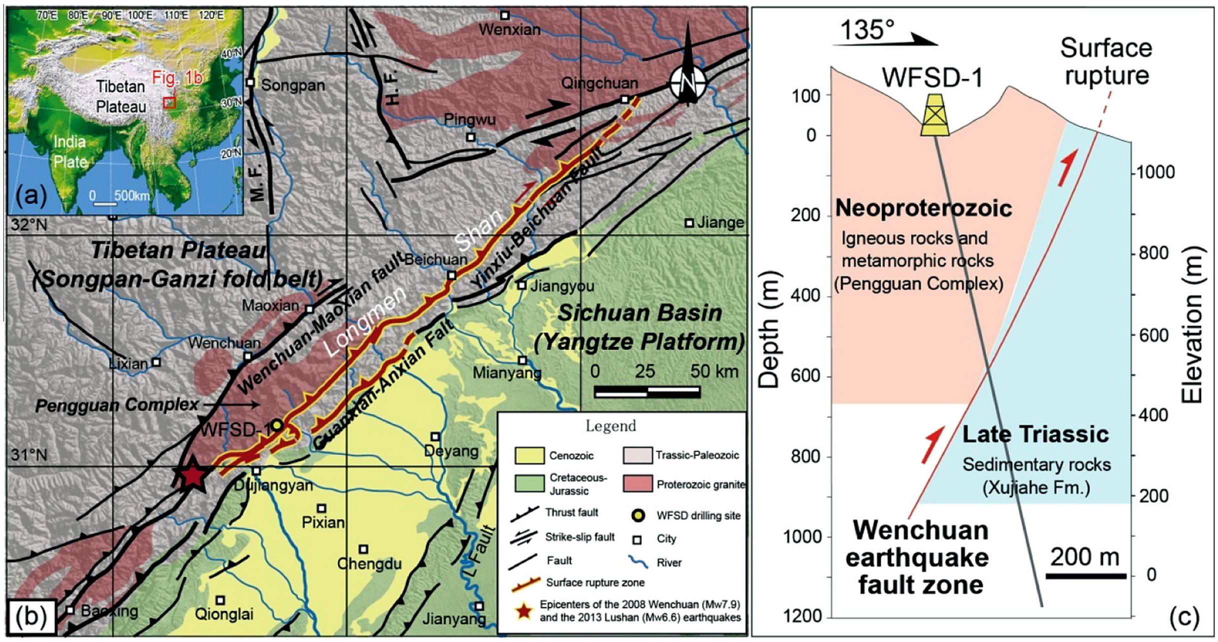

Fig. 1. Simplified geologic and active tectonic map of the Longmen Shan and its adjacent area (modified from Li et al., 2014). (a) Location of the study area. (b) Geological map of Longmen Shan around the WFSD-1 drilling site. (c) Simplified geologic cross-section at the WFSD-1 drilling site.

structures (Yamano and Goto, 2001; Williams et al., 2004; Kano et al., 2006; He et al., 2008; Fulton et al., 2013; Li et al., 2015). For this purpose, this paper summarized the results of 15 repeat temperature logs continuing from 1.3 to 5.3 yr after the Wenchuan earthquake. The thermal conductivity measurements of the drill core were related to the lithology, the geophysical properties and the fracture distribution, in order to probe its behavior during the fracturing process. Compared with the values from the adjacent areas and the modeling, we also briefly discussed the tectonic implications of the heat flow from the WFSD-1.

2. Geological setting

The Longmen Shan fault zone (LMFZ) at the eastern margin of the Tibetan Plateau, adjacent to the Sichuan Basin (Fig. 1a), is characterized by a series of northeast–southwest trending thrust faults (Fig. 1b). Regarded as a typical intracontinental orogenic belt, the LMFZ was originally resulted from the Mesozoic orogeny accommodating the transpressional convergence between the Songpan-Ganzi fold belt and the Yangtze Platform in the Late Triassic, and was reactivated by the Cenozoic outward growth of the Tibetan Plateau following the Indian-Eurasian continental collision (Burchfiel et al., 1995; Wang and Meng, 2009). The Songpan-Ganzi fold belt to the northwest, which demarked the east margin of the palaeo-Tethys, involved a large flysch basinal deposits. All of these flysch rocks were shorted along a series of northwest–southeast folds and thrust faults during the regional northeast–southwest compression by the end of the Triassic or the Early Jurassic (Xu et al., 1992; Roger et al., 2004). It is usually regarded that the Triassic flysch has huge thickness. However, strong internal interfering deformation makes it difficult to determine its true thickness (Wang and Meng, 2009). To the southeast, the Yangtze Platform has a Precambrian crystalline basement overlain by a thick succession of the Latest Proterozoic to the Early Tertiary sedimentary cover (Burchfiel et al., 1995). The Sichuan Basin was located in the western part of the Yangtze Platform, formed in the Late Triassic as a foreland basin. This foreland basin shows a characteristic of asymmetrical thickness of the Late Triassic strata, probably due to tectonic loading of the thrust nappes along the LMFZ (Li et al., 2003; Meng et al., 2006).

Three mega-thrust faults, YBF, GAF and Wenchuan-Maoxian fault form the main LMFZ (Fig. 1b), which have a long history and are recognized as reactivated faults along the previous faults since the Late Triassic (Dirks et al., 1994; Burchfiel et al., 1995). Due to the lack of historical M > 7 earthquake records prior to the Wenchuan earthquake, the LMFZ has potentially experienced a relatively long quiet time to accumulate enough energy to trigger a large earthquake such as that of the Wenchuan earthquake (Li et al., 2014).

The WFSD-1 hole intersects through the boundary of the hanging wall of the upper Neoproterozoic Pengguan Complex and the footwall of the Triassic Xujiahe Fm. sedimentary rocks at a depth of ~589 m (Fig. 1c). The Pengguan Complex here consists of diorite, porphyrite, pyroclastics and other volcanics, while the Late Triassic Xujiahe Fm. here is dominated by sandstone, siltstone and shale, together with some liquefied breccia (Fig. 2a). The fault rocks develop mostly from 589 m to 759 m depth, which here mainly consist of cataclasite and fault breccia from 606 m to 755 m, and mainly consist of fault gouge layers from 585 m to 598 m (Fig. 2b). The multiple faults exist throughout the same depth zone, and a single principle slip surface corresponding to the 2008 Wenchuan earthquake is difficult to identify. Based on the fresh gouge appearance, the microstructures relating to co-seismic slip, the high magnetic susceptibility values (Li et al., 2013), the clay mineral composition in the cores (Si et al., 2014), the borehole logging data (Li et al., 2014), and the drilling mud gas concentrations (Tang et al., 2013), a fault located at the depth of ~589 m is considered as the strongest candidate for the principal slip fault of the Wenchuan earthquake.

3. Data acquisition

3.1. Temperature logging

Most of the geophysical logging was conducted synchronously with the WFSD-1 drilling (Fig. 2c–g). All logs were recorded in a cased borehole. To minimize the disturbances from other logging