Chin. J. Geochem. (2015) 34(2):201–207
DOI 10.1007/s11631-014-0028-0

ORIGINAL ARTICLE

Mercury indicating inflow zones and ruptures along the Wenchuan Ms 8.0 earthquake fault

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Received: 23 September 2014 / Revised: 11 December 2014 / Accepted: 16 December 2014 / Published online: 11 March 2015

Abstract During the Wenchuan Fault Scientific Drilling Project, we determined the values of total mercury (HgT) and gaseous elemental mercury (GEM) from drilled cores and drilling mud, respectively. Geochemical analysis shows HgT values ranging from 0.24 to 6.45 ng/g for the Penguan complex and from 2.90 to 137.54 ng/g for T3 sediment. The average levels of HgT for the Penguan complex and T3 sediments are 1.81 ± 0.26 ng/g and 23.96 ± 4.80 ng/g, respectively. Major anomalous peaks of HgT appear at depth of 614,731,993 and 1,107 m, which correspond to the long-term high seismic activity during crustal deformation in response to tectonic stresses. Gaseous elemental mercury dissolved in drilling mud was also analyzed. We found fluid inflow zones with high GEM at depths of 590–750 m, suggesting that fluid-filled ruptures exist in the LMS fault zone. It indicates that mercury provides geochemical evidence for inflow zones and ruptures/fault zones in the Wenchuan Ms 8.0 earthquake fault.

Keywords Mercury · Rupture · Inflow zone · Geochemistry · Wenchuan 8.0 earthquake

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1 Introduction

A catastrophic Ms 8.0 earthquake occurred on May 12, 2008 along the Longmen Shan (LMS) fault (Fig. 1), leading to a 300 km-long fault with the average slope of 65° (Li et al. 2013). Seismic tomography (Yao et al. 2008) suggested the intrusion of deep flows from the lower crust upwards to the LMS fault. In November 2008, the Wenchuan Fault Scientific Drilling Project (WFSD) was established to investigate the mechanism of the great Wenchuan earthquake. WFSD-1 borehole started shortly (178 days) after the main earthquake down to 1,201 m-depth (WFSD-1, as shown in Fig. 1), and provided geochemical data for analyzing anomalous activities of fluids in the Wenchuan Ms 8.0 earthquake fault. Tang et al. (2014) have monitored the concentrations gaseous components (e.g. H2, CH4, He, and Rn) extracted from the drill mud. Noble gas analysis including helium isotope studies from Wenchuan drill mud gas samples were performed by Tang et al. (2014). They found that major anomalies of all components appear near the Wenchuan Ms 8.0 fault, which provide geochemical evidence for the intrusion of deep fluids.

Geochemical studies found that gaseous elemental mercury (GEM), released from deep tectonic faults (Gregory and Durrance 1985) and driven by gradients of both pressure and temperature, migrates along fractures upward to the surface (Holub and Brady 1981; Zhang and Sanderson 1996). Mercury abundance anomalies accumulated within deep active faults, hot springs (White et al. 1970) and volcanic centers (Nriagu and Becker 2003), and showed obvious anomalies near the LMS earthquake fault scarps (Zhou et al. 2010). Zhang et al. (2014) found the anomalies of mercury isotope in the WFSD-1 borehole. Li et al. (2012) suggested that high mercury content in China

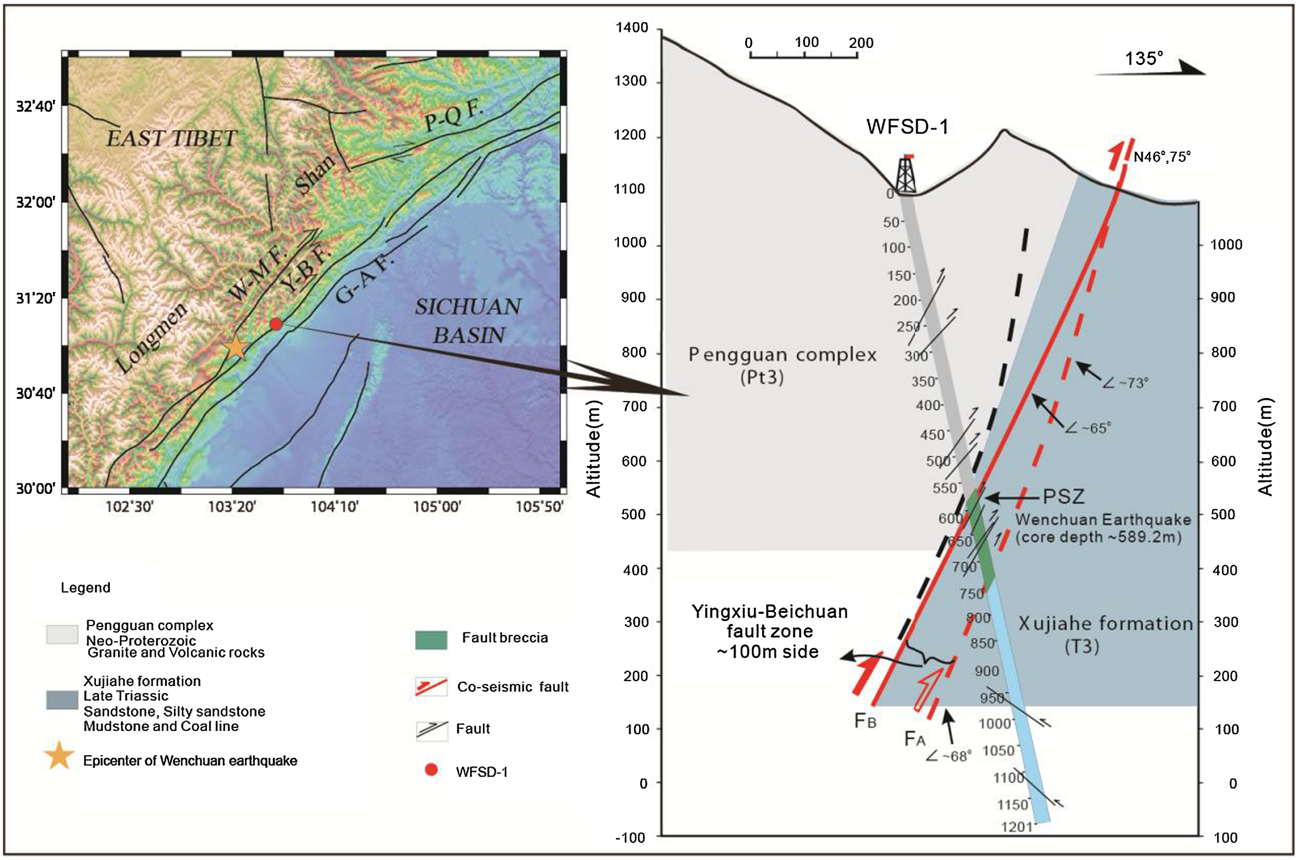

Fig. 1 The geographic location of major faults and the WFSD-1 borehole. *Pt3* represents the Penguan complex, while *T3* represents Xujiahe formation (the tertiary sediment). *Fn* and *Fa* denote the Yinxiu-Beichuan fault zone. *PSZ* indicates the principle slip zone. The depth of WFSD-1 is 1,201.0 m (after Zhang et al. 2014)

is mainly distributed in the active structure background. Geological mercury is often associated with the boundaries of tectonic plates. Significant deposits are located in regions where plate subduction has occurred in combination with a degree of volcanic activity or hot springs.

Erzinger et al. 2004 monitored the concentrations of H2, CH4, He, and Rn from drilling mud to provide geochemical evidence for the intrusion of deep fluids from the upper mantle. Drilling mud gas monitoring studies from drilling through the San Andreas Fault at seismogenic depth (Wiersberg and Erzinger 2008) provide information on the permeability structure and architecture of an active fault zone and the role of deep fluid flow from the mantle.

In the present study, we provide mercury geochemical evidences for the tectonic activities and fluid paths within the LMS fault zone. New geochemical data were presented, including total mercury (HgT) and the rare earth element europium (Eu) from drilled cores of the WFSD-1 borehole at depths of 17–1,201 m. Gaseous elemental mercury from the drilling mud was also investigated. The abundance characteristics of HgT and Eu were observed, and the correlation between geochemical components and inflow zones/fault zones was analyzed. Geochemical results suggest that total mercury and GEM are useful for attesting the long-term high seismic activity of the fault and the inflow zones.

2 Analytical methodology

Li et al. (2012) provided the average content of mercury (0.18 μg/Kg) of natural gas fields in Sichuan basin, but they could not monitor mercury background for different rocks. Here, mercury contents of drilled rocks and drilling mud are monitored from the WFSD-1 borehole.

At the depth above 590 m, quartz monzonite, hornblende syenite, syenite, quartz syenite, syenite porphyry and alkali-feldspar granite are the major components of the Pt3 complex (as depicted in Fig. 1). At the depth below 590 m, fault mud, fault breccia, and cataclasite are the major components of coal-bearing T3 sediments (Li et al. 2013). A total of 76 samples of drilled cores were collected at depths of between 17 and 1,201 m. The fresh drilled core samples were prepared and crushed into powder (e.g.100-micron mesh powder for analyses of mercury and trace elements) to enhance overall reactivity under the monitoring conditions. Total mercury (HgT) was measured with the DMA-80 Direct Mercury Analyzer. Europium was detected using the inductively coupled plasma mass spectrometry (ICP–MS) method (DZ/T0223-2001) with a high-resolution ICP–MS (Element I) instrument. We determined GEM in 114 drilling mud samples at depths of between 177 and 1,201 m. Gaseous elemental mercury was also monitored from drilling mud with the Direct Mercury Analyzer DMA-80. Total mercury, gaseous elemental mercury, Eu, Total organic carbon (TOC) and Baric (Ba) components were detected in the Analysis and Detection Center of the Beijing Research Institute of Uranium Geology.

3 Results

3.1 Mercury characteristics of drilled cores

Figure 2a demonstrates that the concentrations of HgT range from 0.24 to 6.45 ng/g for the Pt3 complex (depth of 17–590 m) and from 2.90 to 137.54 ng/g for the T3 formation (depths of 590–1,201 m). The average levels of HgT are 1.81 ± 0.26 ng/g and 23.96 ± 4.80 ng/g for the Pt3 complex and the T3 formation, respectively. The statistical results are summarized in Table 1. Major anomalous peaks of HgT appear at ~614, 731, 993, and 1,107 m, respectively, primarily corresponding to the ruptures/fault zones discovered in the WFSD-1 borehole (Li et al. 2013), and indicating the long-term high seismic activities of the LMS fault. Downhole Logging data (2014) and fault density statistic data (Li et al. 2014) provides some evidences for long-term fault slip at these depths. HgT concentration peaks indicate that the T3 formation experienced big ruptures or strong earthquakes, and deep fluids enriched with mercury invaded into this formation.

Figure 2b shows concentrations of Eu varying from 0.535 to 2.21 ppm for the Pt3 complex (depth of 17–590 m) and from 0.474 to 2.61 ppm for the T3 formation (depth of 590–1,201 m). The average levels of Eu are 1.232 ± 0.075 ppm and 1.094 ± 0.058 ppm for the Pt3 complex and the T3 formation, respectively. The common upper crustal abundance of Eu is 0.88 ppm (Taylor and McClennan 1985). Eu values were normalized by C1 chondrite (Sun and McDonough 1989). All samples have pronounced negative Eu anomalies, ranging from 0.027 to 0.151, with an average level of 0.067 ± 0.002. The Eu anomaly in sedimentary rocks is usually interpreted as inherited from igneous source rocks. The negative Eu anomalies suggest that the upward migration of materials from the low-velocity zone can generate an enriched reservoir in the lower crust (Sun and McDonough 1989). Here, the latter mechanism should be dominant, as evidenced by lower crustal flow under the LSM fault (Clark and Royden 2000) and the intrusion of deep fluids into the LMS fault (Yao et al. 2008).

As shown in Fig. 3, it is difficult to find the peaks of Eu/chondrite ratio with peaks corresponded to HgT. It indicated a relative small change of Eu and large change of HgT. However, the amounts of Eu/chondrite ratio reside above the critical value of 1, suggesting the historic intrusion of deep-seated fluids within the LMS fault zone.

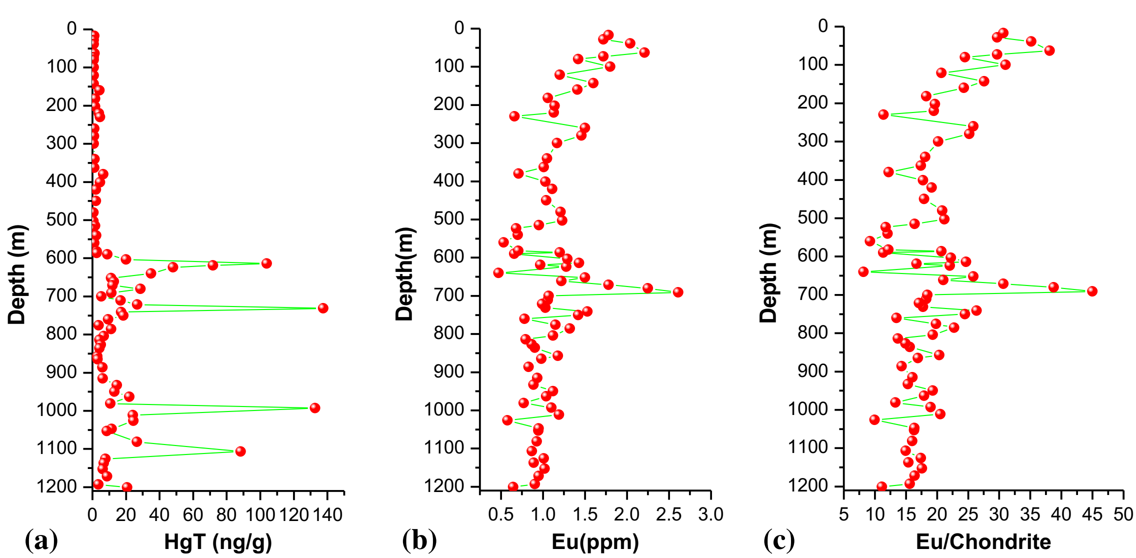

Fig. 2 The abundance-depth profiles of HgT and Eu from the drilled rocks

Table 1 Statistical analysis of HgT and Eu from the drilled rocks

Species	Pt3 Complex (17–590 m)		T3 formation (590–1,200 m)	
	Mean	Sample number	Mean	Sample number
HgT (ng/g)	1.81 ± 0.26	31	23.96 ± 4.80	45
Eu (ppm)	1.232 ± 0.075	31	1.094 ± 0.058	45

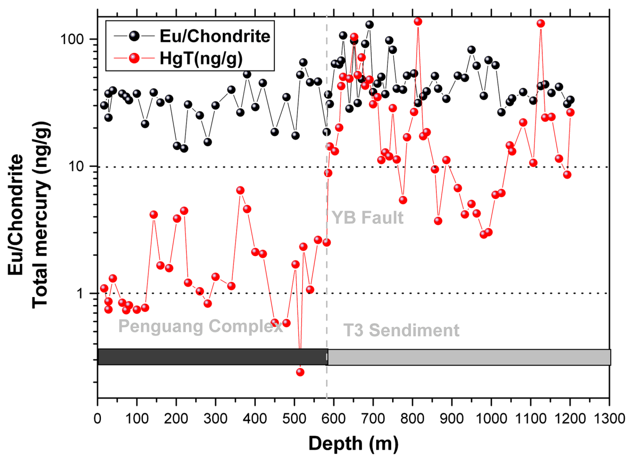

Fig. 3 Depth profiles of europium and total mercury (HgT), and the ratio of europium (Eu) to chondrite. The *black dotted lines* denote an Eu/chondrite ratios of 1 (critical value) and 10. The *dotted light-gray line* represents the Yinxiu-Beichuan (YB) fault. The *gray* and *light-gray* columns represent the Penguan complex and T3 sediment, respectively

Figure 4 shows the depth-profile of concentrations of HgT, TOC and Ba. It found that a weak correlation is observed between Ba and HgT (R = 0.21) for Penguan complex and (R = 0.18) for T3 sediment. No significant correlation between Ba and HgT composition for drill cores is found, which partially implies that barite is not the primary source of HgT and any drilling mud contamination should be irrelevant.

3.2 Gaseous elemental mercury from drilling mud

In order to present geochemical evidences for inflow zones along the LMS fault, GEM from the drilling mud was also detected for 114 drilling mud samples from 170 to 1,201 m-depth. Figure 5 illustrated the abundance of GEM in the drilling mud. At a depth of between 170 and 590 m, the concentrations vary from 0.01 to 1.50 ng/g, with a mean of 0.46 ± 0.06 ng/g. From 590 to 750 m-depth, the concentrations range from 0.94 to 31.32 ng/g, with an average of 17.52 ± 1.38 ng/g. At a depth of 750–1,201 m, the average level is 0.72 ± 0.22 ng/g, with concentrations varying between 0.2 and 1.8 ng/g. The depth profile of GEM is characterized as a multiple peak distribution. Major anomalous peaks appear at 590–750 m-depth, corresponding to the principal slip zone (PSZ) and the Yingxiu-Beichuan fault gouge (Li et al. 2014). This suggestion is also supported by research results, including helium

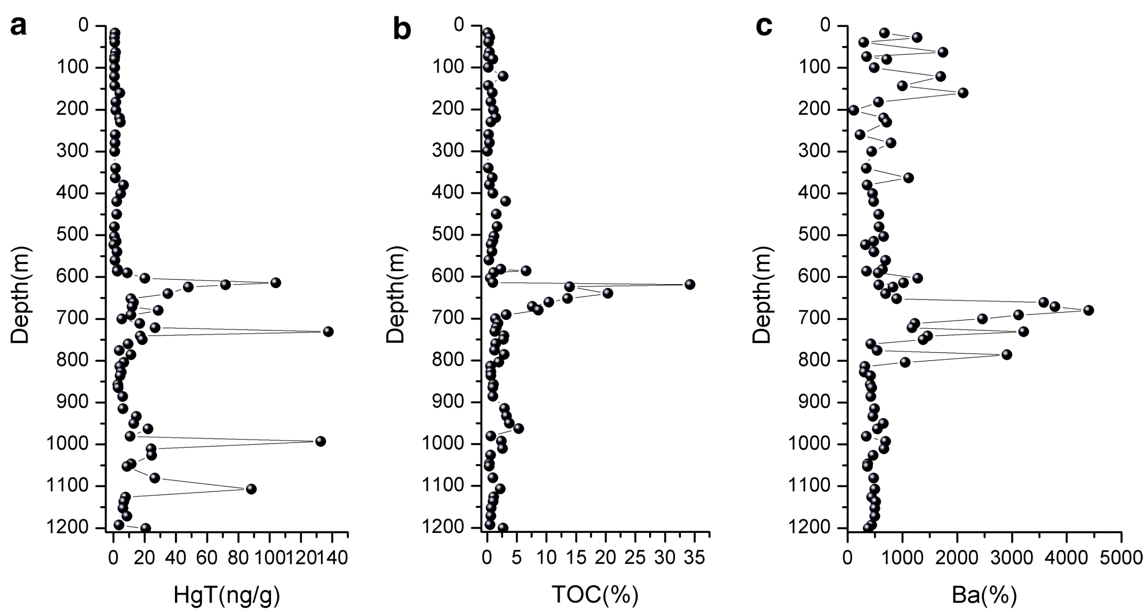

Fig. 4 The abundance-depth profiles of HgT, TOC and Ba from the drilled rocks

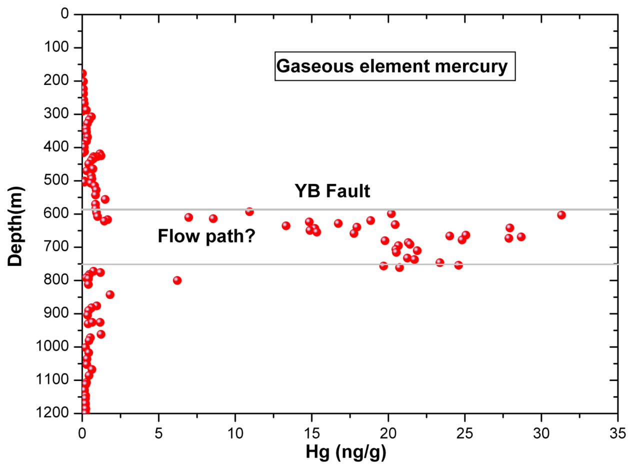

Fig. 5 Depth profile of gaseous elemental mercury from drilling mud. The *olive line* denotes the Yingxiu-Beichuan (YB) fault, while the box shaped with *declined lines* represents fractures or the inflow zones (predominant flow path). The *red balls* indicate gaseous elemental mercury

isotope from Wenchuan drill mud gas samples (Tang et al. 2014), which found that the mud gas such as methane and radon yielded low concentrations above the PSZ, whereas yielded high concentrations under the PSZ (Tang et al. 2014). Zhou et al. 2010 observed mercury anomalies near the LMS earthquake fault scarps (Zhou et al. 2010), which was associated with the variation in the regional stress field and aftershock activities (Ren et al. 2012).Outside the depth of between 590 and 750 m, the distributions of GEM are similar, with some minor peaks observed. At a depth of between 590 and 750 m (−160 m side), it indicated that a dominant flow channel resides within the T3 formation (the sedimentary Xujiahe Formation), along which fluids enriched with GEM migrated upward and built up within the Yingxiu-Beichuan fault zone. Tang et al. (2014) have mentioned the measurements of other gaseous components extracted from the drill mud of the WFSD-1 borehole, e.g. radon, hydrogen and helium. Such data could provide valuable information on the fluid origin by carbon isotopes, noble gas isotopes and fluid migration by radon.

Figure 6 shows that major anomalies of all components appear near the Wenchuan Ms 8.0 fault, which could shed new light on the contribution of deep (mantle-derived) fluids. Ren et al. (2012) also observed anomalous radon levels associated with seismic activities along the Wenchuan fault. Some researches (Koval et al. 2006) found a significant increase in mercury emissions from fault zones during catastrophic seismic events. We preliminarily suggest that GEM is the sensitive gas in the Yingxiu-Beichuan fault zone and can identify faults and inflow zones. Along with helium and radon, mercury of drilling mud can provide valuable information on the fluid origin and fluid migration.

The depth interval of observed anomalous drilling mud mercury levels appear in well agreement with the depths from temperature anomalies (as shown in Fig. 7), indicating the fault zone and inflow zones.

4 Discussion

It stated that the whole drilled core was used as sample material including the core rim, which was soaked with drilling mud, and that an artificial source of mercury (barium, TOC) could not be ruled out. We had not provided mercury content comparison between drilling mud samples in the drilling mud inlet and mud samples from the return line. If the comparison was made, and the data showed low contents of barium, mercury and TOC in the drilling mud inlet line and high contents of barium, mercury and TOC in the return line, the contamination problem should have been resolved.

But the comparison found that a weak correlation is observed between Ba and HgT ($R = 0.21$) from drill cores for Penguan complex and ($R = 0.18$) for T3 sediment. No significant correlation between Ba and HgT composition for drill cores is found, which partially implies that barite is not the primary source of HgT and any drilling mud contamination should be irrelevant.

The occurrence of the mercury isotopes in fault zones (Zhang et al. 2014) provides important information on fluid flow and the permeability architecture of active faults, which enhanced concentrations of Hg in drilled core and drilling mud when intersecting the LMS fault at the seismogenic depth. The mud gas such as helium, hydrant and radon yielded low concentrations above the PSZ, whereas yielded high concentrations under the PSZ (Tang et al. 2014). The presence of radon is sometimes linked with mercury. Along with mercury, Helium isotope data could be helpful to shed new light on the contribution of deep fluids. The drilling mud gas data from Tang et al. (2014) have mentioned that fault gouge formed by the Wenchuan Ms 8.0 seismic slip was found in depths between 586 and 593 m depths in the borehole WSFD-1 (Li et al. 2014), but highest mercury concentration in the present study is observed in drilled core from 614 m depth. The Hg in drilling mud from the present study appears at somewhat shallower depth, in agreement with the depths from Tang et al. (2014).

The relatively weak depth correlation between gaseous Hg from drilling mud and Hg from drilled core may be interpreted with fluid migration through a fracture zone that surrounds the fault core. Hg was added to the drilling mud by penetrating Hg-rich strata. From the point of the drilling engineering process, an explanation would be that the Hg-loaded drilling mud returned back to the surface through

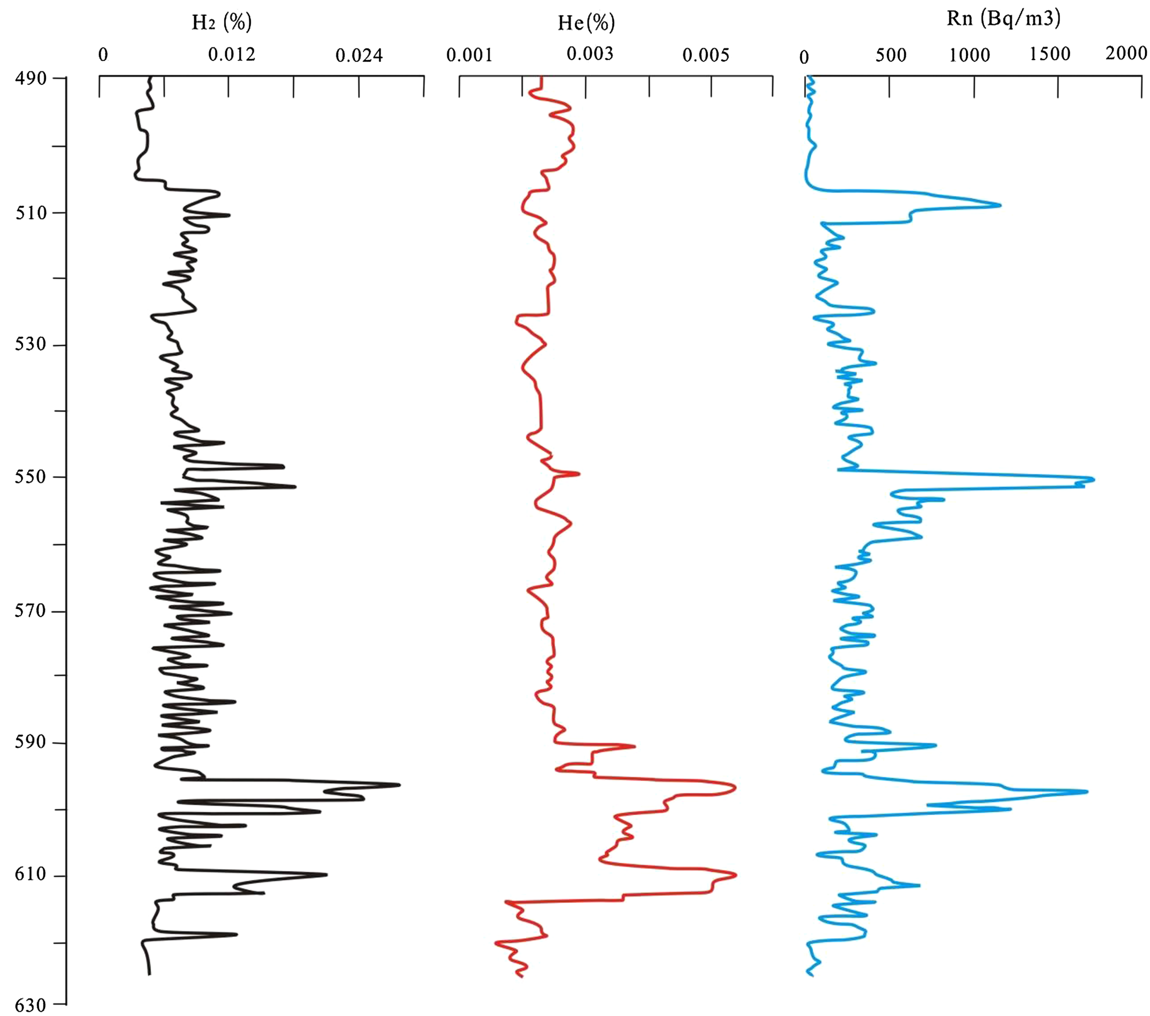

Fig. 6 Concentrations of gaseous components extracted from the drilling mud (Data from Tang et al. 2014)

the annulus between drill string and wall rock. At the surface, the gaseous components were detected. After one turnover of the drilling mud volume (mud tanks, pumpes, pipes), the drilling mud that still contained Hg was again pumped down the drill string, where it passed the freshly drilled core in the core liner.

Major anomalous peaks of HgT from the drilled cores appear at depth of 614, 731, 993 and 1,107 m. Downhole Logging data and fault density statistic data (Li et al. 2014) provides some evidences for long-term fault slip at these depths. HgT concentration peaks indicate that the T3 formation (as shown in Fig. 1) experienced many big ruptures or strong earthquakes, and that deep fluids enriched with mercury invaded into the T3 formation during long-term seismic activities, and contributed to the major anomaly peaks. From this point, HgT highlighted the tracer of the tectonic activities within the LMS fault.

5 Summary

The concentrations of total mercury (HgT) were determined for 76 samples from WFSD-1 borehole drilled cores. The depth concentration profiles are characterized by multiple peaks. Major anomalous peaks of HgT appear at 614, 731, 993, and 1,107 m, which correspond to ruptures/fault zones during crustal deformation in response to tectonic stresses. Gaseous elemental mercury dissolved in drilling mud was also analyzed. Higher concentrations of GEM were detected while drilling in the T3 formation. Major anomalous peaks appear at 586–750 m. We found the fluid inflow zones with high GEM at depths of 586–750 m, suggesting that inflow zones or fluid-filled fractured rock matrices reside in the LMS fault zone. It may suggest that mercury provides geochemical evidences for inflow zones and ruptures/fault zones in the Wenchuan Ms 8.0 earthquake fault. The presence of radon is

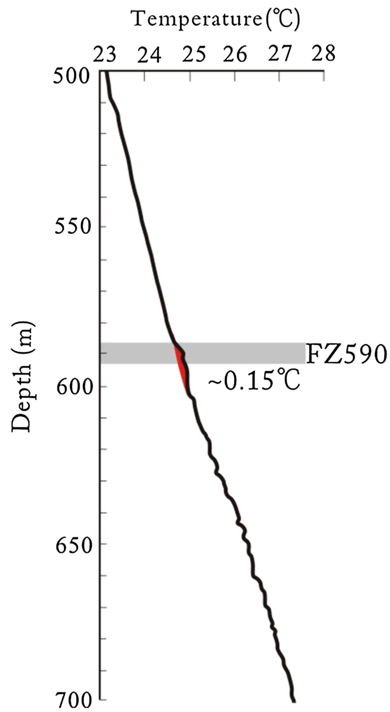

Fig. 7 Temperature downhole logging from 500 to 800 m-depth (Data from Li et al. 2014)

sometimes linked with mercury. Along with mercury, radon and Helium isotope data could be helpful to shed new light on the contribution of deep fluids.

Acknowledgments This work is sponsored by the Wenchuan Fault Scientific Drilling Project (WFSD). Many thanks are also given the anonymous reviewers from Chinese Journal of Geochemistry and Applied Geochemistry for constructive suggestions which much improved the scientific interpretation of this manuscript.

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