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Magnetic properties of the Wenchuan Earthquake Fault Scientific Drilling Project Hole-1 (WFSD-1), Sichuan Province, China

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Abstract

We measured the magnetic susceptibility of the core from the first borehole of the Wenchuan Earthquake (May 12, 2008, *Mw*7.9) Fault Scientific Drilling Project (WFSD-1) at 1-cm intervals. The correlations between magnetic susceptibility anomalies and fault rock occurrence are shown by a few fault zones in the WFSD-1 core. The values for the mass and ferromagnetic material magnetic susceptibility for the sample at 589.25-m depth are higher than those for the other samples. All the thermomagnetic curves display a rapid increase in slope after 380°C, and a marked peak occurs at about 510°C in the heating curves. The cooling curves are clearly higher than the heating curves. The saturation magnetization (Ms) shows a significant peak at a depth of 589.25 m, as do the mass magnetic susceptibility and the ferrimagnetic magnetic susceptibility. The mechanism principally responsible for the high magnetic susceptibility at a depth of 589.25 m might be the production of new magnetite from iron-bearing silicates (e.g., chlorite) or clays caused by frictional heating during seismic slip. Therefore, we suggest that the presence of high magnetic susceptibility fault gouges in the same country rock can be considered as an indicator of earthquakes or seismic signatures.

Keywords: Wenchuan Earthquake; Yingxiu-Beichuan fault; Slip zone; Magnetic susceptibility

Background

The magnetic properties of fault rocks can be used as tracers for physical and chemical alterations caused by frictional heating during earthquakes. Magnetic susceptibility and rock magnetism have commonly been used to understand the physical characteristics and chemical processes of fault slip zones (Enomoto and Zheng 1998; Nakamura and Nagahama 2001; Ferré et al. 2005, 2012). Correlations have been reported between magnetic susceptibility anomalies in borehole log data and the presence of cataclastic zones and faults in the main drill borehole of the German Deep Drilling Project (KTB) (Bosum et al. 1997), but the magnetic susceptibility of drill cuttings in the KTB do not support this correlation (Rauen et al. 2000). A series of studies demonstrated that higher magnetic susceptibilities might result from the production of new magnetic minerals with high magnetic susceptibility caused by frictional heating (Hirono et al. 2006; Mishima et al. 2006; Tanikawa et al. 2008) or from decreases in the grain size of magnetic minerals caused by shearing (Dearing 1999) during large-magnitude earthquakes (e.g., the Kobe and Chi-Chi earthquakes). Recently, the Chi-Chi earthquake gouge layer has been identified from the modern geomagnetic field direction recorded within the gouge layer (Chou et al. 2012).

Motivated by an interest in investigating the mechanism of the 2008 Wenchuan Earthquake, the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD) was launched on November 4, 2008, only 178 days after the Wenchuan Earthquake (Xu and Li 2010). The Wenchuan Earthquake (*Mw*7.9) produced two major surface rupture zones along the Yingxiu-Beichuan and Anxian-Guanxian faults. The Yingxiu-Beichuan Fault crosses heavily populated regions and is associated with destructive earthquakes. The first borehole (WFSD-1) of the project was drilled to investigate the mechanism of the southern segment of the Yingxiu-Beichuan Fault (Li et al. 2012).

In recent studies, fault zone structures have been observed, and friction experiments and rock magnetic

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measurements have been performed on surface samples in the area of the Yingxiu-Beichuan Fault (Lin et al. 2010; Verberne et al. 2010; Togo et al. 2011a, b). The internal structures of the Beichuan fault zone in the outcrop at Hongkou demonstrate that the Beichuan fault zone consists of fault breccias, cataclasite, and fault gouge, although there are differences in descriptions of the width of the fault gouge zone (Lin et al. 2010; Togo et al. 2011a; Wang et al. 2014). Friction experiments proved that the clay-rich sediments of the region might have a damping effect upon ruptures propagating from depth (Verberne et al. 2010). High-velocity friction experiments performed on the Hongkou outcrop clayey fault gouge showed that this rock exhibits dramatic weakening at seismic slip rates, and the steady-state frictional coefficient reduces to as low as 0.1 to 0.2 at a slip rate of 1.3 m/s (Togo et al. 2011b).

Rock magnetic measurements from Zhaojiagou and Dagou showed that the magnetic properties of most of the fault rocks are dominated by paramagnetic components. Although magnetic susceptibility measurements from the Zhaojiagou section showed insignificant anomalies in the gouge, the results from the Zhaojiagou outcrop fault rock measurements suggested that the temperature had been high enough to drive the decomposition of Fe-bearing minerals to form magnetite or maghemite (Yang et al. 2012a, b, 2013; Liu et al. 2014). Preliminary magnetic susceptibility measurement results of the WFSD-1 borehole core (but only within the fault zones) were reported by Pei et al. (2010), but results for all core samples have not yet been published. In particular, in the WFSD-1 borehole, the high magnetic susceptibility patterns obtained from logging data near the primary slip zone of the Wenchuan Earthquake look similar to the pattern at a single fault zone seen at a small scale. There may be a larger-scale high magnetic susceptibility anomaly in the Yingxiu-Beichuan Fault Zone.

All samples from the WFSD-1 borehole underwent preliminary study in the WFSD field laboratory shortly after drilling. They were also studied later using several methods to obtain a complete set of data on the petrophysical, geochemical, and lithological properties (Li et al. 2012).

In this paper, we report the results of the magnetic susceptibility measurements for all core samples of the WFSD-1 borehole, present the magnetic susceptibility characteristics of the core samples, and discuss the difference between the core measurements and the logging data. We also assess the processes that caused the high magnetic susceptibility in the fault gouge by analyzing selected core samples from the primary slip zone in the WFSD-1 borehole. Finally, we discuss the implications of the presence of multi-segment fault rocks with high magnetic susceptibility in the WFSD-1 core.

Geological setting and drilling procedure

Longmen Shan is the main mountain range along and one of the steepest margins of the eastern edge of the Tibetan Plateau in Sichuan Province, China. The significant deformation in western Sichuan has been governed by interactions among three crustal blocks (Songpan, Chuandian, and South China) (Figure 1). The Longmen Shan thrust belt consists of the Wenchuan-Maoxian, Yingxiu-Beichuan, and Anxian-Guanxian faults, at the eastern margin of the Tibetan Plateau (e.g., Burchfiel et al. 2008; Densmore et al. 2007). These faults show long-term activity, and active faults have developed along previous faults since the late Triassic (Deng et al. 1994; Burchfiel et al. 1995; Li et al. 2006; Densmore et al. 2007; Xu et al. 2008). The Wenchuan Earthquake (*Mw*7.9, May 12, 2008) is the largest inland earthquake to have hit southwest China during the past century. Two surface ruptures extend along the northeast, striking Yingxiu-Beichuan and Anxian-Guanxian faults. Most studies found the length of the co-seismic surface rupture to be 200 to 240 km (e.g., Liu-Zeng et al. 2009; Xu et al. 2009; Zhang et al. 2010). However, as the 2008 Wenchuan Earthquake ruptured the Qingchuan Fault, the total length of the rupture zone is approximately 275 km (Xu et al. 2008; Li et al. 2008), possibly even as much as 285 to 300 km (Lin et al. 2012).

The first borehole, WFSD-1, was drilled 178 days after the earthquake through 1,201.15 m of the Neoproterozoic Pengguan complex and the alternating sandstones and siltstones of the Triassic Xujiahe Formation. The borehole is located along the southern segment of the Yingxiu-Beichuan Fault, and designed to be an inclined borehole, with an 80° inclination angle in a 134°NE direction. The borehole recovered 1,368.29 m of core sample (Li et al. 2012). The borehole consists of three segments, 32.17 to 304.26 m, 179.85 to 625.80 m, and 583.07 to 1,201.15 m, due to drilling accidents at depths of 304.26 and 625.80 m (Fan et al. 2009). Two general rock types are found in the borehole cores. Unit 1 is the Pengguan complex, consisting of gray-green diorite, volcanic rocks, and pyroclastic rocks, with ages of 850 to 750 Ma (Yan et al. 2004). This unit is the hanging wall of the Yingxiu-Beichuan Fault and is found at depths shallower than 585.75 m. Pseudotachylyte has been found in an outcrop near the boundary of the Pengguan complex and the Xujiahe Formation, but does not occur in this borehole (Li et al. 2014; Wang et al. 2014). Unit 2 is the Triassic Xujiahe Formation, which consists of gray sandstone, siltstone, and dark gray mudstone with coal beds. This is the footwall of the fault and is found below depths of 598 m.

On the basis of the fault rock distribution and fault density, 12 fault zones with fault gouge, cataclastic rocks, and fault breccias have been identified within the

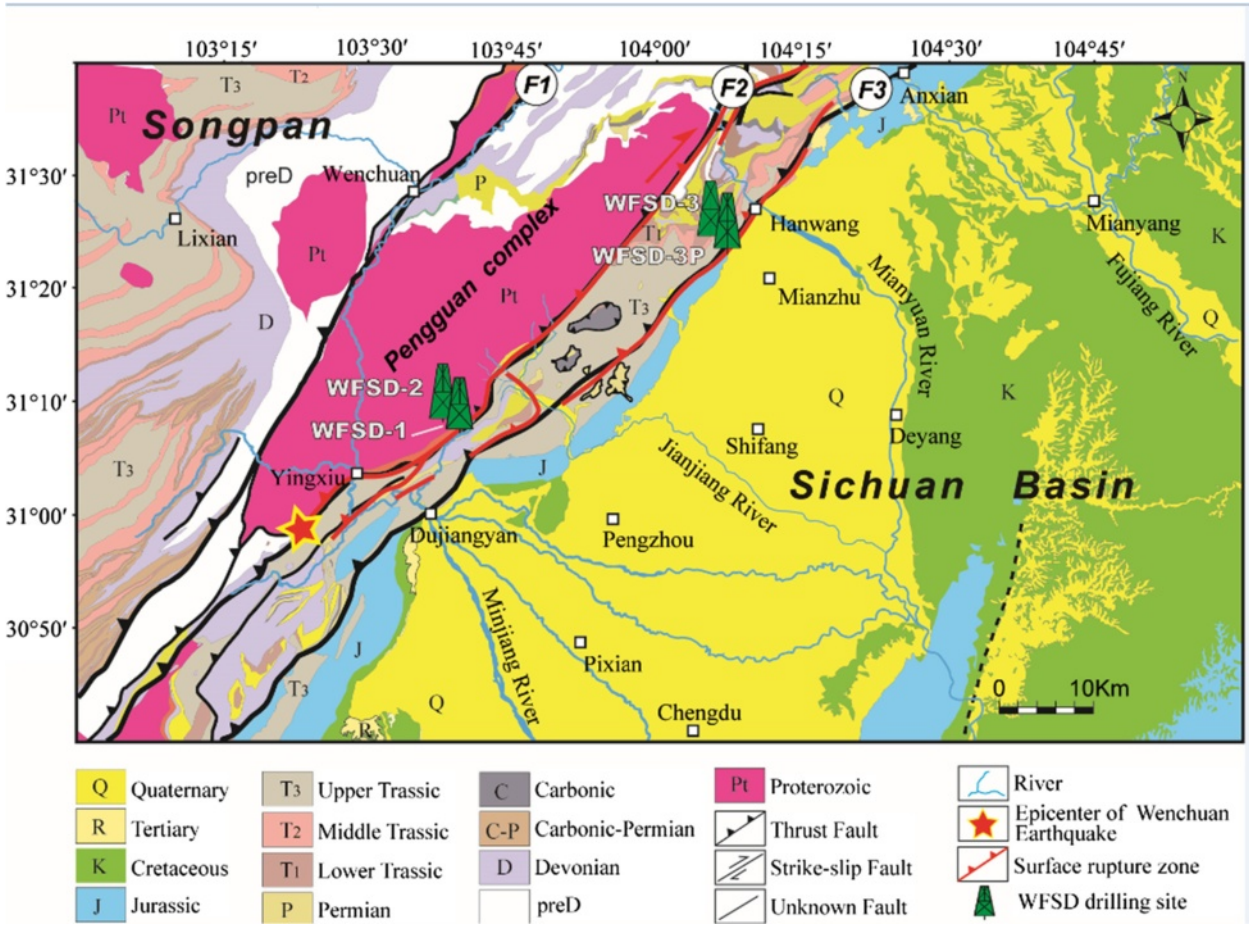

Figure 1 Geological map of Longmen Shan and the western Sichuan basin area. This shows the site of the Wenchuan Earthquake Fault Scientific Drilling and highlights the Wenchuan Earthquake surface rupture (thick red lines) on two faults of the Longmen Shan thrust fault system (F1, Wenchuan-Maoxian Fault; F2, Yingxiu-Beichuan Fault; F3, Anxian-Guanxian Fault) (revised after Li et al. 2012).

WFSD-1 core (Li et al. 2012). The scale of these fault zones ranges from a few centimeters to tens of meters. The thickest fault zone occurs between 585 and 598 m. The fault zones containing significant fault gouge are FZ233 (from 232.2 to 233.9 m), FZ590 (from 575.7 to 595.5 m), and FZ759 (from 753.13 to 759 m). From the analysis of core observations and measurements of physical properties, Li et al. (2012) identified the principal slip zone (PSZ) of the Wenchuan Earthquake as having been at FZ590.

Methods

Magnetic susceptibility was measured on all core surfaces at 1-cm intervals using a Bartington MS2E surface sensor (Witney, Oxon, England). The active region of the MS2E sensor is at the end of a 25-mm diameter ceramic cylinder mounted in line with the electronics unit. The active region of the sensing surface is a 10.5 × 3.8-mm rectangle.

The results include three sections named WFSD-1-1 (32.17 to 304.26 m), WFSD-1-S1 (179.85 to 625.80 m), and WFSD-1-S2 (583.07 to 1,201.15 m) due to the down borehole drilling accidents at 304.26- and 625.80-m depths (Fan et al. 2009). The results for WFSD-1-S1a come from the same core as WFSD-1-S1, but include iron contamination. The drilling tool debris can be easily removed with forceps (Figure 2).

The magnetic susceptibility variation patterns of WFSD-1-1 from 179.85 to 304.26 m resemble those from the same depth interval in WFSD-1-S1, and the variations from 583.07 to 625.80 m in WFSD-1-S1 resemble the same depth interval in WFSD-1-S2, except for the abnormally high values at depths of approximately 594.2 and 629 m (Figure 3). The magnetic susceptibility of the WFSD-1 borehole includes all of WFSD-1-1, 304.26 to 625.80 m of WFSD-1-S1, and 625.80 to 1,201.15 m of WFSD-1-S2 (Figure 3).

The main damaged zone in the FZ590 fault zone consists of at least 12 layers of fault gouges, but the darkest layer of the gouge, including the PSZ position of the Wenchuan Earthquake, can only be seen in one layer

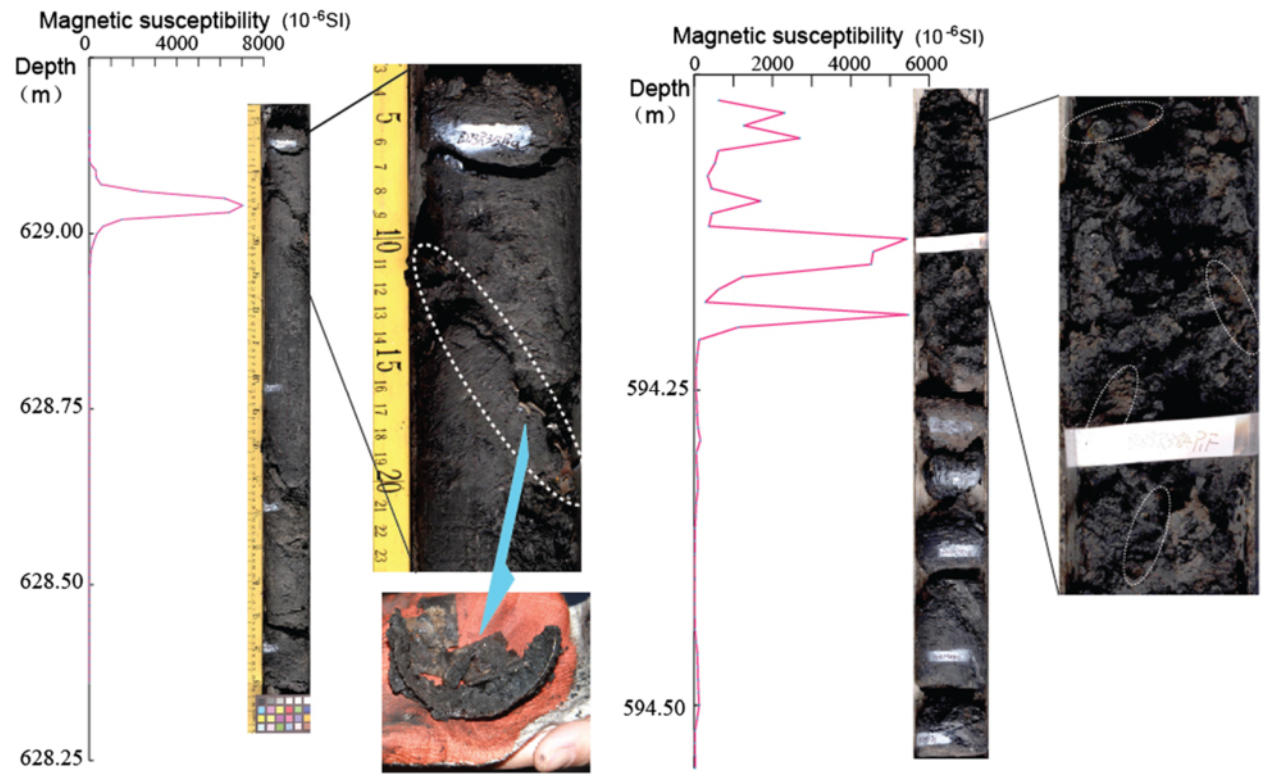

Figure 2 Metallic iron debris and particles found in the WFSD-1 core. The depths are at 628.45 m (left) and 594.1 m (right).

(589.17- to 589.28-m depth), which seems to be the freshest (Figure 3, Li et al. 2012). To understand the high magnetic susceptibility in FZ590, we took six samples within every 10-cm interval between depths of 589.05 and 589.55 m. Thermomagnetic curves (*k-T*) and mass magnetic susceptibility were measured using a Kappabridge (KLY-4, AGICO, Brno, Czech Republic) with a CS-3 high-temperature furnace at the Key Laboratory of Paleomagnetism and Tectonic Reconstruction of the Ministry of Land and Resources, China. Thermomagnetic measurements were conducted in an argon atmosphere and in air, while applying a steady field of 300 A/m. The samples were heated to 700°C and then cooled to room temperature at a rate of 10°C/min.

Magnetic hysteresis loops were measured with an alternating gradient magnetometer (Princeton Micromag 2900, Westerville, OH, USA) at the physics laboratory of Beijing University. The magnetic field was cycled between ±1.0 T. Saturation magnetization (Ms), saturation remanence (Mrs), and magnetic coercivity (Hc) were determined after correction for the paramagnetic contribution. Coercivity of remanence (Hcr) is the field required to erase remanent magnetization permanently; it was obtained by backfield measurements after being magnetized at 1.0 T.

The mass magnetic susceptibility of these six samples ranges from 3.42×10^{-8} to 10.54×10^{-8} m^3/kg. The 589.25-m-depth sample is the highest in magnetic susceptibility, which is similar to the pattern obtained from the surface measurements of the core. The *k-T* curves can help identify magnetic materials (Deng et al. 2001). The *k-T* curves of the selected samples from the FZ590 display a rapid increase in slope after 380°C, and a marked peak occurs at about 510°C in the heating curves. The magnetic susceptibility becomes effectively zero at about 585°C (Figure 4). All the cooling curves show a clear hump between 580°C and 380°C, the value of which is obviously higher than that of the peak in the heating curves.

Results and discussion

Iron contamination

In the WFSD-1 borehole, the high magnetic susceptibility values obtained from logging data near the primary slip zone, between the depths of 505 and 590 m and the depths of 675 and 695 m, seen on a larger scale, look similar to the patterns observed at a single fault zone on a small scale (e.g., the magnetic susceptibility at depths of approximately 589.25, 618, 730, and 732.5 m) (Figure 5). The results for the magnetic susceptibility of the core and logging data are consistent, except for depths between 500 and 700 m (Figure 5).

This significant difference between the core and logging magnetic susceptibility data requires explanation.

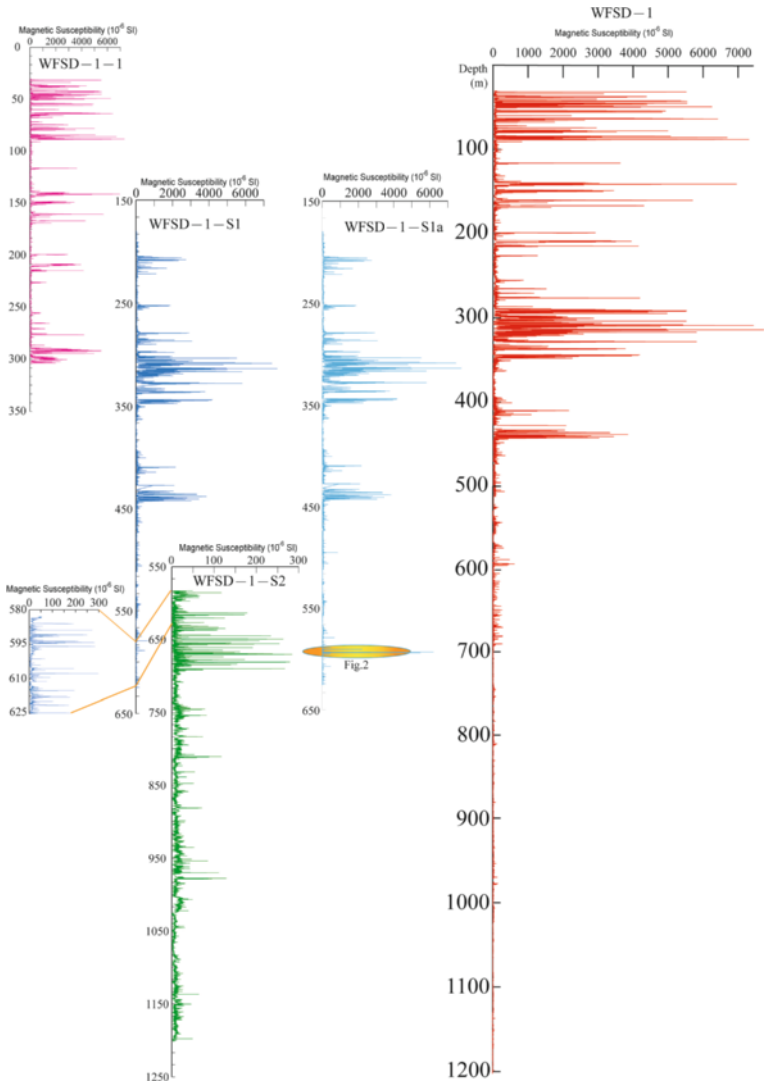

Figure 3 The magnetic susceptibility of the WFSD-1 borehole. The oval indicates an area of high magnetic susceptibility caused by iron debris from the drilling accidents in Figure 2.

Some metallic iron debris was found in this borehole core during analysis around 628.45- and 594.1-m depths (Figure 2). It is also noteworthy that drilling accidents occurred at 590.76- and 625.80-m depths, and drilling was resumed in a separate borehole at 583.07 m (Fan et al. 2009). There are significant amounts of metal particles near 590.76-m depth caused by milling of the lost drill, and some abandoned metal instruments around 625.80-m depth. The significant magnetic susceptibility anomalies in the logging data at depths between 500 and 700 m are caused by these metallic iron particles that originated from the drilling accident.

Relationship between magnetic susceptibility and lithology

Granite and volcanic rocks make up most of the Neoproterozoic Pengguan complex, which occurs above 585-m depth in the WFSD-1 core. Pyroclastics, mainly consisting of celadon tuff, are present from 3- to 181.5-m depth. The main rock types from 181.5- to 291-m depths are porphyries and diorite, with three intervals of volcanic rocks: 189 to 196 m, 226 to 249 m, and 271 to 276 m. Between depths of 291 and 575.6 m, mostly volcanic rocks and pyroclastics occur, except for three intervals of diorite and porphyries located at 362.7 to 394 m, 494 to 512 m, and 545 to 555 m (Li et al. 2012).

The surface magnetic susceptibility values of the Pengguan complex range from hundreds to thousands of 10^{-6} SI, consistent with the great variations in lithology (Figures 5 and 6a). The lithology of the core between about 598- and 759-m depth is mainly gray sandstone, dark-gray siltstone, carbon shale, and coal bed. Below 759 m, the rocks are mainly gray sandstone, dark-

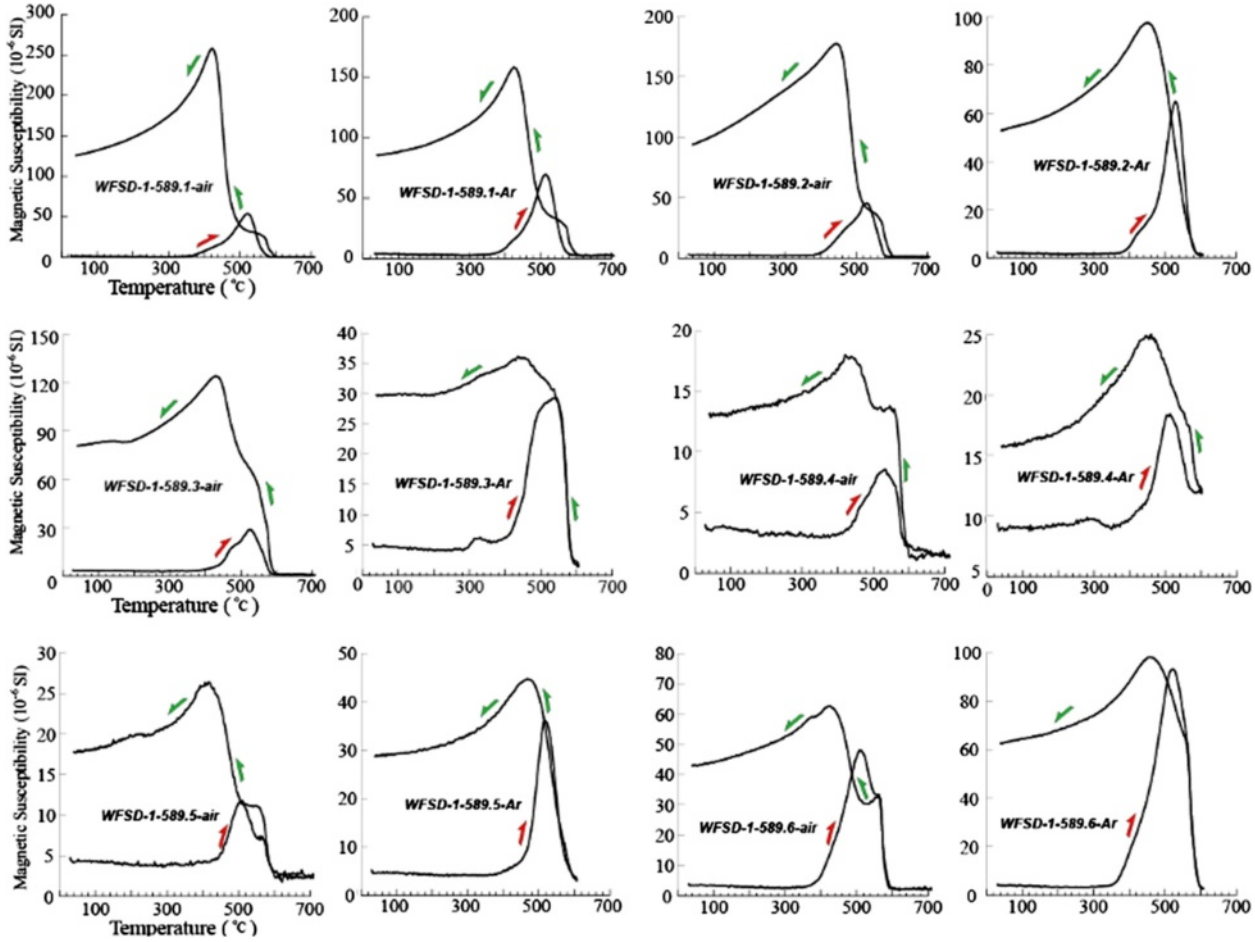

Figure 4 Thermomagnetic susceptibility curves, in air and in argon, of the selected samples. The samples were taken at depths between 589.05 and 589.55 m of the WFSD-1 core.

colored fine sandstone, and liquefied breccias (Li et al. 2012).

The surface magnetic susceptibility values of the Xujiahe Formation usually range from a few to dozens of 10^{-6} SI (Figure 6b,d), and the carbon shale and coal bed rocks from zero to $<10 \times 10^{-6}$ SI (Figure 6c). Furthermore, the liquefied breccia segment cores are composed of gray sandstone and black siltstone, which may be seismites resulting from intense and strong earthquakes during the late Triassic. Higher values are associated with the black siltstone, and lower values with the gray sandstone in these segments (Figure 6e).

The magnetic susceptibility of a rock is strongly influenced by its concentration of ferrimagnetic minerals, mainly iron oxides such as magnetite, titanomagnetite, and hematite (Dunlop and Özdemir 1997). On the whole, the lithology of the WFSD-1 core controls the pattern of the magnetic susceptibility variance. However, the large variations in magnetic susceptibility may not have been caused only by lithological changes (Figure 5).

Relationship between magnetic susceptibility and fault rocks

Correlations between magnetic susceptibility anomalies and the occurrence of cataclastic zones and faults have been reported (Bosum et al. 1997). Recently, a number of examples of high magnetic susceptibility within fault gouges have been described from several faults related to large earthquakes (Enomoto and Zheng 1998; Nakamura and Nagahama 2001; Fukuchi et al. 2005; Hirono et al. 2006; Mishima et al. 2006, 2009). Similarly, some core gouges with high magnetic susceptibility occur within the WFSD-1 core.

In this paper, we present the results obtained from the fault rocks at depths of approximately 589.25, 618, 709, 730, and 732.5 m (Figure 7). These sections contain fault gouges, cataclasite, and host rock. The 589.25-m-depth gouge was generated during the 2008 Wenchuan Earthquake (Li et al. 2012). The magnetic susceptibility of this section shows a significant peak corresponding to the fresh black gouge (Figure 7b). In addition, some fault

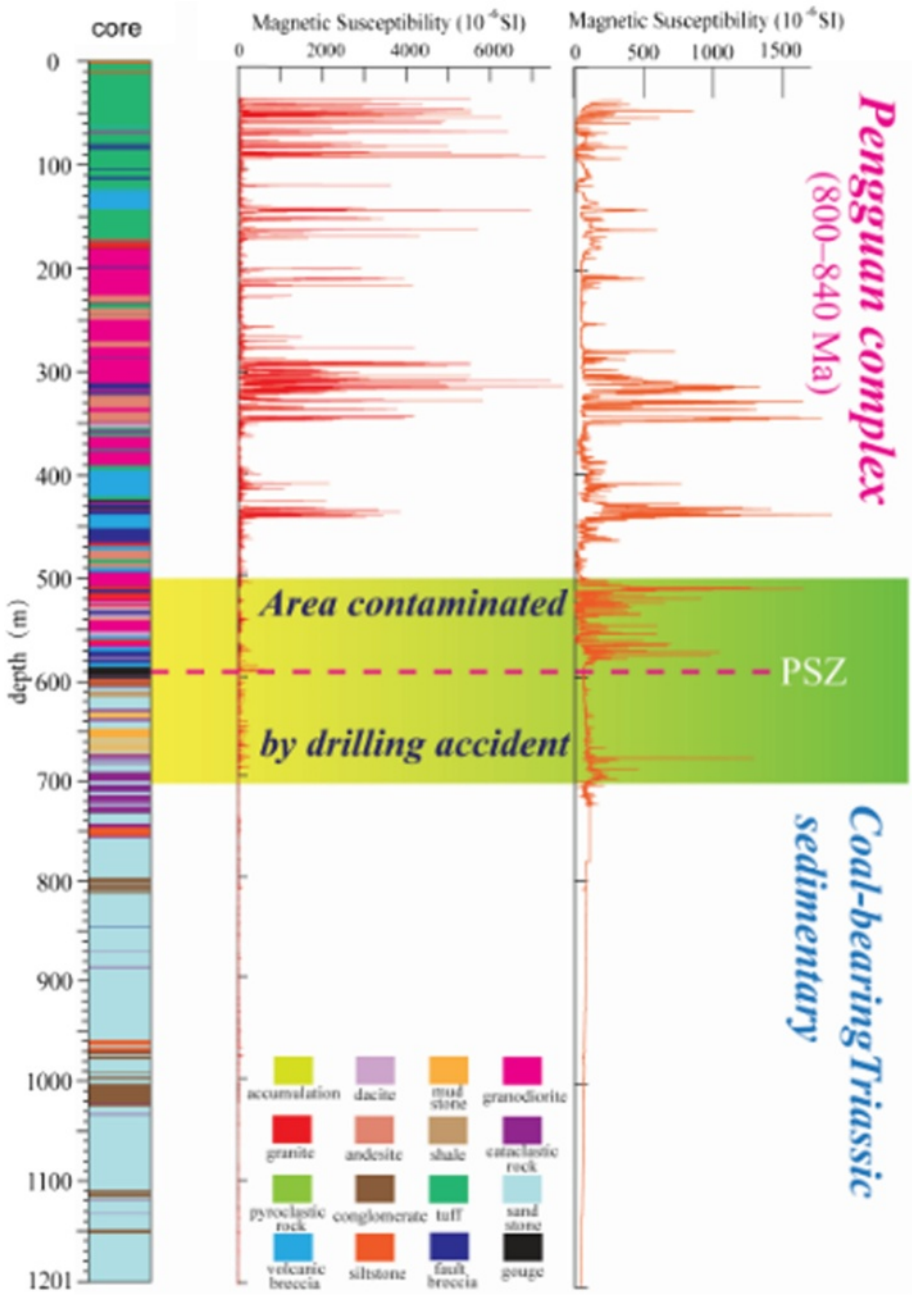

Figure 5 Depth logs. This shows the simplified lithology (left) and magnetic susceptibility of the core and logging data (right) of the WFSD-1 borehole.

gouges are regarded as ancient slip zones because of their hardened features showing distinct highs in magnetic susceptibility (Figure 7c,d,f). However, lower magnetic susceptibilities corresponding to cataclasite or fault breccias also occur in the WFSD-1 borehole (Figure 7e). Moreover, insignificant anomalies were revealed from some fault gouges of the WFSD-1 core (Figure 7a) and sections in the outcrop, including fault gouges and immediate host rocks at the Yingxiu-Beichuan Fault (Yang et al. 2012a, b, 2013). A possible reason for the insignificant variation in magnetic susceptibility of fault rocks (gouge) occurring in outcrop is that high magnetic susceptibility magnetic minerals (e.g., magnetite) transform into low magnetic susceptibility mineral assemblages as a result of surface processes such as weathering, microbial processes, and oxidation-reduction (Liu et al. 2014). Although a correlation between the magnetic susceptibility anomalies and the fault rock (fault gouge)

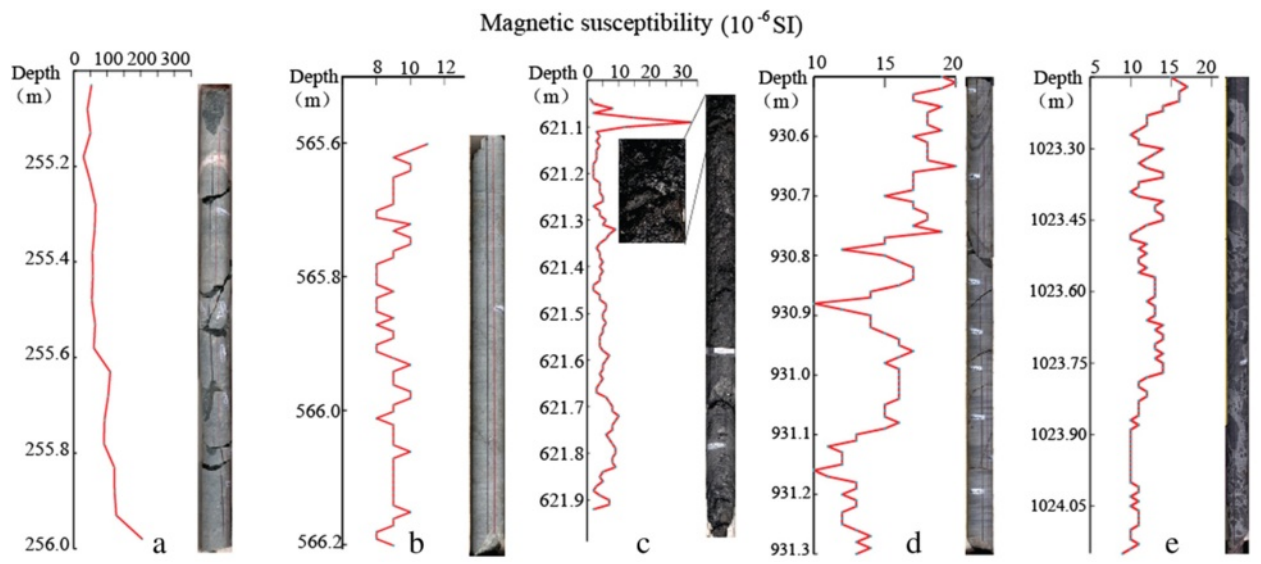

Figure 6 Magnetic susceptibility and lithological sequence of the WFSD-1 core, showing the correlation between the two. (a) Pengguan complex, **(b)** gray sandstone, **(c)** dark-gray siltstone with carbon shale, **(d)** gray and dark-gray siltstone, and **(e)** black siltstone and gray sandstone.

occurrences is present in the WFSD-1 borehole, not all rocks with higher magnetic susceptibility are fault rocks; mafic intrusions can cause similar variations (Ferré et al. 2009). There is another possibility which is that faults can occur in places where the rocks on either side have different compositions, resulting in contrasting magnetic susceptibilities. Therefore, only cases in which high magnetic susceptibility fault rocks (fault gouge) occur in the same country rock can be considered as indicators of earthquakes or seismic signatures.

Mechanism of the magnetic susceptibility enhancement at the Wenchuan Earthquake PSZ and its implications

The results of the mass magnetic susceptibility confirm the high values at the PSZ of the Wenchuan Earthquake near 589.25-m depth (Figure 8i). The mechanism for susceptibility enhancement of fault gouges is still a subject for debate. The anomalies of the Chi-Chi earthquake are, in general, caused by increased amounts of ferrimagnetic minerals in the rocks (Mishima et al. 2009; Chou et al. 2012).

The *k-T* curves of the FZ590 samples show a Curie temperature near 580°C, a cooling curve above the heating curve, and a hump above 380°C during heating. The magnetic hysteresis experiments show the existence of paramagnetic minerals (Figure 8a,b,c,d,e,f,g). Paramagnetic susceptibility (χ_{para}) is determined from the high-field slopes of the hysteresis curves (Table 1 and Figure 8j).

The Curie point near 580°C indicates that nearly-pure magnetite is the magnetic carrier (Dunlop and Özdemir 1997). The high χ_{para} of samples 589-1 and 589-2 indicate that the paramagnetic component is dominant in these samples, but ferrimagnetic susceptibility (χ_{ferri}) shows a similar pattern to χ_{lf} (Table 1 and Figure 8k). Moreover, Ms shows a significant peak at a depth of 589.25 m, as do χ_{lf} and χ_{ferri}; Hc at the 589.25-m depth is lower than those of the other samples (Table 1, Figure 8i,j,k,l,m). The behavior of the heating curves above 380°C is probably associated with the neoformation of magnetite from iron-containing silicates/clays or pyrrhotite (Hunt et al. 1995; Deng et al. 2001; Chou et al. 2012). The high magnetic susceptibility in the 589.25-m-depth sample is directly proportional to χ_{ferri}, and the high Ms may show that new minerals with low Hc were formed during dynamic earthquake faulting. When compared to the theoretical hysteresis trends for SD-SP and SD-MD mixtures (Dunlop 2002a) on a Day diagram (Day et al. 1977), all samples display values generally parallel to the SD-MD mixing model curve (Figure 8n).

The clay minerals of the WFSD-1 PSZ of the Wenchuan Earthquake came to general attention when Si et al. (2010) pointed out the high smectite content, low illite and chlorite levels, and the tiny amount of kaolinite. In contrast, the fault gouge in the outcrop at the Hongkou surface rupture has high illite and chlorite contents and very little smectite content (Si et al. 2010; Togo et al. 2011a). The loss of clay minerals at depth was probably caused by their conversion into magnetite by complex reactions driven by frictional heating and hot fluids injected by the thermal pressurization slip mechanism (Lin 2011). For example, oxidized alteration of chlorite forms some iron oxides (Chamberlain et al. 1999), and siderite changes into pyrite and magnetite under low-oxygen conditions (Tanikawa et al. 2008).

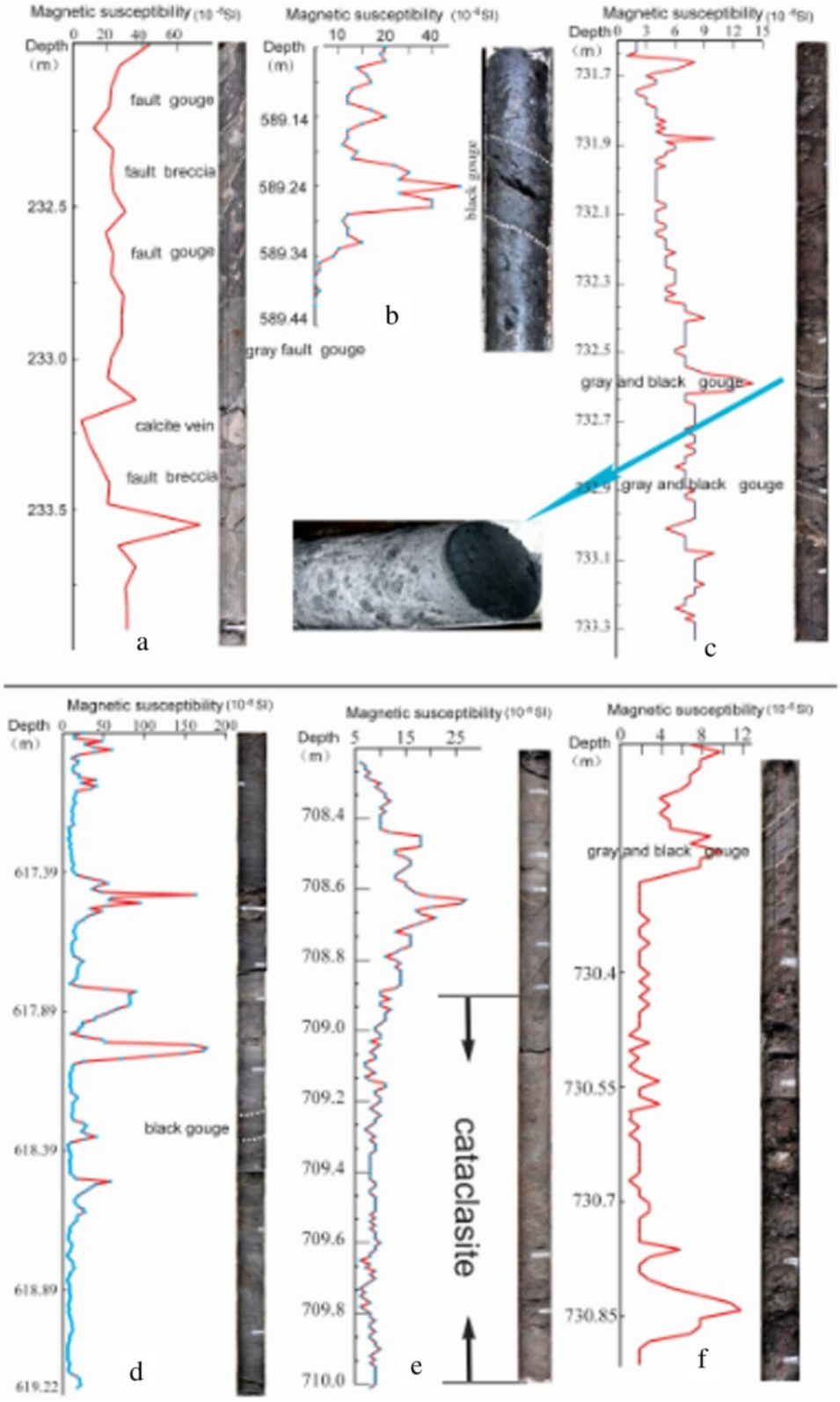

Figure 7 Magnetic susceptibility logs. These are the logs of the WFSD-1 core, showing high magnetic susceptibility gouges at depths of approximately 589.25, 618, 709, 730, and 732.5 m. **(a)** Fault rocks in Pengguan complex, **(b)** black fault gouge at the PSZ, **(c)** gray and black gouge in siltstone with carbon shale, **(d)** black gouge in sandstone, **(e)** cataclasite in sandstone, and **(f)** gray and black gouge in siltstone.

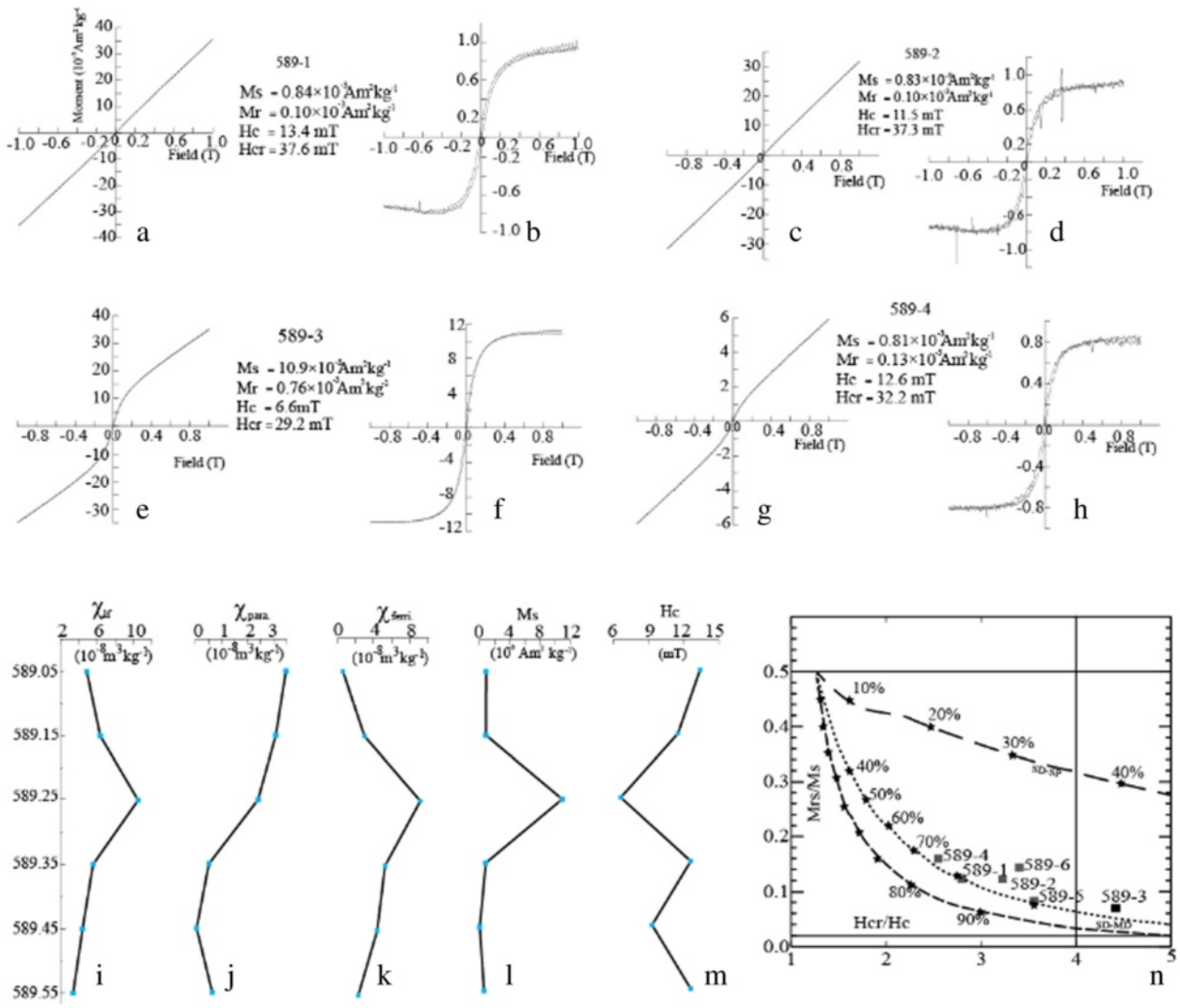

Figure 8 Hysteresis loops, depth logs, and theoretical mixing curves. Magnetic hysteresis loops before **(a**, **c**, **e**, **g)** and after **(b, d, f, h)** paramagnetic correction; depth logs of low-field **(i)**, paramagnetic **(j)**, and ferrimagnetic susceptibilities **(k)**; saturation magnetization (Ms) **(l)**; and coercivity (Hc) **(m)** of selected samples from depths between 589.05 and 589.55 m in the WFSD-1 core. Hysteresis parameters, Mr/Ms, and Hcr/Hc are plotted on a plot by Day et al. (1977) with the theoretical mixing curves **(n)** (Dunlop 2002a, b).

Table 1 Magnetic parameters of the selected samples from depths of 589.05 to 589.55 m in WFSD-1

Sample	χ_{lf} (10^{-8} m^3/kg)	χ_{para} (10^{-8} m^3/kg)	χ_{ferri} (10^{-8} m^3/kg)	Ms (10^{-3} Am^2/kg)	Mrs (10^{-3} Am^2/kg)	Hc (mT)	Hcr (mT)
589-1	4.92	3.47	1.45	0.844	0.102	13.4	37.6
589-2	6.39	3.08	3.31	0.825	0.101	11.5	37.3
589-3	10.54	2.40	8.14	10.916	0.760	6.59	29.2
589-4	5.60	0.51	5.09	0.804	0.126	12.6	32.2
589-5	4.45	0.04	4.41	0.011	0.001	9.29	33.8
589-6	3.42	0.65	2.77	0.560	0.079	12.6	42.7

χ_{lf}, low field magnetic susceptibility; χ_{para}, paramagnetic susceptibility verified by hysteresis measurements; χ_{ferri}, ferrimagnetic susceptibility calculated from the difference between χ_{lf} and χ_{para}; Ms, saturation magnetization; Mrs, saturation remanence; Hc, coercivity; Hcr, coercivity of remanence.

The principal mechanism responsible for the 589.25-m-depth high magnetic susceptibility might have been the production of new magnetite from iron-containing silicates (e.g., chlorite) or clays caused by frictional heating during seismic slip (Yang et al. 2012a). The presence of several layers of fault gouge with high magnetic susceptibility in the WFSD-1 borehole indicates that large earthquakes have occurred repeatedly on the Yingxiu-Beichuan fault.

Conclusions

High-resolution measurements revealed detailed variations in the magnetic susceptibility of the WFSD-1 core. The reason that the results of the core surface measurement and the logging data are obviously different for depths between 500 and 700 m is that drilling accidents produced significant amounts metallic iron debris.

In general, the rock types control the greatest proportion of the magnetic susceptibility. The magnetic susceptibility values of the hanging wall (the Pengguan complex) range from dozens of to several hundred 10^{-6} SI, and the values for the footwall (the Xujiahe Formation) usually range from a few to dozens of 10^{-6} SI. Moreover, possible correlations between the magnetic susceptibility anomalies and the occurrence of fault rocks (fault gouge) are shown by a few fault zones in the WFSD-1 core. The high values of the fault gouge at 589.25-m depth require the formation of magnetic minerals with high magnetic susceptibility, such as magnetite. The production of new magnetite may have been from the breakdown of iron-containing silicates or clays (e.g., chlorite) as a result of the higher temperatures caused by frictional heating during a large earthquake.

Fault gouges with high magnetic susceptibility in the same wall rocks can be considered as a proxy for earthquakes or seismic signatures. That multi-segment fault rocks with high magnetic susceptibility which occur in the WFSD-1 core indicate that repeated seismic activity has taken place on the Yingxiu-Beichuan Fault.

Questions remain, however, whether the high magnetic susceptibility fault gouges were formed by one earthquake; whether the fault gouges of different depths, such as surface outcrop and the drilling core, are of a similar nature; and why the magnetic susceptibility of some fault gouges does not display a significant anomaly. The rock magnetic properties of the WFSD-1 core for different rock types and fault zones will be addressed in future studies.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

JP conceived of the study, carried out the magnetic measurements, and drafted the manuscript. HL participated in its design and coordination. HW participated in the design of the study and carried out the magnetic susceptibility measurements. JS carried out the field works and magnetic susceptibility measurements. ZS participated in the statistical analysis. ZZ performed the rock magnetic measurements. All authors read and approved the final manuscript.

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