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An earthquake slip zone is a magnetic recorder

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ABSTRACT

During an earthquake, the physical and the chemical transformations along a slip zone lead to an intense deformation within the gouge layer of a mature fault zone. Because the gouge contains ferromagnetic minerals, it has the capacity to behave as a magnetic recorder during an earthquake. This constitutes a conceivable way to identify earthquakes slip zones. In this paper, we investigate the magnetic record of the Chelungpu fault gouge that hosts the principal slip zone of the Chi-Chi earthquake (M_w 7.6, 1999, Taiwan) using Taiwan Chelungpu-fault Drilling Project core samples. Rock magnetic investigation pinpoints the location of the Chi-Chi mm-thick principal slip zone within the 16-cm thick gouge at ~1 km depth. A modern magnetic dipole of Earth magnetic field is recovered throughout this gouge but not in the wall rocks nor in the two other adjacent fault zones. This magnetic record resides essentially in two magnetic minerals; magnetite in the principal slip zone, and neoformed goethite elsewhere in the gouge. We propose a model where magnetic record: 1) is preserved during inter-seismic time, 2) is erased during co-seismic time and 3) is imprinted during post-seismic time when fluids cooled down. We suggest that the identification of a stable magnetic record carried by neoformed goethite may be a signature of friction-heating process in seismic slip zone.

INTRODUCTION

The Chi-Chi earthquake (M_w 7.6, 21 September 1999) is the largest inland earthquake to hit Taiwan during the last century. The ~85 km rupture along the Chelungpu thrust extends from the North to the South (Fig. 1A). Five years after the earthquake, two boreholes (holes A and B 40 m apart, Taiwan Chelungpu-fault Drilling Project, TCDP) were drilled through ~2 km of alternating sandstones and siltstones of Early-Pliocene age. The boreholes provided fresh and unaltered material suitable for paleomagnetic investigation. In borehole B, three fault zones, labeled FZB1136, FZB1194, and FZB1243 have been identified within the Chinshui Formation using core observations and physical properties measurements (Hirono et al., 2007) (Fig. 1B). From an independent data set, it was proposed that the 16 cm-thick gouge of FZB1136 contained the principal slip zone (PSZ) of the Chi-Chi earthquake at 1,136.38 m (Boullier et al., 2009). The Chi-Chi PSZ accommodated a co-seismic displacement of ~8 m with a maximum 3 m/s velocity (Ma et al., 2006). To explain some characteristics of the low-friction in the northern part of the fault rupture, several authors have inferred the role of fluids and thermal pressurization processes (Boullier et al., 2009; Ishikawa et al., 2008). Mishima et al. (2009) reported evidence of neoformed magnetite (Fe_3O_4) in Chelungpu gouges possibly due to temperature elevation >400°C. Assuming that magnetite formed by nucleation-growth process, we expect that magnetite has the capability to record durably Earth's magnetic field. To check the existence of this record, we present a paleomagnetic and rock magnetic investigations of the three major fault zones within TCDP hole B. We identify for the first time a magnetic record that is directly related to a large magnitude earthquake. This magnetic record is carried by magnetite within the PSZ and neoformed goethite in the entire gouge.

METHODS

In 2008, U-channels (plastic box of ~20 cm long and 2 × 2 cm large) were used as core samples from the working half of TCDP hole-B within the gouge layers of the three FZB1136 (1,136.22–1,1336.43 m), FZB1194 (1,194.67–1,194.89 m), and FZB1243 (1,243.33–1,243.51 m) fault zones. One U-channel sample was from the wall rock of the Pliocene siltstones of the Chinshui Formation (1,133.55–1,133.69 m). The U-channels are oriented geographically, with an error <20° using the bedding orientation (dip 30° toward N105°; Wu et al., 2008; Yeh et al., 2007). The natural remanent magnetization (NRM) of each U-channel has been analyzed in the automated stepwise AF demagnetization process (up to 100 mT) using a 755 SRM cryogenic magnetometer manufactured by 2G Enterprises. The residual field inside the shielded room is <500 nT. A principal component analysis was used to infer paleomagnetic components. The mean vector was averaged out using Fisher statistics (Fisher, 1953). The stable paleomagnetic components are characterized by declination (D), inclination (I), distribution parameter (κ), and the angle of confidence at the 95% level (α_{95}). To obtain complementary information on the NRM, we performed thermal demagnetization of non-oriented core fragments (<5 mm). The S-ratio profile was measured along each U-channel. The S-ratio ($IRM_{-0.3T}/IRM_{+1T}$, where IRM is the isothermal remanent magnetization) is a proxy of magnetic coercivity (Thomson and Oldfield, 1986). It is measured at room temperature with a magnetic field applied first with 1 Tesla and second in the opposite way with −0.3 Tesla. In practical, an S-ratio close to 1 is an indication of magnetically soft minerals as magnetite. Its decrease points for the presence of magnetically hard minerals as goethite and hematite. A Transmission X-ray Microscope (TXM) image was obtained from a 15 µm-thick gouge sample of FZB1136 using the beamline 01B1 from the National Synchrotron Radiation Research Center (NSRRC) in Taiwan.

RESULTS

Within the Chinshui Formation, the NRM carries multiple paleomagnetic components with a main component of normal polarity (Fig. 1C). Its ~40° counter clockwise deviation from the modern dipole implies that this component is not a modern record. In comparison to the wall rock, the analysis of the FZB1136 gouge reveals a stable and single characteristic remanent magnetization of normal polarity, throughout its 16 cm-thick layer (Fig. 1D). This component is close to the 1999 international geomagnetic reference field from central Taiwan (Fig. 1C). It resides essentially in hard coercive minerals because ~60% of the NRM remains after 100 mT alternating field demagnetization (Fig. 1E). The thermal demagnetization of core fragment reveals a linear decrease of NRM directed straight to the origin without evidence of secondary components (Fig. 2A) . This is confirmed by the analysis of directional data (not shown). The analysis of the FZB1194 and FZB1243 gouges revealed multiple paleomagnetic components with both normal and reverse magnetic polarities (Fig. 1C). These components are lying in a southern direction and at a distance from the 1999 IGRF magnetic dipole field. After comparing the paleomagnetic results within the three fault zones and the wall rock, it is proposed that the single component observed throughout the FZB1136 gouge is the most recent magnetic record, and more than likely contemporaneous with the 1999 Chi-Chi seismic event.

The information is provided on the magnetic carriers of the FZB1136 gouge using the unblocking temperature spectrum of NRM (Fig. 2A), transmission X-ray microscope observations (Fig. 2B) and the magnetic coercivity parameters (Fig. 2C). Within the gouge, the principal maximum unblocking temperature is close to 120 °C (Fig. 2A) and is consistent with the Néel temperature of goethite (α-FeOOH, $T_N = 120$ °C), a magnetically hard antiferromagnet (Hunt et al., 1995). Transmission X-ray microscopy reveals the occurrence of scattered, elongated (<5 µm long) and dense grains in the gouge, which are likely goethite (Fig. 2B). Within the Chi-Chi PSZ (1,136.38 m, Boullier et al., 2009), the maximum unblocking temperature is close to 580 °C (Fig. 2A), which is the Curie temperature of magnetite (Fe_3O_4), a magnetically soft ferrimagnet (Hunt et al., 1995). Thus, the single paleomagnetic component of Chi-Chi PSZ resides, essentially, in magnetite. The record of coercivity parameters (S-ratio) pinpoints the relative contribution of magnetite and goethite within the FZB1136 gouge (Fig. 2C). The S-ratio profile shows one relative minimum (magnetically hard) at 1,136.30 m and one maximum (magnetically soft) within the Chi-Chi PSZ. The S-ratio profile is consistent with a larger distribution of goethite in the center of the gouge layer, and a larger distribution of magnetite in the Chi-Chi PSZ. It shows that the S-ratio profile is an index to identify the most recent PSZ in the Chi-Chi gouge.

DISCUSSION AND CONCLUSIONS

From these observations, a model of the paleomagnetic record is proposed for FZB1136. During an earthquake, we proffer three main types of magnetization that are acquired within the slip zones: 1) a thermo-remanent magnetization (TRM) acquired post-seismically on the cooling of the slip zone (Ferré et al., 2005); 2) a chemical remanent magnetization (CRM) acquired post-seismically and carried by neoformed magnetic minerals (Nakamura et al., 2002); and 3) an IRM acquired co-seismically during earthquake lightning (EQL) (Ferré et al., 2005). An EQL magnetization would be perpendicular to the fault plane (Ferré et al., 2005), which is not the case for the component of magnetization within the Chi-Chi gouge (Fig. 1C). Thus, we propose that EQL may be excluded as a magnetization process and only thermal-related and chemical-related magnetic records are considered in the FZB1136 gouge. Because the magnetic carriers of the magnetic record are different, we have to distinguish scenarios in the Chi-Chi PSZ and in the rest of the gouge. A temperature elevation due to frictional heating is expected during a co-seismic slip (Rice, 2006). Frictional heating depends on the fault slip rate, displacement, friction coefficient, normal stress, and physical properties of the fault rocks. The ultimate phase of this process involves melting, with the formation of pseudotachylytes (Di Toro et al., 2006). The temperature peaks in the gouge and the Chi-Chi PSZ are still being debated, but generally, a lower limit of 400 °C is accepted (Boullier et al., 2009; Mishima et al., 2009). The PSZ cooling lasts only tens of seconds and the thermal aureole extends less than the width of the PSZ (Kano et al., 2006). Upon cooling, a TRM is imprinted in the magnetic minerals contained in the PSZ and the baked contact. Within the 16 cm of gouge that carries the stable paleomagnetic component, only the millimeter-thick heated layers on both sides of the Chi-Chi PSZ have the potential to carry a friction-induced TRM. Experimental heating of the FZB1136 gouge showed that magnetite formed above 400 °C (Mishima et al., 2009). It is therefore proposed that the paleomagnetic record of the Chi-Chi's PSZ and baked contact is partly a TRM carried by former magnetic minerals and partly a CRM carried by neoformed magnetite.

The paleomagnetic record in the 16 cm gouge is essentially carried by goethite and other processes of magnetization should be viewed apart from the Chi-Chi's PSZ and baked contact. To date, this is the first time that goethite has been reported in the Chelungpu fault. Nakamura and Nagahama (2001) observed similar ~5 μm goethite within the Nojima fault gouge (Japan). They suggested that the goethite growth postdates the grain alignment of silicate minerals. Within the FZB1136, scattered ~5 μm elongated goethite could be observed, which supports the theory that goethite growth postdates the broad texture of gouge (Fig. 2B). In order to crystallize, goethite requires water (free energy -488.6 kJ mol^{-1}), $T < 200$ °C, low pH and iron (Cornell and Schwertmann, 2003). Therefore, the goethite attests to the presence of water in FZB1136. Recent geochemical investigations in the FZB1136 gouge suggest the presence of pore fluids with a minimum temperature of 350 °C (Ishikawa et al., 2008). It is then possible that goethite formed upon the cooling of the pore fluids. The source of iron could possibly be brought about by the dissolution of iron sulphide in the FZB1136 gouge (Yeh et al., 2007). The dissolution of pyrite not only releases Fe^{2+} and SO_4^{2-} ions but also decreases the fluid's pH (Nakamura, 2001). It is therefore suggested that goethite is formed post-seismically within a few days of the earthquake's occurrence. Upon growing larger than the ~1800 nm^3 blocking volume (minimum volume for recording remanent magnetization, Cornell and Schwertmann, 2003), the goethite acquired a CRM. The recovery of a single component record from within the FZB1136 gouge, unlike adjacent fault zones, implies the partial or complete removal of the magnetic records of ancient slip zones. It remains to be proven whether or not this behavior is related to earthquakes of large magnitudes (e.g., $M_w > 7$).

The post-seismic magnetic record is instantaneous in the geological time scale, but it has the potential to survive for millions or even billions of years (Néel, 1955). Thus, the fault gouge can retain the magnetic record during inter-seismic time. It is suggested that the fault gouge magnetic record is a record of the latest earthquake event if only a single component is recovered, as in the case of the Chi-Chi gouge. If several components are detected, as in the fault zones FZB1194 and FZB1243, it is possible that the components overlap each other due to perturbation.

Therefore, we propose the following scenario of a cycle of magnetic record during a large earthquake similar to Chi-Chi (Fig. 3). 1) During inter-seismic periods, the magnetic record of the latest large earthquake is preserved within the fault gouge. 2) During the co-seismic period, the gouge acts essentially as a magnetic eraser. Both the temperature elevation above the unblocking temperature of magnetic minerals and the chemical degradation of these minerals lead to the partial-to-complete demagnetization of the gouge. The exact mechanisms remain to be definitively determined but, in the Chi-Chi gouge, the >350 °C hot fluids (Ishikawa et al., 2008) have probably demagnetized the former goethite. 3) During post-seismic period, the gouge acts as a magnetic recorder. The cooling of the gouge and/or fluids leads to a TRM imprint. Similarly, neoformed minerals resulting from any form of chemical process has the potential to carry a CRM. If confirmed by further studies, this proposed seismic cycle of magnetic records opens new horizons for paleoseismology as well as for the PSZ identification and dating. To identify a PSZ, methods based on microscopy (Boullier et al., 2009), geochemistry (Hirono et al., 2008) or physical properties (Wu et al., 2007) are not one-to-one because several PSZ may stack together in the gouge. In this study, the Chi-Chi gouge layer was identified using the orientation of the magnetic record; the location of the mm-thick Chi-Chi's PSZ was pinpointed using rock magnetism characteristics. This constitutes a new, fast and non-destructive way to find the most recent PSZ.

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FIGURE CAPTIONS

Figure 1. Locations, major fault zones and paleomagnetic records. (A) A geological map showing the epicenter of Chi-Chi earthquake (M_w 7.6, 1999) and the Taiwan Chelungpu-fault Drilling Program (TCDP) drilling site at 120.73916°E, 24.20083°N (Modified from Ma et al., 2006). FZB stands for Fault Zone of hole B. (B) A Schematic log of the borehole showing the three major fault zones of the Chelungpu fault within the Chinshui Formation. (C) Equal-area stereo-plot displaying the Chelungpu fault plane and the mean paleomagnetic components

recorded in the three fault zones and wall rock. Due to the orientation of the borehole B, there is an error of ± 20° in declination for all paleomagnetic component. This error is indicated for the FZB1136 gouge component. We plot the orientation of an expected earthquake lightning (EQL) according to the model of Ferré et al. (2005) with 20° error in orientation. The black (open) symbols correspond to the downward (upward) hemisphere. The cross indicates the 1999 international geomagnetic reference field (IGRF) dipole magnetic vector (D = 0.2°, I = 29.7°). The wall rock's main component lies away from the modern magnetic field (D = 322°, I = 48°, $\kappa = 99$, $\alpha_{95} = 4°$; range 10–80 mT). The FZB1136 gouge component (D = 348°, I = 48°, $\kappa = 140$, $\alpha_{95} = 2°$) is the closest to the modern magnetic field and statistically different from a hypothetic EQL. Within the FZB1194 gouge, normal and reverse components are southerly oriented (D = 235°, I = 27°, $\kappa = 110$, $\alpha_{95} = 8°$ and D = 154°, I = -52°, $\kappa = 144$, $\alpha_{95} = 5°$), respectively. Within the FZB1243 gouge, normal and reverse components are also oriented southerly (D = 125°, I = 11°, $\kappa = 189$, $\alpha_{95} = 4°$ and D = 125°, I = -10.0°, $\kappa = 280$, $\alpha_{95} = 3°$), respectively. (D) The natural remanent magnetization (NRM) orthogonal plot of FZB1136 gouge (depth 1,136.33 m). Open (black) circles represent projection of the vector along the vertical (horizontal) plane. (E) Curves of normalized NRM intensity of FZB1136 and wall rock.

Figure 2. NRM thermal demagnetization, TXM photo, and S-ratio. (A) The NRM thermal demagnetization for a gouge sample (depth of 1,136.34 m) and the Chi-Chi's principal slip zone (PSZ) (depth of 1,136.38 m) within FZB1136. In the gouge, there is a break-in-slope near 150 °C where ~80% of the NRM is lost. The remaining part of the NRM has a maximum unblocking temperature close to 580 °C. In the Chi-Chi's PSZ, the maximum unblocking temperature is close to 580 °C. (B) The TXM photo from a 15 μm thick polished-section collected from a gouge within FZB136. Scattered elongated dense minerals with a low aspect ratio 2:25 and

maximum length of 5 μm are likely to be goethite. (C) The S-ratio profile along the U-channel. The lowest value of the S-ratio (magnetically hard) is located at a depth of 1,136.30 m, near the center of the gouge and corresponds to the highest concentration in goethite. The Chi-Chi's PSZ is marked by an enhancement of the S-ratio, which is consistent with a larger contribution of magnetite.

Figure 3. The magnetic record cycle of a fault gouge. 1) During an inter-seismic period, the magnetic record of an old earthquake is preserved within the fault gouge through geological times. 2) During a co-seismic period, the gouge acts as a magnetic eraser. At the PSZ and baked contact the temperature elevation and chemical degradation lead to the partial-to-complete demagnetization of the gouge. The co-seismic hot fluids probably demagnetized the former goethite. 3) During a post-seismic period, the gouge acts as a magnetic recorder. Cooling of the gouge or fluids leads to a thermo-remanent magnetization (TRM) imprint. Neoformed minerals resulting from any form of chemical processes, including cooling, carry a chemical-remanent magnetization (CRM).

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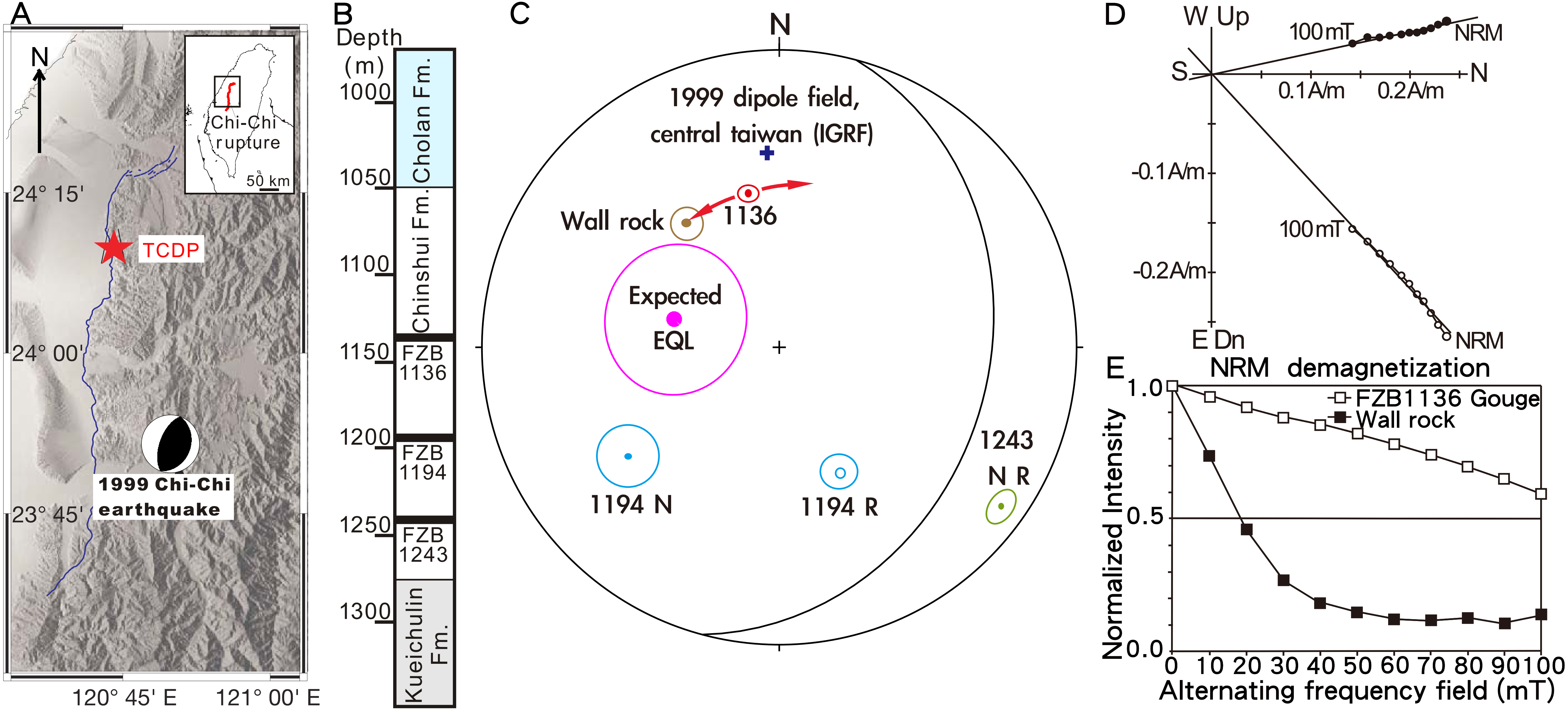
A
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1200
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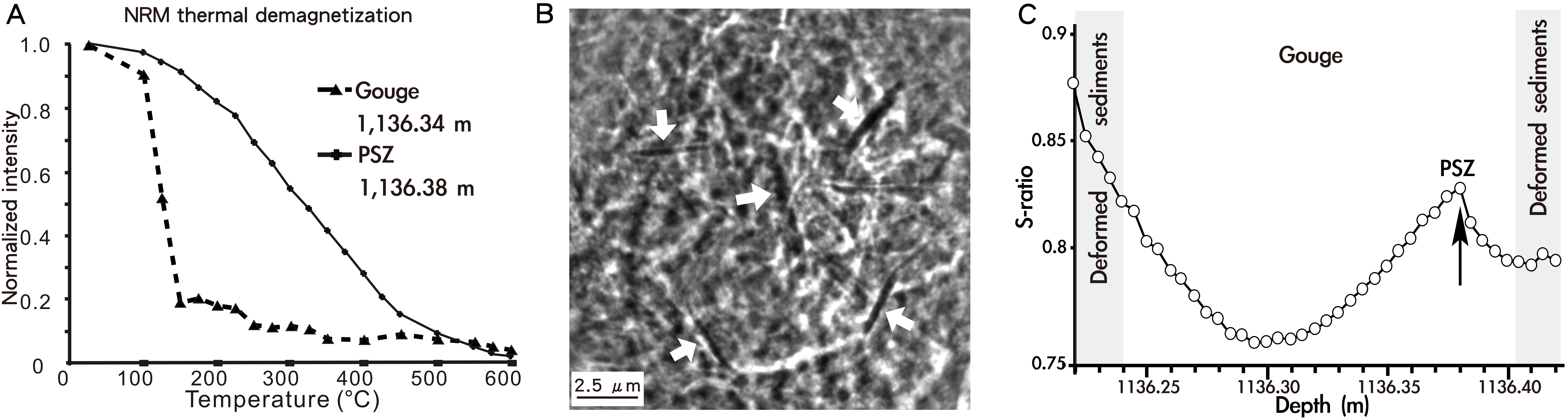
A
NRM thermal demagnetization
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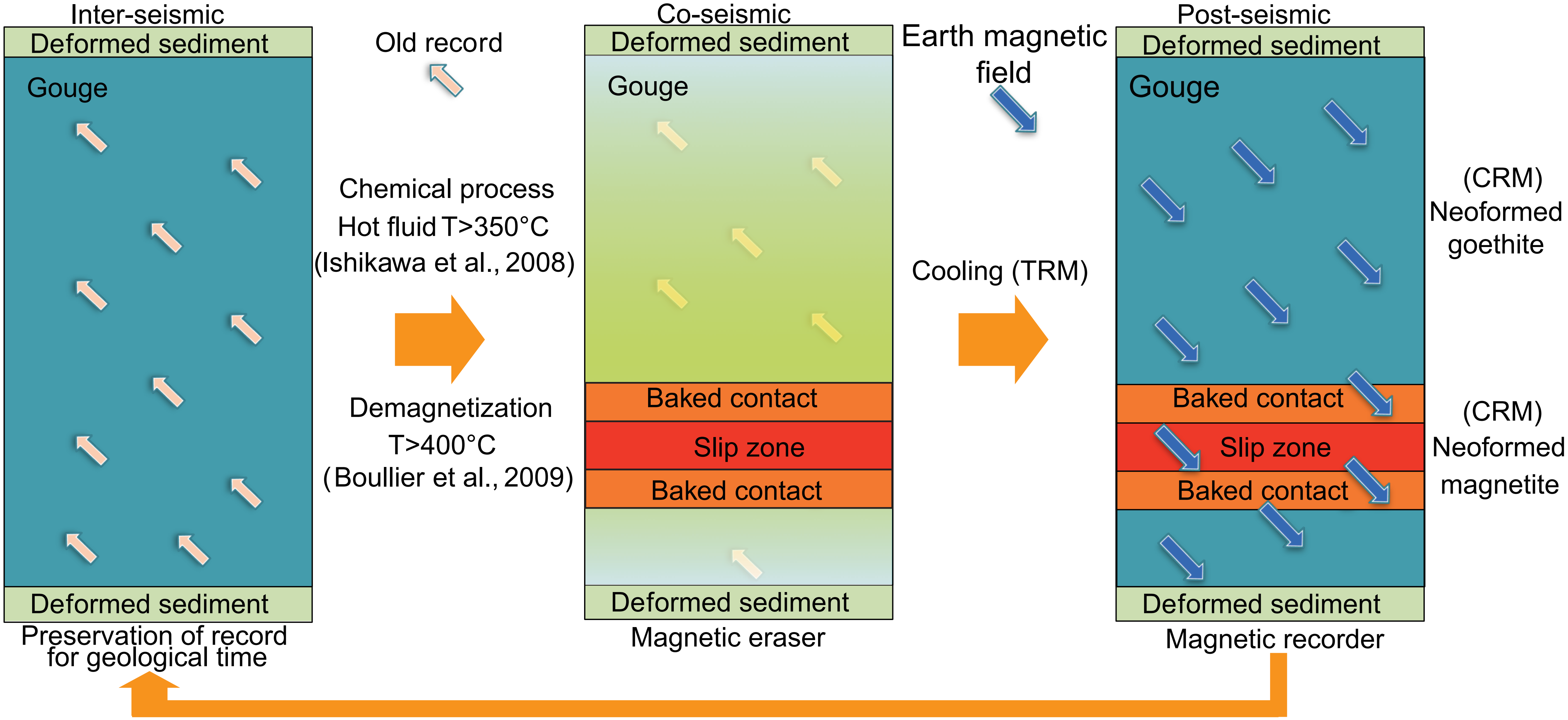
500
600
Temperature (°C)
Gouge
1,136.34 m
PSZ
1,136.38 m
B
2.5 μm
C
S-ratio
0.9
0.85
0.8
0.75
Deformed sediments
Gouge
PSZ
Deformed sediments
1136.25
1136.30
1136.35
1136.40
Depth (m)


Inter-seismic
Deformed sediment
Gouge
Deformed sediment
Preservation of record for geological time
Old record
Chemical process
Hot fluid T>350°C
(Ishikawa et al., 2008)
Demagnetization
T>400°C
(Boullier et al., 2009)
Co-seismic
Deformed sediment
Gouge
Baked contact
Slip zone
Baked contact
Deformed sediment
Magnetic eraser
Earth magnetic field
Cooling (TRM)
Post-seismic
Deformed sediment
Gouge
Baked contact
Slip zone
Baked contact
Deformed sediment
Magnetic recorder
(CRM) Neoformed goethite
(CRM) Neoformed magnetite