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1 **An earthquake slip zone is a magnetic recorder**

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22 **ABSTRACT**

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

38 INTRODUCTION

39 The Chi-Chi earthquake (M_w 7.6, 21 September 1999) is the largest inland earthquake to
40 hit Taiwan during the last century. The \sim 85 km rupture along the Chelungpu thrust extends from
41 the North to the South (Fig. 1A). Five years after the earthquake, two boreholes (holes A and B
42 40 m apart, Taiwan Chelungpu-fault Drilling Project, TCDP) were drilled through \sim 2 km of
43 alternating sandstones and siltstones of Early-Pliocene age. The boreholes provided fresh and
44 unaltered material suitable for paleomagnetic investigation. In borehole B, three fault zones,
45 labeled FZB1136, FZB1194, and FZB1243 have been identified within the Chinshui Formation

46 using core observations and physical properties measurements (Hirono et al., 2007) (Fig. 1B).
47 From an independent data set, it was proposed that the 16 cm-thick gouge of FZB1136 contained
48 the principal slip zone (PSZ) of the Chi-Chi earthquake at 1,136.38 m (Boullier et al., 2009). The
49 Chi-Chi PSZ accommodated a co-seismic displacement of ~8 m with a maximum 3 m/s velocity
50 (Ma et al., 2006). To explain some characteristics of the low-friction in the northern part of the
51 fault rupture, several authors have inferred the role of fluids and thermal pressurization processes
52 (Boullier et al., 2009; Ishikawa et al., 2008). Mishima et al. (2009) reported evidence of
53 neoformed magnetite (Fe_3O_4) in Chelungpu gouges possibly due to temperature elevation
54 $>400^\circ\text{C}$. Assuming that magnetite formed by nucleation-growth process, we expect that
55 magnetite has the capability to record durably Earth's magnetic field. To check the existence of
56 this record, we present a paleomagnetic and rock magnetic investigations of the three major fault
57 zones within TCDP hole B. We identify for the first time a magnetic record that is directly
58 related to a large magnitude earthquake. This magnetic record is carried by magnetite within the
59 PSZ and neoformed goethite in the entire gouge.

60 **METHODS**

61 In 2008, U-channels (plastic box of ~20 cm long and 2×2 cm large) were used as core
62 samples from the working half of TCDP hole-B within the gouge layers of the three FZB1136
63 (1,136.22–1,1336.43 m), FZB1194 (1,194.67–1,194.89 m), and FZB1243 (1,243.33–1,243.51 m)
64 fault zones. One U-channel sample was from the wall rock of the Pliocene siltstones of the
65 Chinshui Formation (1,133.55–1,133.69 m). The U-channels are oriented geographically, with an
66 error $<20^\circ$ using the bedding orientation (dip 30° toward N105°; Wu et al., 2008; Yeh et al.,
67 2007). The natural remanent magnetization (NRM) of each U-channel has been analyzed in the
68 automated stepwise AF demagnetization process (up to 100 mT) using a 755 SRM cryogenic

69 magnetometer manufactured by 2G Enterprises. The residual field inside the shielded room is
70 <500 nT. A principal component analysis was used to infer paleomagnetic components. The
71 mean vector was averaged out using Fisher statistics (Fisher, 1953). The stable paleomagnetic
72 components are characterized by declination (D), inclination (I), distribution parameter (κ), and
73 the angle of confidence at the 95% level (α_{95}). To obtain complementary information on the
74 NRM, we performed thermal demagnetization of non-oriented core fragments (<5 mm). The S-
75 ratio profile was measured along each U-channel. The S-ratio ($IRM_{-0.3T}/IRM_{+1T}$, where IRM is
76 the isothermal remanent magnetization) is a proxy of magnetic coercivity (Thomson and Oldfield,
77 1986). It is measured at room temperature with a magnetic field applied first with 1 Tesla and
78 second in the opposite way with -0.3 Tesla. In practical, an S-ratio close to 1 is an indication of
79 magnetically soft minerals as magnetite. Its decrease points for the presence of magnetically hard
80 minerals as goethite and hematite. A Transmission X-ray Microscope (TXM) image was
81 obtained from a 15 μm -thick gouge sample of FZB1136 using the beamline 01B1 from the
82 National Synchrotron Radiation Research Center (NSRRC) in Taiwan.

83 **RESULTS**

84 Within the Chinshui Formation, the NRM carries multiple paleomagnetic components
85 with a main component of normal polarity (Fig. 1C). Its $\sim 40^\circ$ counter clockwise deviation from
86 the modern dipole implies that this component is not a modern record. In comparison to the wall
87 rock, the analysis of the FZB1136 gouge reveals a stable and single characteristic remanent
88 magnetization of normal polarity, throughout its 16 cm-thick layer (Fig. 1D). This component is
89 close to the 1999 international geomagnetic reference field from central Taiwan (Fig. 1C). It
90 resides essentially in hard coercive minerals because $\sim 60\%$ of the NRM remains after 100 mT
91 alternating field demagnetization (Fig. 1E). The thermal demagnetization of core fragment

92 reveals a linear decrease of NRM directed straight to the origin without evidence of secondary
93 components (Fig. 2A) . This is confirmed by the analysis of directional data (not shown). The
94 analysis of the FZB1194 and FZB1243 gouges revealed multiple paleomagnetic components
95 with both normal and reverse magnetic polarities (Fig. 1C). These components are lying in a
96 southern direction and at a distance from the 1999 IGRF magnetic dipole field. After comparing
97 the paleomagnetic results within the three fault zones and the wall rock, it is proposed that the
98 single component observed throughout the FZB1136 gouge is the most recent magnetic record,
99 and more than likely contemporaneous with the 1999 Chi-Chi seismic event.

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

115 magnetite in the Chi-Chi PSZ. It shows that the S-ratio profile is an index to identify the most
116 recent PSZ in the Chi-Chi gouge.

117 **DISCUSSION AND CONCLUSIONS**

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

138 component, only the millimeter-thick heated layers on both sides of the Chi-Chi PSZ have the
139 potential to carry a friction-induced TRM. Experimental heating of the FZB1136 gouge showed
140 that magnetite formed above 400 °C (Mishima et al., 2009). It is therefore proposed that the
141 paleomagnetic record of the Chi-Chi's PSZ and baked contact is partly a TRM carried by former
142 magnetic minerals and partly a CRM carried by neoformed magnetite.

143 The paleomagnetic record in the 16 cm gouge is essentially carried by goethite and other
144 processes of magnetization should be viewed apart from the Chi-Chi's PSZ and baked contact.
145 To date, this is the first time that goethite has been reported in the Chelungpu fault. Nakamura
146 and Nagahama (2001) observed similar ~5 µm goethite within the Nojima fault gouge (Japan).
147 They suggested that the goethite growth postdates the grain alignment of silicate minerals.
148 Within the FZB1136, scattered ~5 µm elongated goethite could be observed, which supports the
149 theory that goethite growth postdates the broad texture of gouge (Fig. 2B). In order to crystallize,
150 goethite requires water (free energy $-488.6 \text{ kJ mol}^{-1}$), $T < 200 \text{ °C}$, low pH and iron (Cornell and
151 Schwertmann, 2003). Therefore, the goethite attests to the presence of water in FZB1136. Recent
152 geochemical investigations in the FZB1136 gouge suggest the presence of pore fluids with a
153 minimum temperature of 350 °C (Ishikawa et al., 2008). It is then possible that goethite formed
154 upon the cooling of the pore fluids. The source of iron could possibly be brought about by the
155 dissolution of iron sulphide in the FZB1136 gouge (Yeh et al., 2007). The dissolution of pyrite
156 not only releases Fe^{2+} and SO_4^{2-} ions but also decreases the fluid's pH (Nakamura, 2001). It is
157 therefore suggested that goethite is formed post-seismically within a few days of the
158 earthquake's occurrence. Upon growing larger than the ~1800 nm³ blocking volume (minimum
159 volume for recording remanent magnetization, Cornell and Schwertmann, 2003), the goethite
160 acquired a CRM. The recovery of a single component record from within the FZB1136 gouge,

161 unlike adjacent fault zones, implies the partial or complete removal of the magnetic records of
162 ancient slip zones. It remains to be proven whether or not this behavior is related to earthquakes
163 of large magnitudes (e.g., $M_w > 7$).

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

170 Therefore, we propose the following scenario of a cycle of magnetic record during a large
171 earthquake similar to Chi-Chi (Fig. 3). 1) During inter-seismic periods, the magnetic record of
172 the latest large earthquake is preserved within the fault gouge. 2) During the co-seismic period,
173 the gouge acts essentially as a magnetic eraser. Both the temperature elevation above the
174 unblocking temperature of magnetic minerals and the chemical degradation of these minerals
175 lead to the partial-to-complete demagnetization of the gouge. The exact mechanisms remain to
176 be definitively determined but, in the Chi-Chi gouge, the >350 °C hot fluids (Ishikawa et al.,
177 2008) have probably demagnetized the former goethite. 3) During post-seismic period, the gouge
178 acts as a magnetic recorder. The cooling of the gouge and/or fluids leads to a TRM imprint.
179 Similarly, neoformed minerals resulting from any form of chemical process has the potential to
180 carry a CRM. If confirmed by further studies, this proposed seismic cycle of magnetic records
181 opens new horizons for paleoseismology as well as for the PSZ identification and dating. To
182 identify a PSZ, methods based on microscopy (Boullier et al., 2009), geochemistry (Hirono et al.,
183 2008) or physical properties (Wu et al., 2007) are not one-to-one because several PSZ may stack

184 together in the gouge. In this study, the Chi-Chi gouge layer was identified using the orientation
185 of the magnetic record; the location of the mm-thick Chi-Chi's PSZ was pinpointed using rock
186 magnetism characteristics. This constitutes a new, fast and non-destructive way to find the most
187 recent PSZ.

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267 **FIGURE CAPTIONS**

268 Figure 1. Locations, major fault zones and paleomagnetic records. (A) A geological map
269 showing the epicenter of Chi-Chi earthquake (M_w 7.6, 1999) and the Taiwan Chelungpu-fault
270 Drilling Program (TCDP) drilling site at 120.73916°E, 24.20083°N (Modified from Ma et al.,
271 2006). FZB stands for Fault Zone of hole B. (B) A Schematic log of the borehole showing the
272 three major fault zones of the Chelungpu fault within the Chinshui Formation. (C) Equal-area
273 stereo-plot displaying the Chelungpu fault plane and the mean paleomagnetic components

274 recorded in the three fault zones and wall rock. Due to the orientation of the borehole B, there is
275 an error of $\pm 20^\circ$ in declination for all paleomagnetic component. This error is indicated for the
276 FZB1136 gouge component. We plot the orientation of an expected earthquake lightning (EQL)
277 according to the model of Ferré et al. (2005) with 20° error in orientation. The black (open)
278 symbols correspond to the downward (upward) hemisphere. The cross indicates the 1999
279 international geomagnetic reference field (IGRF) dipole magnetic vector ($D = 0.2^\circ$, $I = 29.7^\circ$).
280 The wall rock's main component lies away from the modern magnetic field ($D = 322^\circ$, $I = 48^\circ$, κ
281 $= 99$, $\alpha_{95} = 4^\circ$; range 10–80 mT). The FZB1136 gouge component ($D = 348^\circ$, $I = 48^\circ$, $\kappa = 140$,
282 $\alpha_{95} = 2^\circ$) is the closest to the modern magnetic field and statistically different from a hypothetical
283 EQL. Within the FZB1194 gouge, normal and reverse components are southerly oriented ($D =$
284 235° , $I = 27^\circ$, $\kappa = 110$, $\alpha_{95} = 8^\circ$ and $D = 154^\circ$, $I = -52^\circ$, $\kappa = 144$, $\alpha_{95} = 5^\circ$), respectively. Within
285 the FZB1243 gouge, normal and reverse components are also oriented southerly ($D = 125^\circ$, $I =$
286 11° , $\kappa = 189$, $\alpha_{95} = 4^\circ$ and $D = 125^\circ$, $I = -10.0^\circ$, $\kappa = 280$, $\alpha_{95} = 3^\circ$), respectively. (D) The natural
287 remanent magnetization (NRM) orthogonal plot of FZB1136 gouge (depth 1,136.33 m). Open
288 (black) circles represent projection of the vector along the vertical (horizontal) plane. (E) Curves
289 of normalized NRM intensity of FZB1136 and wall rock.

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

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

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

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