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1 **Fault zone geology: lessons from drilling through the Nojima and**  
2 **Chelungpu faults**

3

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5

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9

10 **Abstract**

11 Several drilling projects have been conducted through active faults with the aim of  
12 learning about the geology of the fault zones and tentatively correlating the structure  
13 and mineralogy of the fault zones with their seismological behaviour during recent  
14 earthquakes. Here we present the major results obtained from structural and  
15 mineralogical studies of core samples retrieved from the dextral reverse strike-slip  
16 Nojima Fault (Japan) within granitic rocks following the Kobe earthquake (1995), and  
17 from the Chelungpu thrust Fault (Taiwan) within alternating silts and shales following  
18 the Chi-Chi earthquake (1999). We show how these projects, despite not fulfilling all  
19 their objectives, have still contributed to a better geological knowledge of the fault  
20 zones, to a better characterization of the slip zones related to the recent earthquakes  
21 particularly of their thickness, microstructures and deformation mechanisms, and to a  
22 better understanding of the nature and role of fluids within the fault zone. They also  
23 have led to new questions, and to new approaches for studying fault rock samples. For  
24 all these reasons, they have stimulated international scientific research about fault zone  
25 geology.

26

27 13098 words, 117 references, 1 table, 6 figures

28

29 Abbreviated title: Fault zone geology

30 In 1993, a conference was held in California on Mechanical Effects of Fluids in Faulting.  
31 This led to a special issue of the Journal of Geophysical Research in the introduction of  
32 which Hickman *et al.* (1995) reported recommendations about three significant topics  
33 for future research, one of which was "fault zone drilling combined with surface-based  
34 geophysical and geological investigations". Since that time, several fault-zone drilling  
35 projects have been conducted around the world, such as the Nojima Fault project  
36 following the 1995 Kobe Earthquake, the Corinth Rift (Greece) Laboratory, the San  
37 Andreas Fault Observatory at Depth (SAFOD) in Parkfield (California), the Taiwan  
38 Chelungpu fault Drilling Project (TCDP) following the 1999 Chi-Chi Earthquake and the  
39 Wenchuan earthquake Fault Scientific Drilling (WFSD) through the Longmen Shan  
40 active fault zone (following the 2008 Wenchuan earthquake, China). Other projects have  
41 drilled plate boundaries along subduction zones, such as the shallow Barbados  
42 accretionary prism (Leg ODP 156) or the NanTroSeize experiment which is still in  
43 progress through the Nankai Trough.

44 In a recent review, Zoback *et al.* (2007) summarize the principal objectives and scientific  
45 goals of fault-zone drilling: "The objective of fault-zone drilling projects is to directly  
46 study the physical and chemical processes that control deformation and earthquake  
47 generation within active fault zones." More recently, the ICDP-SCEC international  
48 workshop on "Rapid Response Drilling: Past, Present, and Future", held in Tokyo, Japan  
49 (November 2008, see Brodsky *et al.* 2009), pointed out the need to know how fault  
50 strength recovers slowly in the long interval between earthquakes and what  
51 combinations of physical and chemical properties of fault rocks lead faults to slip or to  
52 creep. In order to fulfill these objectives, the active fault zone and active slip zone  
53 related to the last earthquake had to be first recognized so their thickness, mineralogy,  
54 chemical composition, and microstructures could be studied. The major geological  
55 questions addressed by fault zone drilling projects are the following: can we interpret  
56 microstructures in terms of deformation mechanisms, strain-rate, slip-weakening or  
57 hardening processes? Can we estimate the fracture and heat contribution in the energy  
58 budget of an earthquake? What is the importance of fluids before, during and after an  
59 earthquake? What are the mechanisms and kinetics of fault healing? What are the  
60 physical properties (seismic velocities, electrical resistivity, density, porosity,  
61 permeability) of fault-zone materials compared to country rocks and how do they vary  
62 in time and space? As predicted by Hickman *et al.* (1995), these drilling programs have

63 partly answered these questions and contributed to a better knowledge of the active  
64 faults, as illustrated by the huge number of scientific papers that have arisen from the  
65 studies of core samples; in fact these are too numerous to cite herein. These studies have  
66 also led to definition of important new questions and have stimulated a large number of  
67 laboratory measurements and experiments.

68 Of course, boreholes are needle points through faults and surface surveys and detailed  
69 studies should not be neglected. However, they provide continuous and unaltered  
70 sampling through the faults. In this paper, I will focus on and tentatively summarize the  
71 main results that have specifically arisen from the Nojima (Japan) and Chelungpu  
72 (Taiwan) drilling projects.

73

## 74 **The Nojima Fault (Japan)**

75

### 76 ***General context***

77

78 The 1995 Hyogo-ken Nanbu earthquake (Kobe earthquake, M7.2) caused 6432 fatalities  
79 and disastrous damage in the Kobe city and Awaji Island area. One year after the  
80 earthquake, five boreholes were successfully drilled through the Nojima Fault in Awaji  
81 Island by the Geological Survey of Japan (GSJ) and the National Research Institute for  
82 Earth Science and Disaster Prevention (NIED) at Hirabayashi, and by the Disaster  
83 Prevention Research Institute (DPRI, Kyoto University) at Ogura, with the aim of better  
84 understanding seismic processes. These boreholes, which were completed within 14  
85 months of the Kobe earthquake, were the first to penetrate through active faults  
86 following a recent earthquake. The Nojima Fault is a north-east striking and south-east  
87 dipping dextral reverse fault running along the west coast of the Awaji Island, which  
88 cuts across the Cretaceous Ryoke granodiorite and its porphyry dykes (Figure 1a). Its  
89 Quaternary offset and average slip rate have been established by Murata *et al.* (2001) to  
90 be 490-540m and 0.4-0.45m/10<sup>3</sup> years, respectively, for the last 1.2 my based on the  
91 displacement of an unconformity below the sedimentary Kobe Group (Figure 1b). The  
92 basal part of this group has been dated to Middle to Late Eocene (Yamamoto *et al.* 2000),  
93 i.e. 40 Ma. These geological data and dates represent important constraints for

94 interpreting the structure and mineralogy of the fault rocks observed in core samples.

95

### 96 ***The active fault zone***

97

98 Drill holes were nearly vertical and at low angle to the orientation that is inferred for the  
99 Nojima Fault from its steeply dipping surface rupture (75° to 85° southeast, Awata &  
100 Mizuno 1998). Conventional borehole logging during drilling illustrated the evolution of  
101 physical properties of rocks with depth. Measured parameters were sonic wave velocity  
102 (Vp), borehole diameter, resistivity, porosity, density, gamma ray, temperature (Ito *et al.*  
103 1996; Ikeda 2001). By combining these data with continuous observation of core  
104 samples on-site, the main fault zone was able to be located at 389.5m, 624.5m and  
105 1140m depth in the DPRI 500, Hirabayashi GSJ and NIED drill holes, respectively (Figure  
106 1b and c). Another borehole approached the fault at ca. 1700m depth (DPRI 1800,  
107 Figure 1b) but did not go entirely through it (Lin *et al.* 2007).

108 The logging tools give a first image of the structure of the fault. In the GSJ borehole for  
109 example, the resistivity decreases regularly above and increases abruptly below all  
110 faults regardless of their importance (Pezard *et al.* 2000). Conversely, the natural  
111 gamma radioactivity displays a wide maximum above the fault, decreases sharply on the  
112 fault and then increases regularly below it, until the base-line (Pezard *et al.* 2000). Both  
113 trends indicate an asymmetry of the fault zone and a tendency towards more extensive  
114 fracturing and alteration of the hanging-wall as the fault is approached. This result  
115 illustrates that logging tools are powerful methods to locate damage and fault zones in  
116 boreholes. The Stoneley wave analysis was used to determine the location of the  
117 permeable zone around the Principal Slip Zone (PSZ, Sibson 2003) in the Hirabayashi  
118 GSJ drill hole within the 623 to 625m depth interval predicted by observations of the  
119 surface rupture (Kiguchi *et al.* 2001). It is important to note that no temperature  
120 anomaly was measured in any borehole.

121

### 122 ***Characterization of the fault zone***

123

124 An identical procedure was followed for core handling for all drill holes (Tanaka *et al.*

125 2001 a; Matsuda *et al.* 2001; Lin *et al.* 2007). Core pieces were fixed using epoxy resin  
126 and cut in two halves. One of these halves was for archiving, but was polished for naked-  
127 eye observations. The other half was made into thin sections, and used for experiments  
128 and analyses. This method presented advantages for microstructural studies because it  
129 allowed multiscale observations of samples from cores to thin sections. However, it  
130 caused complications in the measurement of physical properties of the fault rocks.

131 Formation Micro-Imaging (FMI™; Schlumberger, Houston, Texas), a downhole logging  
132 technique which was performed after the GSJ drilling, provides an image of the electric  
133 resistivity of the borehole and thus indicates the number and orientation of the  
134 fractures. The fractures tend to strike E-W far from the fault, as expected due to the  
135 orientation of the present-day stress field, but they become normal to the fault close to it  
136 and parallel to it within the fault core (Ito & Kiguchi 2005). FMI and images of the core  
137 were compared to reorient the core samples in a geographic coordinate system (Ohtani  
138 *et al.* 2000 a). However, this was not possible for the whole length of the borehole,  
139 particularly in sections with few fractures. Nevertheless, observations of thin sections  
140 normal to the core indicate evidence for two nearly orthogonal directions of  
141 compression in the form of kinked biotites (Boullier *et al.* 2004 a), healed (fluid  
142 inclusion planes) or sealed (calcite) microfractures (Takeshita & Yagi 2001). These two  
143 stress tensors are consistent with the geodynamics of Japan which displays left-lateral  
144 transcurrent faults striking 045° during the Late Cretaceous-Palaeocene (Kanaori 1990),  
145 which were reactivated as right-lateral faults during Late Pliocene to Quaternary times  
146 (Fabbri *et al.* 2004).

147 Systematic studies of polished slabs (see for example Figure 2) and thin sections have  
148 provided important data on the distribution of deformation microstructures,  
149 geochemical composition and mineralogy of the core samples in all boreholes (Ohtani *et*  
150 *al.* 2000 b, 2001; Fujimoto *et al.* 2001; Tanaka *et al.* 2001 a, b, 2007 a; Kobayashi *et al.*  
151 2001; Matsuda *et al.* 2001, 2004; Lin *et al.* 2001, 2007). Most of these studies have used  
152 Sibson's (1977) classification of fault rocks. First, these authors have used distribution  
153 of deformation and alteration textures in order to define the fault core where most of the  
154 displacement is accommodated, and the damage zone that is made of a network of  
155 subsidiary structures between the fault core and the undeformed protolith (Caine *et al.*  
156 1996). The fault core and damage zone are 0.3m and > 46.5m wide, respectively, in the  
157 Hirabayashi GSJ borehole (Ohtani *et al.* 2000 b, 2001; Fujimoto *et al.* 2001; Tanaka *et al.*

158 2001 *a*). The fault damage zone is 70m wide in the Hirabayashi NIED drill hole (Tanaka  
159 *et al.* 2007 *a*) and even larger (130m) if the 1140m and 1312m fault zones are  
160 considered as bounding faults of a fault zone (Lockner *et al.* 2009). The Nojima fault  
161 zone becomes wider and more complex with depth, branching into two faults between  
162 the Hirabayashi GSJ and NIED drill holes.

163 Secondly, correlations between deformation intensity and geochemical composition  
164 were possible thanks to the homogeneity of the starting material, the Ryoke  
165 granodiorite (Figure 2a). Mass balance calculations considering  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  as  
166 immobile elements indicate important volume loss (compaction) in the fault core but  
167 volume gain (dilation) in the damage zone in the Hirabayashi GSJ and NIED boreholes  
168 (Tanaka *et al.* 2001 *a*, 2007 *a*). Volume gain in the damage zone corresponds also to an  
169 LOI (Losses On Ignition) increase and to decrease of the P-wave velocity (Fujimoto *et al.*  
170 2001). These results are consistent with permeability and strength evolution around the  
171 fault as measured by Mizoguchi *et al.* (2008 *a*) on surface samples and by Lockner *et al.*  
172 (2009) on drill core samples. The fault zone is "a thin, low-strength, low-permeability  
173 fault zone core flanked by zones of high permeability rock that have undergone  
174 relatively limited total shear" (Lockner *et al.* 2009).

175

### 176 ***The Principal Slip Zone***

177

178 Although it was a challenging prospect, the Principal Slip Zone (PSZ, Sibson 2003),  
179 where displacement took place during the Kobe earthquake, was located by careful  
180 observations of core samples and polished slabs from three drill holes. In the DPRI 500  
181 drill hole (Figure 1b) the PSZ is localized at the contact between foliated gouges from the  
182 Ryoke granodiorite and from the Osaka group, and is described as a fault surface (Lin *et al.*  
183 2001; Tanaka *et al.* 2001 *b*). This would suggest that PSZ related to the Kobe  
184 earthquake has no apparent thickness at this depth. However, thanks to electron spin  
185 resonance (ESR) intensity measured across the dark gray fault plane by Fukuchi & Imai  
186 (2001), and to comparison of ESR analyses of natural and experimental fault gouge  
187 samples produced from high-speed slip tests (Fukuchi *et al.* 2005), it has been  
188 demonstrated that a thermal effect related to the earthquake was recorded in a 6mm  
189 wide zone, which could be explained by frictional heating of the pore water in the fault

190 gouge above boiling, and its diffusion into the fault gouge (Fukuchi & Imai 2001).  
191 Darkening of the gouge and the presence of an increased ferrimagnetic resonance  
192 (FMR) signal in the PSZ are related to the formation of ferri-magnetic iron oxides and  
193 indicate that frictional heating may have induced temperatures of at least 350-400°C  
194 during seismic slip at 390m depth (Fukuchi *et al.* 2005).

195 In the Hirabayashi GSJ drill hole (Figure 1c), after much debate it was concluded that the  
196 PSZ was found at 625.27m depth in a millimetre-thick slip zone (Tanaka *et al.* 2001 *a*).  
197 In the Hirabayashi NIED drill hole (Figure 1c), Tanaka *et al.* (2007 *a*) located the PSZ at  
198 1140.57 to 1140.66m depth in a 10 mm-thick Ca-rich ultracataclasite layer in which  
199 intense grain-size reduction has occurred, but Lockner *et al.* (2009) suggested that two  
200 activated fault strands were crossed by this drill hole at 1140 and 1312m depth. All  
201 these observations on drill holes through the Nojima fault demonstrate that thickness of  
202 the PSZ increases with depth and that fault healing processes may be very efficient,  
203 making it difficult to recognize the PSZ in all drill holes only one year after the Kobe  
204 earthquake.

205

### 206 ***Pseudotachylytes and seismic processes***

207

208 The most striking rocks observed either in GSJ or NIED drill holes are pseudotachylytes  
209 (Figures 2c and 3a) which are associated with ultracataclasites (Ohtani *et al.* 2000 *b*;  
210 Tanaka *et al.* 2001 *a*; Boullier *et al.* 2001; Otsuki *et al.* 2003). These rocks are rarely  
211 observed in faults as predicted by Sibson & Toy (2006), but clearly result from seismic  
212 slip (Sibson 1975) and therefore provide information on seismic processes and the  
213 energy budget of earthquakes (Kanamori & Heaton, 2000). Otsuki *et al.* (2003)  
214 suggested that the ultracataclasites observed in these drill holes behaved as fluidized  
215 granular material, in which frictional resistance decreased abruptly to nearly zero  
216 during seismic slip. They also proposed that the viscosity of the pseudotachylytic melt  
217 evolved during seismic slip, based on the temperature reached and the percentage of  
218 unmelted grains. As observed in the Hirabayashi GSJ drill hole and surface outcrops, the  
219 pseudotachylytes are laminated with some contorted and folded layers (Figure 3a;  
220 Tanaka *et al.* 2001 *a*; Boullier *et al.* 2001; Otsuki *et al.* 2003) that could be indicators of  
221 high-velocity seismic slip (Mizoguchi *et al.* 2009). The glass is not recrystallized and

222 does not display spherulites or crystallites as often described in pseudotachylytes (see  
223 for example di Toro & Pennachioni 2004). However, there are abundant rounded  
224 vesicles which appear to be fluid inclusions (Figure 3b). Microthermometry on some of  
225 these fluid inclusions indicates that they are filled by a very dense CO<sub>2</sub>-H<sub>2</sub>O fluid. The  
226 intersection of isochoric lines with the present-day 24°C/km geothermal gradient  
227 indicates that the fluid inclusions were trapped at 380°C and 410MPa (Boullier *et al.*  
228 2001) or at 270°C and 250MPa if a 30°C/km geothermal gradient is considered (Boullier  
229 *et al.* 2004 *a*). The lower estimate is probably more realistic as no mylonites were found  
230 in the Nojima fault. Such trapping conditions imply that these pseudotachylytes were  
231 formed at >9km depth in the seismogenic zone before exhumation of the Ryoke  
232 granodiorite and deposition of the Kobe group at 40Ma. They therefore formed during  
233 an early stage of seismic activity on the Nojima Fault (Boullier *et al.* 2001). This  
234 deduction has been confirmed by fission track data of zircon which provided a 56 Ma  
235 age for the pseudotachylytes (Murakami & Tagami 2004). The presence of fluid  
236 inclusions also indicates that the pseudotachylytic melt was saturated in fluids when  
237 cooling which suggests that this frictional melt formed in an already altered initial  
238 material containing fluid as a free phase or/and structurally bound in minerals. Famin *et*  
239 *al.* (2008) measured the CO<sub>2</sub> and H<sub>2</sub>O contents of the pseudotachylytic melts by Fourier  
240 transform infrared (FTIR) microanalysis, illustrating that the younger layers have  
241 decreasing CO<sub>2</sub> contents due to decreasing pressure of formation and that a significant  
242 mass of CO<sub>2</sub> may be exsolved during each pseudotachylyte-generating seismic event.  
243 Consequently, because CO<sub>2</sub> saturation in silicate melts is pressure-dependent, CO<sub>2</sub>  
244 content in pseudotachylytic glass may be used as a proxy for the depth of  
245 pseudotachylyte formation.

246

### 247 ***Energy budget of the earthquake***

248

249 Boullier *et al.* (2001) used the calculations proposed by Kanamori & Heaton (2000) to  
250 evaluate the thermal budget of earthquakes that resulted in pseudotachylyte formation.  
251 Based on the thickness of the pseudotachylyte layers (1mm) and on the temperature  
252 increase due to frictional melting (1000°C), they deduced that each pseudotachylyte  
253 layer corresponds to M6 to M7 earthquakes assuming a 3-4MPa initial frictional stress

254 calculated by Bouchon *et al.* (1998) from the slip model of Irikura *et al.* (1996).  
255 Therefore, the pseudotachylytes observed now at 625m depth in the Hirabayashi GSJ  
256 borehole were formed during *ca.* 56Ma old earthquakes similar in magnitude (M6 to M7  
257 versus Mw 6.9) to the recent Kobe earthquake.

258 Grain-size distribution (GSD) has been recently used by many authors to characterize  
259 fault rocks and gouges related to seismic events, with the aim of estimating the fracture  
260 energy of earthquakes (see a review in Keulen *et al.* 2007). This technique has also been  
261 used to characterize aseismic faulting and cataclasis accompanying hydrothermal  
262 alteration in a the Cajon Pass drill hole (Blenkinsop & Sibson 1992). Keulen *et al.* (2007)  
263 measured GSD in cataclasites from the Hirabayashi GSJ drill hole and in experimentally  
264 deformed granitoids. In both cases GSD were not fractal and two slopes (D) were  
265 observed in all log-log GSDs. In experimental or natural examples, D-values of 0.9-1.1  
266 were measured for grains smaller than *ca.* 1  $\mu\text{m}$ . Two different D were measured for  
267 cracked grains (1.5-1.6) and gouges (2.0 to 2.6) for grains larger than 1  $\mu\text{m}$ , which is the  
268 grinding limit of quartz. These results show that grain size reduction in fault zones  
269 develops by a two-stage process: rupturing creates cracked grains; further displacement  
270 of fragments causes further comminution by wear and attrition. Healing processes may  
271 also modify GSD as demonstrated by experiments of hydrostatic or non-hydrostatic  
272 healing of fault gouges (Keulen *et al.* 2008). Thus, we should be cautious when using GSD  
273 for calculating the fracture energy of an earthquake because GSD is the sum of several  
274 cumulated seismic events and is the product of different mechanisms occurring during  
275 the whole evolution of the gouge zone.

276

### 277 ***Fluids: before, during and after earthquakes***

278

279 Multi-stage alteration of fault rocks has been recognized by Ohtani *et al.* (2000 *b*),  
280 Fujimoto *et al.* (2001), Tanaka *et al.* (2001 *a*, 2007 *a*) and Boullier *et al.* (2004 *a*), as  
281 summarized in Table 1. Using the relationships between hydrothermal minerals and  
282 structures, it is possible to correlate hydrothermal alteration with deformation episodes.

283 The older hydrothermal stage is weak, static and characterized by chlorite. It is  
284 attributed to the cooling of the granodiorite between 90 and 74 Ma (Takahashi 1992;

285 Murakami *et al.* 2002).

286 The second stage is widespread and, at least in the Hirabayashi GSJ drill hole, is  
287 represented by zeolites. Laumontite, the most common mineral formed in this stage, is  
288 observed throughout the damage zone as an alteration product of plagioclase, filling  
289 veins and sealing fractures. The hydrothermal alteration in the low-strain damage zone  
290 in the Hirabayashi GSJ drill hole is very similar to that observed in the Cajon Pass drill  
291 hole (Blenkinsop & Sibson, 1992) in terms of starting material (granitic rock), alteration  
292 product (laumontite formed at the expense of plagioclase) and deformation textures  
293 (almost no crack-seal textures, extensional fractures with flow structures and dilatant  
294 cataclasis). Some dilatant microstructures could thus result from aseismic deformation  
295 related to volume change induced by replacement of plagioclase by laumontite  
296 (Blenkinsop & Sibson, 1992). Laumontite is present as clasts in ultracataclasites (pale  
297 green in Figure 2b); in particular in those associated with pseudotachylytes. This  
298 indicates that the first stage of seismic activity and alteration occurred before 40Ma  
299 under decreasing pressure and temperature conditions between the formation of  
300 pseudotachylytes at  $>270^{\circ}\text{C}$  and  $>250\text{MPa}$  (see above), and the stability field of  
301 laumontite, which is between  $280^{\circ}\text{C}$  and  $150^{\circ}\text{C}$  depending on the pressure (Zen &  
302 Thompson 1974). These observations are also consistent with the decreasing  $\text{CO}_2$   
303 content of the pseudotachylytic glass measured by Famin *et al.* (2008).

304 The third stage of alteration is characterized by thin veinlets of siderite emplaced within  
305 the flattening plane in cataclasites and ultracataclasites (reddish brown zones in Figure  
306 2b) within the core of the main fault zone around 625m in the Hirabayashi GSJ drill hole  
307 (Boullier *et al.* 2004 *a*) and within the 1140m, 1300m and 1800m fault cores of the  
308 Hirabayashi NIED drill hole (Boullier, unpublished observations). These veins are not  
309 associated with any significant phase of deformation, nor with structures resulting from  
310 dilatancy and are deformed in later gouge zones or cross-cut by later carbonate veins  
311 (see Table 1 and Boullier *et al.* 2004 *a*). For these reasons they have been correlated  
312 with a quiescence stage by Boullier *et al.* (2004 *a*).

313 The fourth hydrothermal stage is characterized by hydraulic fractures filled by small  
314 grain-size euhedral ankerite and siderite crystals (pale honey-coloured fractures in  
315 Figure 2b; Fujimoto *et al.* 2001; Boullier *et al.* 2004 *b*; Moore *et al.* 2009). Undeformed  
316 hydrofractures of this type are mainly localized in the hanging-wall of the main fault

317 zone in the Hirabayashi GSJ drill hole but they are also observed below the fault where  
318 they are deformed by late gouge zones (Figure 3c). Their internal structure strongly  
319 suggests that they were induced by coseismic hydraulic fracturing and fast nucleation of  
320 carbonates due to a sudden fluid or CO<sub>2</sub> partial pressure drop due to fracturing (Boullier  
321 *et al.* 2004 *b*).

322 The latest stage of alteration is characterized by clays. Smectite has been found in the  
323 GSJ 625m (Fujimoto *et al.* 2001) and NIED 1140m (Matsuda *et al.* 2004) fault zones. Illite  
324 is also observed in small conjugate low-angle reverse shear zones located below the  
325 principal 625m fault core (Figure 3c) in which it displays a C/S microstructure (Figure  
326 3d). These small shear zones lie below the principal 625m fault core and may be  
327 observed on the FMI images (Ito & Kiguchi 2005). They also correspond to the 625-  
328 635m depth interval where deformation of the borehole has been seen on the BHTV  
329 (BoreHole TeleViewer) acoustic scans (C  lerier *et al.* 2000).

330 The present-day fluids which are circulating in the GSJ 625m fault zone have been  
331 analyzed. Their chemical composition is in equilibrium with the carbonates precipitated  
332 in the hydraulic fractures described above and with illite and Ca-montmorillonite. This  
333 also indicates that the fluids are flowing upwards and originate from a reservoir situated  
334 at 4km depth (Fujimoto *et al.* 2007) based on the 24  C geothermal gradient measured in  
335 the Hirabayashi GSJ borehole (Kitajima *et al.* 1998). Lin *et al.* (2003) have proposed that,  
336 because these fluids are meteoric in origin, they have infiltrated the active Nojima Fault  
337 by a fluid suction-pumping process inspired by the so-called seismic pumping model  
338 (Sibson *et al.* 1975).

339

### 340 ***Processes of healing by dissolution-precipitation***

341

342 Fluids are also involved in the chemical compaction of gouges, ultracataclasites or fine-  
343 grained vein-filling material by dissolution-precipitation processes, although fluid  
344 advection is not necessary. Evidence for these processes has been found in the 625m  
345 fault zone of the Hirabayashi GSJ borehole in the form of stylolitic surfaces in fine-  
346 grained laumontite dilatant veins of the second hydrothermal stage (Boullier *et al.* 2004  
347 *a*) and indentation of grains in gouges or in fine-grained carbonate veins of the third  
348 hydrothermal stage (Boullier *et al.* 2004 *b*). The dissolution-precipitation processes are

349 diffusion controlled, and therefore dependent on the diffusion distance between the  
350 source and sink of solute, and on the mineral which is dissolved (Gratier *et al.* 2003).  
351 Consequently, although these are very slow processes, they may be very efficient under  
352 low stresses in fine-grained material such as those mentioned above and therefore  
353 contribute to the post-seismic or interseismic sealing of the fault , to the decrease in  
354 permeability of very fine-grained ultracataclasites as measured by Lockner *et al.* (2009)  
355 and to stress build up in the lead-up to the next seismic rupture. Minerals involved in  
356 these processes are mostly laumontite during the first and carbonates during the second  
357 stages of seismic activity of the Nojima Fault. Decrease in permeability should result in  
358 an increase in fluid pressure. However, there are no observational data, such as  
359 horizontal extensional veins, that would suggest that an abnormal fluid pressure regime  
360 existed in the case of the Nojima Fault as for the fault-valve model (Sibson *et al.* 1988;  
361 Sibson 1990).

362

### 363 ***Lessons from the Nojima Fault drilling projects.***

364

365 The first lesson from the Nojima Fault drilling projects is that geology of this fault is  
366 considerably more complex than initially thought. The fault-zone thickness, structure  
367 and mineralogy are the result of two distinct periods of seismic activity accompanied by  
368 intense hydrothermal alteration separated by a period of quiescence. All these stages  
369 are recorded in the fault rock microstructures. The recognition of very peculiar  
370 pseudotachylytes in the core of the fault that are attributed to the first period of activity  
371 has induced significant interest in this type of rocks. As a result, a number of high  
372 velocity rotary shear friction experiments have been performed on « hard » rocks (for  
373 example Hirose & Shimamoto 2005; Di Toro *et al.* 2004). Natural gouges from the  
374 Nojima Fault have also been used as initial material for similar high velocity  
375 experiments to investigate their behaviour during seismic slip (Mizoguchi *et al.* 2009).

376 Observations of the internal structure of the Nojima Fault have also illustrated that we  
377 need more information on the permeability and thermal properties of faults to  
378 understand and predict their seismological behaviour (for example Wibberley &  
379 Shimamoto 2003, 2005; Uehara & Shimamoto 2004; Mizoguchi *et al.* 2008 *a*; Lockner *et*  
380 *al.* 2009). Permeability is highly dependent on fracturing and healing processes, and

381 rates and kinetics of these processes are of considerable importance. Recently, highly  
382 permeable pulverized rocks have been discovered along the San Andreas Fault by Dor *et al.*  
383 *al.* (2006) and along the Arima-Takatsuki tectonic line (Mitchell *et al.* 2009). Some  
384 textures of dilatant fractures at depth in the Hirabayashi GSJ drill hole are similar to  
385 naturally (Rockwell *et al.* 2009) and experimentally (Doan & Gary 2009) pulverized  
386 samples. Could they be the expression of pulverization at depth or high strain-rate  
387 brittle deformation in the fault zone? This question illustrates that the determination of  
388 strain-rate on the basis of microstructures in fault rocks remains a major question, and  
389 more comparisons need to be made between experimentally and naturally deformed  
390 samples.

391 Hirabayashi NIED borehole intercepted three fault zones (Tanaka *et al.* 2007 *a*), while  
392 the DPRI 1800 borehole intercepted two (Lin *et al.* 2007). Some of these fault zones  
393 were activated by the Kobe earthquake, but others were not. As illustrated by the fact it  
394 was difficult to identify the principal slip zone of the Kobe earthquake only one year  
395 after this event, healing processes may be very efficient and rapidly obliterate the  
396 evidence of localised slip. Therefore, we can still ask whether the non-activated faults  
397 are locked or inactive? Detailed comparative, collaborative studies by the principal  
398 investigators of each of these drill holes are needed to provide more information on the  
399 deformation and healing microstructures and mechanisms to address this question.

400 Nevertheless, the Japanese drill holes through the Nojima Fault have confirmed the  
401 international interest in fault zone geology, and progressed the general knowledge on  
402 faulting and seismic processes in basement rocks.

403

## 404 **The Chelungpu Fault (Taiwan)**

405

### 406 ***General context***

407

408 The Chi-Chi earthquake (21 September 1999,  $M_w = 7.6$ , *ca.* 2400 fatalities) produced a  
409 surface rupture of 80 km, with up to 10 m offset on the northern part of the Chelungpu  
410 thrust fault (Figure 4a, 4b; Kao & Chen 2000). From reconstruction of balanced cross  
411 sections, Yue *et al.* (2005) determined that the Sanyi-Chelungpu thrust system has

412 accommodated 14 km total displacement, and that 0.3 km total slip has been  
413 accommodated on a newly propagated North Chelungpu Chinshui detachment within  
414 the Chinshui Shale, where the Chi-Chi earthquake occurred (Figure 4b). Thus, in contrast  
415 with the Nojima Fault, the Chelungpu Fault has a relatively simple tectonic history.

416 The Chi-Chi earthquake was recorded by the very dense Taiwan Strong Motion and GPS  
417 Networks allowing models of spatial slip distribution (Ma *et al.* 2001), as well as  
418 determination of rupture velocity (Chen *et al.* 2001), and of coseismic and postseismic  
419 deformation (Pathier *et al.* 2003; Yu *et al.* 2003). During the Chi-Chi earthquake, the  
420 northern segment of the Chelungpu Fault was characterized by large displacement (8 to  
421 10m), high slip velocity (2-4m/s) and low level of high-frequency radiation. In contrast,  
422 smaller displacement (3-4m), lower slip velocities (0.5m/s) and higher accelerations of  
423 the ground motion were measured in the southern part (Ma *et al.* 2003).

424 Initially, two shallow boreholes penetrated the Chelungpu Fault in March 2001 at 455m  
425 (northern site, Fengyuan) and 211m (southern site, Nantou). These provided initial  
426 important observations, such as a temperature rise in the northern site on the suspected  
427 fault zone activated by the Chi-Chi earthquake (Tanaka *et al.* 2002) and differences in  
428 fault zone architecture: clay-rich injections (Otsuki *et al.* 2005; Ujiie 2005) and  
429 pseudotachylite fragments (Otsuki *et al.* 2005) are described in the northern and  
430 southern boreholes, respectively. As the lithofacies and geological structure are similar  
431 at both northern and southern sites, the difference in fault rock microstructures are  
432 interpreted as indicating different frictional properties of the fault in these two  
433 segments (Otsuki *et al.* 2005; Ujiie *et al.* 2005).

434

### 435 ***The active fault zone***

436

437 The Taiwan Chelungpu Fault Drilling Project (TCDP, Figure 4) was started in 2002. The  
438 TCDP site was chosen near the town of DaKeng, about 2 km east of the surface rupture  
439 (Figure 4b) in order to allow investigation of the slip-weakening mechanisms  
440 responsible for the seismological characteristics of the Chi-Chi earthquake in the  
441 northern part of the Chelungpu Fault. Two vertical boreholes were drilled 40 m apart  
442 (2000.3 m deep Hole A in 2004 and 1352.6 m deep Hole B in 2005), and a side-track was

443 drilled from a depth of 950m to 1280m from hole B (hole C in 2005). TCDP holes  
444 penetrated through Pliocene and Upper Miocene alternating sandstones, siltstones and  
445 shales (Figure 4b; Song *et al.* 2007).

446 One major feature in the TCDP cores is the colour change of the rocks (from light grey to  
447 dark grey, and black) that accompanied deformation. This has been used as a  
448 macroscopic on-site criteria for locating fault-zones (Yeh *et al.* 2007). Three major fault  
449 zones were recognized in the Chelungpu Fault system in Hole A at 1111, 1153 and  
450 1221m depth (Song *et al.* 2007; Hung *et al.* 2007; Yeh *et al.* 2007; Sone *et al.* 2007) which  
451 may correlate to fault zones at 1136, 1194 and 1243m depth, respectively, in Hole B  
452 (Figure 4c; Hirono *et al.* 2007). In Hole B the recognition of fault zones was facilitated by  
453 the use of systematic non-destructive and continuous measurements performed on the  
454 retrieved cores at the Kochi Institute for Core Sample Research (JAMSTEC) such as  
455 density, porosity, magnetic susceptibility, natural gamma ray radiation and gamma ray  
456 attenuation, magnetic susceptibility and X-ray Computed Tomography (X-ray CT)  
457 (Hirono *et al.* 2007). Some, but not all, fault zones also include cm-thick fault-parallel  
458 disks of hard black ultracataclasites: at 1153 and 1221m depth in Hole A (Yeh *et al.*  
459 2007) and at 1194, 1243 and 1341m depth in Hole B (Hirono *et al.* 2007).

460 Among these fault zones, the one located at 1111m in Hole A (FZA1111, Figure 4c) was  
461 determined on-site as the fault-zone activated by the Chi-Chi earthquake on the basis of  
462 several arguments: high-resolution shallow seismic reflection profiles predicting a  
463 depth at 1200m with 10% error; high strain fault kinematics were determined as thrust  
464 by fault plane and slickenside orientations consistent with the measured focal  
465 mechanism of the Chi-Chi earthquake; high fluid content (Ma *et al.* 2006; Yeh *et al.*  
466 2007; Song *et al.* 2007), fracture density and physical properties measured by logging  
467 tools, in particular low resistivity, low density, and distinct Vp and Vs (Hung *et al.* 2007).  
468 The total thickness of the FZA1111 fault zone is 5.5m (Yeh *et al.* 2007). It corresponds to  
469 the fault zone at 1136m in Hole B (FZB1136, Figure 4c) which has a 3.5m total thickness  
470 and is characterized by a lower contrast related to higher permeability on X-ray CT  
471 images (Hirono *et al.* 2008).

472

473 ***Energy budget of the earthquake***

474

475 One major question arising from the TCDP project concerns the thermal budget of the  
476 earthquake, and many papers have been devoted to that point. First, temperature  
477 measurements were performed in 2005 in Hole A. A 0.06°C anomaly was found around  
478 the FZA1111 (Kano *et al.* 2006), consistent with the 0.1°C anomaly measured earlier in  
479 the shallow boreholes (Mori & Tanaka, 2002; Tanaka *et al.* 2006). As discussed by Kano  
480 *et al.* (2006) and Tanaka *et al.* (2006, 2007 *b*), the temperature anomaly may occur as (i)  
481 residual heat generated during the Chi-Chi earthquake or (ii) may be the result of  
482 fluctuations of geothermal gradient related to changes of physical and thermal  
483 properties of fault rocks or (iii) be the result of warm fluid upflow in the fault zone due  
484 to its high permeability deduced from hydraulic tests (Doan *et al.* 2006) and  
485 measurements on core samples (Tanikawa *et al.* 2009). Unfortunately, it is not yet  
486 possible to resolve these possibilities in the TCDP boreholes.

487 Ma *et al.* (2006) calculated the grain size distribution in the very fine-grained gouge  
488 recognized as the Chi-Chi PSZ by Kuo *et al.* (2005) in order to better constrain the  
489 energy budget of earthquakes. By comparison with the seismic surface fracture energy  
490 determined from near-field seismic data, they concluded that the contribution of gouge  
491 surface energy represents 6% of the earthquake breakdown work, which is slightly  
492 higher than the <1% value obtained on mature Californian faults by Chester *et al.* (2005)  
493 and Rockwell *et al.* (2009).

494

### 495 ***The Chi-Chi PSZ***

496

497 The Chi-Chi PSZ was recognized by Kuo *et al.* (2005, 2009) in the lower part of FZA1111  
498 (Figure 5), just above a hard, but fragile black disk, which broke into pieces during on-  
499 site core handling. This interpretation was based on the absence of reworking  
500 microstructures such as later fractures in the very fine-grained gouge, veins or  
501 schistosity and on the presence of smectite as the dominant clay mineral. The authors  
502 also observe the presence of glassy material in small quantities (<25%) and suggest that  
503 melting of clay minerals due to strong shear heating occurred in the PSZ and that most  
504 of the resulting pseudotachylyte was promptly converted into smectite (Kuo *et al.* 2009).

505 Boullier *et al.* (2009) presented a detailed study of the FZA1111 fault zone, focusing on

506 the Chi-Chi PSZ. The latter is a 2cm thick, very fine grained, isotropic gouge (Figure 6a)  
507 and contains matrix-supported clasts and Clay Clast Aggregates (CCAs, Figure 6b) which  
508 are microstructures that have been reproduced by Boutareaud *et al.* (2008, 2010)  
509 during high velocity rotary shear experiments where a liquid to vapour transition  
510 occurred in the pore water. As such, CCAs are new symptomatic markers of seismic slip  
511 in clay-rich gouges, like pseudotachylytes are in "hard" rocks (Sibson 1975). Clasts of the  
512 lower black ultracataclasites are also present in the PSZ and display an inverse grain  
513 size segregation according to the Brazil Nut Effect (Boullier *et al.* 2009). All these  
514 microstructural criteria lead Boullier *et al.* (2009) to propose that the gouge was  
515 fluidized as the result of a 300-400°C coseismic temperature rise inducing thermal  
516 pressurization (Sibson 1973). This phenomenon may explain the gouge injections  
517 observed above the FZA1111 (Figure 5) and in the northern shallow borehole (Otsuki *et al.*  
518 *et al.* 2005; Ujiie 2005). The Chi-Chi PSZ in FZB1136 is very different from the PSZ in  
519 FZA1111; it is a thin (<0.3 cm versus 2 cm) ultracataclasite, locally exhibiting a layering  
520 defined by variations in concentrations of clay minerals and clasts (Boullier *et al.* 2009)  
521 similar to foliated gouges experimentally reproduced by Boutareaud *et al.* (2008) and  
522 Mizoguchi *et al.* (2009).

523 Continuous in-situ and non-destructive measurement of the magnetic susceptibility in  
524 Hole B has shown that fault zones, and FZB1136 in particular, are characterized by an  
525 important increase of the magnetic susceptibility which has been interpreted by Hirono  
526 *et al.* (2006) as due to the production of ferrimagnetic iron oxydes induced by frictional  
527 heat as experimentally reproduced during high-speed frictional testings (Fukuchi *et al.*  
528 (2005). Recently, Chou *et al.* (2009, 2010) and Aubourg *et al.* (2010) performed a very  
529 detailed and complete analysis of magnetic properties on FZB1136 using a U-channel  
530 sample. They measured the magnetic susceptibility, the isothermal remanent  
531 magnetization and S-ratio, and the anhysteretic remanent magnetization every cm,  
532 together with low-temperature magnetic properties to identify the magnetic minerals.  
533 Their measurements have been precisely compared with microstructures described by  
534 Boullier *et al.* (2009). The principal results are as follows: (i) a paleomagnetic  
535 component close to the modern dipole is recovered all along the FZB1136, (ii) very  
536 small amounts of fine-grained magnetite and pyrrhotite constitute the magnetic  
537 assemblage in the PSZ, and (iii) authigenic goethite has been clearly identified by TEM in  
538 and above the PSZ and attributed to circulation and post-seismic cooling of hot fluids in

539 the FZB1136 (Chou *et al.* 2009, 2010; Aubourg *et al.* 2010). Therefore, they confirm that  
540 frictional heating occurred in the Chi-Chi PSZ.

541 Through measurement of major and trace element chemistry, as well as isotope ratios of  
542 core samples, Ishikawa *et al.* (2008) illustrated that the three fault zones exhibit sharp  
543 compositional peaks of fluid-mobile elements and strontium isotopes. They suggest that  
544 coseismic hot (>350°C) fluids circulated and interacted with the fault rocks where they  
545 mobilized these elements. Hashimoto *et al.* (2008) attribute the low iron content of  
546 chlorite in the fault zone to result from a temperature rise and rock-fluid interactions in  
547 the three fault zones (FZB1136, FZB1194 and FZB1243). All these results are consistent  
548 with the magnetic characteristics of FZB1136 quoted above.

549 Coseismic rise of temperature in the fault zones has been documented in a number of  
550 other publications about the TCDP. Because the hard disks of black ultracataclasites are  
551 noticeable feature of the TCDP core samples, they have been investigated using different  
552 methods. Hirono *et al.* (2006) have shown that the anomalies in magnetic susceptibility  
553 measured on the black ultracataclasites in FZB1194 and FZB1243 coincide with the  
554 evidence for frictional melt and a decrease in inorganic carbon that they attribute to  
555 thermal decomposition of carbonate minerals at ca. 850°C. However, the effect of  
556 thermal decomposition of carbonates may be very complex if the mass and energy  
557 balance, and the kinetics of the endothermic reaction of calcite decomposition, are taken  
558 into account (Sulem & Famin, 2009). Otsuki *et al.* (2009) confirm that the hard black  
559 disks correspond to pseudotachylytic layers indicative of a single (FZB1314) or multiple  
560 (FZB1194, FZB1243) seismic events, and that co-seismic temperature rise has been  
561 heterogeneous in the pseudotachylytic layer and may be estimated in the 750° to  
562 1750°C range.

563 In conclusion, although different authors agree frictional heating occurred on fault zones  
564 in the Chelungpu Fault, they propose different values for the temperature rise. It  
565 appears that the coseismic thermal rise was around 300-400°C in the Chi-Chi PSZ in  
566 FZA1111 and FZB1136 (Ishikawa *et al.* 2008; Boullier *et al.* 2009) and may have reached  
567 750°C or more in the hard disks of black ultracataclasites observed in Hole B on  
568 FZB1194 and FZB1243 fault zones which correspond to ancient seismic events (Hirono  
569 *et al.* 2006; Otsuki *et al.* 2009).

570 Several gouge layers corresponding to ancient seismic events are visible in the FZA1111

571 and FZB1136. They differ from the PSZ because they display a sequence of small  
572 conjugate shear zones, a fault-parallel schistosity associated with deformed calcite veins,  
573 both being folded together in some places, and dissolution seams around hard objects  
574 (Boullier *et al.* 2009). These microstructures are consistent with a fault-normal  
575 shortening and are symptomatic of a low-rate deformation by dissolution-precipitation  
576 processes which occur during the post-seismic or the interseismic stage (Gratier &  
577 Gueydan, 2007).

578

### 579 ***Fluids: before, during and after earthquakes***

580

581 Boullier *et al.* (2009) described thin calcite veins above the Chi-Chi PSZ in FZA1111  
582 within compacted gouges, which form 3D dilational patches and display evidence of  
583 increasing strain with increasing distance from the PSZ. They were formed by hydraulic  
584 fracturing, and are undeformed just above the PSZ where they are interpreted by  
585 Boullier *et al.* (2009) as induced by fluid escape, fracturing and sealing related to the  
586 Chi-Chi earthquake. Farther from the PSZ, veins are planar or shortened and folded, and  
587 orientated at high angle to the fault. In the damage zone, the silty and sandy layers are  
588 dilated, fractured and sealed by calcite while shaly layers are not. This suggests that  
589 clay-rich layers may have acted as impermeable caps allowing compartmentalization of  
590 fluids in the sandy sediments and formation of small-size so-called "Hill fault/fracture-  
591 meshes" (Sibson 1994).

592 It has been shown earlier that fluids played an important role during the Chi-Chi  
593 earthquake because they have been coseismically thermally pressurized. However, the  
594 relative scarcity of calcite veins in the active damage zone compared to the large volume  
595 of laumontite and carbonate veins in the Nojima Fault demonstrates that the volumes of  
596 fluids involved in deformation on the Chelungpu Fault are much smaller than those  
597 involved in the Nojima Fault. Regardless, their role in the Chelungpu faulting process  
598 illustrates that fluids may greatly influence the seismological behaviour of faults even if  
599 they are present in small quantities.

600

### 601 ***Lessons from the Taiwan Chelungpu Fault Drilling Project.***

602

603 One major lesson from the TCDP project concerns the thermal budget of an earthquake.  
604 In order to measure frictional heat arising from the fault slip, the temperature must be  
605 measured in the vicinity of the PSZ as quickly and as deep as possible after an  
606 earthquake (Brodsky *et al.* 2009). However, observations from the TCDP illustrate that  
607 part of the frictional heat produced by the earthquake may be transformed into  
608 mechanical (thermal pressurization) and chemical (mineral transformations, fluid-rock  
609 interactions) work. One major contribution of TCDP to earthquake understanding has  
610 been the demonstration that the energy budget of an earthquake cannot be separated  
611 into simple fracturing, radiation and thermal terms but should also take into account  
612 chemical and mineralogical transformations.

613 As the Chelungpu Fault occurs in sedimentary rocks made of alternating silts and shales,  
614 clays are important minerals within the fault zone. The TCDP results show that the  
615 behaviour of clays during co-seismic slip is fundamental in order to understand slip-  
616 weakening mechanisms. Therefore, for the same reasons that the Japanese drilling  
617 projects have stimulated experiments on "hard" rocks, the TCDP project has stimulated  
618 high velocity rotary shear friction experiments on "soft" rocks from the Chelungpu Fault  
619 (Mizoguchi *et al.* 2008 *b*; Tanikawa & Shimamoto 2009; Sone & Shimamoto 2009) and  
620 numerical modelling of the thermal pressurization related to dehydration of clays  
621 (Sulem *et al.* 2007). The high-velocity experiments on clayey gouges have produced  
622 microstructures that have been recognized in the Chi-Chi PSZ and are keys for  
623 interpreting natural fault gouges. For example, Clay Clast Aggregates (CCAs); new  
624 indicators for seismic slip, thermal pressurization and slip weakening have been  
625 described (Boutareaud *et al.* 2008, 2010).

626 The studies undertaken on the TCDP samples have demonstrated that the mineralogy of  
627 the PSZ is of considerable importance and that chemical and mineralogical  
628 transformations may occur in the PSZ due to the frictional heat produced there.  
629 However, the proposed values for the frictional heat differ significantly between  
630 different publications. The effect of thermal decomposition of minerals may be very  
631 complex and to model its mechanical effects such as slip weakening due to thermal  
632 pressurization it is necessary to take into account the mass and energy balance and the  
633 kinetics of the chemical decomposition (Sulem & Famin 2009).

634 Again, the distribution of physical properties, and transport properties in particular,

635 within the core and the damage zones of the fault is of primary importance to  
636 understand the coseismic slip behaviour of the PSZ and thermal pressurization in  
637 particular. The permeability structure of the Chelungpu Fault has been investigated in  
638 several studies using the TCDP samples (Tanikawa *et al.* 2009; Wang *et al.* 2009; Chen *et*  
639 *al.* 2009; Louis *et al.* 2008) which have demonstrated that drilling projects through  
640 active faults should include such measurements. To do so, core handling is of primary  
641 importance. The core-handling workflows were different for Hole A and Hole B samples.  
642 The results of continuous non-destructive analyses performed on Hole B samples only,  
643 were made available a short time after drilling. However, it has been shown that these  
644 rock analyses are not sufficient and that detailed studies are necessary to provide  
645 precise information on microstructures and mineralogy. For example, whole-rock  
646 analyses pointed to the fact that there is an important magnetic susceptibility record in  
647 the black ultracataclasites, that may be significant in terms of mineral transformations  
648 and thermal pressurization (Hirono *et al.* 2006). However, only detailed subsequent  
649 investigations have deciphered the exact nature of this magnetic signal and shown that  
650 the Chi-Chi PSZ records the present-day Earth's magnetic field (Chou *et al.* 2010). TCDP  
651 has led to numerous analyses of magnetic properties of fault rocks which contributed to  
652 the development of new techniques and approaches of the fault zone geology.

653 The work done on the TCDP so far represents significant progress in understanding fault  
654 zone processes, but we still need more information on clay mineralogy, composition and  
655 volume of pore fluids before and after the earthquake, in order to fully understand the  
656 mechanical and slip-weakening effects of mineral transformations in the PSZ.

657 Regardless, the numerous studies on TCDP samples have contributed to a better  
658 knowledge of thrust faults in clay-rich rocks and, consequently, have provided good  
659 preparation for the international community for other drilling projects such as  
660 NanTroSeize in the Nankai Trough.

661

## 662 **Conclusions**

663

664 This paper has focussed on the contributions of the Japanese and Taiwanese drilling  
665 projects to a better knowledge of the geology of fault zones. Some results have probably  
666 been missed as it is impossible to cite all the papers published on the subject. Each

667 project has provided its own unique set of results because the faults crosscut different  
668 parent rocks and occur in different geodynamic and tectonic contexts. Consequently,  
669 different processes and deformation mechanisms have been activated during  
670 earthquakes on the Nojima and Chelungpu faults. In addition, large volumes of fluids  
671 were involved in the alteration of the Nojima wallrocks while only small volumes of  
672 fluids were present in the Chelungpu Fault system. This illustrates that there is no  
673 unique process applicable to all faults around the world. Fortunately, other projects are  
674 in progress that will investigate other fault types: the San Andreas Fault Observatory at  
675 Depth (SAFOD) in Parkfield (California), the Wenchuan earthquake Fault Scientific  
676 Drilling (WFSD) through the Longmen Shan active fault zone (China), the NanTroSeize  
677 project through the Nankai accretionary prism and subduction zone and the Deep Fault  
678 Drilling Project (DFDP) through the Alpine Fault (New Zealand). With the help of these  
679 projects combined with surface studies, we can expect to obtain some answers to  
680 remaining questions.

681 Drilling projects, although not the only way to do so, have been performed to  
682 understand earthquakes as large-scale phenomena recorded by seismologists and have  
683 triggered many micro-scale studies that have led to a better knowledge of the Principal  
684 Slip Zone which controls the seismological behaviour of faults during earthquakes  
685 (Sibson 2003). Thus, questions at a macroscale have stimulated research at a microscale.  
686 Reciprocally, answers provided from micro-scale studies have explained some  
687 macroscopic behaviours of active faults. We may cite as an example the recognition of  
688 thermal pressurization in the Chi-Chi PSZ which explains the peculiar seismic behaviour  
689 of the northern segment of the Chelungpu Fault during the Chi-Chi earthquake.

690 Let us reconsider the objectives of drilling projects through active faults (Zoback *et al.*  
691 2007) designed "to directly study the physical and chemical processes that control  
692 deformation and earthquake generation within active fault zones". It is apparent that we  
693 still need information on the thermal signature and heat production of earthquakes, the  
694 pressure and composition of pore fluid, the healing processes and their kinetics, and the  
695 mechanisms of aseismic creep on faults. On-going and future drilling projects through  
696 active faults will certainly improve our knowledge, and provide supplementary  
697 information to address these questions by stimulating intense and fruitfull  
698 collaborations between geologists and seismologists.

699

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714

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1080

1080 **Table 1**

1081 Table 1 - Principal occurrences and features of the hydrothermal minerals in the GSJ  
1082 drill hole (modified from Boullier *et al.* 2004 a).

1083

1084 **Figure captions**

1085 Fig. 1 - (a) Geological map of the northern part of the Awaji Island and location of the  
1086 DPRI, Hirabayashi GSJ and NIED drill sites [after *Ohtani et al.* 2000 a]. (b) Cross-section  
1087 showing the vertical offset of the Nojima Fault and the orientation of the DRPI 500 and  
1088 DPRI 1800 boreholes at Ogura (after *Lin et al.* 2007). (c) Cross-section showing the  
1089 orientation of the GSJ and NIED boreholes at Hirabayashi (after *Tanaka et al.* 2007 a).

1090

1091 Fig. 2 - Photographs of polished drill core slabs from the Hirabayashi GSJ borehole. The  
1092 depths of the upper and lower limits of the samples are specified at the top of each  
1093 image (top of the core always to the left). The sample number (bottom) indicates the  
1094 number of the drill core box and the number of the sample within that box. The scale  
1095 marker is 2.5 cm long. (a) Undeformed and almost unaltered Ryoke granodiorite. (b)  
1096 Very fine-grained compacted ultracataclasite in the core of the fault. Note the reddish  
1097 colour related to siderite veinlets and the pale honey-coloured veins filled by  
1098 siderite+ankerite. (c) Very fine-grained compacted ultracataclasite (bottom left)  
1099 associated with layered pseudotachylytes in the core of the fault.

1100

1101 Fig.3 - Microphotographs of thin sections from the Hirabayashi GSJ borehole. (a)  
1102 Pseudotachylyte from the sample 99-05 (Fig. 2c, upper right corner). Note the flow  
1103 structures in the dark brown layer. Plane polarized light. (b) Transparent  
1104 pseudotachylyte fragment in the ultracataclasite from sample 99-05 (Fig. 2c, lower left  
1105 corner) which contains numerous CO<sub>2</sub>-rich fluid inclusions (FI). Plane polarized light. (c)  
1106 Scan of a thin section in sample 100-35 at 633.07m depth showing a clay-rich, low-angle  
1107 reverse shear zone deforming the fine-grained carbonate veins (short thick arrows). (d)  
1108 Detail of the shear zone in Fig. 3c showing the C/S arrangement of clays (presumably  
1109 illite). Crossed polars.

1110

1111 Fig.4 - (a) Sketch of the western Taiwanese foothills showing the principal thrust faults,

1112 the Chi-Chi earthquake epicenter and the location of TCDP drill site. (b) Schematic cross-  
1113 section passing through the TCDP drill site indicating the principal sedimentary  
1114 formations and the principal faults (after Hung *et al.* 2007). (c) Correlation between the  
1115 principal fault zones of the Chelungpu Fault system in Hole A and B (after Hirono *et al.*  
1116 2007).

1117

1118 Fig.5 - Sketch (a) and unrolled scanning image (b) of the fault zone of FZA1111 showing  
1119 the principal structural characteristics of the fault zone activated during the Chi-Chi  
1120 earthquake. PSZ: Principal Slip Zone (Sibson, 2003) where slip occurred during the Chi-  
1121 Chi earthquake (after Boullier *et al.* 2009).

1122

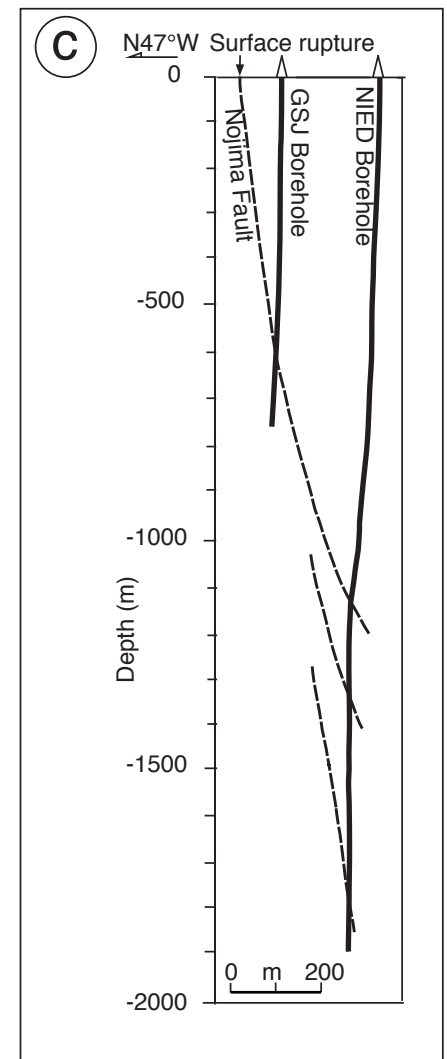
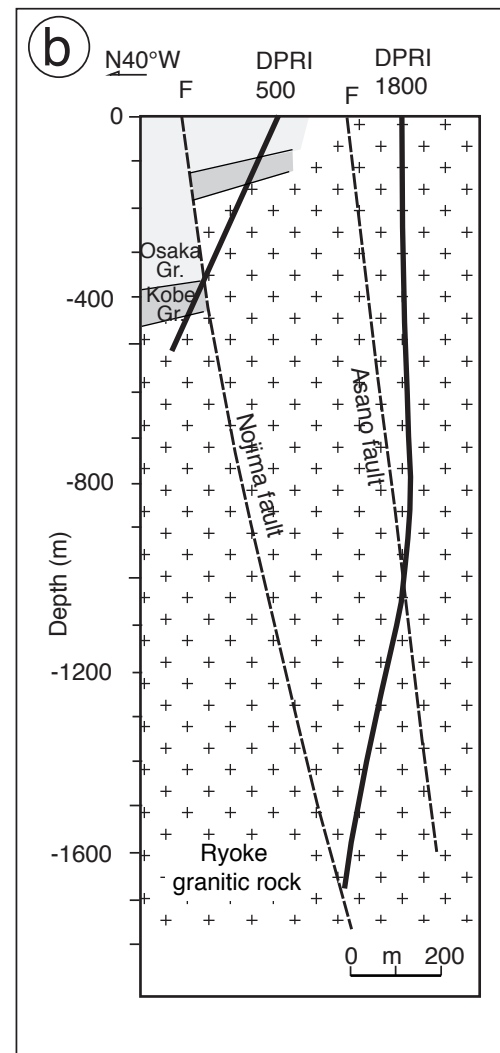
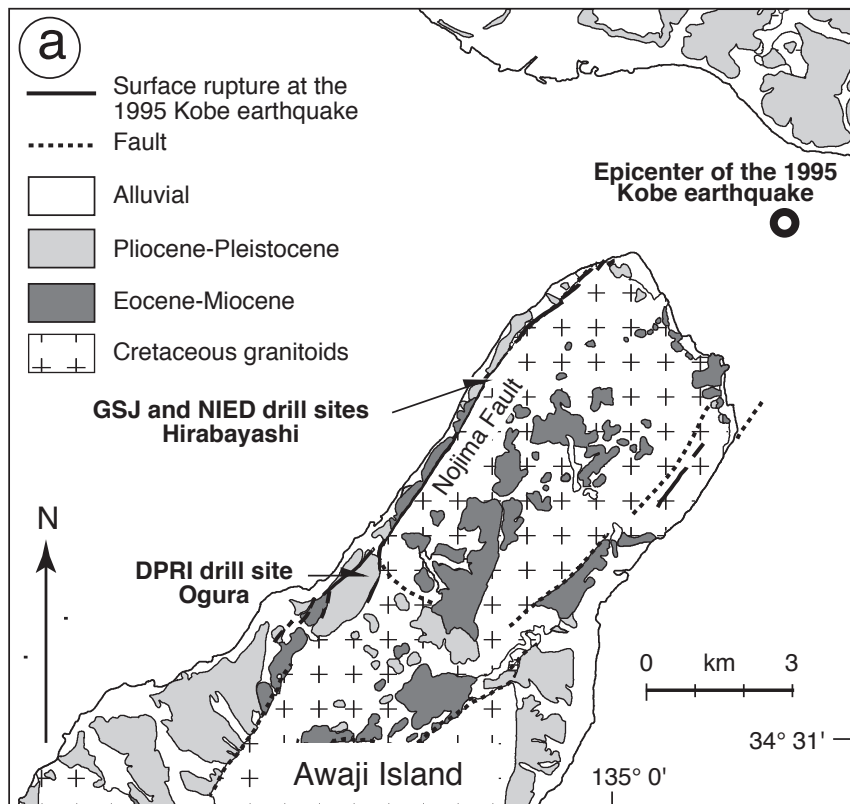
1123 Fig. 6 - Microstructures in the isotropic gouge within the PSZ shown in Fig. 5 (after  
1124 Boullier *et al.* 2009). All microphotographs are oriented as in Fig. 5. (a) General view of  
1125 the isotropic gouge showing the matrix-supported clasts which are either  
1126 monomineralic, such as fractured quartz fragment (Q), or fine-grained polymineralic  
1127 gouge fragments (G). Plane polarized light. (b) Clay-clast aggregate (CCA) with a round  
1128 quartz core and a brownish cortex made of clays. Plane polarized light.

1129

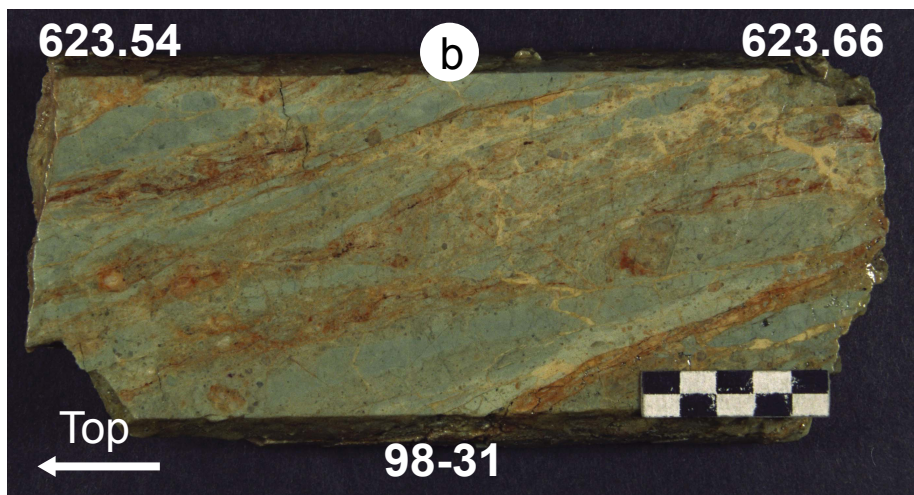
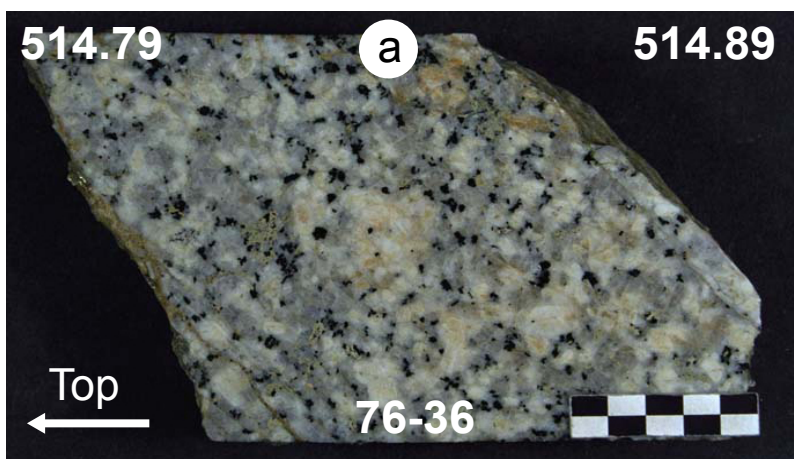
Table 1 - *Hydrothermal episodes in the Nojima Fault*

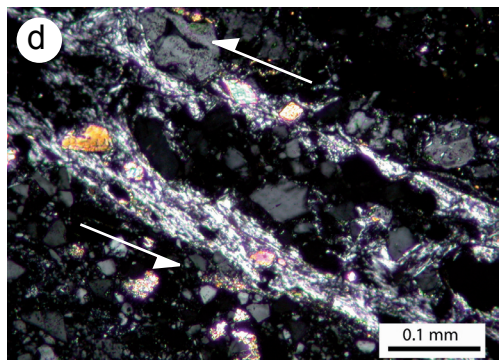
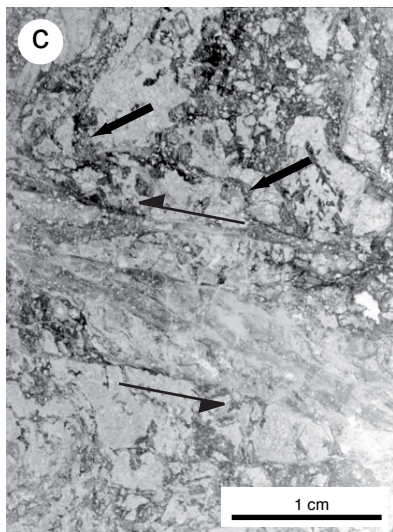
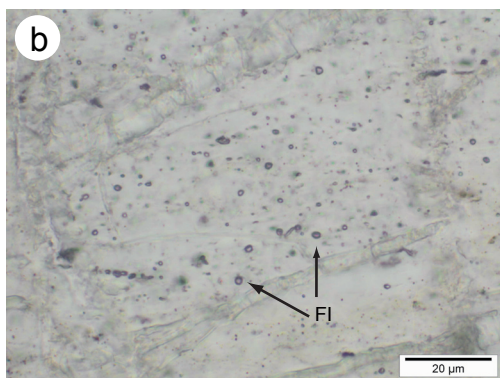
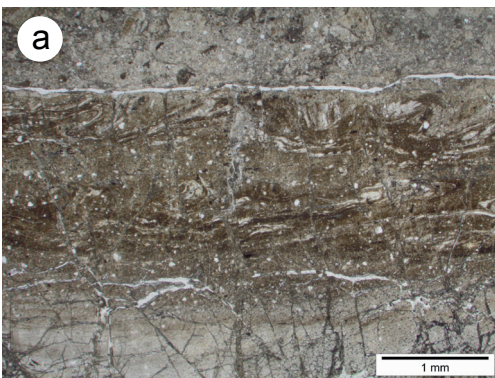
<b>Mineral</b>	<b>Chlorite</b>	<b>Zeolite: laumontite Minor calcite</b>	<b>Siderite</b>	<b>Ankerite and siderite</b>	<b>Clays</b>
Temperature	ca. 300°C	ca. 150-280°C		< 100°C	
Texture	As rosettes in small cavities (ripidolite) In cracks together with albite	In blocky coarse-grained veins In hydraulic fractures, with small fragments of cataclasites or minerals	In thin veinlets parallel to the flattening plane within the core of the fault zone	In hydraulic fractures including fragments of cataclasite and minerals, located above the slip zone	Alteration and replacement of minerals, in fractures, Very fine grained crystals
Replaced mineral	Biotite and amphibole	Plagioclase		Plagioclase, biotite and amphibole	Plagioclase, micas, laumontite
Mechanisms of formation	Hydrothermal processes during cooling of the granodiorite	In-situ replacement Vein filling Hydraulic fracture-fill	Taber growth	Hydraulic fracture-fill	In-situ replacement
Subsequent deformation		Cataclasis Dissolution-precipitation processes: stylolites and veins	Cataclasis	Dissolution-precipitation processes: stylolites and schistosity Cataclasis in thin fine-grained gouge zones	Cataclasis in thin fine-grained gouge and shear zones Orientated parallel to schistosity
Age	Prior to the Kobe Group deposition Between 90 and 74 Ma (*)	Contemporaneous with pseudotachylytes Prior to the Kobe Group deposition ca. 56 Ma (†)	Quiescence stage: between 56 and 1.2 Ma	Younger than ca. 1.2 Ma (‡)	Contemporaneous with or younger than carbonates (§)

(\*) After Takahashi (1992) and Murakami and Tagami (2002) - (†) After Murakami and Tagami (2004) - (‡) After Murata et al. (2001) - (§) After Lin et al. (2007).



Boullier Figure 1





Boullier Figure 3

