Microstructures and their implications for faulting processes
—Insights from DGLab core samples from the Gulf of Corinth

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A B S T R A C T

We have examined microstructures, mineralogical composition, geochemical alteration, and texture of four selected fault rock samples from the Deep Geodynamical Laboratory (DGLab) Gulf of Corinth project using optical microscopy, cathodoluminescence microscopy (CL), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and synchrotron X-ray diffraction measurements. The fault core is composed of red and gray clayey gouge material and surrounded by a damage zone of brecciated limestones. Pressure solution features, calcite veins and calcite clasts in the breccia and gouge material attest the presence of paleo-fluids and fluid-driven mass transfer during deformation. Differences in CL-colors between the matrix and calcite vein cement and inside the vein cement suggest repeated infiltration of fluids with different composition from various sources (formation water and meteoric water). Twin lamellae densities estimated in calcite veins are used as paleo-piezometer. The deduced differential stress is ~140 ± 70 MPa for the older vein generation and appears to be higher than stress for the youngest veins (45 ± 23 MPa). In spite of the relatively small clay content in both samples, newly formed clay minerals have been observed in gray as well as red clayey gouge material. Differences between gray and red clay gouge material are found in fault rock composition, porosity and clay fabric. The proportion of chlorite in the red gouge is significantly less than that in the gray gouge whereas the initial porosity is significantly higher than in the gray gouge material. The detection of a well-oriented clay fabric in red clay gouge samples is unique in comparison to other major fault zones.

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1. Introduction

The Gulf of Corinth, in western Greece, is one of the most seismically active regions in Europe and renowned for high extension rates with up to 1.5 cm/year (Moretti et al., 2003; Cornet, 2007; McNeill et al., 2007). This fast opening is associated with an active seismogenic low angle detachment zone localized at depths between 6 and 12 km dipping in northern direction (Bernard et al., 1997, 2006). Five earthquakes of magnitude larger than 5.8 have been observed in this region within the last forty years (Cornet et al., 1997). Among many possible drilling targets in the Gulf of Corinth, the active Aigion fault was selected as an ideal site to investigate in situ fault related deformation processes by drilling into the fault zone (Cornet, 2007) because this area is a place where one may expect a moderate to large earthquake (M > 6) to occur in the coming decades (Bernard et al., 2006).

The Deep Geodynamical Laboratory (DGLab) Gulf of Corinth project was part of a set of projects clustered under the generic name “Corinth Rift Laboratory” to test fundamental questions regarding earthquake and fault mechanics (Cornet et al., 2004). One of the primary objectives of the DGLab project was to understand the relationships between faults, fluid flow and strain in a seismic zone. In addition, fault-healing processes that might affect the fault were also part of the investigation (Moretti et al., 2002). The borehole (AG10) was drilled in July and August 2002 (Cornet et al., 2004). Previous investigations on core samples provided a macroscopic description of fault rocks (Daniel et al., 2004; Micarelli et al., 2006). In addition, fault gouge material was used for the experimental characterization of the thermo-poro-mechanical properties (Sulem et al., 2004, 2005).

Although the AG10 was already drilled in 2002, a microstructural analysis of fault core material has only recently been...
conducted. Core samples from the DGLab borehole provide a unique opportunity to analyze microstructures of fresh fault rocks representing the state of the fault before it ruptures. In this paper, we provide an overview of dominant microstructures at micro-to-nano scale (e.g. brittle fracturing, dissolution precipitation processes, twinning, intracrystalline plasticity, nano-porosity) in four selected samples from damage zone and fault gouge. The observations made using optical microscopy, scanning electron microscopy (SEM), high-resolution transmission electron microscopy (HRTEM) techniques with focused ion beam preparation and synchrotron X-ray diffraction measurements. Based on these investigations we discuss our results with regard to faulting processes and compare our findings with results from the Taiwan Chelungpu fault Drilling project (TCDP), the San Andreas Fault Observatory at Depth (SAFOD) and the Japan Trench Fast Drilling project (JFAST), which represent co-seismic weakening and creeping processes respectively, thereby facilitating a comparison of faults from different tectonic regimes.

2. Geological setting

The Gulf of Corinth is a 120 km long, 30 km wide asymmetric marine basin (Grabon) that lies within the Aegean extensional province (Fig. 1). The graben separates the Peloponnesus south of the Gulf from the rest of mainland Greece (Roberts and Stewart, 1994). The basin is characterized by active N–S directed extensional tectonics (10 mm/y) accommodated by WNW-ESW and ENE-WSW striking normal faults (e.g. Helike, Aigion; Roberts and Koukouvelas, 1996). The faults generally dip to the north with a slope angle of 37° (Koukouvelas and Doutsos, 1996). It was slightly reactivated during the magnitude 6.2 Aigion offshore earthquake that occurred in 1995 (Cornet et al., 2004). The current slip rate is about 2–5 mm/year and the vertical offset is about 150 m (Moretti et al., 2003). The upper portion of the Aigion fault transects a sequence of Cretaceous carbonate rocks and Plio–quaternary clastic sediments (Rettenmaier et al., 2004). Below the fault, brecciated limestones constitute the damaged zone. The stratigraphic sequence is shown in Figs. 1 and 2.

The DGLab-project is centered on the south shore of the Corinth rift near the city of Aigion (Fig. 1). Four wells, 500–1200 m deep, intersecting the active Aigion-fault have been proposed, but only the 1000 m deep well was realized. The cored section between 710 and 791 m is a sequence of Cretaceous carbonate rocks (Olonos-Pindos platy limestone formation) intercalated with several cataclastic bands, marls and thin shaly layers (Daniel et al., 2004). Pressure solution features and pressure shadows in calcite crystals of the cataclastic bands are interpreted as indicators for dip-slip displacement.

Fig. 1. Simplified S–N geological cross section through the Helike and Aigion fault modified after Doutsos, & Poulimenos, 1992 and Giurgea et al., 2004. The insert shows the geographical position of the survey site.
At 760 m the Aigion fault was crossed by the borehole. The dip of the fault contact (55°/60° N) between the hanging wall (limestone) and the footwall (radiolarite) is coherent with the dip of the Aigion fault plane on the surface (Rettenmaier et al., 2004). The fault offset constitutes a hydraulic barrier that sustained a 0.5 MPa differential fluid pressure (Cornet et al., 2004).

The fault core is about 1 m thick and is composed of clay-rich material surrounded by a damage zone of brecciated limestones that are affected by pressure solution processes (Sulem et al., 2004). The thickness of the damage zone is 3 m above the fault and 9 m below (Daniel et al., 2004). The clayey core is divided by a shear plane into two distinct parts recognizable by the gray color of the upper part, hereafter referred to as “gray clayey gouge” and the red brown color of the lower one, hereafter referred to as “red clayey gouge” (Fig. 2, Sulem et al., 2005). The origin of clay is a matter of controversy. Daniel et al. (2004) assumed that the clay is derived from radiolarites, whereas Koukouvelas and Papoulis (2009) suggested the underlying Pindos Unit flysch as the probable source of clay minerals.

3. Methods

First, microstructures in the core samples were inspected optically in thin sections. If possible, we quantified density of calcite twins within the calcite grains to arrive at an estimate of the paleostresses governing deformation after vein formation. The density of twins was measured using an optical microscope (Leica DM RX) with an attached high-resolution digital camera (Leica DFC 420). Measurements were performed on polished thin sections. To determine the twin density, the number of twins perpendicular to the twin boundaries of individual grains was counted and normalized to a unit length of 1 mm (compare Rowe and Rutter, 1990). For grains containing multiple twin sets we applied this procedure on each orientation and calculated the average density. We restricted the measurement of twin densities to twins visible by optical microscopy (≥1 µm). In order to estimate the peak differential stress we use the twin density piezometer proposed by Rybacki et al. (2013):

$$\sigma = (19.5 \pm 9.8) \sqrt{N_L \cdot N_t} \quad \text{twin density} \quad (N_t = \# \text{twins/mm}) \quad (1)$$

Cathodoluminescence (CL) microscopy was used to identify different cement zonations. Variations in the cathodoluminescent properties of carbonates are usually attributed to a different trace element composition of the original fluids from which the calcite precipitated.

A Zeiss FESEM Ultra 55 Plus (Schottky-type field emission scanning electron microscope) complemented with an energy-dispersive system by Thermo Fisher Scientific (UltraDry silicon-drift detector) and a FEI Tecnai G2 F20 X-Twin transmission electron microscope (TEM/AEM) equipped with a Gatan Tridiem energy filter, a Fischione high-angle annular dark field detector (HAADF), and an energy dispersive X-ray analyzer (EDS) were used to analyze microstructures at micro- and nano-scale and to determine chemical composition. To avoid preparation-induced damage, the samples for TEM studies were prepared with a focused ion beam.

### Table 1a
Mineral composition of gray fault clayey gouge (sample 99).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz (wt.%)</th>
<th>Chlorite (wt.%)</th>
<th>Calcite (wt.%)</th>
<th>Albite (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay particles &lt;80 µm</td>
<td>49</td>
<td>47.4</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>Clay matrix &lt;400 µm</td>
<td>56</td>
<td>34</td>
<td>6.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Fragments and gravels</td>
<td>61</td>
<td>24</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 1b
Mineral composition of red fault clayey gouge (samples 100 and 101).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz (wt.%)</th>
<th>Chlorite (wt.%)</th>
<th>Illite (wt.%)</th>
<th>Albite (wt.%)</th>
<th>Hematite (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay particles &lt;80 µm</td>
<td>74</td>
<td>3</td>
<td>10</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Clay matrix &lt;400 µm</td>
<td>66</td>
<td>2</td>
<td>15</td>
<td>13</td>
<td>3.5</td>
</tr>
<tr>
<td>Fragments and gravels</td>
<td>73</td>
<td>2</td>
<td>9</td>
<td>8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
(FIB) device (FEI FIB200TEM) at GeoForschungsZentrum (GFZ; for more details see Wirth, 2004, 2009).

To determine the crystallographic orientation of clay minerals, synchrotron X-ray diffraction measurements were conducted at the high-energy beam line ID-11C of the Advanced Photon Source (APS) at Argonne National Laboratory. A monochromatic X-ray beam with a wavelength of 0.10803 Å and 0.7 × 0.7 mm in size was used. Diffraction images were recorded with a Perkin Elmer amorphous...
silicon large area detector with $2048 \times 2048$ pixels and mounted about 2110 mm from the sample. Cylindrical samples, 2 mm in diameter, were mounted on a goniometer with the axis perpendicular to the incoming X-ray. During the 30 s exposure the sample was translated 1–2 mm parallel to the cylinder axis to provide a better volume average. The sample was rotated in increments of 15° from $-90^\circ$ to $+90^\circ$ producing 12 images to derive the preferred orientation pattern. For calibration purposes an image of a CeO$_2$ standard was recorded at identical conditions. Details of sample preparation and diffraction measurements are described in Wenk et al. (2014). The images were then analyzed with the Rietveld method to quantify orientation distributions and phase volume fractions. The program MAUD (Materials Analysis Using Diffraction) was used because it provides the best options for texture analysis (Lutterotti et al., 1997). For texture analysis the EWIMV method was employed. Step-by-step tutorials have been developed for synchrotron images (Lutterotti et al., 2014; Wenk et al., 2014).

The crystallographic orientation of calcite occurring in veins was determined in a colloidal-silica polished thin-section by electron backscatter diffraction (EBSD, compare Adams et al., 1993). We have used the FEI Quanta 3D FEG SEM/FIB equipped with an EDAX–TSL Digiview IV EBSD detector and TSL–OIM system (v. 5.31) also operated at GFZ. The operating parameters include an accelerating voltage of 20 kV, beam current of 8 nA, working distance of 12 mm and a step size of 10 μm. Post-indexation filtering included the grain confidence index (CI) standardization using a grain tolerance angle of 5° and the neighbor CI correlation, assuming a CI of 0.1. Only data with confidence index $>0.2$ was considered in further calculations. Orientation distribution functions and pole figures were calculated with the harmonic method, expanding the series to 24 and Gaussian half-width of 8°.

4. Results

4.1. Sample composition and macroscopic description

Four fault rock samples obtained from the fault gouge and the adjacent limestone breccia (Fig. 2) of DGLab cores were used to analyze the microstructural record (referred to as 98, 99, 100 and 101). The mineralogical composition of the selected fault gouge samples estimated by XRD analyses has already been reported by Sulem et al. (2004, 2005) and is summarized in Table 1 (the mineral composition is normalized to 100%).

Sample 98 was taken from a strongly brecciated band at 759,70 m (Fig. 2), which belongs to the Olonos-Pindos platy limestone sequence. The inspected pure limestone shows no macroscopic fossils. The fault breccia sample is completely healed by calcite cement and several veins of different thickness with crosscutting relations can be distinguished (Fig. 3a, see below). The matrix is composed of a fine-grained micritic carbonate mixed with greenish-gray angular to subrounded carbonate fragments. The fragments show little if any evidence of frictional attrition. The size of fragments ranges from a few millimeters to several centimeters. The transition between brecciated limestone and the gray clayey fault-gouge zone is sharp and distinct.

Sample 99 was collected from the gray clayey gouge zone at 760 m. The dark gray sample with many fragments of different size and thin veins contains 55% quartz and 35% chloride and amorphous material (not included in Table 1a; Figs. 2 and 3b). In addition, calcite (7%) and albite (2%) are further mineral constituents of the sample (Table 1a). Minor chrysotile was recognized only by High–Resolution Electron Microscopy (HREM) imaging and TEM-EDS analyses. Polished slip surfaces with striation on the slip plane are macroscopically discernable.

Sample 100 and 101 were taken from the red clayey gouge (Figs. 2 and 3c; Table 1b). The contact between gray and red gouge is marked by a shear plane. Both red samples are characterized by a high amount of quartz (71%) due to the presence of silicified biological fragments (radiolarians; Fig. 3f,g). Further mineral constituents of the red gouge samples are illite (11%), albite (10%), and hematite (3%) responsible for the red coloration. The proportion of chloride (2.3%) is significantly smaller compared to the gray clayey gouge. SEM analyses allowed the detection of chamosite (Fig. 4). Calcite was not detected by XRD analyses but was visible under the cathodoluminescence microscope. Minor amount of chrysotile and newly formed apatite were detected by TEM-EDS analyses.

4.2. Microstructural analysis

In contrast to the mesostructural deformation patterns, microstructures reveal considerable differences in deformation intensity between fault gouge samples and brecciated limestone sample. Microscopic observations have been predominantly performed on the brecciated limestone sample because calcite grains have the required size to characterize the different types of cement and to observe microstructures. The gray and red clayey gouge samples are usually too fine-grained and SEM and TEM were mainly used for the microstructural characterization of clayey gouge samples.

![Fig. 4. Element distribution from scanning electron microscopy (SEM) at grain scale. The localized concentration of Fe (green color) and the more distributed concentration of Mg (red color) indicate the presence of chamosite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
4.2.1. Limestone breccia

At microscopic scale, the brecciated limestone sample 98 contains a micritic matrix, veins, pores filled with sparry cement (Fig. 3a,d) and non-carbonated detrital grains (mostly quartz). CL microscopic observations show conformities and differences in CL colors between vein cement and host rock and also inside the vein cement (Fig. 5a–b, right columns). Variations in the CL-colors of calcite cements are attributed to the initial trace element composition in the fluid and/or to changes in redox conditions at the site of precipitation (Meyers, 1974). For example, the outside edge of the

**Fig. 5.** Photomicrographs of main microstructural features observed in thin sections under parallel polarizers (left), crossed polarizers (middle) and Cathodoluminescence (CL) images of the same region. Note the difference in CL-colors between the gray and red clayey gouge. (a) Micritic matrix (M) with three vein generations (CV1-CV3). (b) Micritic matrix with bright rim and the youngest vein generation (CV3). (c) Densely packed matrix with calcite fragments. (d) Matrix with quartz grains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
matrix calcite crystals has a brighter CL color (Fig. 5b; right column), indicating more luminescence activators (Mn) in the rim. At least three vein generations are distinguishable (Fig. 5a–b). The older generation (CV1) is made of dull calcite cement with equal coarse grain sizes (Fig. 3a). It luminesces in the same dark orange color as the fine-grained micritic matrix (Fig. 5a, right column). The CV1 generation is cross cut by veins (CV2) with red/orange CL colors, slightly darker than the host rock color (Fig. 5a, right column). The youngest veins (CV3) are filled with euhedral blocky calcite and calcite with columnar habit at the margin of the vein (Figs. 3d and 5b, right column). Columnar calcites show growth zones with different CL-colors. The central zone luminesces brightly orange whereas the luminescence color of the outer zone is dull orange (Fig. 5b; right column).

Calcite grains of the older vein generation (CV1) are intensely twinned implying that they suffered a strong (fault-related?) deformation. The twinned crystals display one or two sets of straight or bent twins. The twin densities measured in the sample vary between 10 and 94 twins/mm with a mean density of 54 twins/mm. Using twin density piezometry, the peak differential stress is about 140 ± 70 MPa (Fig. 6). The high uncertainty may result from local stress heterogeneity or from different deformation events recorded in the microstructure (for the methodological constraints compare Rybacki et al., 2011, 2013). Twin densities measured in CV2 calcite grains vary between 9 and 79 twins/mm with a mean density of 35 twins/mm and the peak differential stress is about 115 ± 60 MPa (Fig. 6). Vein filling of the youngest generation (CV3; fibrous and blocky calcite) is less twinned or not twinned, suggesting that these calcite crystals underwent a weaker deformation than the older calcite cement generations. The mean twin density is 5 twins/mm and the peak differential stress is about 45 ± 23 MPa (Fig. 6). Compared to the in-situ state of stress data, the estimated peak differential stress values for CV1 and CV2 are unusually high (see discussion).

Pressure solution seams in the matrix and dissolved calcite grain boundaries suggest considerable activity of dissolution-precipitation processes (inset in Fig. 7a). In SEM images pores represent unconnected voids in 2D, mainly located between calcite grains and around larger quartz grains or grain fragments (Fig. 7a). The grains are commonly sub-angular and do not display a preferred alignment.

We also have measured the crystallographic orientation of calcite occurring in veins cross-cutting the main foliation in our samples (Fig. 8a). The predominantly coarse-grained (CV1) vein (bottom SW and top NE), with grain sizes varying between 0.4 mm—4 mm, contains crystals with well-developed subgrain boundaries (Fig. 8a). This vein is then crosscut irregularly by a second vein generation (CV3), with grains varying from 70 to 300 μm (central part of the orientation map, Fig. 8a). The smaller crystals in this portion of the map also present subgrain boundaries, as indicated by the low angle grain boundaries drawn on the map (Fig. 8a). The calcite crystallographic preferred orientation (CPO) in the coarse-grained vein (CV1) is weak and is characterized by three maxima of [0001] distributed symmetrically along a great circle, with the <2-1-10> maxima parallel to the center of the net and two secondary (weaker) maxima (Fig. 8b). Although the multiples of random distribution indicates the presence of a weak CPO in this sample, the maxima of 3.5 likely result from the insufficient number of grains on the scanned area for this calcite vein and the crystallographic orientation is probably close to random. The [0001] axes of calcite of fine-grained veins (CV3) is characterized by a incomplete, broad single girdle along NW—SW in the pole figure (Fig. 8c), while the <2-1-10> are distributed along broad, great circle girdles, normal to one of the [0001] maxima.

4.2.2. Gray clay gouge

The strongly fractured gray clayey gouge sample 99 is composed of angular to subrounded large quartz (cryptocrystalline chert/radiolarite) and calcite fragments embedded in a dark-brown, fine-grained clayey gouge matrix (grain size <1 μm; Fig. 3b and 3e, Fig. 5c, 7b). Some fragments and matrix patches have a preferred aligned orientation exhibiting a weak fabric (Fig. 3b). TEM images of this sample reveal a densely packed fabric composed of clay particles and quartz patches (Fig. 9a), which consist of small recrystallized quartz grains (Fig. 9c). Few patches are wrapped by thin sheet silicates (Fig. 9c), resembling clay-clast aggregates (CCAs; Boudreaud et al., 2008). At some places, dislocation cores ending at the surface of the quartz grains are dissolved and newly formed clay minerals are growing into the open spaces (Fig. 9e). The few calcite grains are characterized by highly sutured grain boundaries indicating pressure solution (Fig. 7b). They are intensely twinned with a similar twin density (49 twins/mm) as in the older vein generation of sample 98. Accordingly, twinning paleo-piezometry yields a peak differential stress magnitude of 137 ± 68 MPa, comparable with calcite grains of the older vein cement (CV1) in sample 98 (Fig. 6). However, the calcite grains contain no or only few dislocations, whereas the twin lamella contain dislocation clusters (Fig. 9f). Under CL, the calcite fragments luminesces yellow-orange and the outer growth rim has a dark-orange color (Fig. 5c), suggesting the precipitation from formation water under burial conditions (Meyers, 1978). The gray gouge sample is too heterogeneous to analyze the crystallographic preferred orientation of clay minerals.
4.2.3. Red clay gouge

Similar to sample 99, samples 100 and 101 consist of angular to subrounded fragments and a red-brown, fine-grained clayey gouge matrix (Fig. 3c,f and g; 5d; 7c). Microscopically, some patches of the gouge matrix show a weak foliation defined by preferred orientation of phyllosilicates (Fig. 3c). Besides chert and matrix fragments (Fig. 7c), a high amount of round radiolarian chert is visible in thin sections and SEM images (Figs. 3g and 7d). CL microphotographs show orange luminescent calcite particles, even though XRD analyses revealed no calcite. Quartz grains in chert fragments luminesce blue (Fig. 5d), indicating a hydrothermal origin (Götze et al., 2001). In contrast to sample 99, the clay matrix of the red gouge is characterized by stacked clay flakes arranged in a card-house fabric with open pore spaces between the flakes (Fig. 9b and d). The initial porosity of the material is about 19.7% and therefore significantly higher than in the gray clayey gouge sample (Cornet et al., 2003). The stacked phyllosilicates domains are locally aligned parallel to each other. They are not or only slightly bent suggesting that they were newly formed (Figs. 7f and 9d). At other places, SEM observations reveal a fabric with bent and folded clay flakes resembling poorly developed S-C fabrics (Fig. 7e). Quantitative crystallographic preferred orientation analyses were performed on two samples of the red gouge of two adjacent regions. Phase fractions from Rietveld analysis are similar to XRD analysis with dominating quartz (49–65 wt%), illite-mica (15–48 wt%), and chlorite (3–19 wt%). Pole figures are displayed for illite-mica and chlorite (Fig. 10). The
orientation patterns for both phyllosilicate minerals are very similar. All pole figures show relatively strong fabrics (with maxima up to 3.7 m.r.d.), but especially in sample 100 with considerable local heterogeneity (spot 1 versus spot 2). In sample 101 the selected areas were more homogeneous. The preferred orientation of both minerals in the selected areas is significant.

5. Discussion and conclusion

The microstructural and mineralogical evidence presented above reveal different deformation mechanisms and preferred orientation patterns in the three analyzed fault components (limestone breccia with veins/damage zone; gray gouge/fault core; red gouge fault core). Published data from neighboring faults and international drilling projects are used to draw general conclusions for faulting processes.

5.1. Limestone breccia

In the limestone breccia above the fault contact, dissolution-precipitation processes act as dominating deformation mechanism as is demonstrated by pressure solution seams, dissolution along grain boundaries and healed (cemented) fractures. Taking into account the small number of grains, we still observed a weak preferred orientation of calcite in the coarse-grained veins. Previous texture analyses of calcite fabric patterns in SAFOD samples reveal that aseismic creep promotes the development of a weak to moderate calcite fabric (Janssen et al., 2014). In contrast, Verberne et al., 2013 described nanocrystalline slip zones in calcite fault gouge that are characterized by grain size reduction and an intense crystallographic preferred orientation.

In SEM images, many pores between the vein calcite grains appear to be unconnected in 2D. They were possibly filled with fluids but we found no evidence to suggest that elevated fluid pressure existed. Such a possible high pore fluid pressure could reduce fault strength very effectively (Hubbert and Rubey, 1959).

Similar CL-colors in matrix and calcite veins and differences in CL-colors inside the vein cement suggest repeated infiltration of fluids with similar and/or different composition from various sources. For instance, the correspondence in CL-color between host rock and CV1 vein suggests that the vein calcite was locally derived from the matrix (Gotze, 2000). The dull-to-bright luminescent color of columnar calcites of CV2 indicates that this cement did not precipitate from near-surface meteoric water under oxidizing conditions (Verhaerst et al., 2004a,b). Therefore, it is more likely that the younger veins precipitated under reducing conditions typical for a deep-burial environment (Boggs and Krinsly, 2010). Labaume et al. (2004) documented similar variations in vein calcites (and related fluid sources) of the neighboring Pirgaki fault. However, they suggest that the younger vein calcite is related to circulation of external (meteoric) water during both seismic and interseismic periods, suggesting a hydraulic connection to the surface and hydrostatic fluid pressure. In contrast, first generation vein calcite precipitated from fluids with a formation water composition (Labame et al., 2004). Bussolotto et al. (2015) suggest that all calcite cements in fault rocks from Corinth rift normal faults precipitated from meteoric fluids in a close or open circulation system depending on depth. Also, stable isotope and thermometry data indicate a development from a closed system with fluid—rock equilibrium during brecciation to a more open one with influx of meteoric water (Benedicto et al., 2008). Helium isotopic ratios of fossil fluids trapped in both calcite generations indicate an absence of a mantle-He signal in the Corinth rift fluids suggesting that the fault system is rooted in the upper crust (Pik and Marty, 2009).

In summary, fluid-assisted weakening mechanisms and fluid-assisted healing processes (cementation) are the dominant microstructures in the limestone breccia. Especially mass transfer by pressure solution is widespread and favor aseismic creep. Such fluid-assisted weakening mechanisms are common in many fault zones (e.g. Hadizadeh et al., 2012; Richard et al., 2013; Janssen et al., 2014). Bussolotto et al. (2015) suggest that the brecciation process was probably responsible for a mechanical weakening of the fault zone and favored further faulting deformation.

The unusual high stress values measured in the older veins (140 MPa; CV1 and CV2) may indicate episodes of high local stress on the grain scale that could be attributed to former seismic events. These stress values are similar to those estimated in SAFOD samples (92—251 MPa; Rybacki et al., 211).

The authors suggest that twinning represents the maximum local (grain-) scale paleo-stresses possibly produced by localized high transient stress during seismic events. The orientation of the principal stresses is locally almost parallel and perpendicular to the fault axis (Sulem 2007). The considerable number of united grains in the youngest calcite veins (VC3) suggests that healing processes outlasted the period of brittle faulting.
5.2. Clay gouge

Fault rock composition of the selected gray and red gouge samples reveal some similarities with the mineralogy of fault rock samples from the neighboring Helike Fault, which is also characterized by the presence of quartz, plagioclase, illite, calcite and Fe-oxides (Koukouvelas and Papoulis, 2009). However, unlike DGLab samples, no chlorite was detected. Koukouvelas and Papoulis (2009) suggest for the Helike as well as Aigion and Pirgaki faults a weak hydrothermal alteration by meteoric water at shallow levels. Calcite (vein) fragments embedded in a dark-brown, fine-grained clayey gouge matrix indicate that the gouge matrix formed at least in part after the vein formation (compare Labaume et al., 2004).

In comparison to fault gouge samples from other drilling projects (SAFOD, TCDP, JFAST), a significant difference is a relatively low clay content in general and a complete absence of smectite in particular. For instance, SAFOD gouge material from the creeping...
section contains ~70% saponite/smectite (Moore and Rymer, 2012; Janssen et al., 2014). Smectite is abundant (up to ~80%) in the principal slip zone (PSZ) of the Chelungpu fault that ruptured during the 1999-Chi-chi earthquake (Kuo et al., 2009) and in samples from the plate-boundary decollement zone between the Pacific and North American plate (JFAST; Janssen et al., 2015; Kameda et al., 2014). Similar to SAFOD, TCDP and JFAST fault gouge samples, in DGLab samples, too, clay minerals are in part newly formed, likely during inter- and post-seismic phases of the earthquake cycle.

Based on the assumption that the clay mineral content contributes significantly to fault weakening (Solum et al., 2004; Di Toro et al., 2011) the question arises to what extent the relative low clay content in DGLab fault gouge samples may have influenced the mechanical behavior of the Aigion fault. Friction experiments from Collettini et al. (2009) and De Paola et al. (2014) demonstrate that fault weakness can occur in cases where weak mineral phases (phyllosilicates) constitute only a small percentage of the total fault rock assemblage. Deformation experiments on DGLab samples show that the small clay fraction has a significant influence on the thermal-mechanical properties of the fault material in terms of fluid pressurization inside the Aigion fault (Sulem et al., 2004, 2005). Permeability estimates for fault gouge samples vary with stress and ranges from \(10^{-18}\) to \(10^{-10}\) m\(^2\) (Cornet et al., 2004). Taking into account the strong clay fabric, we suggest that the small amount of clay minerals was sufficient enough to reduce the fluid permeability.

CCAs are regarded as possible indicators of large slip at coseismic velocity with thermal pressurization (Boutareaud et al., 2008). They are described for many clay-bearing fault gouges including TCDP and SAFOD samples (Boullier et al., 2009; Janssen et al., 2014). However, their presence in SAFOD samples within and outside of the deforming zones rule out that CCAs were exclusively formed during seismic slip (Janssen et al., 2014); the authors suggest that the observed CCAs are rather formed by rotation of clast (rolling process) over a wide range of slip rates as

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**Fig. 10.** (001) and (100) pole figures for illite/mica and chlorite of red clayey gouge samples 100 and 101 determined on 2 spots. Equal area projection, contours in multiples of a random distribution (m.r.d.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
suggested by Han and Hirose (2012).

The detection of a preferred clay fabric orientation of red clay gouge samples by synchrotron X-ray diffraction measurements is different compared to other major fault zones. Recent analyses of gouge samples conducted on several other fault zones (e.g. Alpine Fault, Warr and Cox 2001; Moab Fault, Solum et al., 2005; Carbonera Fault, Solum and van der Pluijm 2009; Bogd fault, Buitar et al., 2012; San Andreas Fault, Wenk et al., 2010; Janssen et al., 2014, 2014; Chelungpu fault) showed only very weak preferred orientation of sheet silicates, regardless of their origin. It is supposed that the lack of a strong fabric in clay-rich samples may be attributed to newly formed phyllosilicates, that grew in many orientations, and to fault-related kinking and rotation of clay particles (Janssen et al., 2014). For the red clay gouge samples, we assume that patches of oriented clay particles may be tectionally emplaced into the Aigion fault.

Interestingly Sulem et al. (2005) found a high amount of amorphous material detected by XRD analyses (20% for the red gouge and 40% for the grey gouge; not included in Table 1). However, TEM and SEM images show no melt textures such as vesicles ever, TEM and SEM images show no melt textures such as vesicles amorphous material detected by XRD analyses (20% for the red.

Janssen et al., 2010).


