Journal of Structural Geology 86 (2016) 62–74

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

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

C. Janssen [a,*], H.-R. Wenk [b], R. Wirth [a], L. Morales [a], H. Kemnitz [a], J. Sulem [c], G. Dresen [a]

[a] GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam, 14473, Germany
[b] Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA
[c] CERMES — Laboratoire Navier Ecole des Ponts Paros Teche, 6-8 Av. Blaise Pascal, Cite Descartes Champs sur Marne, 77455, Marne la Vallee Cedex 2, France

A R T I C L E I N F O

*Article history:*
Received 7 August 2015
Received in revised form
9 March 2016
Accepted 15 March 2016
Available online 16 March 2016

*Keywords:*
Microstructure analysis
Fluid-rock interaction
Fault rock composition
EBSD
Clay fabric
Dissolution-precipitation
Gulf of Corinth

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.



## 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

* Corresponding author.
*E-mail address:* jans@gfz-potsdam.de (C. Janssen).

http://dx.doi.org/10.1016/j.jsg.2016.03.008

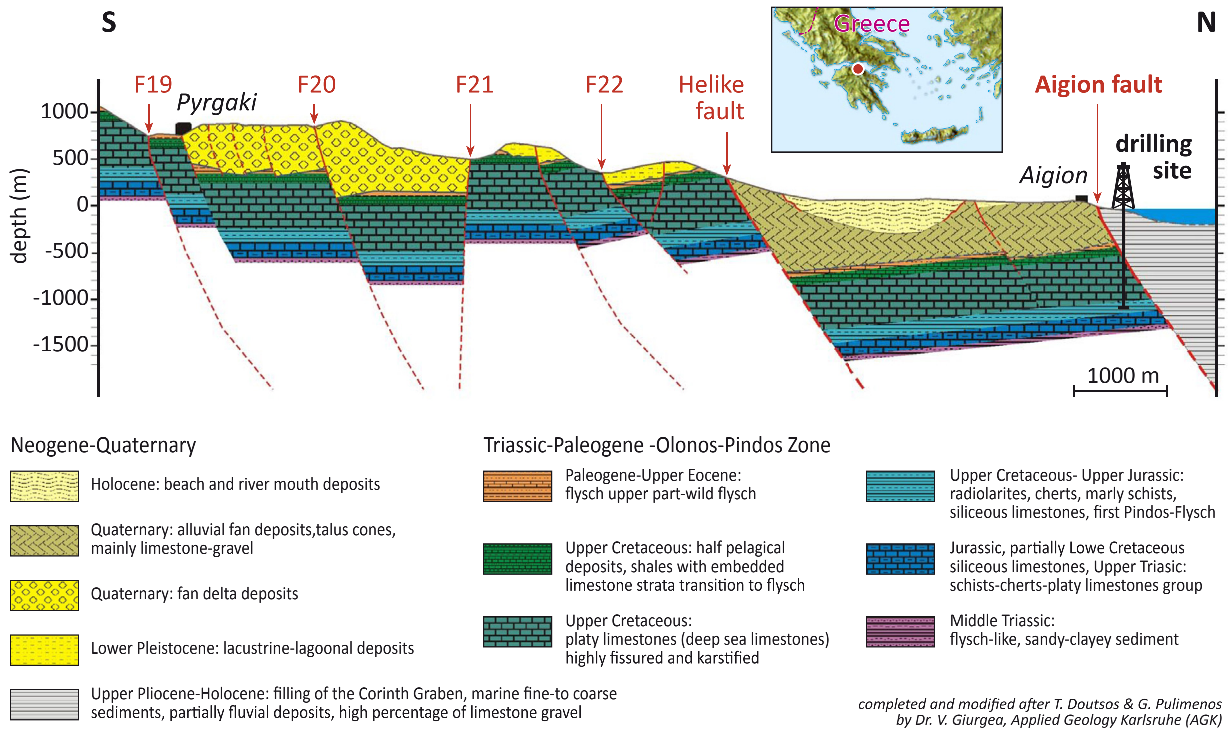


**Fig. 1.** Simplified S–N geological cross section through the Helike and Aigion fault modified after Doutsos, & Poulimenos, 1992 and Giurgea et al., 2004. The insert shows the geographical position of the survey site.

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 (graben) 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-ESE and ENE-WSW striking normal faults (e.g. Helike, Aigion; Roberts and Koukouvelas 1996). The faults generally dip to the north with maximum cumulative fault throws of around 3 km (Roberts, 1996). They have produced destructive earthquakes in the past centuries (Chery, 2001). Earthquake clusters and their related fault plane solutions, located between 6 and 11 km depth, suggest the existence of a detachment zone beneath the Gulf of Corinth. All the large active normal faults appear to connect downwards with the proposed northward dipping detachment fault at around 10 km (Rigo et al., 1996). The Gulf of Corinth therefore presents a remarkable example of an association between high-angle and low-angle faulting during the same tectonic phase (Chery, 2001). Most of the normal fault zones are developed within Mesozoic carbonates although a small number of faults affect Mesozoic ophiolites and siliciclastic rocks. Existing fault slip data indicate that the orientation of the inferred stress field varies along faults and earthquake ruptures (Roberts and Ganas, 2000).

The Aigion normal fault is one of the youngest normal faults in the Gulf of Corinth (McNeill, 2007) and belongs to a system of WNW-ESE and ENE-WSW striking active faults that are related to the opening phase of the Gulf of Corinth, which started during Pliocene (Micarelli et al., 2003). At the surface, the 12 km long fault forms a fault escarpment from about 40 to 100 m with an average 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