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STRUCTURAL CHARACTERISTICS OF QUATERNARY FAULT ZONES IN THE SOUTH-WESTERN GULF OF CORINTH (GREECE)

CONTENTS

ABSTRACT

We tested structural quantitative analysis as a tool for evaluating the size of the fault zone components and the degree of fracture connectivity on two Quaternary fault zones in the south-western sector of the Gulf of Corinth: the Pirgaki and the Helike faults. Moreover, microstructural analysis has been used to define the characteristics of fault rocks. One-dimensional analysis across fault zones shows that the total fault zone width does not depend on the affected lithology, whereas the size of fault core is strongly related to lithology and seems to be not related to fault throw. In the Pirgaki fault plane it is possible to recognize foliated cataclasites that record at least two intense cataclastic phases, while the fault rocks constituting the Helike fault plane are related to one tectonic phase. Latest microstructures are sub-vertical extensional fractures that are progressively sealed by clear calcite and display degrees of connectivity increasing towards the fault core. This system of highly connected fractures may play a major role in varying permeability properties of damage zones.

KEY WORDS: Gulf of Corinth, fracture connectivity, cataclasite microstructures, damage zone

1. INTRODUCTION

In order to describe deformation-related features developed in limestones on fault zones in the south-western part of the Gulf of Corinth (a Quaternary rift undergoing a fast north-south extension; for regional setting see MORETTI *et alii* 2003a), we carried out microstructural studies and tested the applicability of quantitative analysis on the Helike and Pirgaki faults.

The two faults are located approximately 5 and 10 km respectively south from the southern shoreline of the Gulf (Fig. 1a). The Helike fault displays an average N100° strike direction, dips of about 55°-65° to the north and a N025/50° oriented slip vector. The length of the outcropping fault zone is about 25 km, but its total length is probably up to 35 km. The fault affects both Cretaceous limestones and Quaternary conglomerates and the maximum offset is 700-800m (MICARELLI *et alii* 2003). The Pirgaki fault displays an average N095-100 strike direction. The total length of the outcropping fault zone is at least 30 km and the maximum offset is 800-1000 m. In general, the fault zone marks the contact between the calcareous series of the Pindos tectonic unit, and Quaternary marine/lacustrine marls and conglomerates, but major planes marking contacts limestone-limestone are also present.

In this paper, we compare fracture patterns and connectivity at different distances from fault zones. Then, we characterize microstructures that play a major role in fault permeability structure for the purpose of evaluating to what extend the lithology is important for localization of strain. Finally, we evaluate the sizes of the different fault zone components.

2. METHODOLOGY

Quantitative data on fabrics of the Helike and Pirgaki fault zones and surrounding areas were collected by means of geological cross-sections (one-dimensional techniques) and maps (two-dimensional techniques).

One-dimensional sampling (scan line analysis) collects data of a fracture network outcropping along a line normal to the fault strike. Distances from the origin, orientation data and morphologic and geologic characteristics of each discontinuity are measured. The spacing measurement ranged from 1 mm to 100 cm and the discontinuities were recovered from the established distance from the outcrop (approximately 1m), for collecting data at the same resolution. Possible errors associated with these data are less than 10%.

Two-dimensional sampling (scan area analysis) allows the study of spatial distribution of discontinuities on a specified area. At the outcrop-scale, the sampling resolution was the same as used in scan line analysis; the studied areas had the size of approximately 1-2 m^2 and all discontinuities countable at a distance of approximately 1m have been taken into consideration. Scan area data provide a discontinuity trace map from which it is possible to derive the fracture connectivity and the fractal dimension of fabric elements, by means of the "box counting method". This procedure has been applied as defined by several authors (BARTON & LARSEN, 1985; HIRATA, 1989; WALSH & WATTERSON, 1993; POULIMENOS, 2000).

For the microstructural analysis, oriented samples were collected on the two studied fault zones. Three mutually perpendicular thin sections were prepared from each sample. Thin sections have been analyzed under optical microscopy

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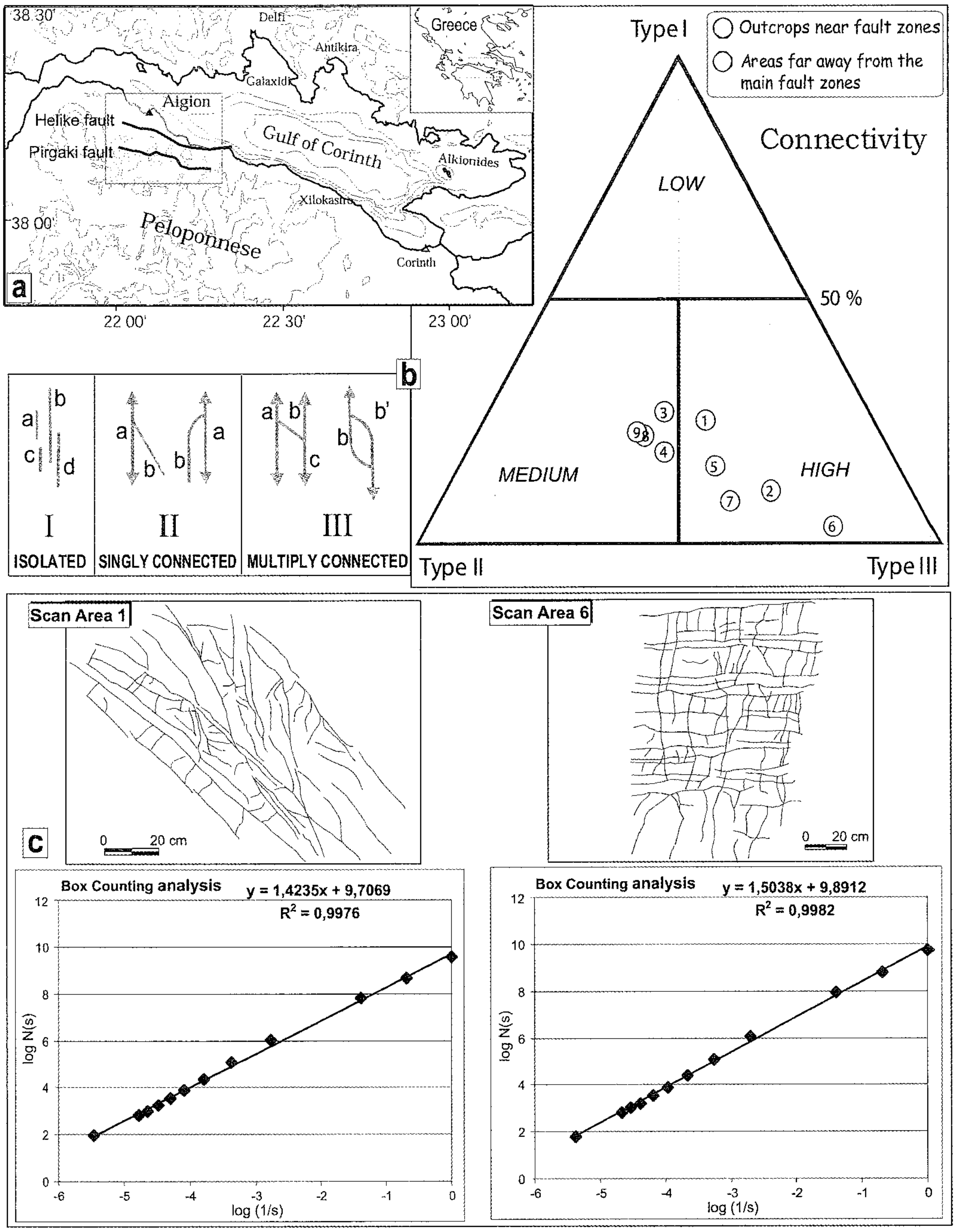

Fig. 1 - (a) Sketch showing the location of the studied area. (b) Degree of connectivity of fracture networks within the limestone series. (c) Discontinuity trace maps and relative box counting curves from scan areas at different distances from the main fault zones.

in order to characterize the different fault-related features. In this paper, we focused on microstructural analyses in fault cores, for defining the microstructures characterizing the fault rocks associated with the studied faults.

3. TWO-DIMENSIONAL DATA: FRACTURE CONNECTIVITY

We carried out two-dimensional sampling mainly to point out how the fracture connectivity varies at different distances from fault zones.

Connectivity is a fundamental property of fracture populations with respect to the fluid flow. It can be evaluated semi-quantitatively from image analysis of scan areas by assessing the degree of physical connection among fractures within a network (sketch in Fig. 1b) and by representing the results in a triangle diagram. Here, the ratio of the number of fractures which are isolated (type I), simply-connected (type II), or multiply-connected (type III) over the total number of fractures in the network may be shown (Ortega & Marret, 2000). The degree of connectivity is in general higher within limestones and marls outcropping near the studied fault zones, between 500 and 1000 m away from the main fault, than in those outcropping far from main fault zones. This suggests that the dis-

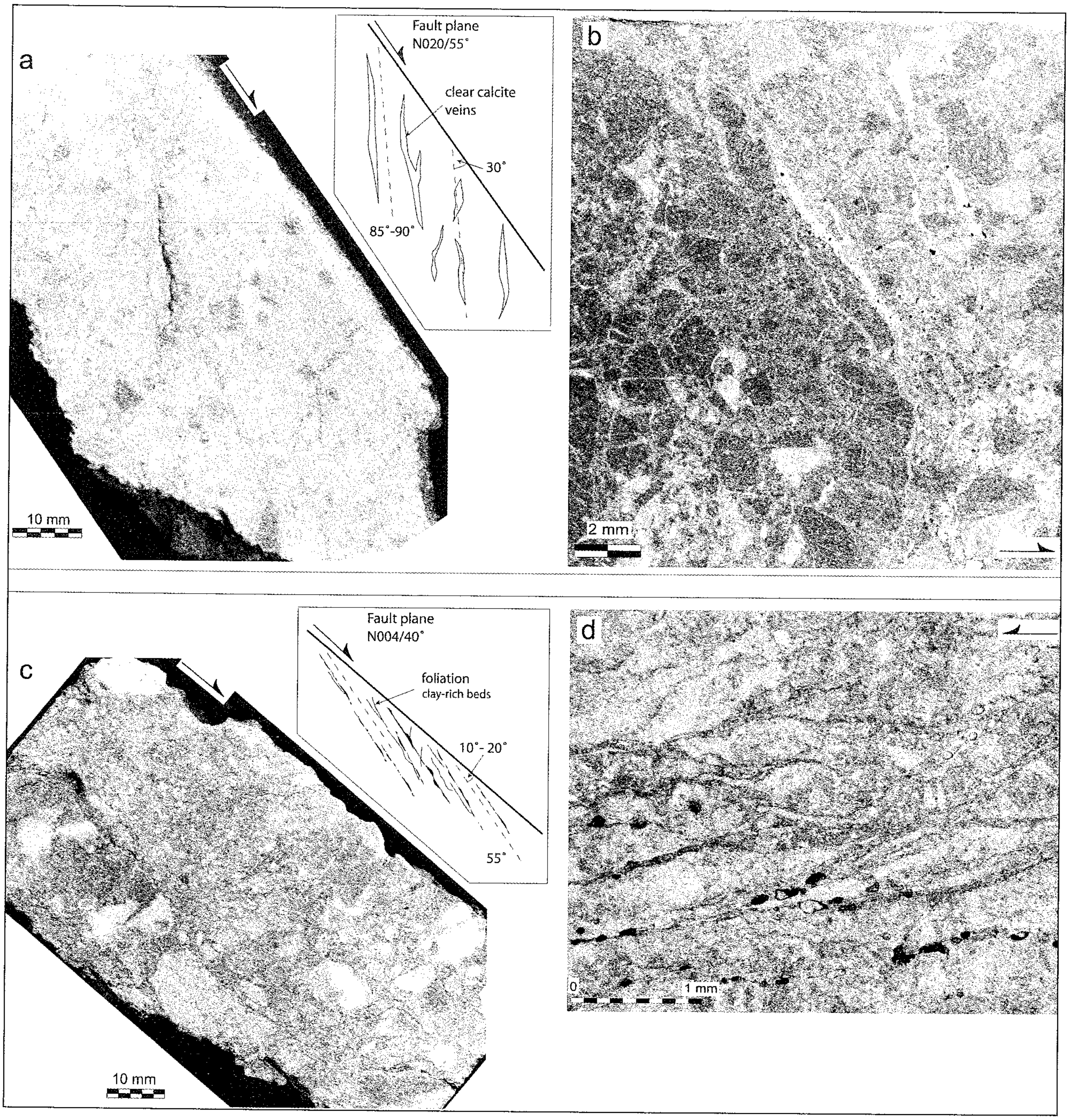

Fig. 2 - (a) Helike fault core: cemented cataclasite displaying a closely-spaced system of veins, cutting all the other microstructures (cut sample). Sketch shows the orientation of the main microstructures compared to the fault plane. (b) Cataclasite displaying a system of preferentially oriented veins (see sketch in Fig. 2a), totally or partially filled by subhedral calcite (plain light microphotographs). (c) Pirgaki fault core: cataclasites and ultracataclasites displaying foliated fabric (cur sample). Sketch shows the orientation of the main microstructures compared to the fault plane. (d) Foliated ultracataclasite: elongated aggregates and preferentially oriented alignments of fine-grained mineral grains sub-parallel to the sense of shear (plain light microphotographs).

tance from main fault zones plays a fundamental role on fracture connectivity.

This seems to be confirmed by box counting analysis that we performed on images from scan areas especially located at different distances from fault zones. In general, the slopes of inferred straight lines increase from the host-rocks to the faults (Fig. 1c). Increases of both fractal dimension and connectivity suggest that rock volumes near the faults and particularly in the damage zones, have a higher fracture geometric complexity and a higher number of connected discontinuities, which could increase the permeability.

4. FAULT PLANES

The fault rocks that characterize the Helike fault plane mainly consist of cemented, matrix-supported cataclasite (Fig. 2a, b), displaying a random fabric with limestone and calcite fragments ranging mostly from tens of mm to 1-2 μ in diameter (Fig. 2b). The matrix is commonly light brown-yellow in colour and is mainly made of very small calcareous elements. The cataclasite is affected by a closely-spaced system of veins, which cut all the other microstructures and therefore record the latest deformation process (Fig. 2b). Veins are totally or partially filled by clear, not-twinned, subhedral calcite. They are systematically sub-vertical and form, therefore, an angle of about 30° with the fault surface (see sketch in the top of Fig. 2a).

On the other hand, the Pirgaki fault plane locally displays also foliated fabric, characterizing cataclasites and ultracataclasites (*sensu* SIBSON, 1977; Fig. 2c). The foliation observed under an optical microscope is defined by a system of clay-rich and oxide-rich beds, with an average spacing 50-200 μ (Fig. 2d), and limestone and calcite fragments and lens ranging from tens to hundreds of mm in size. The clay- and oxide-rich beds, related to shear and pressure-solution and processes, form systematically angles of 10°-20° with the fault plane (see sketch in Fig. 2c) and are interpreted as R-surfaces of a Riedel's network. They cut systematically older structures, defining the elongated shape of the calcite-rich fragments. Therefore, these lens-shaped fragments testify an older phase of intense cataclastic deformation, characterized by precipitation of calcite cement. On the contrary, the latest phase is not associated with cement precipitation.

5. FAULT ZONE COMPONENT SIZE

One-dimensional sampling (scan line analysis) of the discontinuities along a line normal to the fault strike, allows defining from a quantitative point of view the fault core, the fault damage zone and the protolith (Fig. 3; see also MICARELLI *et alii*, 2003).

The Helike fault displays an approximately 2.5 m thick *core* within the limestones. It mainly consists of poorly cemented crush breccia (*sensu* SIBSON, 1977) and little cataclasite, with bands of incohesive gouge. The footwall *intensely deformed damage zone* is 7 m thick (9.5 m including the *core*), and is affected by the highest percentage of fault-related fractures. In the *weakly deformed damage zone* (approximately 22 m wide), the deformation in the limestone is concentrated within some major shear zones, and along some subsidiary minor fault planes. The density of subsidiary faults and fractures decreases progressively away from the core of the Helike fault to low, regional background levels at about 32 m from the plane.

When the Helike fault affects the conglomerates, the main fault plane displays an only 15-20 cm thick highly cemented *core*. The first 7 m close to the main fault plane constitute the *intensively deformed damage zone*. The whole footwall damage zone, characterized by some secondary fault planes, is 30 m wide at least, therefore displaying the same width as in the limestones (Fig. 3). In the conglomerates, the deformation appears strongly localized along some slip planes, by comparison to that affecting the limestones, and at a distance of only a few centimeters from the planes, the host rock is not deformed.

The Pirgaki fault zone structure is more complex, but, in general, above the main fault plane it is possible to recognize a 2-4 m thick *core* (Fig. 3). It is characterized by the occurrence of high-angle shear planes having strike direction about N100, and by foliation planes, sub parallel to the main fault plane. Much foliated clay and calcite have been recognized, but foliation features also affect the limestone fragments, displaying typical elongated shapes and pervasive fractures. In general a second major fault plane bounds to the north the hangingwall *intensely deformed damage zone*, which is approximately 14-18 m wide. Finally, the total width of the hangingwall fault zone is estimated to be up to 50 m.

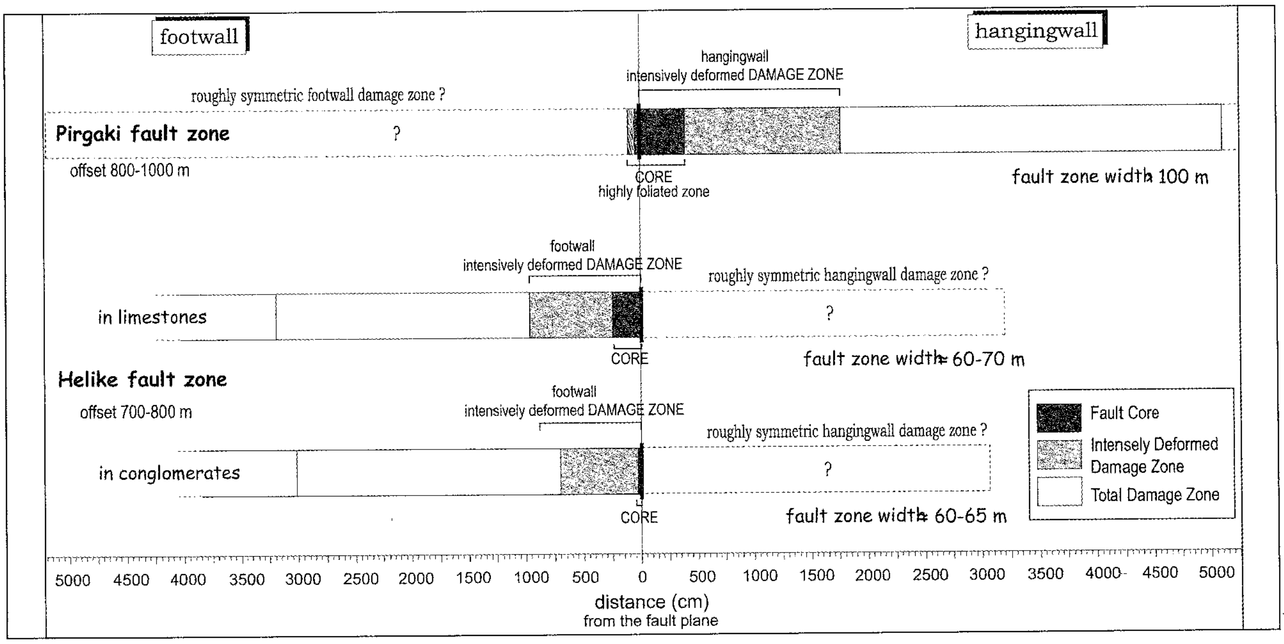

Fig. 3 - Sketch summarizing quantitative data on fault zone architectures and relative fault zone component sizes.

6. DISCUSSION AND CONCLUSION

Our analysis shows that fracture connectivity and fractal dimension relative to scan area meso-scale images are linked and increase from the host-rock to the faults. We think that in the low-porosity limestones constituting the host-rock, mainly the higher number of connected discontinuities plays a major role on the gradual increase of the structural permeability of the damage zone towards the fault plane. Note that the same network of increasing connected discontinuities has been described by MICARELLI *et alii* (2003), MORETTI *et alii* (2003b) and DANIEL *et alii* (*in press*), in the cores obtained from the AG10 well bored in the frame of the "Corinth Rift Laboratory project" (MORETTI *et alii*, 2002). The high connectivity (and the consequent high D values) of fracture networks modifies the rock behaviour with respect to fluid flow and defines an "open", high-permeability cataclasite developing in the first meters close to the fault.

One-dimensional sampling allowed to constrain fault zone widths that result to be not related to the affected lithological context. The Helike fault zone, in fact, shows similar widths (60-70 m, supposing a rough symmetry of the damage zone size) in both limestone and conglomerate series. On the contrary the fault core width appears to be related to lithology, displaying a very smaller size in the conglomerates (0.2 m) with respect to limestones (2-3 m). Cores instead show similar widths for both the Helike and Pirgaki faults when affecting the same limestone series (2-4 m). The lithology of host-rocks seems therefore to play an important role in the localization of deformation, whereas the width of the *core* and of the brecciated zone appears poorly correlated with the throw.

Different fault rocks characterize the two studied fault zones. In the Pirgaki fault plane, foliated ultra-cataclasites are present, characterized by clay- and oxide-rich shear micro-planes. There are neither late veins nor calcite precipitation. Older cataclasite blocks or elongated elements are involved in a newly formed texture, therefore recording multiple phases (at least two) of intense cataclastic deformation. On the other hand, the Helike fault plane fabrics show that only brittle processes at the surface environment were responsible for the development and evolution of the analyzed fault rocks. Cataclasites are affected by sub-vertical calcite micro-veins that are very late in the fault rock evolution. These fractures are thought to have acted as short-lived, inter-connected, fluid flow conduits that rapidly sealed to form a barrier to flow, when open pore space was filled by mineral precipitation following deformation.

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