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Tectonics

Deformation mechanisms and fluid-driven mass transfers in the recent fault zones of the Corinth Rift (Greece)

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Abstract

Normal fault zones affecting the pre-rift limestones in the Corinth Rift comprise breccia corridors separated by slip surfaces, but also numerous stylolites and calcite veins attesting the importance of fluid-driven mass transfer during a(inter)seismic episodes of fault activity. Cathodoluminescence microscopy shows that external (meteoric?) waters circulated in the fault zones, whereas mass transfer in the surrounding rocks implied a closed system with water chemically equilibrated with the host limestone. From these observations, we propose preliminary qualitative models of structural development and fluid flow in active normal fault zones in superficial conditions, with a tendency to concentration of deformation and fluid-flow-related to fault-tip propagation. ***To cite this article: P. Labaume et al., C. R. Geoscience 336 (2004).***
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Résumé

Mécanismes de déformation et transferts de matière assistés par les fluides dans les zones de failles récentes du rift de Corinthe (Grèce). Les zones de failles normales affectant les calcaires pré-rift du rift de Corinthe comportent des couloirs bréchiques séparés par des surfaces de glissement, mais aussi de nombreux stylolites et veines de calcite, attestant l'importance des transferts de matière dans les fluides pendant les épisodes a(inter)sismiques de l'activité des failles. La microscopie en cathodoluminescence montre que des eaux externes (météoriques ?) ont circulé dans les zones de failles, alors que le transfert de matière dans les roches adjacentes correspondait à un système fermé, avec des eaux chimiquement équilibrées avec le calcaire hôte. À partir de ces observations, nous proposons un modèle qualitatif préliminaire de développement structural et de circulation de fluides dans des zones de failles normales actives en conditions superficielles, avec une tendance à la concentration de la déformation et de l'écoulement, en relation avec la propagation de l'extrémité de la faille. ***Pour citer cet article : P. Labaume et al., C. R. Geoscience 336 (2004).***
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Mots-clés : rift de Corinthe ; zone de faille ; veine de calcite ; stylolite ; brèche de faille ; transfert de matière assisté par les fluides ; cathodoluminescence

Version française abrégée

Les zones de failles normales affectant les carbonates pré-rift dans le rift de Corinthe sont caractérisées par des couloirs de brèche séparés par de grandes surfaces de glissement [11,12]. Cependant, l'abondance des stylolites et des veines de calcite, qui caractérise l'importance du transfert de matière assisté par les fluides dans l'activité de ces failles superficielles, n'a pas été soulignée jusqu'ici. Nous décrivons ici ces structures, observées sur un affleurement de la zone de faille majeure de Pirgaki [3,7] (Figs. 1 et 2).

La microscopie en cathodoluminescence révèle deux générations principales de ciments de calcite, présentes sur tout l'affleurement (Fig. 2) : G1, de luminescence orange similaire à celle du calcaire hôte, et G2, non luminescente. Il existe aussi (i) une génération intermédiaire (G1–2), moins luminescente que G1, et (ii) une calcite de luminescence orange vif (G2′) formant des zonations dans les cristaux G2 et des veinules tardives.

À l'extérieur des failles, la déformation extensive est marquée par des stylolites et des veines de calcite majoritairement G1, les veines G2 étant peu développées à absentes (T4 dans Fig. 2). Dans les zones endommagées périphériques au couloir de brèche formant le cœur de la faille F2, les structures deviennent plus fréquentes. Au toit, on aboutit à une brèche dilatante scellée, à calcite G2 majoritaire (T5 dans la Fig. 2). Au mur et le long de F3, une fabrique cisaillante de type S–C [4] est caractérisée par une forte densité de stylolites associés à des veines G2 cisaillantes et extensives (T14 dans la Fig. 2). La brèche du cœur de faille est non cohésive, avec des clastes calcaires issus de bancs différents et contenant des veines G1 et G2 antérieures, et une matrice dérivée des lits argileux (T8 dans la Fig. 2). La faille F4 montre des veines G1 présentes dans toute la zone de faille et la zone externe, alors que les veines G2 sont surtout présentes dans le cœur de faille et les veines G1–2 dans la zone endommagée (Fig. 2).

Les veines et stylolites distribués à l'extérieur des failles sont interprétés comme une déformation d'extrémité de la faille lors de sa propagation [13] (Fig. 3). Il s'agit de structures de transfert de matière par dissolution–cristallisation sous contrainte, un mécanisme lent, a(inter)sismique [5]. Dans les zones endommagées, leur densification locale en fabrique S–C est probablement liée à des courbures ou relais compressifs de surfaces de glissement, alors que les brèches dilatantes scellées se formeraient par implosion cosismique au niveau des courbures ou relais extensifs [9]. Dans les cœurs de failles, les brèches polymictiques non cohésives résultent de l'attrition liée à un déplacement important en régime sismique et asismique [9]. Nous intégrons la genèse de ces structures dans un modèle de concentration de la déformation au cœur de la faille par affaiblissement tectonique [8], jusqu'à la localisation du glissement sur de grandes surfaces discrètes (Fig. 3). La chronologie entre les structures scellées, puis non scellées, indique la diminution de l'efficacité du transfert par dissolution sous contrainte en conditions de plus en plus superficielles lors du soulèvement et de la dénudation du compartiment de mur de la faille.

La luminescence de la calcite G1 suggère un transfert en système clos, dans une eau en équilibre chimique avec le calcaire hôte, alors que la calcite G2, non luminescente, aurait précipité en système ouvert dans une eau non équilibrée. La concentration de G2 dans et autour des cœurs de failles indique que celles-ci drainent des eaux externes (météoriques ?) lorsque les structures deviennent suffisamment connectées (Fig. 3). La luminescence intermédiaire de la calcite G1–2 pourrait résulter d'un mélange d'eaux dans la zone endommagée, et les zonations G2′ pourraient traduire des variations de chimie des eaux lors d'épisodes de déformation perturbant le système de circulation.

Des analyses chimiques (éléments et isotopes) des différentes calcites, couplées à de nouvelles observations structurales, permettront de déterminer la nature des eaux et leurs interactions avec l'encaissant, et de tester et développer les modèles préliminaires proposés ici. La faille d'Aigion carottée dans le puits AIG 10 du Corinth Rift Laboratory (Fig. 1) montre des structures analogues à celles décrites ici [6,7], indiquant que nos conclusions devraient aussi s'appliquer à cette faille active.

1. Introduction

A fault is generally not a single slip surface, but comprises a band of deformed rocks adjacent to the main slip(s) surface(s) and forming the 'fault zone', with a highly deformed 'fault core' and adjacent moderately deformed 'damage zones' [1]. The integration of structural and chemical analyses of deformation features and cements located in fault zone is critical for understanding the deformation mechanisms and fluid behaviour associated with fault activity. The neotectonic fault zones in carbonates of the Aegean region have been described by Steward and Hancock [11,12] as mainly constituted by fractures and different types of breccia corridors separated by large slip planes. These authors also cite the occurrence of stylolites and calcite veins, but did not describe the actual importance of these structures, and hence the role of fluid-driven mass transfer in the activity of these superficial fault zones.

Here, we point to the importance of this role from the structural/microstructural study of a segment of the Pirgaki Fault zone, a major recent fault of the southern rim of the Corinth Rift outcropping 10 km south of the city of Aigion [3,7] (Fig. 1). We performed a microstructural analysis of deformed carbonates using both conventional and cathodoluminescence (CL) microscopy that allows us to distinguish the different deformation mechanisms and generations of calcite cements. Based on these results, we propose preliminary qualitative models of structural development and fluid flow in the fault zone. In particular, we attempt to distinguish structures formed during coseismic motions from those related to a(inter)seismic deformation.

2. Structures and cements in the Pirgaki Fault zone

The Pirgaki Fault trends N100° and dips steeply (60–70°) to the north. The throw exceeds 1000 m and juxtaposes synrift sands and conglomerates in the hanging wall with the prerift series in the footwall.

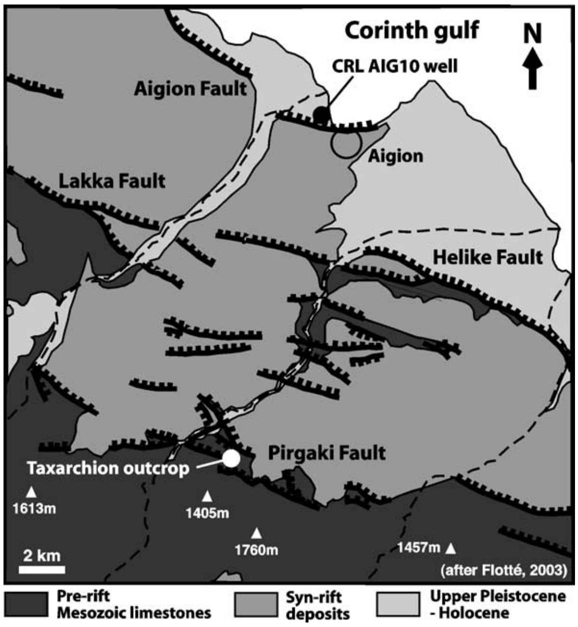

Fig. 1. Geological map of the Aigion area, with location of the main normal faults (thick decorated lines) and studied outcrop (Taxarchion).

Fig. 1. Carte géologique de la région d'Aigion, avec localisation des failles normales majeures (traits crénelés épais) et de l'affleurement étudié (Taxarchion).

The latter include Mesozoic basinal carbonates with intercalations of radiolarian clays and radiolarites, and are repeated in Alpine west-verging thrust slices forming the Pindus tectonic unit [2].

In the study area, the Pirgaki Fault zone is about 700 m-wide in the footwall prerift series. The studied outcrop is located in the middle part of this deformation zone, on the road ascending from the Taxarchion monastery toward the village of Pirgaki (Fig. 1). The outcrop exposes a 70 m-long section normal to the fault trend, featuring a complex extensional deformation with several normal faults that correspond to second order faults within the major Pirgaki Fault zone. These faults have variable dips toward north (synthetic) or south (antithetic) and undetermined throws, and affect centimetre-thick-bedded micritic limestones and metre-thick radiolarian clay layers (Fig. 2). Extensional deformation associated with these faults is marked by stylolites, extensional calcite veins, slip surfaces possibly associated with calcite shear veins, unsealed fractures and breccia.

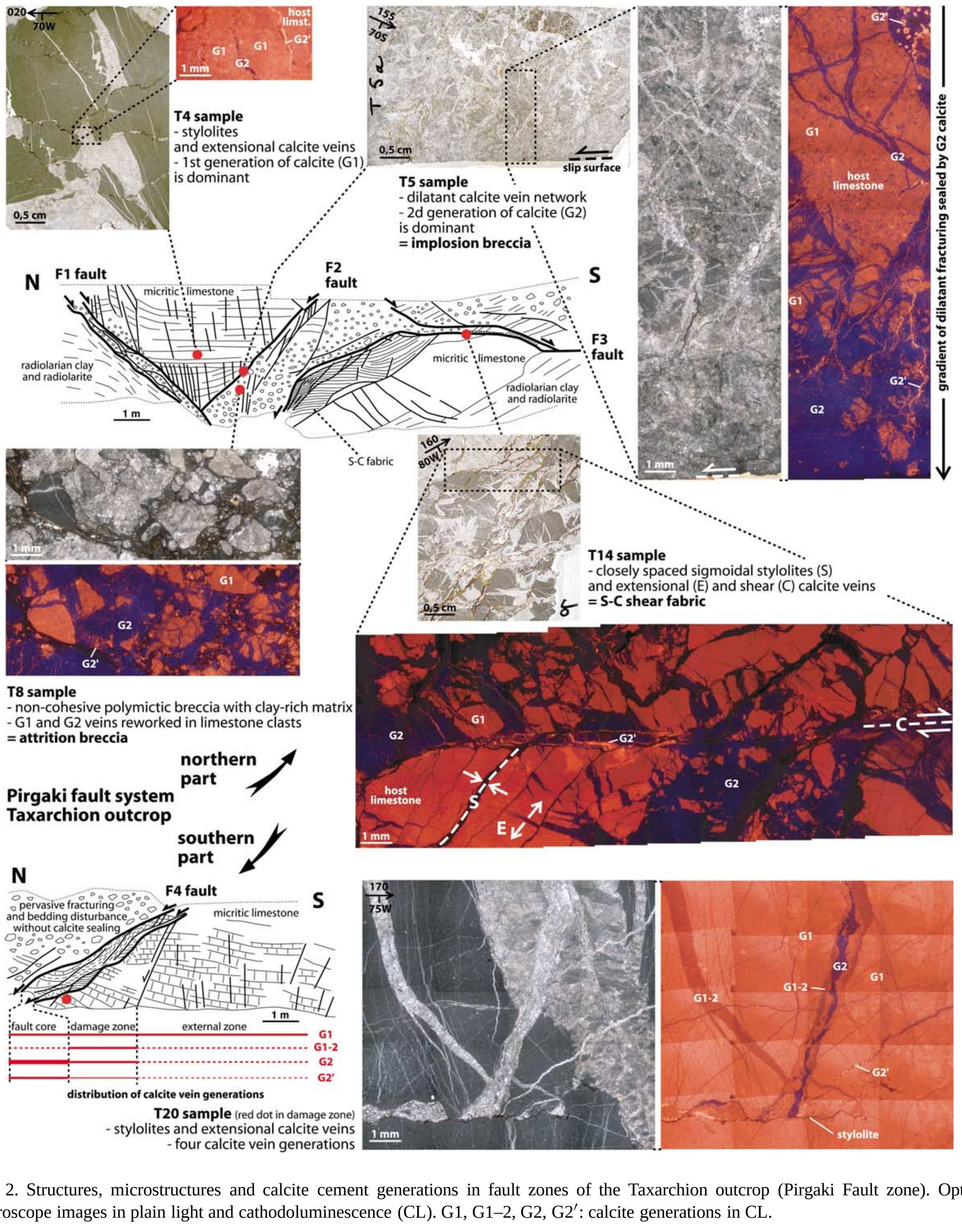

Fig. 2. Structures, microstructures and calcite cement generations in fault zones of the Taxarchion outcrop (Pirgaki Fault zone). Optical microscope images in plain light and cathodoluminescence (CL). G1, G1–2, G2, G2′: calcite generations in CL.

Fig. 2. Structures, microstructures et générations de ciments de calcite dans les zones de failles de l'affleurement de Taxarchion (zone de faille de Pirgaki). Images de microscopie optique en lumière naturelle et cathodoluminescence (CL). G1, G1–2, G2, G2′ : générations de calcite en CL.

The latter comprise both calcite-sealed breccia and non-cohesive breccia with variable amounts of clay-rich matrix derived from the radiolarian clay layers. The stylolites and calcite-sealed structures occur throughout the whole outcrop, with strong gradients of frequency at $\sim$10 cm scale around the faults. The large scale slip planes typical of faults affecting limestones in the Corinth Rift [11,12] are not present on the Taxarchion outcrop but are well exposed a few hundreds metres southward near the boundary of the Pirgaki Fault zone [7].

An exhaustive description of the outcrop is beyond the scope of this paper. Here, we only highlight the dominant deformation and cementation features in limestones from examples taken in fault zones F2, F3 and F4 (Fig. 2). We first present the main generations of calcite cements recognised in CL microscopy, and then we describe the main structure and cement associations in the fault zones.

The CL microscopy shows two main calcite cement generations present through the whole outcrop, and whose chronology is determined by cross-cutting relationships of veins: G1 calcite with the same orange luminescence as the host-limestone, and younger G2 calcite, dark-blue to non-luminescent (Fig. 2). Also found are (*i*) a chronologically intermediate generation (G1–2) with a weaker orange luminescence than G1 and present only in the F4 fault zone, and (*ii*) a bright orange luminescent calcite (G2′) present in minor amounts on the whole outcrop and forming zonations in G2 crystals or late veinlets.

The fault core of F2 is a 2 m-wide corridor of non-cohesive breccia made of limestone clasts in a clay-rich matrix (Fig. 2). The deformation a few metres away from the fault is marked by systems of stylolites and calcite veins, corresponding mainly to sub-horizontal extension: stylolites sub-parallel to bedding with sub-vertical peaks and extensional veins sub-normal to bedding. A few shear veins along bedding are also present. The G1 veins are the most numerous and widest, compared to the G2 ones that cut or re-open them, and G2′ is minor (sample T4 in Fig. 2). The G1 veins show a higher density of twinning, implying they suffered a more intense and longer stress history. Structures inherited from the Alpine deformation are also present. The most obvious ones are sub-vertical stylolite surfaces with sub-horizontal peaks (sample 4 in Fig. 2), some of them being opened as calcite veins related to extension. Some of the oldest (G1) veins may also be Alpine, but they are difficult to discriminate at the present stage of our work. The frequency of structures related to extension increases dramatically within a few decimetres in the damage zones surrounding the fault core, but with a structural style markedly different on both sides.

In the hanging wall, the vein systems become complex, with extensional veins of various directions and dips giving a dilatant texture, up to a calcite-sealed breccia bordering slip surfaces. The G2 veins are the most numerous and their frequency and width increase at the millimetre-scale toward the slip surfaces along which they form the macroscopically striated calcite (sample T5 in Fig. 2). We have observed up to three crosscutting generations of G2 veins at the thin section scale. The widest (up to a few mm) G2 veins can be geodic, with well-developed G2′ zonations. The frequency of G2′ late veinlets shows the same trend as the G2 veins. Stylolites are rare to absent at the centimetre-scale and post-date the dilatant vein networks.

The contact of the sealed breccia with the fault core non-cohesive breccia is either abrupt along a slip surface with striated calcite (sample T5 in Fig. 2), or irregular. The limestone clasts of the non-cohesive breccia contain older G1 and G2 veins analogous to those observed in the adjacent damage zone, and show various microfacies implying mixing of clasts derived from various beds (sample T8 in Fig. 2). There is no calcite cement associated with this breccia, except rare G2′ veinlets possibly related to the brecciation process. Compaction of the breccia is marked by stylolites at clast contacts, coeval with those post-dating the adjacent sealed breccia.

In the footwall of F2, as well as along the F3 slip surfaces, the limestone is affected by a macroscopic, low-dipping, rough foliation that increases in density toward the fault cores and corresponds to closely spaced stylolites (Fig. 2). The macrostructure is also marked by slip surfaces between which the stylolites have a sigmoidal geometry, resulting in an S–C shear structure [4] kinematically coherent with the normal movement of faults. Thin sections show numerous G2 extensional veins normal to the stylolites and cutting older G1 veins, as well as G2 shear veins along the slip surfaces, implying that the S–C structure developed in relation to G2 calcite precipitation (sample T14 in Fig. 2). G2′ veinlets often post-date the shear structures.

Between F3 and F4 is a 50 m-long outcrop with pervasive fracturing and bedding disturbance, locally up to a generalised brecciation. This deformation is not sealed by calcite and post-dates the calcite-sealed structures. The F4 fault core is constituted by limestone lenses in a sheared clay-rich matrix (Fig. 2). The lenses show variable intensity of deformation by veins and stylolites, up to local S–C shear fabrics along the main slip surfaces. The lower limit of the fault core is marked by a well-defined slip surface, below which is a 2 m-wide damage zone with some bedding disturbance, but weak frequency of veins and stylolites. In the external zone, these structures have also a very low frequency and bedding is not disturbed. The G1 veins are present in the fault core, damage zone and external zone with a decreasing frequency (Fig. 2). However, the G2 veins show higher variations of frequency according to their structural position: they are more numerous and developed than the G1 ones in the fault core, much less numerous and thinner in the damage zone and rare in the external zone. The minor G2′ calcite shows the same trend of frequency as G2. The G1–2 veins, chronologically intercalated between the G1 and G2 veins, are mainly present in the damage zone, where they are less developed than the G1 ones but more than the G2 ones (sample 20 in Fig. 2).

3. Discussion

Two groups of structures can be differentiated both by the deformation mechanisms and their chronology, interpreted from crosscutting relationships. The first formed structures are those associated with mass transfer, i.e., the stylolites and various types of veins and sealed breccia. The younger structures are the unsealed fractures and non-cohesive breccia. Mass transfer by pressure solution is a slow, aseismic process of deformation [5], thus implying that coseismic motion is not the only mode of fault activity. The Corinth Rift faults being known for their seismic character, aseismic deformation probably results from stress accumulation during the interseismic periods. The geological context, in particular the lack of syn-rift deposits in the footwall of the Pirgaki Fault, suggests that the whole deformation sequence occurred at a depth not exceeding 1–2 km.

The stylolite-vein systems that are present with a low frequency outside fault zones may correspond to fault-tip deformation related to fault propagation (cf. the process zone of Vermilye and Scholz [13]) (Fig. 3). The presence of this distributed deformation could relate to the relative ease with which hydraulic extension fractures may develop under hydrostatic regime in the uppermost crust in an extensional regime before the development of a through-going normal fault [10]. Alternatively, distributed deformation may develop after fault propagation as a result of stress adjustment around the faults following seismic ruptures, perhaps as a consequence of rupture irregularities [Sibson, pers. comm.]. Inside the fault zones, the local increase of pressure-solution up to the development of an S–C shear fabric in lenses along the main slip planes probably corresponds to the concentration of deformation at contractional releasing jogs or bends. By contrast, the dilatant calcite vein networks also locally present along slip surfaces may correspond to dilation at releasing jogs or bends and are tentatively interpreted as resulting from abrupt de-confining during coseismic slip (cf. the implosion breccia of Sibson [9]). In these networks, crosscutting G2 veins may correspond to several successive seismic ruptures. The non-cohesive breccia in the fault cores formed at least in part after the vein systems since the latter are reworked in the limestone clasts. The mixing of different lithologies also indicates that this breccia results from (relatively) large displacement. These characters suggest that it is an attrition breccia that can be related to both seismic and aseismic episodes [9]. The aseismic activity is marked in the breccia by compaction with stylolites at clast contacts, and may also have implied shearing in the clay-rich matrix.

Combining the observations and inferences exposed above, we propose a model of fault zone development related to the upward propagation of a normal fault tip, derived from the model proposed by Steward and Hancock [11,12] for the faults in limestones of the Aegean region. In our model, the central part of the fault develops with a tendency to concentration of deformation from distributed stylolites and veins at the fault tip through disconnected then connected slip surfaces, attrition breccia and eventually formation of

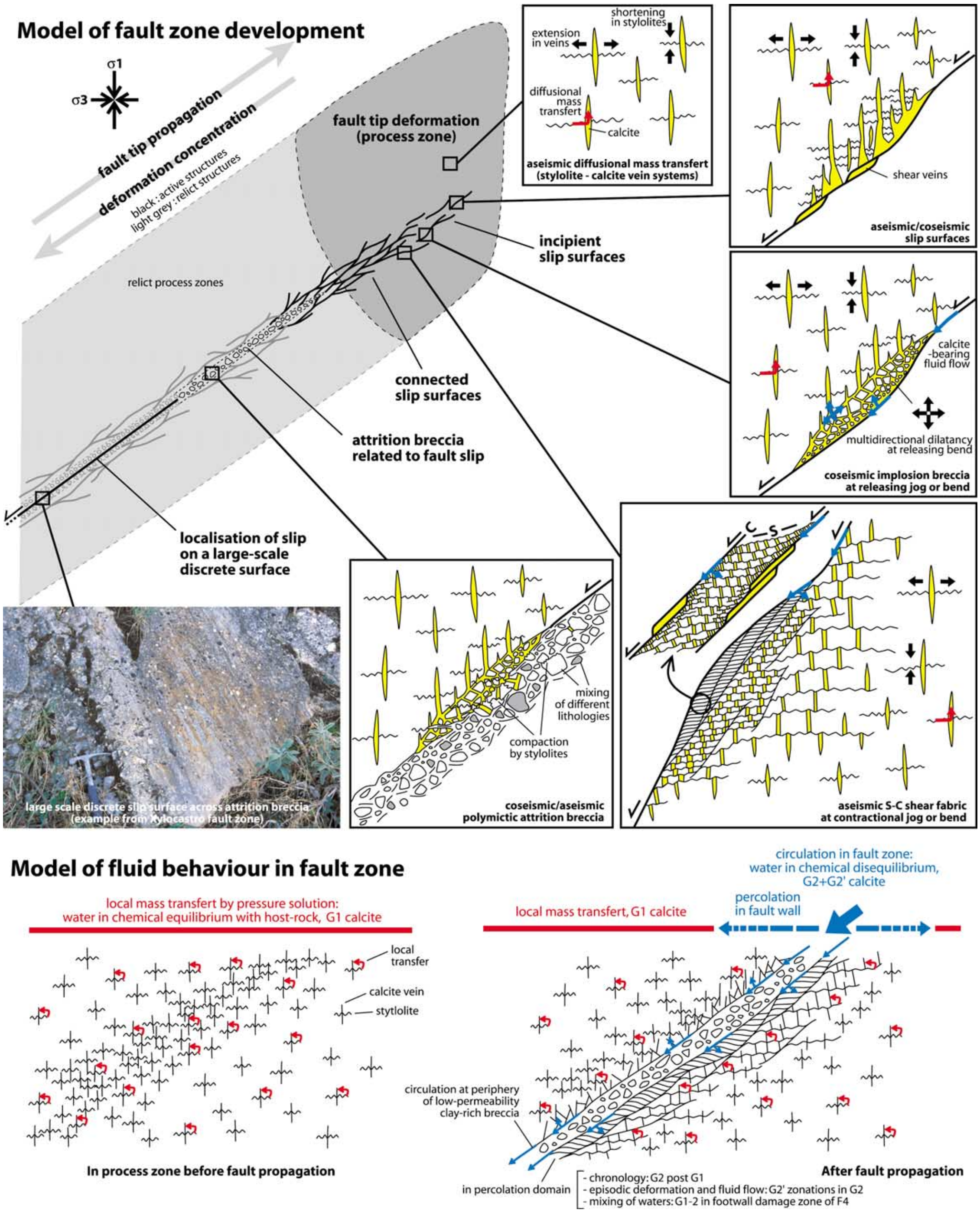

Fig. 3. Models of structural development and fluid behaviour in normal fault zones affecting carbonates in the Aigion area. See comments in the text.

Fig. 3. Modèles de développement structural et de comportement des fluides dans les zones de failles normales affectant des carbonates dans la région d'Aigion. Voir les commentaires dans le texte.

a large-scale discrete slip surface within the breccia (Fig. 3). This evolution corresponds to a weakening of the fault zone, probably due to concentration of fractures that make the fault-rock less cohesive than the protolith, combined with the development of fabrics (slip surfaces and S–C structures) that tend to localise movement [8]. The fact that the most recent structures are not associated with important mass transfer may be related to the decreasing efficiency of pressure solution when the rocks are deformed in progressively shallower superficial condition during footwall uplift and erosion. We must note that the model above only accounts for the development of a perfectly planar fault propagating in its own plane. Indeed, as it is inferred above, rupture irregularities, in particular resulting from a more complex fault geometry with changes of fault dip or/and connectivity between different faults, may induce second-order deformations outside fault zones, thus tending to fault-zone widening interfering with the deformation concentration related to fault-tip propagation. This may be the case for the studied faults that actually show such complex geometries (Fig. 2).

The differences in CL of the different calcite generations suggest variations of fluid composition and origin during the evolution of the fault. Their distribution also sheds light on the evolution of fracture connectivity in the fault zone. The first veins (G1) have the same orange luminescence as the host limestone, suggesting water in chemical equilibrium with the latter. This indicates a closed hydrological system and accounts well for a fault-tip deformation before fault propagation. The younger G2 veins have different CL characteristics than the host limestone, suggesting water in chemical disequilibrium. The G2 calcite is typically associated with the most developed fault structures (shear veins along slip surfaces and adjacent high strain domains such as implosion breccia and S–C shear fabrics), with steep gradients of decreasing abundance when going away the faults. These features indicate that the G2 calcite is related to circulation of external waters during both seismic (implosion breccia) and a(inter)seismic (shear veins, S–C shear fabrics) episodes. Circulation is concentrated along the main slip surfaces and deformation zones and percolates in the damage zones with a dramatic decrease within a few tens of centimetres. The G2′ zonations may correspond to chemical variations related to deformation episodes perturbing the system of water circulation. The G1–2 calcite may result from mixing in the F4 fault damage zone of external waters circulating along the fault core with formation water present outside the fault zone. A further step of our work will be to perform chemical analyses (elements and isotopes) of the various generations of calcite cements and their host limestones to validate our assumptions and determine the nature of the different aqueous fluids and their interactions with the host rocks. By reference to recent C and O isotope analyses in calcite cements from various faults of the Corinth Rift [3], we speculate that the G2 calcite may be related to circulation of meteoric water, activated when the structures forming the fault zone are sufficiently connected to the surface.

The fault core breccia of the studied faults is probably poorly permeable due to the presence of a clay matrix. This situation is not general in the Corinth Rift fault zones, where the attrition breccia typically displays unsealed pervasive fracturing [10,11]. In this case, only a centimetre-thick band of calcite-sealed breccia occurs along the slip planes, probably due to water circulation along the latter.

4. Conclusions

Our observations point to the importance of fluid-driven mass transfer by pressure solution both inside and outside fault zones, implying that aseismic deformation during the interseismic period must be taken into account when modelling the activity of faults in the uppermost crust. The strong development of these mechanisms in association with brittle deformation is probably favoured by the solubility of carbonate rocks. We also show that the faults act as drains for the circulation of external waters, with limited percolation over distances of a few decimetres outside the fault zones. New structural observations, and chemical analyses of calcite cements and their host rocks will be achieved to test and develop the preliminary qualitative models proposed here. Preliminary observations of the core recovered in the Corinth Rift Laboratory AIG10 well (Fig. 1) show that the active Aigion fault zone, sampled around 760 m deep, affects limestones and radiolarian clays with deformation structures similar to those found in the Pirgaki Fault zone [6,7]. The models derived from the study of outcropping fault zones may therefore apply to this active fault.

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