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## RESEARCH LETTER

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## Key Points:

- Multiplets reveal details on multiscale fault structure and permeability
- Microseismicity is triggered by pore pressure migration, with marginal creep
- Fault intersection with a brittle geological layer creates a permeable corridor

## Supporting Information:

- Readme
- Movie S1
- Figure S1a
- Figure S1b
- Table S1

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## The 2003–2004 seismic swarm in the western Corinth rift: Evidence for a multiscale pore pressure diffusion process along a permeable fault system

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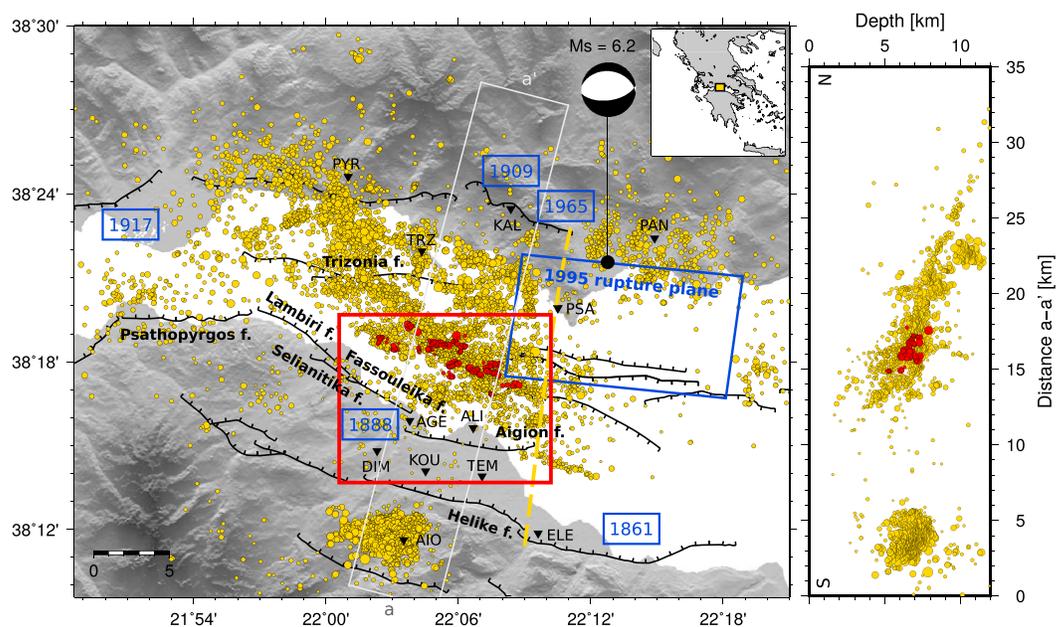
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**Abstract** Microseismic multiplets occurring in the western Corinth rift, Greece, during a large swarm are analyzed to retrieve their spatiotemporal characteristics. These multiplets activated small subfaults at depth (~7 km), up to 1 km long, at the root of two parallel active normal faults. The swarm migrates westward nearly horizontally over 10 km at an average velocity of 50 m/d with a diffusivity of 0.5 m<sup>2</sup> s<sup>-1</sup>. It successively activates the Aigion fault, a relay zone in its hanging wall, and the Fassouleika fault. Within each multiplet, hypocenters also migrate with diffusivities ranging from 0.001 to 0.4 m<sup>2</sup> s<sup>-1</sup>. The largest internal diffusivities appear at the core of the layer defined by the clusters. These results are interpreted as a hydroshear process caused by pore pressure migration within permeable corridors resulting from the intersection of the major faults with a brittle geological layer inherited from the Hellenic nappe stack.

### 1. Introduction

The characterization of the structure of active fault zones is essential for understanding earthquake nucleation, dynamic rupture, and fault evolution and can thus contribute to quantify the probability of major earthquake triggering. Our knowledge of fault zone structure and properties is mostly provided by geological and geomorphological studies based on direct observations of exhumed faults [e.g., Allen, 2005] and drilling projects that intersect active faults at depths [e.g., Janssen et al., 2014; Cornet et al., 2004]. Other inferences are obtained through indirect observations based on geophysical studies such as seismic reflection profiles [e.g., Long and Imber, 2012; Bell et al., 2008] and tomographic investigations [e.g., Allam and Ben-Zion, 2012; Latorre et al., 2004]. In particular, in the last decade, hypocentral locations of clustered events with double-difference techniques described the complex geometry of faults at depth, with a high-resolution [e.g., Waldhauser et al., 2004; Valoroso et al., 2014; Lambotte et al., 2014]. Adding the temporal information to the spatial distribution allows studying the mechanical processes at work within fault systems during the migration of seismic swarms. In numerous cases, such migrations are associated with aseismic creep [e.g., Lohman and McGuire, 2007]. In other cases, fluid circulations at depth are invoked to explain spatiotemporal variations of the seismicity, as for induced earthquakes due to man-made pore pressure perturbations [Shapiro et al., 1997; Hainzl, 2004]. Whether the controlling factor of a given seismic swarm is transient creep or pore pressure, their mutual cross-triggering and coupling with microseismicity is expected to produce complex mechanical processes [e.g., Bourouis and Bernard, 2007]. As these phenomena are controlled by the geometry, permeability, and frictional properties of the faults, often poorly known, a better understanding of the role of the fault zone structure on seismic and aseismic activities is a challenging issue.

These questions are addressed here with the detailed analysis of the 2003–2004 microseismic sequence that occurred in the western Corinth rift, Greece. We assume that the pore pressure mainly controls the observed swarm activity, as proposed by Pacchiani and Lyon-Caen [2010] for the nearby 2001 swarm. In this study, we first present the tectonic context and the data along with the tools used for characterizing the geometry of the multiplets and the seismicity diffusion process. We then present the global activated structures, in relationship with major faults, followed by our interpretation of the multiscale space-time evolution of the activity in terms of pore pressure migration. We finally discuss the inferred permeable channels and the pore pressure source.



**Figure 1.** Map and vertical section of historical earthquakes and microseismicity between 2000 and 2007. Microseismicity (circles) was recorded by the network CRLNET (black triangles) and relocated by *Lambotte et al.* [2014]. Red circles represent the studied microearthquakes occurring in 2003–2004. The yellow dashed line locates the microseismicity transition between the highly seismic western zone and the quiescent eastern zone. Historical earthquakes (blue framed dates) are from *Papazachos et al.* [1997] and *Bernard et al.* [1997]. Focal mechanism is from *Bernard et al.* [1997]. Main active faults have been compiled by *Moretti et al.* [2003], *Palyvos et al.* [2005], *Bell et al.* [2008], and M. Ford (personal communication, 2014). The red box corresponds to the map of Figure 2.

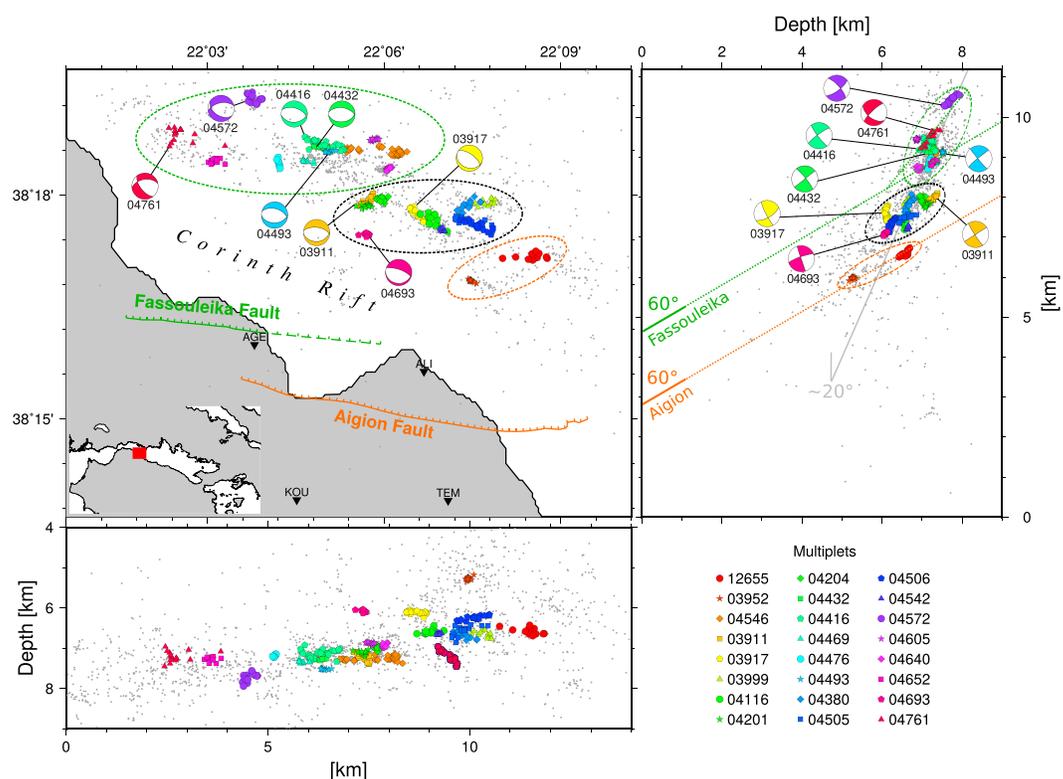
## 2. Seismotectonics and Seismological Data

The Corinth rift is a highly active seismic region, with six earthquakes of magnitude  $M_S > 6$  during the last century, all related to major normal faults developed by the back-arc extension of the Hellenic subduction and the dextral shear of the North Anatolian Fault [e.g., *Armijo et al.*, 1996; *Palyvos et al.*, 2005]. In the western rift, the last damaging earthquake occurred in 1995 ( $M = 6.2$  [*Bernard et al.*, 1997]) and activated a low-angle, north dipping blind normal fault beneath the Gulf. On the southern coast, the last large earthquakes were felt in 1861 and 1888 [*Papazachos et al.*, 1997; *Boiselet*, 2014], respectively, activating the north dipping Helike and Aigion faults (Figure 1). Revisiting and integrating instrumental and historical earthquakes, *Boiselet* [2014] finds that there is around 50% chance to expect a  $M_S > 6$  in the next 30 years in this region.

A permanent dense seismic network with 12 short-period three-component stations, the Corinth Rift Laboratory Network (CRLNET), has been installed since the years 2000–2001 in the western part of the rift. It has recorded about 10,000 earthquakes per year with  $M_W > 1.0$  [*RESIF*, 2014], and the activity is strongly clustered in time and space (<http://crlab.eu/>). The swarms last days to months and extend from 1 to 10 km long, so that the daily seismicity rate ranges from 10 events per day in quiet periods to several hundreds during swarms. A clear drop in microseismicity rate is observed to the east, delimited by a NS discontinuity in the fault system (Figure 1). This discontinuity has the same strike as the Hellenic nappe stack [*Jolivet et al.*, 2010] inherited from the convergence tectonics, that constitutes the upper 5–10 km of the crust.

Recently, a detailed analysis of the microseismicity (multiplet identification, double-difference hypocenter relocation, and focal mechanism determination) between 2000 and 2007 in the western rift has revealed the complex internal structure of the main microseismic, 1–3 km thick brittle layer, that gently dips to the north between 5 and 9 km depth [*Lambotte et al.*, 2014; *Godano et al.*, 2014], questioning the original model of a major, crustal detachment proposed by *Rigo et al.* [1996]. This multiplet database, with highly correlated waveforms, provides the opportunity to better understand the fault zone structure and the seismic-aseismic coupling processes during swarms.

Here we focus on the largest swarm (October 2003 to June 2004) in which 24 multiplets were recorded, with more than seven events in each of them (Figure 2). They consist of 411 earthquakes, with magnitudes up to



**Figure 2.** Map, EW, and NS vertical sections of the 2003–2004 swarm. The 24 main multiplets have specific colored symbols. The background microseismicity is represented as gray dots. The Aigion and Fassoouleika faults dipping about 60° at surface are the two main structures illuminated at depth by, respectively, 2 (dashed orange ellipses) and 11 (dashed green ellipses) multiplets. A third structure (dashed black ellipses) between these faults is highlighted by the remaining multiplets and assimilated to a relay zone. Focal mechanisms are from Godano *et al.* [2014].

2.9 ( $b$  value  $\approx 1.2$ ), located at a depth of about 7 km, within the main seismic layer (Figure 1). Their absolute location error is less than 1 km, and their relative one is about 10 m [Lambotte *et al.*, 2014]. Composite focal mechanisms for multiplets have been determined by jointly inverting the  $P$  polarities with the  $Sv/P$ ,  $Sh/P$ , and  $Sv/Sh$  amplitude ratios of direct waves [Godano *et al.*, 2014].

### 3. Multiplet Geometry and Pore Pressure Changes

The geometry of the 24 multiplets (length, thickness, and orientation of the best fitting plane) was defined by calculating ellipsoids containing 95% of earthquakes. The methodology is described in the supporting information and Table S1 reports the results.

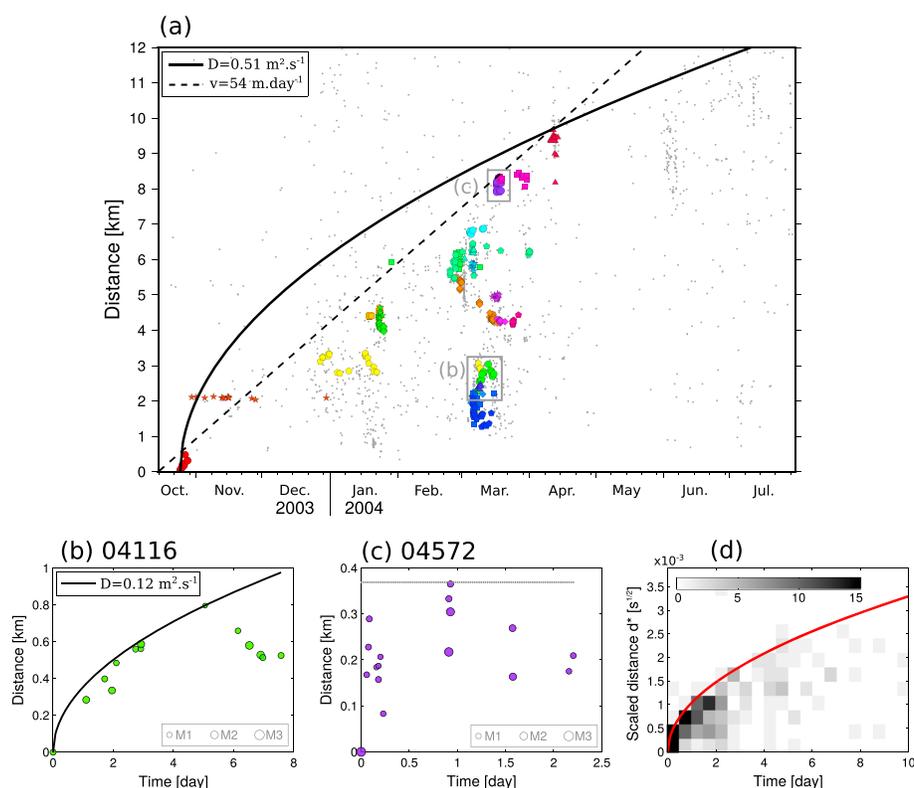
We calculated the internal diffusivity of each multiplet by assuming a pore pressure diffusion process and analyzing the spatiotemporal variations of seismicity. Based on Darcy's law and poroelasticity with a viscous fluid, the pore pressure perturbation  $p$  due to high-pressure fluid intrusion in the rock mass can be described by the diffusion's equation:

$$\frac{\partial p}{\partial t} = D \nabla^2 p \quad (1)$$

where  $D$  is the hydraulic diffusivity, typically ranging between 0.01 and 10  $\text{m}^2 \text{s}^{-1}$  in the Earth's crust [Scholz, 2002] and proportional to the permeability. When applied to seismicity induced by a transient injection of fluid from a point-like source, and considering a homogeneous isotropic medium, the distance (radius)  $d$  to the diffusing pressure front triggering the seismicity can be approximated by

$$d = \sqrt{4\pi Dt} \quad (2)$$

where  $t$  is the relative start time of the injection [Shapiro *et al.*, 1997].



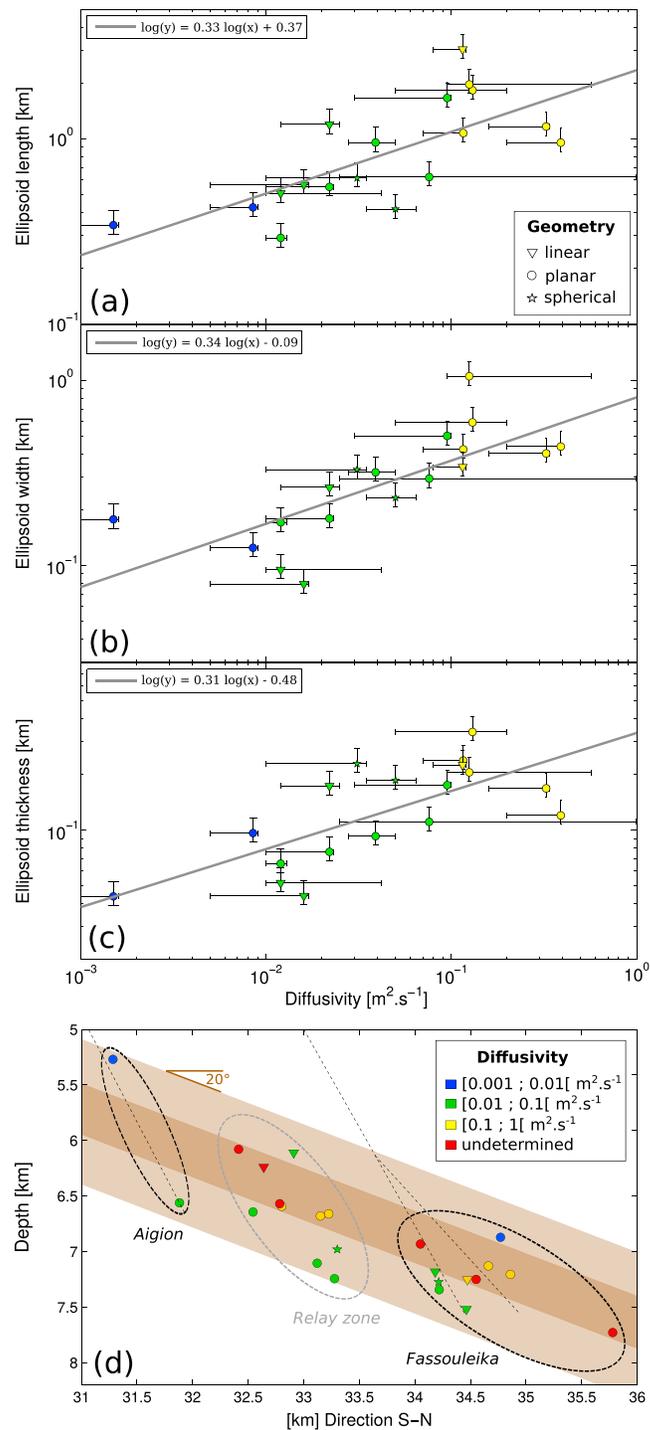
**Figure 3.** Microseismicity migration. (a) Distance-time graph considering the first event of the 2003–2004 crisis as the spatial origin. Colored symbols indicate the events of the 24 main multiplets. Gray dots show the background microseismicity. The black curve represents the theoretical diffusion law (equation (2)) with a diffusivity of  $0.51 \text{ m}^2 \text{ s}^{-1}$ . The dotted line shows a constant migration velocity of  $54 \text{ m/d}$ . (b) Example of diffusion (04116 multiplet). (c) Example of fast activations (04572 multiplet). (d) Space-time event density for the 18 multiplets associated with a diffusion law, considering the first event of each multiplet as the origin. For each multiplet  $i$  with diffusivity  $D_i$ , the y axis is defined by  $d^* = d/\sqrt{D_i} = \sqrt{4\pi t}$ .

The application of this model to natural earthquakes is, however, not straightforward because (1) the location of fluid source and its geometry is unknown and (2) earthquakes must occur at an early stage of the pore pressure diffusion to resolve the time dependence of the radius as  $\sqrt{t}$  [Pacchiani and Lyon-Caen, 2010]. The initial propagation of pore pressure could be seismically silent. Here diffusion coefficients are estimated considering the first event of the multiplet as an injection point and assuming an isotropic pore pressure diffusion. This starting point approximates the place of first fracturation, connecting the fluid reservoir to the activated faults.

## 4. Results

### 4.1. Fault and Multiplet Location

In the following we show, with the joint analysis of multiplet location, geometry, and focal mechanisms, that the swarm is mostly related to the activation of the two parallel north dipping normal faults of Aigion and Fassouleika, outcropping on the southern coast of the rift. First, the southern border of the large microseismically active zone (Figure 1) matches at depth the youngest Lambiri-Selianitica-Fassouleika-Aigion fault system [Lambotte *et al.*, 2014]. On a smaller scale (Figure 2), the first and easternmost two multiplets (12655 and 03952) are located in the downdip continuity of the Aigion fault, near its eastern edge, considering the reported dip angle of  $50\text{--}60^\circ$  inferred from the AIG10 borehole [Cornet *et al.*, 2004] and the 2000–2007 microseismicity [Lambotte *et al.*, 2014]. The westernmost multiplets (04761 and 04652) are coincident with the downdip continuity of the onland Fassouleika fault scarp assuming a similar dip angle. Eastward, the location of eight multiplets with similar normal focal mechanisms and depths shows a tight alignment with the two previous ones, potentially outlying an eastward, yet unmapped, off-shore extension of the Fassouleika fault. Eleven other multiplets appear to be located in between the above clusters, showing a complex geometry of the



**Figure 4.** Relation between intradiffusivity, dimensions, and location of multiplets. (a) Ellipsoid length, (b) width, and (c) thickness of multiplets versus intradiffusivity of multiplets in log-log scale. (d) Multiplet mean location in depth along the SN section. Undetermined diffusivities (red) correspond to the six multiplets showing nearly simultaneous ruptures along large distances. They reflect fast phenomena assimilated to very high diffusivities. High diffusivities (red-yellow) are concentrated in a 400 m thick, ~20° dipping layer (dark brown) central to the microseismogenic zone (light brown).

Aigion-Fassouleika (AF) fault system at depth and suggesting the activation of a relay zone between these two en echelon faults. These events seem to draw a third fault zone, with similar dip and azimuth as the AF fault system.

The 2003–2004 multiplets are located within the large-scale microseismic layer identified by *Lambotte et al.* [2014] at the intersection with the AF fault system. Considering that (1) the planar 04572 multiplet about 1.5 km north of the main structure has a  $\sim 45^\circ$  dipping plane, (2) the normal focal mechanisms of the Fassouleika multiplets show dip angles slightly lowering with depth, from  $60^\circ$  to  $50^\circ$  [*Godano et al.*, 2014], and (3) no microseismicity is reported beneath the seismogenic layer [*Lambotte et al.*, 2014], we propose that the AF fault system roots in this layer. The complexity and the thickness of the multiplet structures (Table S1) would then be consistent with the broadening of the fault damage zone at its root [*Kim et al.*, 2004].

## 4.2. Migration of the Microseismic Activity

### 4.2.1. Along and Across Fault Migration

The spatiotemporal analysis of microseismicity shows an overall migration from ESE to WNW at around 50 m/d, as already estimated by *Bourouis and Cornet* [2009]. This globally westward (over 10 km) and slightly downward (1 km) migration highlights the successive activation of the Aigion fault, of the relay zone, and of the Fassouleika fault. The swarm starts with the easternmost 12655 multiplet and first propagates upward along the Aigion fault to the 03952 multiplet. The latter, tightly clustered and breaking the same patch of 50 m diameter [*Duverger*, 2014], remains active during a whole month, suggesting repeater-like behavior, and thus some aseismic creep. The activity then jumped a few kilometers to the WNW, 500 m within the hanging wall. From then on, small migrations started from central to western multiplets within the relay zone, whereas the main migration continued northwestward, activating multiplets on the Fassouleika fault. The illumination of the central multiplets on the latter led to a backpropagation of activity to the eastern multiplets of the relay zone, whereas the main migration reached the western end of the Fassouleika fault (Movie S1). From equation (2) [*Shapiro et al.*, 1997] the global diffusivity is about  $0.5 \text{ m}^2 \text{ s}^{-1}$  for the whole seismic crisis (Figure 3a), but one notes a better fit with simple constant migration velocity. The latter could be favored by an increased permeability of the fault zone resulting from its dilatancy during the creep [e.g., *Cappa*, 2009] induced near the pore pressure front.

### 4.2.2. Small-Scale Migration on Subfaults

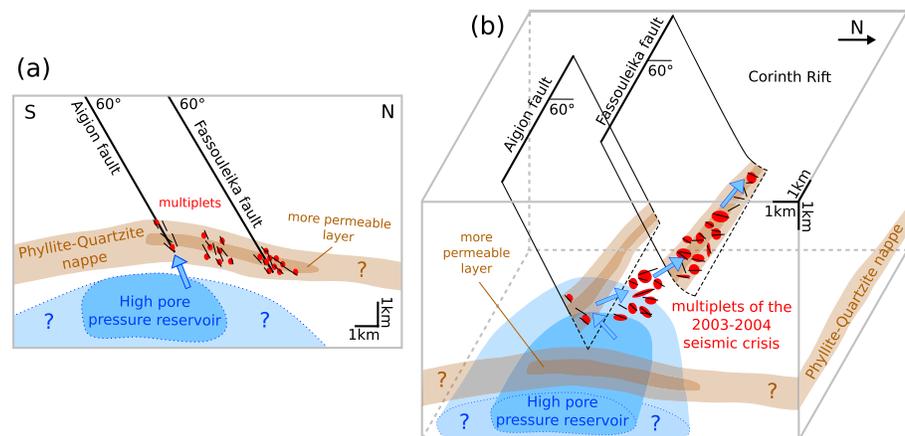
At a smaller scale, we could estimate the internal diffusivity for 18 of the 24 multiplets (Figures 3b, 3d, and S1). The six remaining multiplets (04432, 04505, 04506, 04572, 04640, and 04693) show nearly simultaneous distant ruptures (Figures 3c and S1), so that no diffusion law could be adjusted to them. The estimated diffusivity values range between  $0.001$  and  $0.4 \text{ m}^2 \text{ s}^{-1}$  (Table S1) and present a positive correlation (cubic root scaling trend) with the multiplet dimension, as shown in Figures 4a–4c. We also note that for the subfaults, the diffusivity pressure front triggers most of the activity during 2–3 days (Figure 3d), providing a possible evidence for a back front [*Parotidis et al.*, 2004].

Internal diffusivity was then jointly analyzed with the geometry and location of multiplets (Figure 4d). Using fitting ellipsoids and their aspect ratios, 18 multiplets are defined “planar,” 5 “linear,” and 2 “spherical” (see Text S1 for details). With this classification, the geometry does not seem to be correlated with the intradiffusivity or the multiplet epicentral position. However, on a SN vertical section, multiplets with high diffusivities ( $\geq 0.1 \text{ m}^2 \text{ s}^{-1}$ ), or with nearly simultaneous activations, are concentrated within the core of the microseismic layer, along a thin band about 400 m thick, dipping  $20^\circ$ , whereas multiplets with lower diffusivities ( $< 0.1 \text{ m}^2 \text{ s}^{-1}$ ) are above or below this band.

## 5. Discussion

### 5.1. Origin and Diffusion Mode of the Fluids

The global and intramultiplet diffusivities ( $0.5 \text{ m}^2 \text{ s}^{-1}$  and  $0.001$ – $0.4 \text{ m}^2 \text{ s}^{-1}$ , respectively) are typical values of fluid diffusion found in fault zone contexts at crustal depth [*Scholz*, 2002]. In the geothermal Vogtlang/Bohemia region, *Parotidis et al.* [2003] report similar space-time swarm patterns, modeled with a diffusivity of  $0.27 \text{ m}^2 \text{ s}^{-1}$ . In Corinth rift, the migration velocity of 50 m/d ( $\sim 2 \text{ m/h}$ ) compares with that of a pore pressure front diffusion [e.g., *Chen et al.*, 2012] but is significantly smaller than that estimated for creeping faults, on the order of 100–1000 m/h [e.g., *Roland and McGuire*, 2009]. However, the multiplets found with nearly simultaneous distant ruptures suggest stress transfer or creep propagation. There is thus some evidence for marginal local creep or earthquake triggering by stress transfer, but the global swarm activity appears to be dominantly fluid driven.



**Figure 5.** Sketch of proposed mechanisms for the 2003–2004 swarm. (a) SN section. (b) Three-dimensional view. The intersection of a Hellenic nappe with the AF system creates permeable corridors allowing the microseismicity diffusion forced by a deep capped high pore pressure reservoir. A fault-valve behavior [Sibson, 1992] may initiate the seismic crisis.

A few processes can lead to a slow build up of pore pressure at large crustal depths. A meteoric water overpressure effect is proposed by [Bourouis and Cornet, 2009] for the 2003–2004 swarm. However, our observation of an upward propagation of the seismicity in the early stage (from 12655 multiplet to 03952 multiplet) updip the Aigion fault contradicts this hypothesis. The overpressurized reservoir is thus probably at depth, fed either by upgoing mantellic fluids produced by the African subducting plate 50 km beneath the rift (as proposed by Bourouis and Cornet [2009] for the 2001 swarm) or by metamorphic processes within phyllosilicate-rich rocks in the seismogenic zone which may release structural water by dehydration reactions [Latorre *et al.*, 2004].

Whatever the process for a slow pore pressure increase near the root of the fault system, it has eventually led to large-scale hydroshear processes on preexisting faults, triggering the detected microseismicity. These processes were possibly accompanied by transient creep, as was reported for Soultz [Bourouis and Bernard, 2007]. This large-scale fracturation along several successive 0.1 to 1 km subfaults, is expected to have increased the local permeabilities within the fault system, which may explain the persistence of a large migration velocity.

## 5.2. Fault Zone Structure and the Geological Seismogenic Layer

The detailed multiplet geometries provide new insights on the AF fault system. Our proposed system, consisting of two main subparallel en echelon normal faults both dipping around 50–60°, provides the simplest explanation of the multiplet activity. The termination depth of both faults also fits standard values of aspect ratio (fault length-to-width ratio) [Wells and Coppersmith, 1994], with a 8–10 km length and 8–10 km width. Considering a Fassoileika fault restricted onland, a more complex fault model might also be proposed in which the northeastern multiplets mark the south dipping Trizonia fault at depth, consistent with the nodal planes of focal mechanisms (within 15° dip angle).

At subfault scale, the cubic root dependence of the multiplet size with its diffusion coefficient suggests that the larger the multiplet is, the higher the degree of fracturation is, increasing the permeability. This may arise from scale-dependent permeabilities [Guéguen *et al.*, 1996], as larger fractured rock volumes statistically sample more permeable paths. The reported highly fractured permeable layer, around 400 m thick, centered within the microseismically active layer, may be the core part of a thicker (1–2 km) brittle geological layer of the Hellenic nappe stack [Jolivet *et al.*, 2010]. Indeed, according to Latorre *et al.* [2004], the regional velocity change at 5–7 km depth seen from seismic tomography data could correspond to the tectonic contact between the karstic Gravrovo-Tripolitza limestone and the low-permeability Phyllite-Quartzite geological series. The latter, called Phyllade nappe, consists of phyllites, schists, and quartzites with local intercalation of metavolcanic rocks [Koukouvelas and Papoulis, 2009]. Latorre *et al.* [2004] emphasized that the specific characteristic of this geological unit, as well as its depth, may explain the seismicity concentration at about 6–8 km depth. Our study then strongly suggests that the intersection of the AF system with this layer produces a fractured zone building a long narrow permeable corridor in a low-permeability bulk, explaining the 1-D pore pressure migration. The presence of a higher diffusivity in the core of this layer might be enhanced by the fault terminations, as faults tips are generally associated with high damage zones.

### 5.3. High Pore Pressure Reservoir

The tomographic images by *Gautier et al.* [2006] also show a high  $\frac{V_p}{V_s}$  anomalous zone at 8–9 km close to the bottom of the microseismic layer near the root of the Aigion fault, possibly revealing the top of a high pore pressure reservoir. This interpretation requires that the bulk of the geological layer sitting on top is impermeable and acts as a cap, except, temporarily along the channels created by the cross-cutting faults.

A schematic diagram (Figure 5) shows our interpretation of the mechanisms involved during the 2003–2004 swarm. We propose that slow changes of either strain or fluid pore pressure conditions near the deep fault system eventually reached a strength limit leading to a sudden permeability increase. This would create a hydraulic connection between a deeper reservoir, capped by the Phyllade nappe, and the bottom of the Aigion fault plane, following a process similar to the fault-valve model of *Sibson* [1992]. The pore pressure migration would then have continued along the most permeable paths, in the fractured corridor built within the geological layer and maintained by the seismic cycle of the AF fault system.

## 6. Conclusion

The detailed analysis of the multiplets activated around 7 km in depth during the 2003–2004 seismic swarm in the western Corinth rift reveals a hydromechanical process, involving the migration of a pore pressure transient over 10 km along a complex, permeable, and fractured structure. It reaches an average velocity of 50 m/d and a diffusivity of  $0.5 \text{ m}^2 \text{ s}^{-1}$ . This structure is defined by the intersection of two major normal faults with a deep low-permeability geological layer, possibly the Phyllade nappe. The highest local diffusivities, appearing in the core of the seismic layer, can be related to the largest subfault structures defined by the multiplets, and to the highest damage near the tip of the fault. The high  $\frac{V_p}{V_s}$  region imaged by tomography below the main seismic layer is most likely a signal of high pore fluid pressure. This reservoir, capped by an impermeable layer, would be sporadically connected to the root of the faults above by sudden permeability changes of fractured channels. The pore pressure source, as well as the amount of aseismic creep in the area, still have to be investigated in more detail, in particular for quantifying their potential to trigger a large earthquake on the AF system. More refined tomographic images along with new studies of the most recent swarms in this area are still needed for a better characterization and quantification of the permeable paths and of the fluid pressure sources. Finally, this multiscale, high-resolution approach of natural microseismicity diffusion is also relevant for the study of microseismicity induced by man-made fluid injection, bringing valuable information on fault structure and permeabilities, useful for production and safety purpose.

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