Influence of Fluid-Assisted Healing on Fault Permeability Structure

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Abstract  Microcracks in fault damage zones can heal under thermally controlled processes. If a flow communication exists between a fluid source and the fault damage zone, warm fluids can migrate into it, change its thermal conditions, and assist healing. The crack life span depends on the local temperature and is, thus, modified by the infiltration of warm fluids. The features of the initial fault architecture govern how the fluids will propagate within the fault damage zones. This affects the rate of healing and the rate of permeability reduction. The region infiltrated by fluids will then show a significant decrease in its permeability, as seen in many field examples like the Alpine Fault. Conventionally, the damage zones immediately near the fault core have a high permeability that decays as we go further away. However, the region adjacent to the fault core, in the Alpine Fault, New Zealand, has the lowest permeability in the current interseismic period. As shown by our simulations, this can be due to healing and sealing, favored by the localized high geothermal gradients (confirmed by the drilling data) and the upward fluid migration through the fault relay structure, which accelerated mass diffusion and minerals precipitation.

1. Introduction
During and after an earthquake, the hydraulic and mechanical properties of the rock matrix change due to mechanical damage. This leads to an increase in the permeability of the fault damage zones and a reduction in their mechanical properties. In the postseismic and interseismic period (Aben et al., 2017), the rock matrix recovers its strength and its permeability decreases due to an interaction between mechanical, hydrological, and chemical processes. Thus, the fault permeability structure is complex and keeps evolving during the earthquake cycle.

Various factors can shape the structure and transport properties of damage zones around faults: lithology, the chemical conditions, the mechanical deformation, the stress system (Kim et al., 2004), and dolomitization (Korneva et al., 2017). The percentage of damage zone relative to the overall fault zone makes the fault act as a conduit, barrier, or combined conduit-barrier system (Caine et al., 1996). The core may act as a conduit during deformation and as a barrier after compaction and cementation. Also, the damage zone can act as a conduit when its microcracks are opened and as a barrier when they are filled by mineral precipitation, prone to healing by diffusive mass transfer under high temperatures and pressures, closed by pressure solution creep (Gratier et al., 2014; Renard et al., 2000), or undergone mechanical recovery by backsloping on wing crack geometries (Brantut, 2015). Thus, it is essential to understand the mechanical, chemical, and hydraulic conditions of the fault to justify how the fault structure evolved to its current state.

In faults, cracks constitute either open or closed paths for fluid diffusion (Caine et al., 1996; Gratier, 2011). Fractures, during deformation and postfracturing creep, create fluid paths through the faults. Then, fault healing processes progressively close these fluid conduits, resulting in fault strengthening and permeability reduction and a consequent delay in fluid pore pressure diffusion. Such transient behaviors have major consequences on the evolution of the permeability structure of faults and the reoccurrence of earthquakes (Gratier, 2011). Numerical simulations (Finzi et al., 2011) of long-term crustal deformation show the importance of damage and healing in the structural evolution of fault systems (Ben-Zion & Lyakhovsky, 2003) and how the ratio between healing and loading time scales would control the complexity of the fault architecture (Ben-Zion et al., 1999; Lyakhovsky et al., 2001), which in return has a direct effect on the fault permeability structure.
Despite the mentioned complexities, we can still create a general description of the fault zones. They can be characterized by a narrow highly granulated low-permeability fault core bordered by damage zones (tens of meters in scale), with a relatively higher permeability (T. M. Mitchell & Faulkner, 2009) as shown in Figure 1. This general architecture will be used, in our work, as a background permeability structure, and we will show how this can evolve into a completely different architecture by the effect of fluid-rock interaction. Since fluid-rock interaction is a highly complex interconnecting phenomenon, we focus on the role of fluids in assisting the healing by diffusive mass transport. Such processes are highly affected by fluid pressure and temperature. This requires a model that couples fluid flow, heat transfer, and microcrack healing.

The structure of the paper is organized as follows: In section 2, we explain how fluid-rock interaction affects the fault permeability structure. In section 3, we give examples of permeability reduction in fault zones from observations and field studies. We, then, describe, in section 4, the coupled heat transfer, fluid flow, and healing model and show how the various conditions and parameters affect the healing kinetics. In the simulation section 5, we present different scenarios where healing can reshape the fault structure and show the effect of fluid circulation on healing and permeability reduction. Extensive study is done on the Alpine Fault to validate if the reduction in permeability, localized in a region near the fault core, is due to fluid-assisted healing. Finally, we discuss the results and draw conclusions on the mutual effects the fault architecture and fluid circulation have on each other. High-permeability damage zones in faults enhance fluid diffusion, and in return, fluid circulation accelerates the healing of microcracks and affects the permeability structure of the fault.

2. Fluid-Rock Interaction

Fluid-rock interaction is mainly governed by geochemical processes and diffusive mass transport. Precipitation of minerals, such as iron oxides, quartz, calcite, and others, decreases the fault zone permeability. It is driven by temperature and pressure changes, fluid mixing, and chemical reactions (Person et al., 2007). While the role of fluid migration in all of these mechanisms is crucial, little is known from where these fluids originate, how they migrate, or what is their composition. Fault zones can be regions of both upward and downward migration of fluids or act as barriers to flow. In the shallow layers, fluids are most likely introduced.
through the surface. At deep levels, faults can be potential sites for upward fluid transport driven by topography and mechanical faulting, and for pressure perturbation due to prograde or retrograde metamorphism (Yardley, 1989).

Microcrack porosity and pore structure are important in determining the mechanical and transport properties of rocks. We identify a few mechanisms that help reduce the permeability of a rock matrix and where fluids play an important role. Mechanisms based on chemical reactions, like dissolution-precipitation and pressure solution, can cause microcracks in fault zones to heal with time scales that differ due to temperature and magnitude of fluid transport (Person et al., 2007). Dissolution-precipitation reactions are driven by chemical potential gradients, while pressure solution is a stress-driven mass transfer process. Both require the presence of fluid to be effective.

Healing by diffusive mass transfer (DMT) is defined as the ability of crack boundaries to recede and change their shape due to differences in chemical potential from strain and surface energy (Suo & Wang, 1994). Atoms are driven from an interface of high to low chemical potential. If the medium is not saturated with fluids, cracks cannot heal unless their faces are in contact. And as experiments show (Pluymaker & Niemeijer, 2015), healing is much slower in dry samples than in fluid saturated ones. So the presence of a fluid creates a medium for ion exchange. However, as shown from various studies (Pecher, 1981; Shelton & Orville, 1980; Smith & Evans, 1984), healing is highly affected by temperature. Thus, local changes in temperature can drive healing to become more rapid. It is important to highlight that, in the subsurface, the local temperature relates to depth, so thermal gradients are expected. Upward fluid migration, favored by fault structural complexities, might cause local temperature changes and thus enhance healing rates.

Another mechanism is sealing by secondary mineral precipitation, like quartz and calcite, transported from distant sources (Elkhoury et al., 2015). In this case as well, both fluid migration and temperatures play an important role. The fluids transport the minerals, and specific thermal conditions enhance their precipitation rates.

Most fault systems have increased structural complexities with fractures of a wide range of orientations (Kim et al., 2004, 2005; Sibson, 1996). Relay ramps of complex faults and damage zones of single, isolated faults (Fossen & Rotevatn, 2016; Kim et al., 2005) represent pathways for vertical diffusion of fluid pore pressure. Therefore, these high-permeability regions represent an important control on fluid transport and its interaction with the rock matrix (Fossen & Rotevatn, 2016). One such example is the segmented rift system in New Zealand (Rowland & Sibson, 2004), where geothermal fields are concentrated, caused by the enhanced vertical permeability of the fault structure (Fossen & Rotevatn, 2016). Also, an increased geothermal fluid activity, in fault systems, was reported by Curewitz and Karson (1997) and Dockrill and Shipton (2010).

From the above examples, we deduce that the circulation of warm subsurface fluids is an expected phenomenon whenever pathways (high permeability) from damage zones exist. Warm infiltrating fluids are the main ingredient to accelerate the majority of healing processes. In this work, we focus on the role of warm fluid circulation in accelerating healing mechanisms and reshaping the fault permeability structure.

3. Observations and Healing Mechanisms

The M7.9 Wenchuan earthquake that occurred in 2008 was reported as the largest seismic event in China in the past 50 years. Shortly after the event, the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD) conducted a series of boreholes that penetrated the main rupture zone. A significant decrease in permeability in the fault zones was noted, which reflected high healing/sealing rates (Xue et al., 2013). The permeability healing recovery rates range from $2.1 \times 10^{-17}$ to $4.1 \times 10^{-16}$ m²/year. These high healing rates suggest that fluids must be circulating in its fault damage zone. This assumption is confirmed by the high values of average hydraulic diffusivity that were measured in the site ($2.4 \times 10^{-2}$ m²/s; Xue et al., 2013). While this example shows the essential role of fluid circulation in healing/sealing, it does not give any evidence on the healing mechanism that occurred.

For the 1995 Kobe earthquake, the permeability measured by injection experiments in 2000 shows a decrease of 50% from the value in 1997 (Kitagawa et al., 2002). The permeability in the Nojima fault then stabilized within 8 years after the occurrence of the earthquake. The decrease in permeability was attributed to a decrease in the granite fracture apertures width or their closure (Kitagawa & Kano, 2016). This suggests that
surface diffusion might be the healing mechanism, and the stabilizing permeability is reached when crack shape equilibrium was achieved.

So, what is the role of fluids in all the mentioned mechanisms? First, the presence of a fluid phase facilitates the atoms exchange. Also, fluid advection affects the local temperatures and creates temperature gradients. The warm infiltration of fluids from the surface, in shallow layers, or from the subsurface in deeper layers through the high-permeability fault zones induces high local increase in temperatures and increases the fluid diffusion coefficient and the dissolution and precipitation rates. These healing processes, that is, surface diffusion, dissolution-precipitation, and sealing by nonlocal minerals, are thermally controlled, and warm fluid circulation accelerates their rates by increasing the local temperature. In the section of numerical simulations, we give scenarios where warm fluid migration thermally enhances healing, which then reduces the permeability of the fault zone.

Fault architecture has an essential control on fluid migration (Yehya et al., 2018), and in return, fluid migration affects the healing and sealing processes in rocks. Cementation along the Moab Fault (Utah) was mainly focused at the regions of fault intersection (Eichhubl et al., 2009), hence, where fluids are most likely to be conducted. Moreover, the chemical alteration has been most extensive at faults intersections in the Zagros Mountains of Iran (Sharp et al., 2010), suggesting that fluids were migrating along not across sealing faults. We use the idea of fluid transport along the fault in the first scenario in our simulations.

However, in fractured low porosity rocks, the variety in the orientation of the fractures promote the flow across the fault and thus lead to a higher overall effective permeability (Berkowitz, 1995; Fossen & Rotevatn, 2016). The cross-fault scenario is studied in our second simulation.

While fluid migration plays a major role in healing/sealing processes, the fault permeability structure is critical in controlling these processes. Thus, different fault structures heal in different ways, depending on how fluids circulate within the fault damage zones. Healing can change the conventional form of permeability structure (high near the fault core and decaying away from it). This is more elaborated in our last scenario inspired by the Alpine Fault case.

As deduced from the observations, permeability reduction mechanisms are enhanced by fluid circulation. It is important to study the controlling mechanism for each fault, but the complexity of the processes and the possibility of different mechanisms happening in parallel make this challenging. For simplicity, we will focus on the fact that healing is thermally activated or controlled and that temperatures play an important role in that. Thus, the lifetime of a crack is considered to be dependent on the temperatures.

## 4. Crack Healing Model

One mechanism of crack healing is based on a diffusion process induced by a chemical potential difference due to surface curvature (Smith & Evans, 1984). Forces to reduce high surface energy cause mass transport from crack tips to more planar crack walls. The initially sharp crack tips become round and ultimately form cylindrical voids, which are unstable and eventually turn into arrays of isolated spherical inclusions (Hickman & Evans, 1987). In this case, the healing rates are controlled by temperature, pressure, and crack geometry.

The following proposed crack healing model is based on the assumptions of a single 2-D crack in the direction perpendicular to the crack front and on the assumption that the healing kinetics are not affected by the rate of fluid transport, only by the change in temperature. As long as the fluid is chemically saturated in the mineral component, this assumption can be argued. However, if the fluid is either oversaturated or undersaturated relative to the minerals present, then the permeability change could be much different. Nevertheless, we rely on these assumptions to simplify the calculation of the permeability.

Consider 2-D cracks of initially elliptical cross section with semimajor axis \(a\) and semiminor axis \(b\). The lifetime \(\lambda\) of a crack (Smith & Evans, 1984) follows an Arrhenius-type equation. From experiments, if the lifetime \(\lambda\) of a crack at a given temperature is known to be \(\lambda_0\) at \(T = T_0\), then

\[
\lambda = \left(\frac{\lambda_0 T}{T_0}\right) \exp\left(\frac{Q}{R(1/T - 1/T_0)}\right)
\]

where \(Q\) is the activation energy for surface diffusion, obtained from experiments by Brantley et al. (1990) and \(R\) is the molar gas constant. The range of the activation energy, based on the Brantley et al. (1990)
Figure 2. Evolution of porosity in a single 2-D crack of elliptical cross section, for $n_h = 0.4$, $T_0 = 600^\circ C$, and $\lambda = 4$ hr, $p_i = 1$ MPa, $k = 10^{-17}$ m$^2$.

The evolution of porosity in a single 2-D crack of elliptical cross section, for $n_h = 0.4$, $T_0 = 600^\circ C$, and $\lambda = 4$ hr, $p_i = 1$ MPa, $k = 10^{-17}$ m$^2$.

Experiments, is between $Q = 50$ and 110 kJ/mol. Then, the distance $r$ from the center of the crack to the healing front at the elapsed time $t$ is (Engvik et al., 2009)

$$r/a = 1 - (t/\lambda)^{n_h}$$

where $n_h$ is a dimensionless constant related to the rock type and can also be obtained from experiments and site data. The volume flow, $q$, through a single elliptical tube of cross section with semiaxes $a$ and $b_r$ (Boussinesq, 1868; Lamb, 1932) is

$$q = -\left(\pi p a b_r / 4\eta\right) \left(r^2 b_r^2 / (r^2 + b_r^2)\right)$$

Equation 3 is related to Darcy fluid velocity by $q = u \pi r b_r$ with $u = -k / (\pi \eta) \nabla p$, where $k$ is the permeability, $\phi$ is the porosity, $\eta$ is the dynamic viscosity, and $p$ is the fluid pressure. The kinetics of permeability of the damage zones is governed by the change in transmissivity in a direction perpendicular to the 2-D crack of elliptical cross section. This assumption precludes the consideration of changes in crack connectivity. Then the permeability can be estimated as

$$k = (\phi r^2 b_r^2 / 4) / (r^2 + b_r^2)$$

The ratio between the initial permeability $k_0$ and the temporally changing permeability is obtained (Engvik et al., 2009) by substitution in (2):

$$k/k_0 = (\phi / \phi_0) (1 - r_0^2 / \lambda^2)^{n_h}$$

$$a^2 + b_r^2 / a^2(1 - r_0^2 / \lambda^2)^2 + b_r^2$$

If $b_r$ is very small compared to $a$, the initial crack length, then the permeability is independent of the crack width $b_r$ and proportional to the ratio between the temporal and initial porosity values (Engvik et al., 2009).

$$k/k_0 = \phi / \phi_0 = (\pi r b_r / \pi a b_r) = r_0 / a = 1 - (t/\lambda)^{n_h}$$

Equation 6 can be used to study healing under a stationary temperature. We define $n_h = 0.4$, $T_0 = 600^\circ C$, and $\lambda = 4$ hr, as obtained from the laboratory experiments done by Smith and Evans (1984) on the effect of geometry on crack healing rate in quartz. The calculated reduction of porosity, initially equal to 0.02, is described in Figure 2. The decrease in porosity leads to the decrease in permeability, which eventually decreases the fluid velocity. Figure 3 shows the effect of healing (permeability reduction) on the propagation of the fluid front. The front of an infiltrating fluid propagates a distance proportional to $\sqrt{t}$ for uniform and constant flow properties (Figure 3a). During healing, the fluid front decelerates and is blocked from propagating once the cracks fully heal (Figure 3c).

Equation 6 cannot be applied when the temperature varies with time. Engvik et al. (2009) introduced a dimensionless healing parameter $Z$ that reflects the history of the healing process and is defined as

$$Z = \int_0^t \frac{1}{\lambda(T)} \, dt$$

The dimensionless healing parameter $Z$, basically, describes how far is the state of the cracks from being fully healed. $Z$ is calculated at every position in a cracked region of elliptical-shaped microcracks. The evolution of porosity is then

$$\phi / \phi_0 = 1 - Z^{n_h}$$

Based on the above, we use a model that couples the heat and fluid flow equations through fault zones with a temporally varying permeability to fluid-assisted and heat enhanced crack healing. The average fluid velocity $\bar{u}$ in the porous media is described by Darcy,

$$\bar{u} = - (k / (\phi \eta)) \nabla p$$
Figure 3. Fluid front position: (a) constant permeability (no healing), (b) variable permeability (with healing) for $n_h = 0.4$, $T_0 = 600^\circ C$, and $\lambda = 4$ hr. $p_i = 1$ MPa, $k = 10^{-17}$ m$^2$. The fluid diffusion stops when healing occurs and the cracks close.

where $\eta$ is the dynamic viscosity and $p$ is the fluid pressure. In the saturated porous medium, the moving front of the zone of excess in pore pressure (over the hydrostatic pressure) is characterized by a vanishing value of this excess of pore pressure. If the fluid pressurization diffuses in one direction, the position $y$ of the pressure diffusion front is then obtained by

$$\frac{dy}{dt} = k \frac{p_i}{(\phi \eta y)}$$  \hspace{1cm} (10)$$

where $p_i$ is the driving pressure for fluid pressure diffusion. The temperature field $T$ is calculated by the heat transfer equation:

$$\rho_{eff}(C_p)_{eff} \left( \frac{\partial T}{\partial t} \right) + \rho_{eff}(C_p)_{eff} \vec{u} \cdot \vec{\nabla} T = \vec{\nabla} \cdot (K_{eff} \vec{\nabla} T)$$  \hspace{1cm} (11)$$

where $\rho_{eff}$ is the effective density, $(C_p)_{eff}$ is the effective heat capacity, and $K_{eff}$ is the effective thermal conductivity of the porous matrix. Note that for a parameter $X$, the averaged property of a representative elementary volume of the porous matrix is $X_{eff} = \phi X_{fluid} + (1 - \phi)X_{matrix}$. $\vec{u}$ is the fluid velocity, which increases the heat transfer by convection and may carry subsurface warmth when fluids infiltrate upward.

The lifetime of a crack is obtained from (1), the dimensionless healing parameter is calculated by (7), the porosity by (12), and the permeability is related to porosity by (13) described below. To relate both parameters, we use the power law, first proposed by Rose (1945), based on Archie’s law (Archie, 1942) for analogy between electrical resistivity and reservoir properties. The exponent $n$ is the cementation exponent that ranges for most rocks between 1.7 and 4.1 (Verwer et al., 2011). However, experiments on Fontainebleau sandstone, which has a very low porosity, showed that the exponent can reach up to 8 (Bourbie & Zinszner, 1985). In our calculation, we choose a plausible value of 3. Note that the choice of the healing exponent $n_h$ is independent of the choice of the cementation exponent $n$. The first is a parameter used to describe the healing rate of a single crack, and the second relates the crack geometry to the permeability of the cracked rock.

$$\phi(t) = \phi_0 [1 - Z^{nh}]$$  \hspace{1cm} (12)$$
In Figure 4, the main crack reaches a temperature $T_0$, which diffuses heat to the surrounding damage zone. Figure 4a shows the ratio of $T/T_0$, and Figure 4b shows the predicted reduction in porosity as cracks heal under different temperatures. Approaching the reference temperature $T_0$ for healing in the fault core (main crack) can cause rapid healing which decays as we go further away where the temperature drops. Cracks are expected to fully heal within $\lambda_0$ time at a temperature equal to $T_0$. However, under temperatures below the reference temperature, the cracks will need more time to heal. Cracks at further distances do not show porosity reduction since their temperature is much less than the reference temperature. They were not thermally activated to heal rapidly. This shows that even slight changes in temperatures (around the reference temperature) can have major effects on healing, and at temperatures much lower than that, no significant healing is obtained during the considered time. Previous experiments (Smith & Evans, 1984) suggest that modest increases in temperature can allow crack healing in intracrystalline microcracks in quartz to become quite rapid. Fluids play a major role in healing. As warm fluids circulate, they enhance the thermal conditions of the medium leading to a decrease in the life span of the crack (from (1)) and consequently result in faster healing. Equations 12 and 13 are the porosity and permeability equations after healing. The common aspect in most of the healing and sealing mechanisms is that they are thermally controlled, and that is reflected in the above equations.

In summary, regardless of what healing mechanism is dominant, we can assume that under a reference temperature $T_0$, a crack fully heals after a specific time duration called the crack lifetime $\lambda_0$. If the crack temperature is far from that reference temperature $T_0$, it will need a time to heal much more than the crack.
Table 1
Table of Parameters Used in the Simulations

| Parameter       | Value                  |
|-----------------|------------------------|
| \( \rho_{\text{fluid}} \) | 1,000 kg/m\(^3\) |
| \( \rho_{\text{matrix}} \) | 2,700 kg/m\(^3\) |
| \( (C_p)_{\text{fluid}} \) | 4,200 J/(kg K) |
| \( (C_p)_{\text{matrix}} \) | 790 J/(kg K) |
| \( K_{\text{fluid}} \) | 0.6 W/(m K) |
| \( K_{\text{matrix}} \) | 2.7 W/(m K) |
| \( \eta \) | 10\(^{-3}\) Pa s |
| \( \phi_0 \) | 0.02 |
| \( Q \) | 50,000 J/mol |
| \( R \) | 8.31 J/(mol K) |

lifetime \( \lambda_0 \). We ignore the connectivity of cracks, and the rate of fluid transport only affects the temperature field. When cracks heal, the porosity is reduced and consequently a reduction in permeability is achieved. While there are a lot of simplifications and limitations for this model, it can still give us an insight on how thermal and hydraulic conditions play a role in reshaping the permeability structure of faults.

5. Simulation Cases: Results for Different Scenarios

Mature fault zones, in general, are characterized by a low-permeability fault core bordered by high-permeability damage zones (tens of meters in scale). This permeability decays further away from the fault core (T. M. Mitchell & Faulkner, 2009; see Figure 1). While this assumption of fault architecture is valid in a lot of faults, others can have a completely different permeability structure (Caine & Forster, 1999; Caine et al., 1996). Understanding the fault architecture is important to study fluid circulation and pore pressure diffusion from any nearby pressure perturbation (Yehya et al., 2018). As fault architecture affects fluid circulation, under suitable conditions, fluid propagation in return affects the permeability structure of faults by accelerating the healing processes. Using the fluid flow model coupled with heat transfer and crack healing (Equations 9 to 13), we model different scenarios for which healing can shape the architecture of the fault zone. The parameters used in the simulations are gathered in Table 1.

5.1. Scenario 1: Asymmetric Healing

The first case is represented in Figure 5, for which the vertical fault zone has a low-permeability fault core \( (k = 10^{-21} \text{ m}^2) \) bordered by high-permeability damage zones \( (k = 1.5 \times 10^{-15} \text{ m}^2) \). A reservoir underlies the left side of the fault and is considered the source of migrating fluids. The host rock has a permeability of \( k = 10^{-19} \text{ m}^2 \). Fluid pore pressure, under high temperature, diffuses upward from the reservoir, through the left side of the damage zone due to its higher permeability. The fault core acts as a barrier to block the cross fluid flow into the right side of the damage zone. Hence, the warm fluid pore pressure diffuses mainly in the left side (L) but not in the right side (R). The increase in the temperature in the left damage zone, due to the warm fluid infiltration, accelerated the healing rates. This results in a rapid decrease in the permeability of the left side of the damage zone in comparison to that of the right side, where the temperatures remained close to the initial temperature of the medium. Equation 10 is solved with a driving pressure of 1 MPa at \( z = 0 \), and for the heat transfer equation a temperature equal to \( T_0 \) (greater than the initial temperature).

Figure 5. Schema of the fault for “Scenario 1”. The warm fluids infiltrate upward through a reservoir underlying the left damage zone. They do not cross to the right side due to the low-permeability fault core.
Figure 6. Simulation results for Scenario 1 depicted in Figure 5. (a) Fluid propagation front and (b) permeability within the fault zone at different times show an asymmetric distribution.

is set at $z = 0$ ($x$ being horizontal and $z$ vertical in Figure 5). The choice of how much $T_0$ is higher than the initial temperature affects the time needed for producing a significant reduction in permeability.

The fluid pore pressure diffuses upward by the effects of pressure difference and high permeability. Figure 6a shows the position of the propagating fluid front. The pore fluid pressure decreases at a constant rate starting with higher pressure at the inlet and to a negligible pore fluid at the front. Thus, the region invaded by the fluid front is the region of excess pore fluid pressure. As excess warm fluid pressure diffuses, it accelerates healing in the left side (L). This results in an asymmetry in the permeability structure (Figure 6b) between the left and right sides of the damage zones.

Asymmetric damage zones, with a contrast in fracture intensities, can be observed in several faults. Lithological differences and contrasting deformation histories and depths can be a major reason for that (Kristensen et al., 2016). However, localization of healing/sealing or hydrothermal alteration in one side of the damage zones can be observed in some faults. In the normal faults of the Rapolano geothermal area (Northern Apennines, Italy; Brogi, 2008), the fault cores, up to 25 cm thick, acted as barriers to fluid flow during the latest stage of faulting due to cementation caused by quartz and iron oxide precipitation. In the damage zones, fractures are infilled by minerals (carbonates, oxides, and sulfides). This is caused by hydrothermal circulation that probably originated from meteoric waters whose thermal condition is influenced by the geothermal gradient anomaly (Brogi, 2008). Diffuse hydrothermal alteration took place in the footwall damage zones, and the fault cores prevented fluids from upwelling. However, the barrier was probably laterally discontinuous, which allowed cross fluid flow. This justifies the hydrothermal alteration only along vertical fractures in the hanging wall damage zone set by the communication between them and the cross fault flow.
5.2. Scenario 2: Fluid Flow Across the Damage Zones

The width of damage zones in faults can recede with time to a more localized fracture network, either due to strain localization (T. Mitchell et al., 2013) or receding of the cracks by healing processes. In the below simulation, the borders of the healed region advance across the damage zone due to fluid flow assisted and thermally controlled healing.

Figure 7 shows the schema of the second scenario, which shows a top view of a fault at a certain depth, with damage zone of permeability $k = 1.5 \times 10^{-16}$ m$^2$. Unlike the previous scenario (where the fluid flow was migrating upward along the fault), the flow in this case is a cross-fault flow. As the simulation shows, when the fault is hydraulically connected to a fluid source at higher temperatures, warm fluids can flow across the damage zone and reduce its permeability by thermally controlled healing. Equation 10 is solved with a driving pressure of 1 MPa at $x = 0$, and for the heat transfer equation, a temperature equal to $T_0$ is set at $x = 0$ (x being horizontal and y vertical in Figure 7). Results in Figure 8 show that borders of the region, which has significantly healed within the damage zones, advance with time as fluids propagate across the fault. The two studied scenarios show how fluid-assisted healing can reshape the fault damage zones by creating regions of low permeability within it. The healing mechanism can be either by surface diffusion or by mineral precipitation. In real cases, analyzing the core samples from the site can give an indication on the mechanism. The Gole Larghe fault, for example, is a strong case on the reduction of permeability by fluid circulation mainly by minerals precipitation, since the cracks show clear filling with no reduction in fracture density (T. Mitchell et al., 2013). This suggests that cracks did not recede (heal by surface diffusion) but were sealed by precipitation of nonlocal minerals. Attributing the mechanism to healing by surface diffusion requires scanning images that show a reduction in both permeability and fracture density.

5.3. Scenario 3: The Alpine Fault

The third scenario is inspired by the Alpine Fault (see Figure 9) in New Zealand. The Alpine Fault has a length of 850 km (about 660 km onshore) along the west side of the South Island of New Zealand (Williams, 2017). The largest earthquake last occurred in 1717 CE (Common Era; De Pascale & Langridge, 2012; Wells et al., 1999). The Alpine Fault has a return period of 400–450 years, so it is in the end of its interseismic cycle, which adds interest to studying the evolution of its damage zones (Chester et al., 1993; Lin et al., 2007; Townend et al., 2009; Wasteby et al., 2014). The schema of the fault is depicted in Figure 9b. A drilling project, Deep Fault Drilling Project (DFDP; Williams, 2017), was assigned for the site, and two vertical boreholes were made in the first phase: DFDP-1A to a depth of about 100 m and DFDP-1B to a depth of about 152 m. Figure 9c shows the characteristics of the layers obtained from these boreholes. The second phase of the DFDP-2 reached a vertical depth of about 820 m.

The borehole log analysis revealed that in the current late interseismic state of the Alpine Fault, the damage zone directly adjacent to the fault core is not the region with the highest permeability (Sutherland...
et al., 2012), as would be generally expected and presumably as was the case just after the last great rupture. In the vicinity of the fault core or principal slipping zone (PSZ), a high geothermal gradient was discovered (about 125°C/km). This factor combined with fluid circulation increases the healing rates of microcracks and decreases the permeability. A healed/alterated low-permeability zone of width around 20–40 m is observed adjacent to the preferential slip zone (PSZ in Figure 9c). This is the zone marked by “HW calcite” in PSZ in Figure 9c. The borehole log analysis (Williams, 2017) shows lower crack density in the damage zone immediately adjacent to PSZ. This is unlike the previous studies of fault damage zones that find an increase in crack density near the fault core and clear decays in fracture density with increasing distance from it. Moreover, the footwall shows fewer cracks than the hanging wall but Williams (2017) notes that the footwall has a different lithology and this can control the fracture density since different mechanical properties imply a different response.

The low-permeability PSZ or the fault core acts as a barrier to cross-fault fluid flow and thus delays the pore fluid diffusion in the direction perpendicular to the fault. When fluids reach the PSZ, they do not cross into the footwall but rather migrate upward along the fault damage zone, due to their thermally enhanced buoyancy (Allis & Shi, 1995; Menzies et al., 2016; Upton et al., 1995). This hydrogeologic system, combined with the rapid advection of hanging wall rocks (Koons, 1987), leads to an increase in the geothermal gradient (40–60°C/km) within the Alpine Fault (Sutherland et al., 2012; Toy et al., 2010) and can locally exceed 125°C/km (Sutherland et al., 2017) in specific regions. This is shown in Figure 10.

Studies show that high geothermal gradient is localized in the region 50 m from the PSZ (Sutherland et al., 2017). Interestingly, low-permeability values are also obtained in this region. The high-pressure gradient across this region may be caused by the sealed cemented layer acting as a barrier and where fluid
pressure builds up. All the above conditions favor thermally activated fluid-assisted healing for microcracks in the zone immediately adjacent to the PSZ.

Initially, the fault zone has a low-permeability fault core and high-permeability fault damage zone. Fluids flow along the fault driven by the topological gradient and the anisotropy of the fault structure. The migrating warm fluids activate healing and accelerate the mass diffusion and mineral precipitation processes to ensure faster healing.

5.3.1. Healing/Sealing Mechanisms and Rates

As shown in many researches, the alteration zone in the Alpine Fault is defined by enhanced levels of phyllosilicate and calcite mineralization compared to the surrounding rocks (Boulton et al., 2017; Sutherland et al., 2012). Immediately after the earthquake, the permeability within the fault damage zone might be enhanced by 3–8 orders of magnitude. This transiently enhances the fluid circulation and consequently the healing and sealing processes (Allen et al., 2017). Renard et al. (2000) proposed a mechanism for crack seal and creep, in damage zones, by solution dissolution and precipitation mass transfer, which is fully described.
Figure 10. (a) Fluid pressure increases with depth and promotes the upward infiltration of warm fluids and (b) geothermal gradient in the Alpine Fault obtained from the Deep Fault Drilling Project DFDP-2. (Sutherland et al., 2017).

by the surface chemical potential. The rate of precipitation on pore or vein surface is expressed as follows:

\[ R_p = k_p \Omega \left( 1 - \frac{c_p}{K_{eq}} \right) \]  

(14)

where \( k_p \) is the kinetics constant for mineral precipitation and \( K_{eq} \) the equilibrium constant for the reaction of dissolution/precipitation, \( \Omega \) is the molar volume of the dissolving solid, and \( c_p \) is the concentration in the pore or vein. \( K_{eq} \) is temperature dependent. In quartz, under stress-free state

\[ \log(K_{eq}) = 1.881 - 0.002028T - 1560/T \]  

(15)

In calcite,

\[ \log(K_{eq}) = -171.065 - 0.0077993T + 2839.319/T + 71.595 \log(T) \]  

(16)

Renard et al. (2000) calculated the porosity reduction due to pressure solution by stylolitization and precipitation in quartz and calcite veins as a function of time. While the microstructural features in the Alpine Fault do not show evidence for pressure solution (Schuck et al., 2020; Williams, 2017), the calculation provided by Renard et al. (2000) can still be helpful in determining the time scale for the sealing process. Modifying the calculation for a geothermal gradient of 60°C/km to 125°C/km and average crack aperture of \( a = 600 \mu m \), we obtain in Figure 11 the duration, in years, for reducing the porosity from 0.02 to 0, or in other words fully sealing the cracks. In the region where the geothermal gradient is 60°C/km (continuous lines in Figure 11), the permeability reduction occurs between 0 and 3.7 km because of calcite precipitation in open fractures. The reverse solubility of calcite, which results in lower solubility at high temperatures, will lead to slow precipitation after 3.7 km. Below 4.5–5 km, the kinetics of quartz dissolution and precipitation are fast enough to allow vein sealing. As noted by Renard et al. (2000), there
Table 2
Table of Parameters Used for Healing Time Scales (Freer, 1981; Parks, 1984; Rimstidt & Barnes, 1980; Weaver et al., 1979)

| Parameter                  | Value                        |
|----------------------------|------------------------------|
| Quartz molar volume        | 22.690 \times 10^{-6} m^3/mol|
| Quartz surface energy      | 335 – 385 mJ/m²              |
| \(D_0\) of Si              | 1.08 \times 10^{-15} m²/s    |
| \(E_a\) of Si              | 132.7 kJ/mol                 |
| \(D_0\) of O               | 2.00 \times 10^{-10} m²/s    |
| \(E_a\) of O              | 230.0 kJ/mol                 |
| Quartz dissolution rate \(k_a\)| 1.1174-2.028 \times 10^{-3}T - 4158/T |

The number of years needed for healing to occur in quartz if surface diffusion is the dominant mechanism (black and gray curves) or precipitation-dissolution is the dominant mechanism (blue curves). As we conclude from Figure 12, the surface diffusion in quartz (SiO₂) is controlled by the surface diffusion coefficient of Si and O. For the allowable healing period of the Alpine Fault, diffusion driven by crack geometry can only play a role at very high temperatures >800°C which is found below 6 km for a geothermal gradient of 125°C/km and below 13 km for a geothermal gradient of 60°C/km. The rates are highly affected by the aperture size, which suggests that this mechanism can be significant for smaller cracks. Dissolution-precipitation driven healing is effective (<400 years period for healing) at temperatures that range between 150°C and 200°C, depending on the aperture. This corresponds to depths below 1.5 km for a geothermal gradient of 125°C/km and below 3 km for a geothermal gradient of 60°C/km. These depths will increase even higher for \(a = 600 \mu m\). On the other hand, in Figure 13, we plot the time scale for surface diffusion driven by crack geometry for calcite versus the time scale for dissolution-precipitation in quartz. We deduce that at the above mechanism, which is based on local elements dissolution and precipitation and pressure solution, is not the dominant, and other parallel processes should have occurred in parallel. In the Alpine Fault, the fluids that circulate in the hanging wall are dominantly meteoric in origin and calcite saturated (Williams, 2017). This further enhances the sealing of fractures. Within the so-called alteration zone, migration of carbonate-saturated meteoric fluids in chemical disequilibrium with the rock would promote the precipitation of carbonate, and phyllosilicate minerals, resulting in a transient decrease in permeability and sealing. The width of this alteration zone is determined by the steep topography and anisotropy of the damage zones which facilitate updp migration of hotter fault zone fluids and constrained its diffusion across the zone. As a result, a gradual reduction in porosity and permeability occurred by a combination of healing by dissolution and precipitation of local minerals, which is thermally activated and enhanced by the presence of fluid, and sealing through precipitation of transported minerals, which is also thermally activated but requires advective fluid flow and infiltration (Boulton et al., 2017). In our model, the rate of fluid advection is given by Equation 10.

To understand what mechanisms can be responsible for creating the alteration zone in the Alpine Fault, let us compare the different rates for different processes. The time scale for surface diffusion is \(t_{sd} \sim RTa^{3/2}/D_\delta_s\), where \(D_s\) is the surface diffusivity \((D_s = D_0 e^{-E_a/RT})\), \(\delta_s\) is the thickness of the diffusion layer usually assumed to be equal to \(\Omega^{1/3}\), and \(\Omega\) is the molar volume. The time scale for dissolution is \(t_p \sim 1/\Omega \delta^2_s\), where \(k_p\) is the dissolution rate. The values for the parameters controlling the different processes are grouped in Table 2. The rate of surface diffusion in calcite is extremely low at low temperatures, but the rate starts to increase substantially as we go deeper. We will first do the comparison for quartz, which is active in deeper levels. At shallow levels, calcite dissolution and precipitation is the dominant mechanism. Figure 12 shows the number of years needed for healing to occur in quartz if surface diffusion is the dominant mechanism (black and gray curves) or precipitation-dissolution is the dominant mechanism (blue curves). As we conclude from Figure 12, the surface diffusion in quartz (SiO₂) is controlled by the surface diffusion coefficient of Si and O. For the allowable healing period of the Alpine Fault, diffusion driven by crack geometry can only play a role at very high temperatures >800°C which is found below 6 km for a geothermal gradient of 125°C/km and below 13 km for a geothermal gradient of 60°C/km. The rates are highly affected by the aperture size, which suggests that this mechanism can be significant for smaller cracks. Dissolution-precipitation driven healing is effective (<400 years period for healing) at temperatures that range between 150°C and 200°C, depending on the aperture. This corresponds to depths below 1.5 km for a geothermal gradient of 125°C/km and below 3 km for a geothermal gradient of 60°C/km. These depths will increase even higher for \(a = 600 \mu m\). On the other hand, in Figure 13, we plot the time scale for surface diffusion driven by crack geometry for calcite versus the time scale for dissolution-precipitation in quartz. We deduce that at
temperatures $>1250\,^\circ C$, the mechanism of surface diffusion driven by crack geometry in calcite approaches the healing by dissolution-precipitation in quartz. This suggests that rock matrix containing calcite will heal by surface diffusion at depths $>12\,\text{km}$, where calcite solubility is low. So based on the calculated rates, both surface diffusion and mineral precipitation could be contributing to the healing/sealing of the Alpine Fault, depending on the depth and thermal conditions. All these mechanisms are thermally controlled and enhanced by fluid diffusion. As a way to combine all the mechanisms, we propose to define the lifetime of a crack by Equation 2 which depends on temperature and an activation energy for crack healing/sealing. The constants are fitted to give crack lifetimes within the estimated interseismic period of the fault (around 400–450 years).

5.3.2. Simulations Results
To simulate the third scenario, we use the coupled fluid flow, heat transfer, and crack healing model. An important parameter in this model is the healing exponent $n_h$. Based on the observations, in the Alpine Fault, the earthquake return period, and current permeability values (estimated from borehole log analysis (Williams, 2017)), we deduce the most suitable healing parameter for our simulations. The last major rupture of the Alpine Fault was in 1717 CE (De Pascale & Langridge, 2012; Wells et al., 1999), and the fault is in its late interseismic cycle. Different values of the healing exponent would give different crack lifetime values. Since we know from observations that the permeability in the zone adjacent to the PSZ is about 2–3 orders of magnitude less than that at distances greater than 150 m from PSZ, this suggests (by (6)) a relation between the crack lifetime and the healing exponent $n_h$, taking $t$ equal to 300 years. The plot in Figure 14 shows how the crack lifetime varies with the choice of the healing exponent.

We use the exponent obtained in the experiments (Hickman & Evans, 1987; Smith & Evans, 1984) $n_h = 0.4$, which corresponds to a plausible crack lifetime of about 380 years. Basically, this means that at the chosen reference temperature the fault cracks will fully heal after 380 years.

The high geothermal gradient observed in the region adjacent to the fault core, and its absence further away, suggests that this high gradient might be caused by the circulation of subsurface fluids (convective heat transfer) within the initially high-permeability damage zone (before being healed). We test if the heat transfer by convection can create such temperature variation. For this, we solve the 1-D heat convection-diffusion equation along the fault (Figure 9). Initial conditions for the temperature field follow the $60\,^\circ C/\text{km}$ gradient (for each $x$ [in km] belonging to the model $z = 5x/7.8$ and $T = 60\,^\circ C/\text{km}[z]$). Results, in Figure 15b, show that a gradient close to $125\,^\circ C/\text{km}$ can be obtained in 300 years, with an average fluid infiltrating velocity of $10^{-7}\,\text{m/s}$. This value is plausible for the pressure values measured. We then use the fluid pressure data (Figure 10a) to calculate the fluid infiltration velocity $u_f = k/\phi\eta(\Delta p/\Delta z)$, plotted in Figure 15a, within the upper 800 m of the fault and introduce it in the heat convection diffusion equation. Results for $t = 300$ years are represented in Figure 15b. The model predicted temperatures that are plausibly close to the field data. In the simulation, we used a constant permeability of $10^{-16}\,\text{m}^2$, which is not the real case, especially as the permeability is expected to vary spatially and temporally. But this assumption is acceptable since the aim is to understand if the heat anomaly can be created by fluid circulation in the damage zone. Based on the results (Figure 15b), the geothermal gradient is created by heat convection and is localized within 50 m from the fault core since it is the region of fluid circulation. Consequently, it is plausible to assume that warm fluids circulating in this zone can accelerate healing in this region.

Taking the field temperature data from Sutherland et al. (2017; Figure 16a), we apply the thermally activating crack healing model along the depth (1-D simulation) and obtain the porosity and permeability
Figure 15. (a) Fluid infiltration velocity. (b) Temperature values obtained in the model compared to field data.
reduction in Figure 16. The calculated porosity (Figure 16b) and permeability (Figure 16c) within 50 m from the fault core (PSZ) have reduced values, indicating a healed region. This matches the observations. The highest permeability values are those corresponding to regions 150 m or more away from PSZ, where the temperature gradient is much lower. This is consistent with the assumption that healing is accelerated at higher temperatures. We take the reference temperature $T_o$ to be 40°C. This means that for healing at exponent $n_h = 0.4$, it will take the cracks 380 years to fully heal at this temperature.
To better understand how the low-permeability region in the damage zone near the fault core is created, we simulate the Alpine Fault section, represented in Figure 9c, using the coupled heat transfer, fluid flow, and crack healing model. We assume that warm fluids are infiltrating from the subsurface through the damage zone at \((x = 0 \text{ and } -160 \text{ m} < z < -100 \text{ m})\) with a pressure of 0.5 MPa \((x\) being the horizontal and \(z\) the vertical). This causes the diffusion of excess pore pressure along the fault zone. No-flow boundary conditions are taken for the fluid flow equations. Fluid flow, driven by topological and pressure gradients, requires an anisotropic permeability \((k_{xx} \gg k_{zz})\), in the fault zone, to localize fluid circulation and healing in a region of 20–40 m, as seen from observations and field studies. The fluid front is defined by the surface on which \(p\) vanishes, where \(p\) is the pressure excess above hydrostatic pressure. We denote by \(l_f\) the infiltrated region, so that \(l_f = 1\) in this region and 0 elsewhere.

The surrounding temperature in the upper 200 m is about 20°C, but the warm fluids \((>20^\circ\text{C})\) infiltrating through the damage zone (previously having high permeability) from deeper levels accelerate healing of the microcracks. We add a heat source term to (11) carried by the warm infiltrating fluid and taken equal to \(C_p l_f/\lambda_0 T_0\), where \(\lambda_0\) and \(T_0\) are chosen to result in substantial healing after 300 years equivalent to observations \((\lambda_0 = 400 \text{ years and } T_0 = 40^\circ\text{C})\). \(k_{xx} = k_{11}\) is chosen initially to be around \(10^{-14} \text{ m}^2\) and \(k_{zz} = k_{22}\) equal to \(10^{-16} \text{ m}^2\). This will force mass and heat diffusion parallel to PSZ and localize healing in 20–40 m adjacent to it, as the drilling project results reveal. The initial permeability structure, that is, just after the 1717 CE event, is taken as higher permeability near fault core and linearly decaying as we go away (Figure 17, continuous line).

Figure 17 shows the permeability across the fault zone, and Figure 18 shows the permeability evolution with time at different locations in the fault zone. Figure 19 shows the map of predicted permeability results. Reduction (healing) is localized within 40 m from the upper PSZ. Healing is enhanced in the region near PSZ, and substantial reduction in the permeability is obtained. The permeability in closer regions to PSZ will have the lower permeability after about 100 years. Our results can be supported by the recent work of Schuck et al. (2020) who analyzed the XRF data by employing the Isocon method (Grant, 1986) to evaluate the role of fluid migration in rock alteration and mineral precipitation. By this method, enrichment or depletion of an element relative to the host rock can be determined. The Isocon analyses showed that all investigated fault rocks have been substantially altered by fluids. It also confirmed that fluid circulation occurs only in the hanging wall. The Isocon analyses of DFDP-1A samples show increasing degrees of fluid-assisted alteration toward the PSZ with the highest values immediately close to it (Schuck et al., 2020).
Figure 19. Permeability reduction (healing) is localized within 40 m of PSZ (fault core—marked by a thick yellow line) at different time periods after the 1717 event: (a) initially (immediately after the EQ), (b) after about 100 years, and (c) after 300 years.

6. Conclusion

Healing and sealing processes are thermally controlled, and their rates are accelerated by the presence of fluids and high geothermal gradients. We used a fluid flow model coupled with heat transfer and crack healing to simulate healing processes in fault zones. Crack healing is based on a kinetic equation deduced from the healing experiments by Smith and Evans (1984) and Brantley et al. (1990). Healing is affected by pressure, temperature, and fluid chemistry. The kinetics of microcrack healing vary with chemical composition. However, in our model, we did not explicitly consider the changes in concentrations of different minerals. For a more comprehensive analysis, a different kinetic equation should be used, in such case. Brantley et al. (1990) performed experiments on the effect of fluid chemistry on the lifetime of microcracks in quartz. The rate of healing was found to be enhanced by the presence of salt (NaCl and CaCl₂) and delayed by the presence of CO₂, but it was noted that the healing rates are less affected by fluid chemistry than by crack geometry.
Fluid circulation can be a factor to enhance healing and sealing. Upward migration of warm fluids, through relay fault ramps, is expected due to the thermal and pressure gradients and differences in permeability between layers. The idea is based on that the crack life span depends on the local temperature. The local temperature can be modified by the infiltration of warm fluids. The features of the initial fault architecture govern how the fluids will propagate. This affects the rate of healing and thus the rate of permeability reduction. The region infiltrated by fluids can show a significant decrease in its permeability as seen in many field examples, like the Alpine Fault.

Field studies, in the Alpine Fault, showed the presence of a cemented layer of 20–40 m in width, directly adjacent fault core. This is dissimilar to previous studies of fault damage zones (T. M. Mitchell & Faulkner, 2009) that find clear decays in permeability with increasing distance from the fault core. As shown in our simulations, this can be due to thermally activated and controlled healing and sealing, favored by the high geothermal gradients and fluid migration. A substantial anisotropy of the initial fault damage zone is required to localize the healing process in a 20–40 m zone. In other words the fluid diffusion will be along the fault and not across it. Consequently, the resulting 20–40 m healed zone then acts as a barrier and changes the fault thermal and hydraulic conditions, which affects its rupture conditions. As another example, a zone of increased calcite cementation, of 1 km in width, is found along the hanging wall of Dombjerg Fault (Greenland; Kristensen et al., 2016). The determined cementation temperatures (Salomon et al., 2020) require temperatures higher than the normal geothermal gradient and that can relate to upward fluid migration along the fault. Hence, thermal and hydraulic conditions play an important role in the fault permeability structure and its evolution during the interseismic period. It is necessary to take that into consideration when studying the seismic cycles of the faults.

Data Availability Statement
The data related to this work can be accessed through the following link (https://data.4tu.nl/articles/Data_underlying_the_research_into_the_role_of_fluids_in_assisting_the_healing_process_of_micro-cracks_in_fault_damage_zones_/12763718).

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