

TERNARY FAULT PERMEABILITY DIAGRAM: AN INNOVATIVE WAY TO ESTIMATE FAULT ZONES HYDRAULICS.



Irène Aubert, Juliette Lamarche, Philippe Léonide



Aix-Marseille Université, CNRS, IRD, Cerege, Um 34, 3 Place Victor Hugo (Case 67), 13331 Marseille Cedex 03, France



**Ternary diagram
overview**



Operating principle



**From permeability
to drain properties**



**Application
to case studies**

*If you need further
informations click on*



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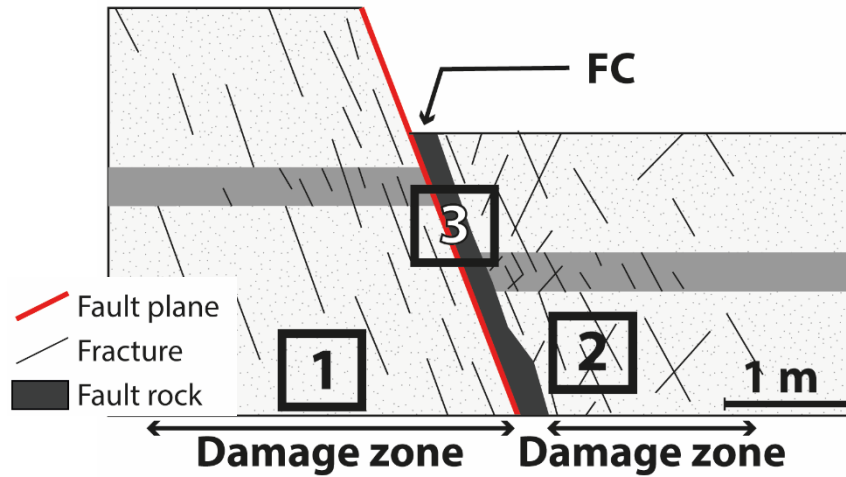
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TERNARY DIAGRAM OVERVIEW

Fault zones are either barriers enhancing reservoir sealing, or drains breaching the reservoir seals. To quantify the impact of fault zones on reservoir fluid dynamics through geological time, it is important to decipher the fault zone hydraulic properties.



The bulk permeability depends of 3 permeability components: fracture, fault core and matrix, as well as their spatial arrangements in three dimensions.

If you need further informations on the permeability components click on



METHODS TO DEFINE FAULT ZONE DRAIN PROP.

To determine the fault zone permeability/drain properties several methods have been developed, that can be sorted into 3 approaches :

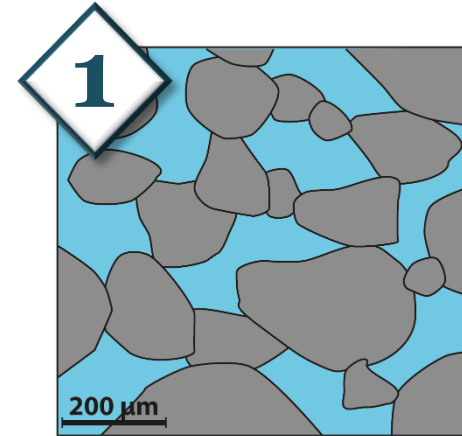
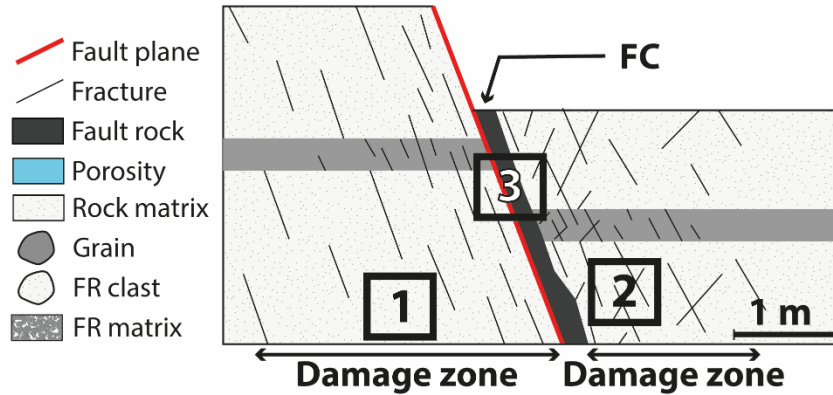
- 1: The fault properties are measured and modelled in each fault zone parts
- 2: The fault drain properties are determined through lithologic juxtapositions
- 3: The fault zone seal properties are determined through the use of algorithms

Up to date none of them integrate simultaneously the 3 components : fracture, fault core and matrix permeabilities and their evolution with time

We present a ternary plot integrating simultaneously fracture, fault core and matrix permeability :
the TERNARY FAULT PERMEABILITY DIAGRAM

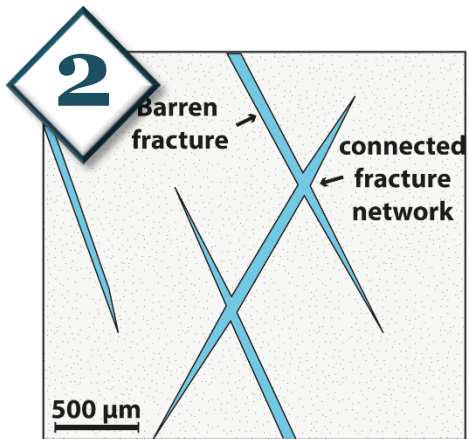
Fault zone permeability depends of 3 permeability

components:



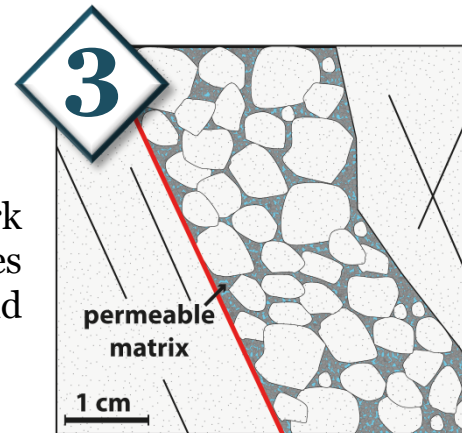
The matrix

The matrix permeability is dependent on the intrinsic rock porosity which does not include fracture porosity as rock type, pore size and diagenesis.



The fractures

In the damage zone, the fracture network permeability depends on fracture properties including aperture, connectivity, and cementation.



The fault core

Composed of breccias, gouges and other cataclastic rocks with lenses of the surrounding damage zone, the permeability in the fault core depends on the degree of cataclastic processes, the nature of the matrix, and the fault rock cementation.

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The ternary plot can be used **qualitatively and/or quantitatively**. To use it, one can measure or estimate permeability values of each components in a fault zone.

The ternary plot can be used to characterize fault zones in **underground reservoirs** as well as **exposed fossil faults**, in an **efficient and simple way**.

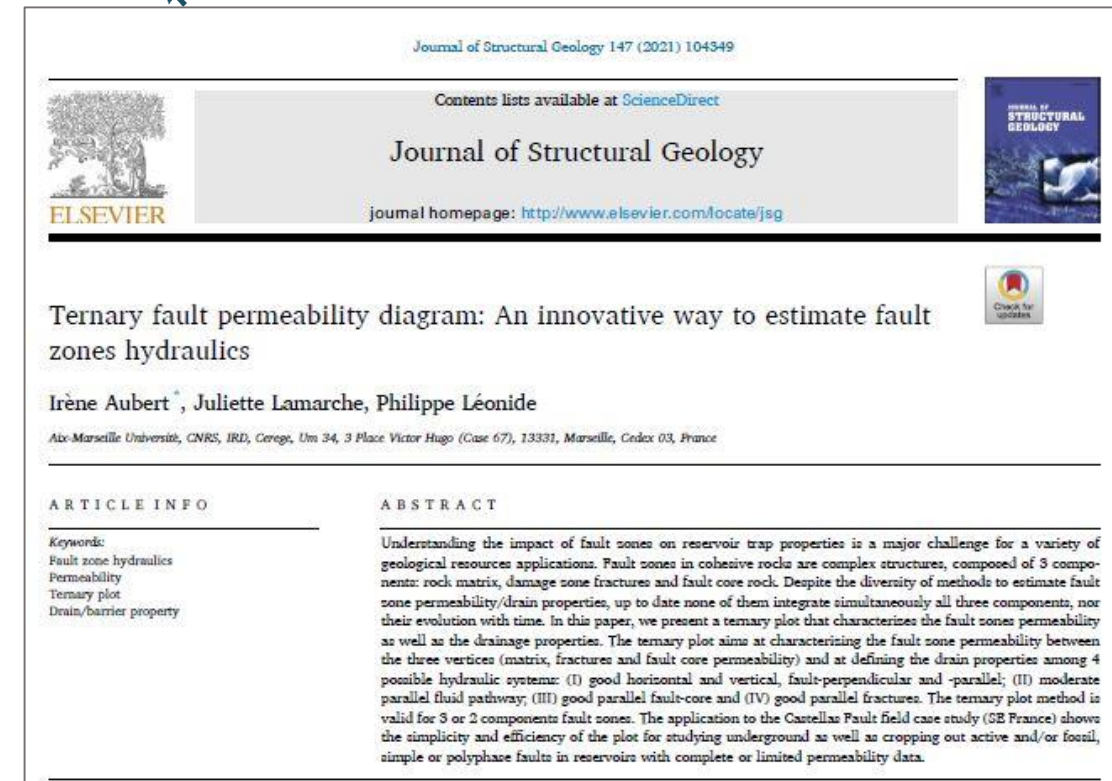
This method might be a **powerful tool** to capture the predictions of complex hydraulic systems in **faulted reservoirs modelling**.

The systematic use of the proposed method allows a straightforward and useful **comparison for faults in different reservoirs, countries, lithologies in a consistent diagram**.

This presentation shows the results exposed in the following publication:



Ternary fault permeability diagram: An innovative way to estimate fault zones hydraulics
Irène Aubert, Juliette Lamarche, Philippe Léonide



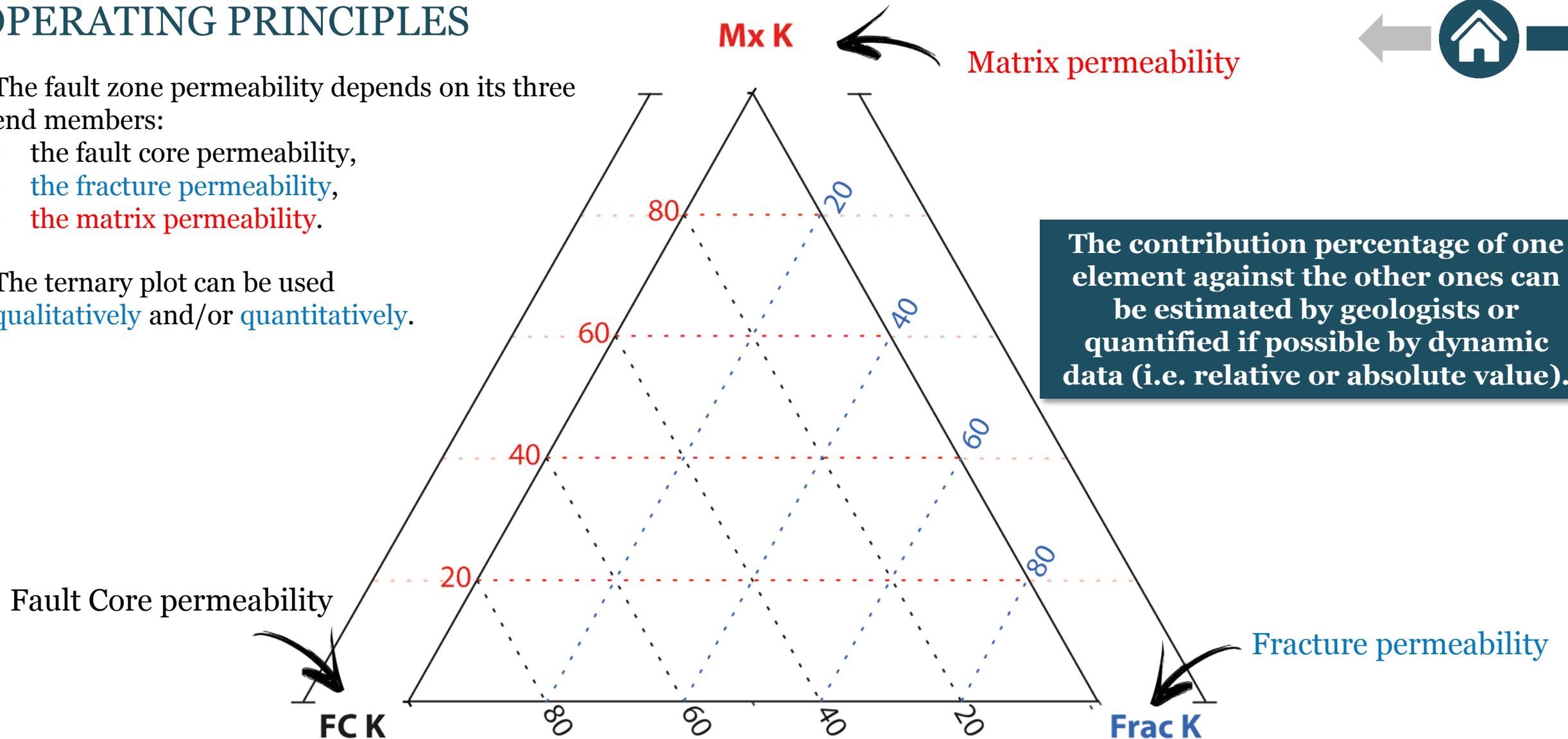


OPERATING PRINCIPLES

The fault zone permeability depends on its three end members:

- the fault core permeability,
- the fracture permeability,
- the matrix permeability.

The ternary plot can be used qualitatively and/or quantitatively.

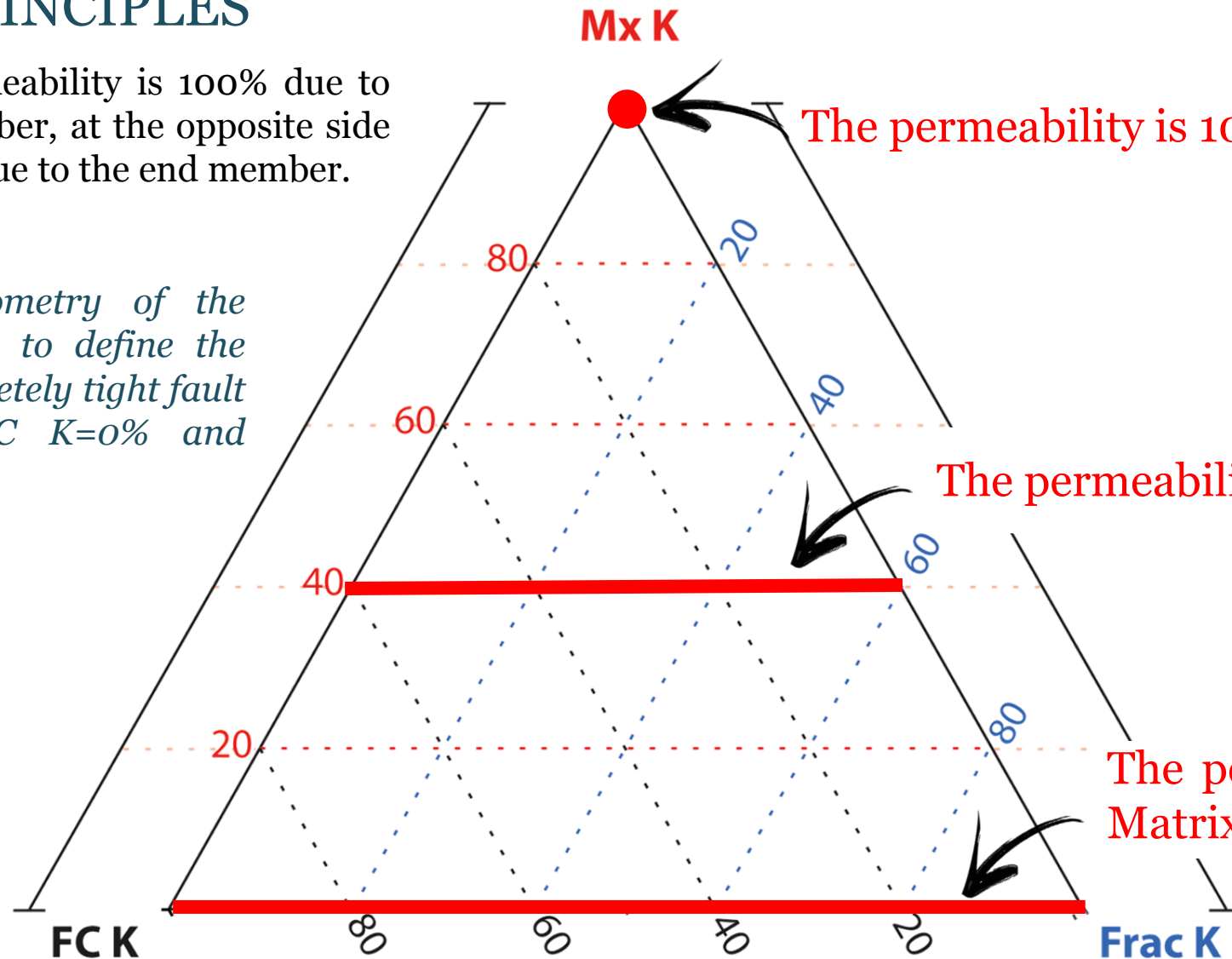




OPERATING PRINCIPLES

At the vertex, the permeability is 100% due to the concerned end member, at the opposite side the permeability is 0% due to the end member.

The concept and geometry of the diagram do not allow to define the characteristics of completely tight fault zones ($Mx\ K=0\%$, $FC\ K=0\%$ and fracture $K=0\%$).



The permeability is 100% due to Matrix

The permeability is 40% due to Matrix

The permeability is 0% due to Matrix

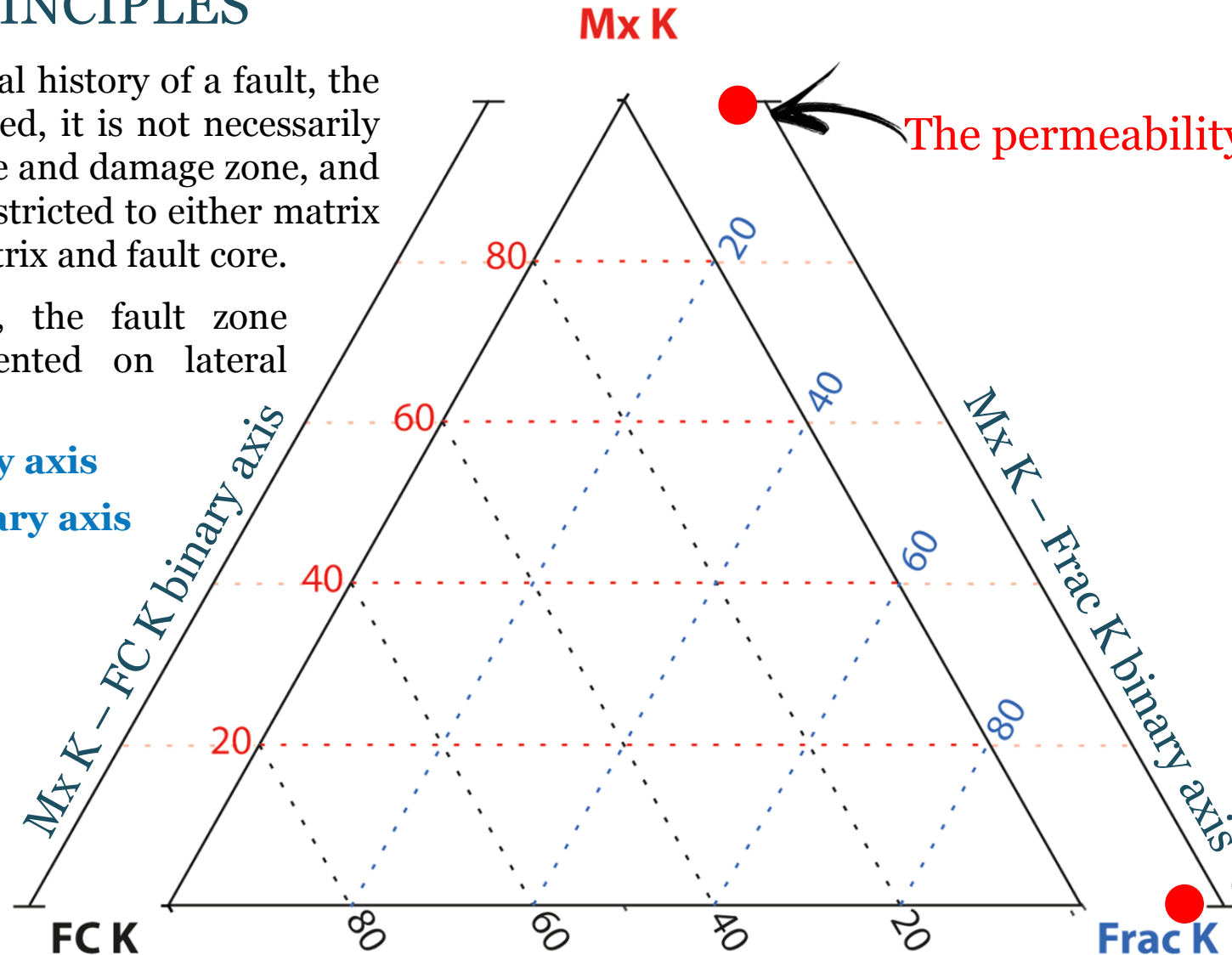


OPERATING PRINCIPLES

Throughout the geological history of a fault, the rock matrix always existed, it is not necessarily the case for the fault core and damage zone, and the fault zone may be restricted to either matrix and damage zone, or matrix and fault core.

Hence, in these cases, the fault zone permeability is represented on lateral **binary axes** :

- **Mx K – FC K binary axis**
- **Mx K – Frac K binary axis**

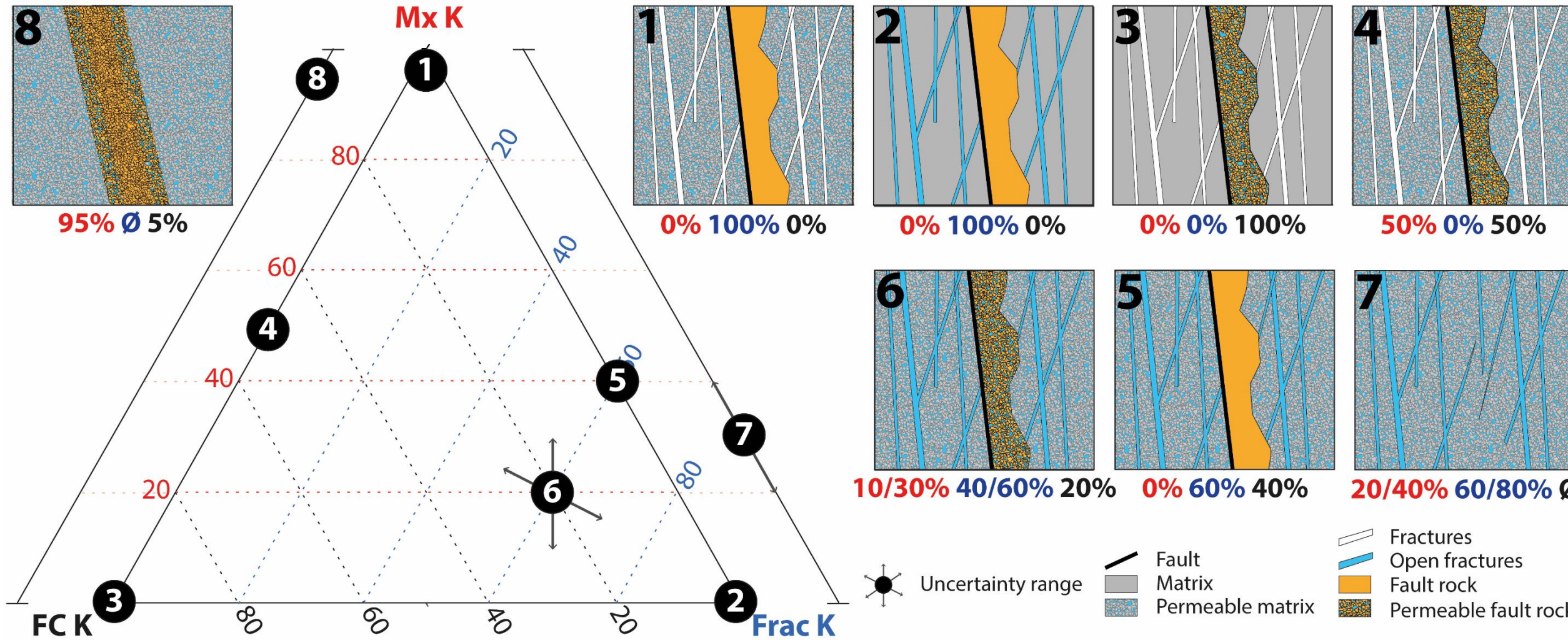


The permeability is 0% due to Matrix

TERNARY FAULT PERMEABILITY DIAGRAM



OPERATING PRINCIPLES - EXAMPLES



TERNARY FAULT PERMEABILITY DIAGRAM



FROM PERMEABILITY TO DRAIN PROPERTIES

4 types of hydraulic systems can be inferred from fault zone permeability

i **Type I:** good horizontal and vertical, fault-perpendicular and -parallel

Implication: the system acts as if the fault zone has no barrier effect on fluid flow.

i **Type III:** good parallel fault-core

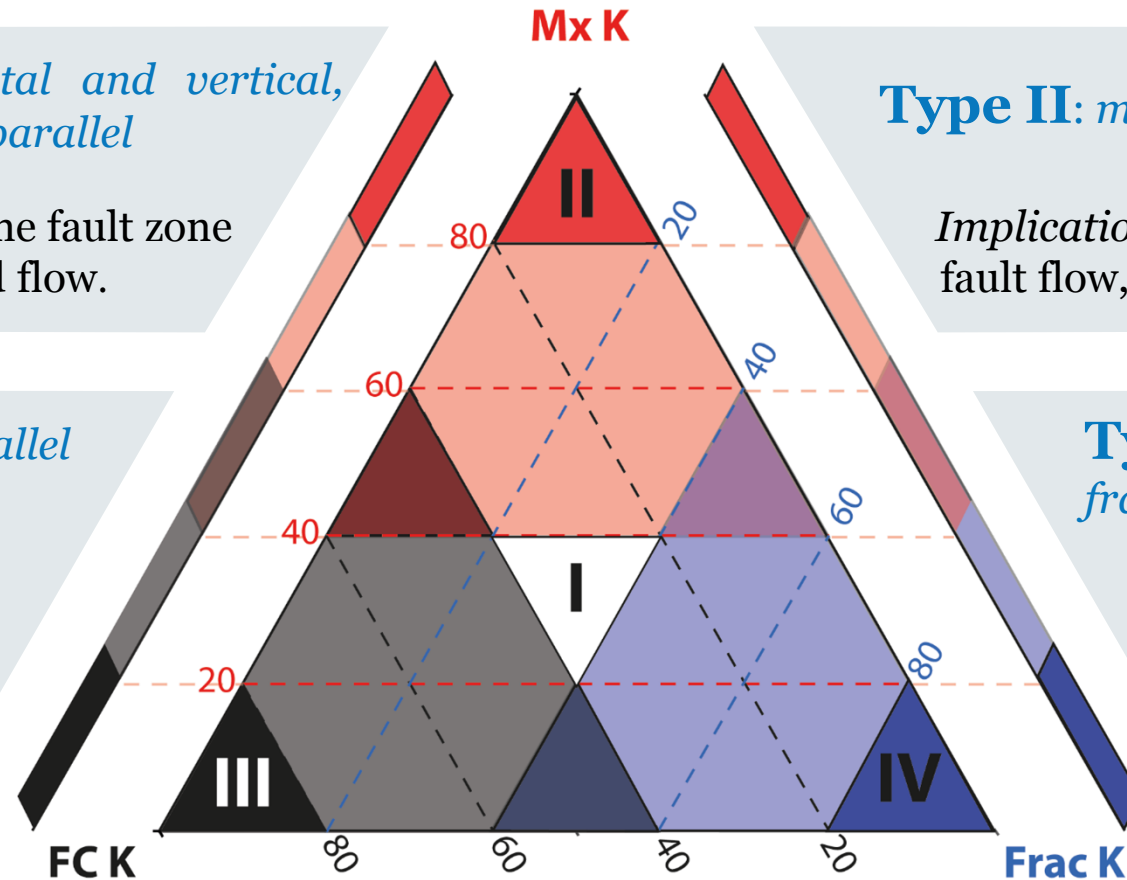
Implication: the fault zone forms a narrow, localised conduit with the damage zone acting as a barrier.

i **Type II:** moderate parallel

Implication: the fault is a barrier to across-fault flow, and there is no localised conduit.

i **Type IV:** good parallel fractures

Implication: the fault zone forms a parallel to fault conduit but an across-fault barrier.



i **Binary fault systems**

Fractures influence zone
Fault core influence zone
Matrix influence zone

For types illustration
click on

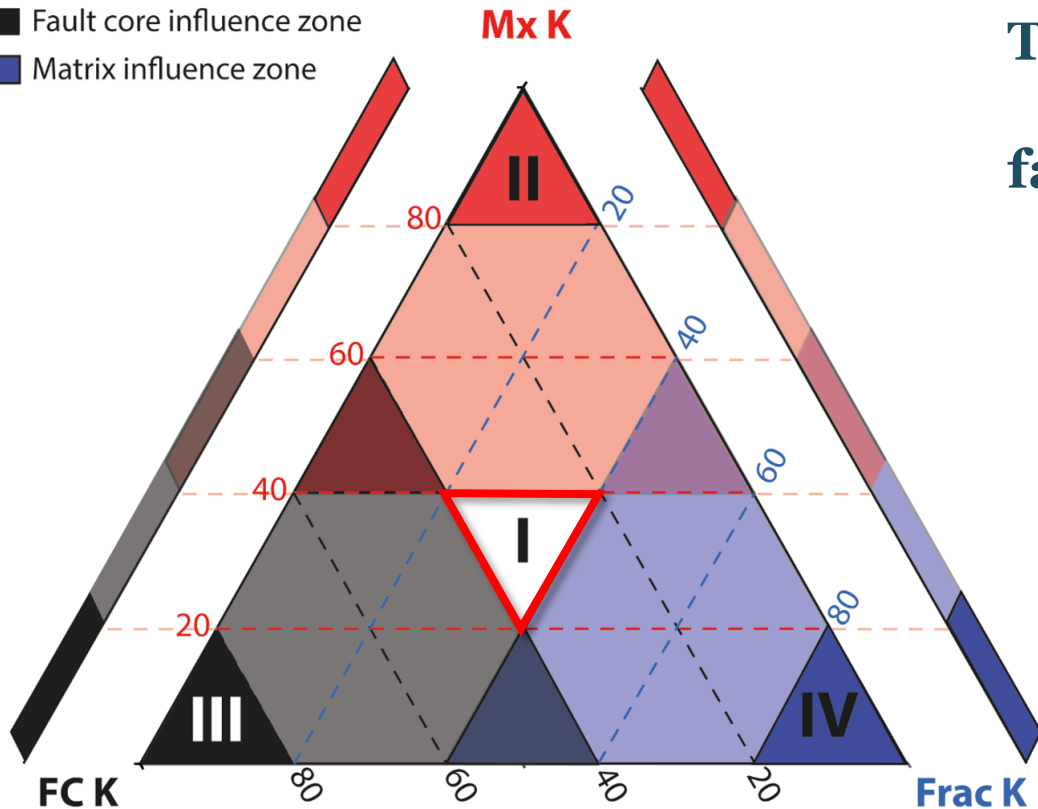


FROM PERMEABILITY TO DRAIN PROPERTIES

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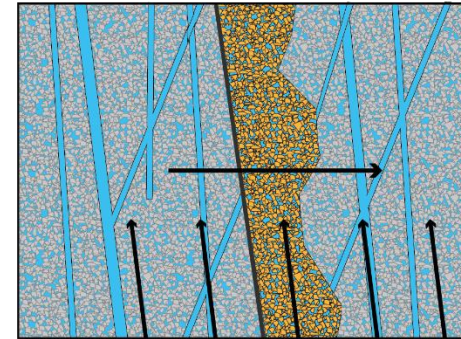


- Fractures influence zone
- Fault core influence zone
- Matrix influence zone



Type I: good horizontal and vertical, fault-perpendicular and -parallel.

The fault zone combines fracture, matrix and fault core permeability in almost equal proportions. The fault zone forms a good horizontal and vertical, fault-perpendicular and fault-parallel fluid pathway.



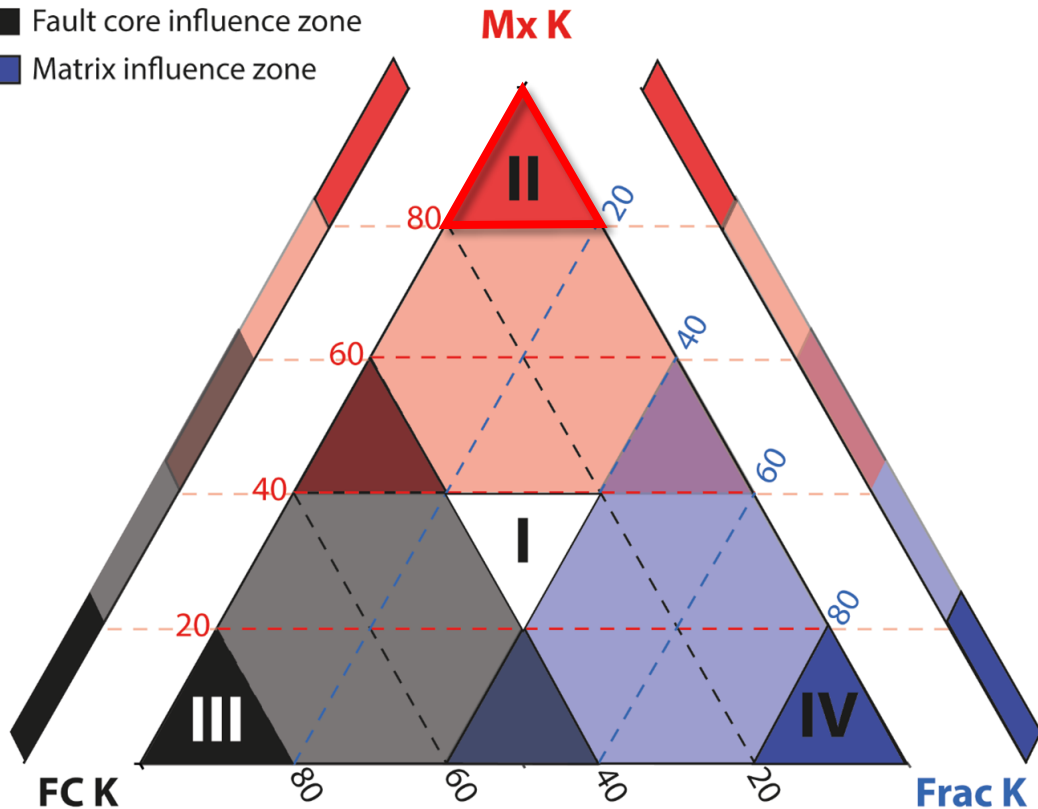
- Absence of fluid pathway
- Moderate fluid pathway
- Good fluid pathway
- Matrix
- Permeable matrix
- Fractures
- Permeable fractures
- Fault rock
- Permeable fault rock

Implication: the system acts as if the fault zone has no barrier effect on fluid flow.



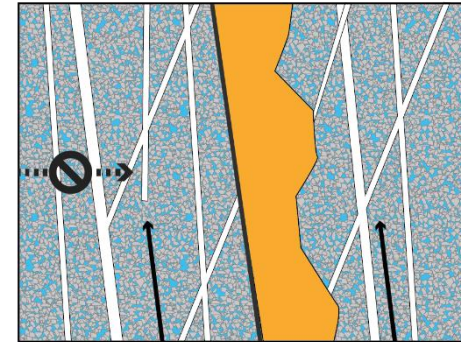
FROM PERMEABILITY TO DRAIN PROPERTIES

- Fractures influence zone
- Fault core influence zone
- Matrix influence zone



Type II: moderate parallel.

The permeability is only provided by the matrix. The fault core and fracture network are tight. The fault-perpendicular flows are not possible because the fault core is a barrier. The fault-parallel flows are limited because the fracture network is tight. The drain properties are conditioned by the rock type, the pore size and the diagenesis of the matrix.



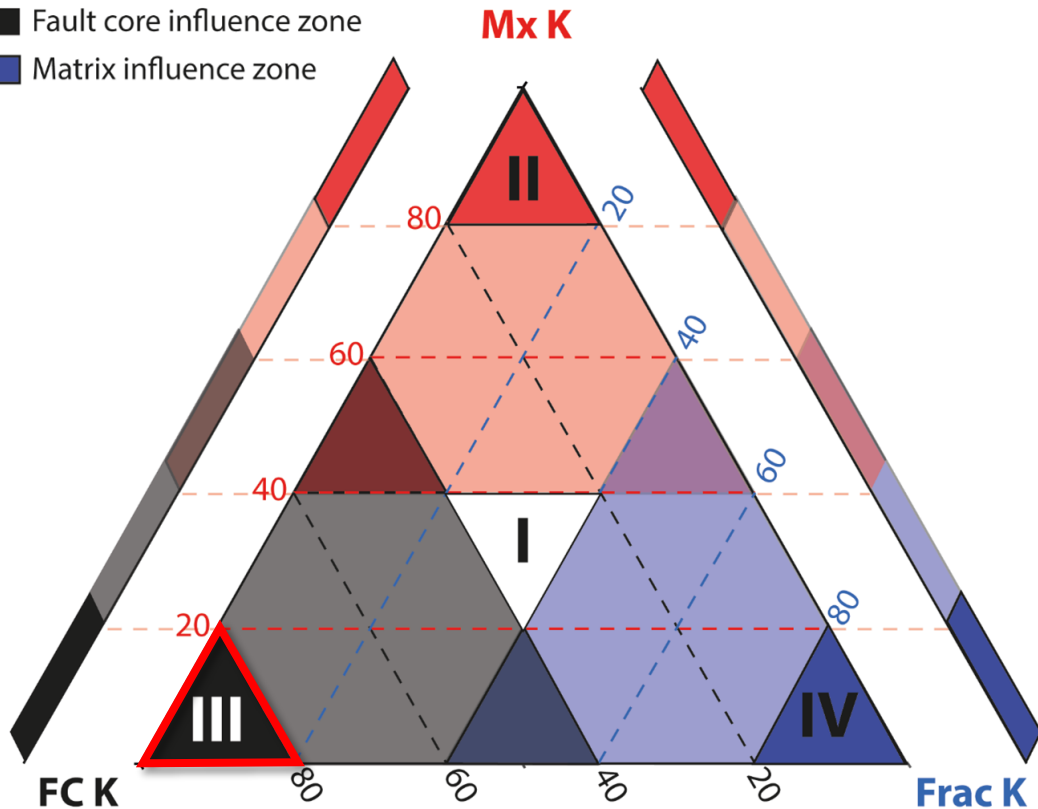
- Absence of fluid pathway
- Moderate fluid pathway
- Good fluid pathway
- Matrix
- Permeable matrix
- Fractures
- Permeable fractures
- Fault rock
- Permeable fault rock

Implication: the fault is a barrier to across-fault flow, and there is no localised conduit.



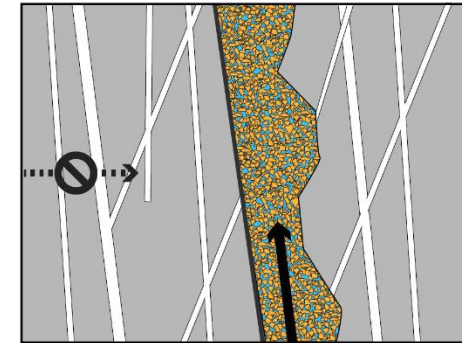
FROM PERMEABILITY TO DRAIN PROPERTIES

- Fractures influence zone
- Fault core influence zone
- Matrix influence zone



Type III: good parallel fault-core.

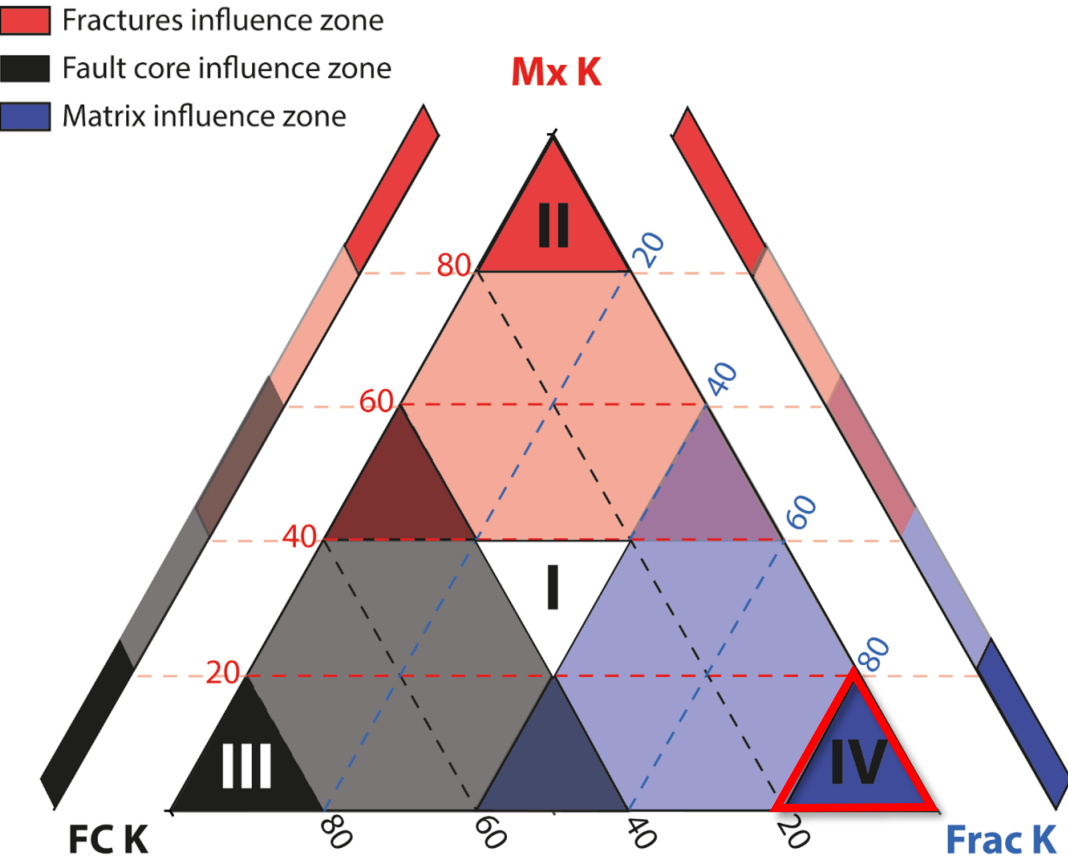
The permeability is only induced by the fault core. The matrix and fracture network are tight (or the fracture non-existent – or non-percolating). The fault zone is a fault-parallel drain limited to the fault core. The fractures and matrix are barriers to perpendicular flows. The fault zone drain properties are reliant on the degree of deformation, on the presence/absence of clays and on the cementation of the fault rock in the core.



Implication: the fault zone forms a narrow, localised conduit with the damage zone acting as a barrier.

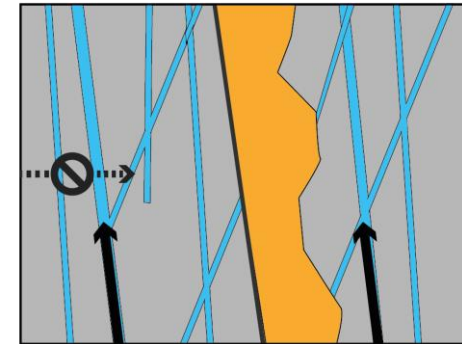


FROM PERMEABILITY TO DRAIN PROPERTIES



Type IV: good parallel fractures.

The permeability is only induced by the fracture network. The matrix and fault core are tight. The fault zone forms a drain along the fracture network leading to fault-parallel flows. The tight fault core forms a barrier to perpendicular flows. The average fault zone drain properties are strongly dependant on fracture aperture, connectivity and cementation.



- Absence of fluid pathway
- Moderate fluid pathway
- Good fluid pathway
- Matrix
- Permeable matrix
- Fractures
- Permeable fractures
- Fault rock
- Permeable fault rock

Implication: the fault zone forms a parallel to fault conduit but an across-fault barrier.

FROM PERMEABILITY TO DRAIN PROPERTIES

Binary fault systems

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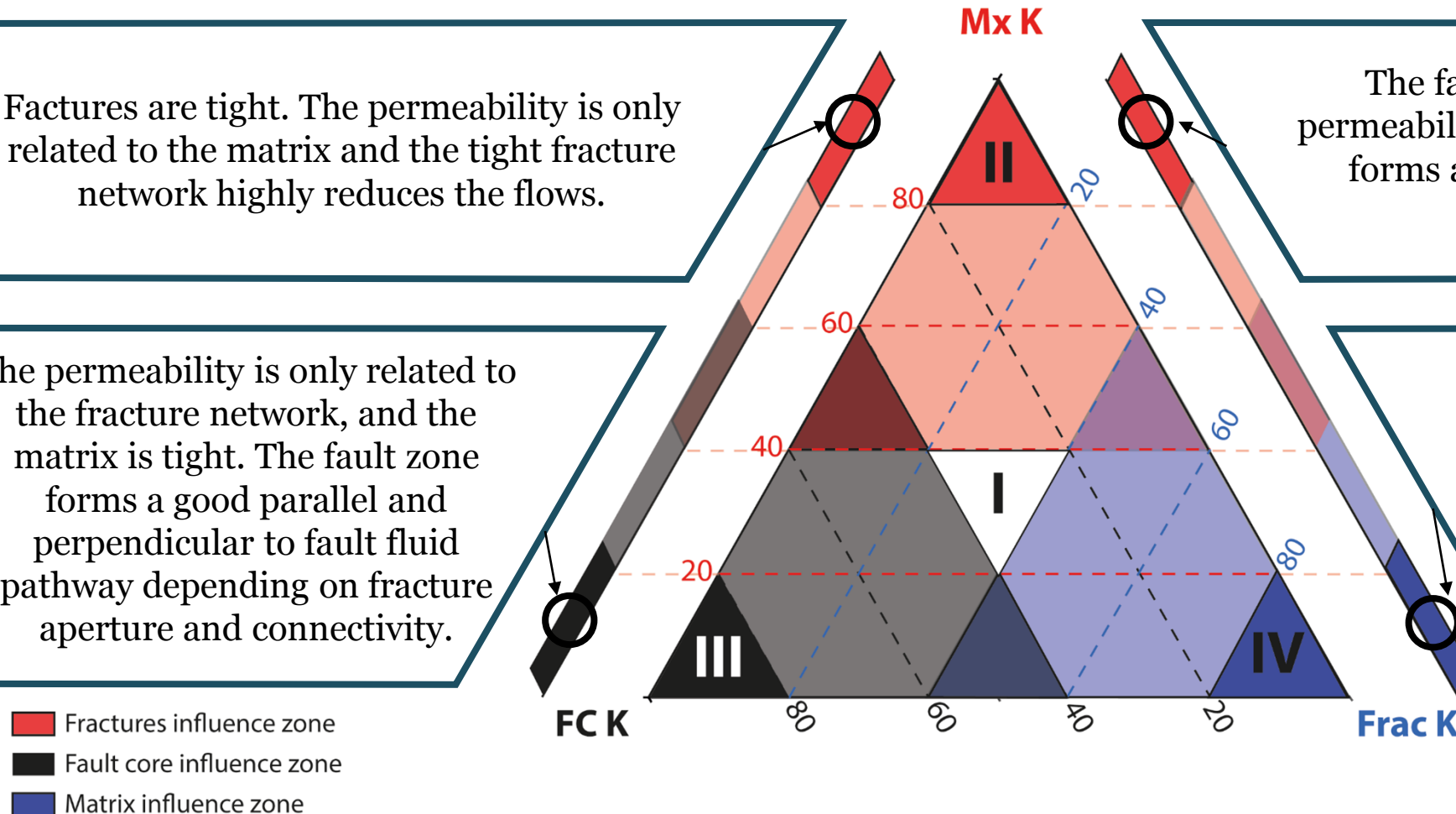


Fractures are tight. The permeability is only related to the matrix and the tight fracture network highly reduces the flows.

The fault core is tight. The fault zone permeability is only related to the matrix and forms a moderate parallel to fault fluid pathway.

The permeability is only related to the fracture network, and the matrix is tight. The fault zone forms a good parallel and perpendicular to fault fluid pathway depending on fracture aperture and connectivity.

The permeability is only related to the fault core, and the matrix is tight. The fault zone forms a good parallel to fault fluid pathway limited to the fault core.



APPLICATION TO CASE STUDIES

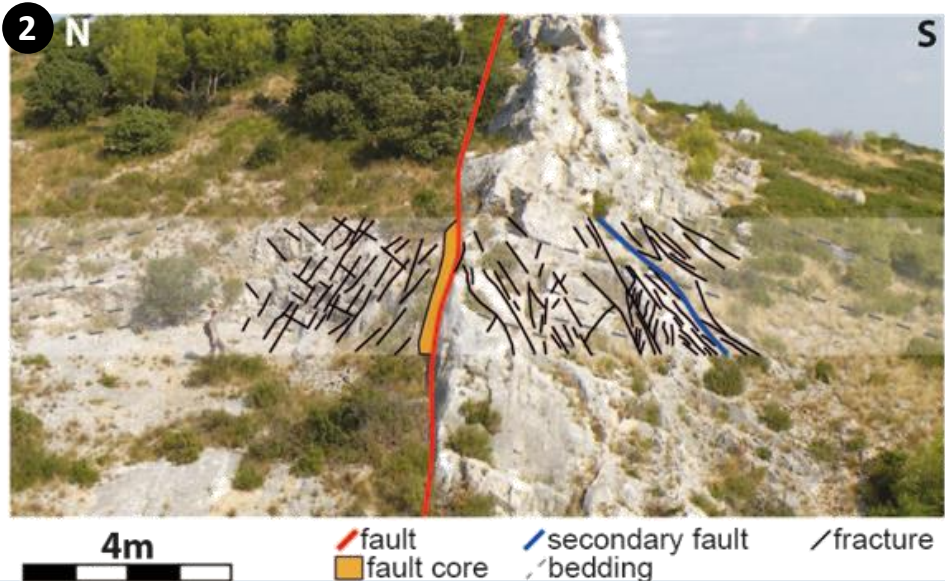
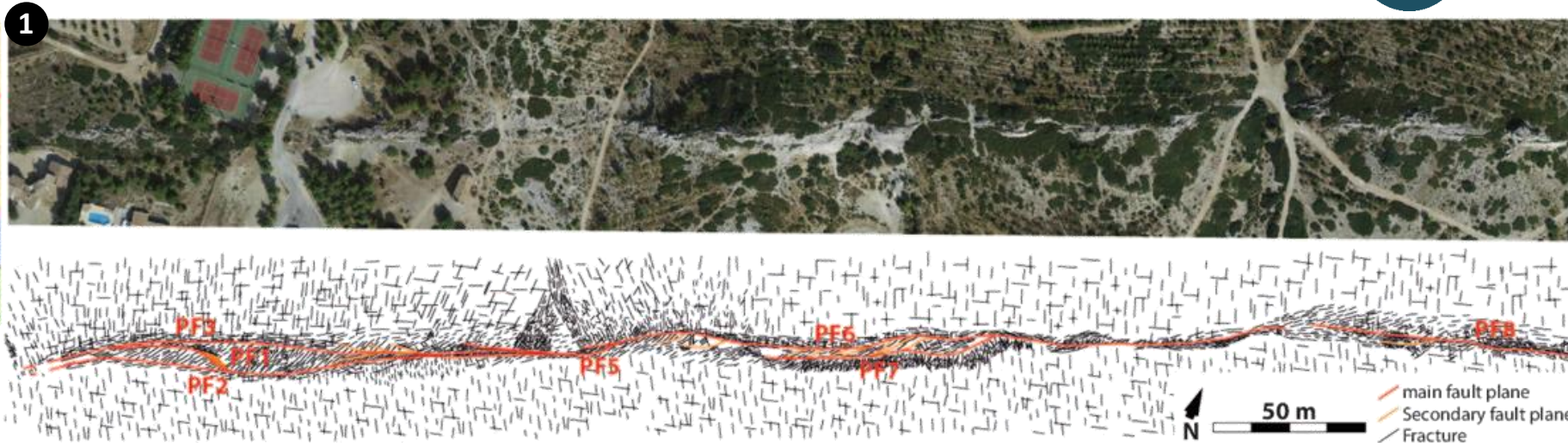
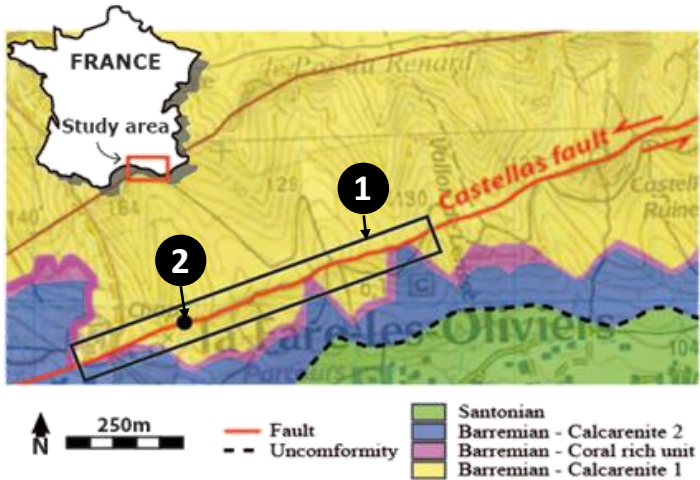


**CASTELLAS FAULT ZONE
(SE FRANCE)**



**EXAMPLES FROM THE
LITERATURE**

APPLICATION TO CASE STUDIES – CASTELLAS FAULT ZONE



The fault strikes N070° 70N



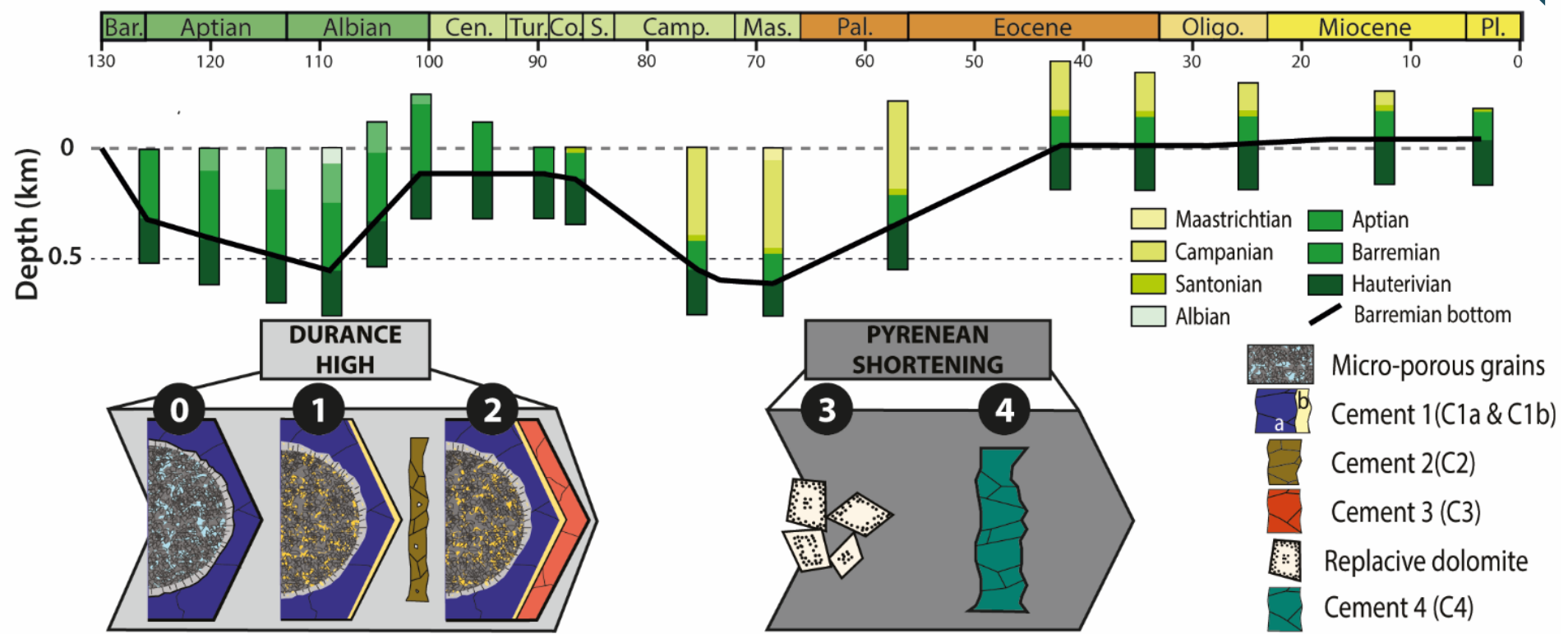
The fault affects early Barremian calcarenites of La Fare anticline (SE France)



The damage zone is composed of anastomosed fault planes



APPLICATION TO CASE STUDIES – CASTELLAS FAULT ZONE

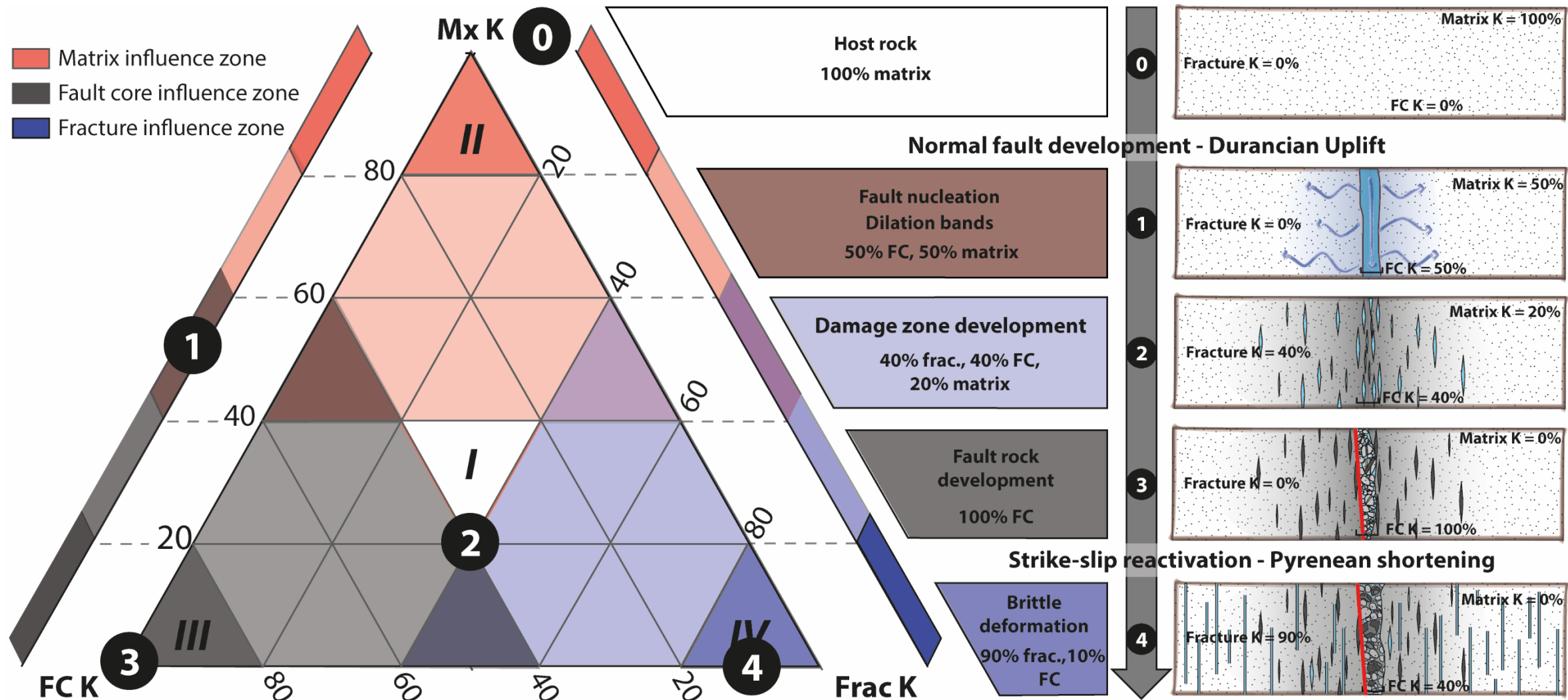


- The Castellás fault initiated during the mid-Cretaceous Durancian uplift as a normal fault. During the Pyrenean shortening, the La Fare anticline formed, and the Castellás fault was reactivated as sinistral strike-slip.
- Five types of cements have been discriminated. Their description combined with isotopic measurements (^{18}O and ^{13}C) allowed to decipher the fault zone paragenetic sequence described in details in Aubert et al. (2020)



APPLICATION TO CASE STUDIES – CASTELLAS FAULT ZONE

From the Barremian times to the present-day, the diagenesis and tectonics have resulted into 4 hydraulic systems :



APPLICATION TO CASE STUDIES EXAMPLES FROM THE LITERATURE

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Name & location	reference	kinematic	host rock	Throw	permeability properties			Position ternary plot
					Matrix	Fracture	Fault core	
Fault member #2 Tablate area, Granada Basin	Agosta et al., 2012	Normal	Carbonates	10cm	cemented	Widely developed fracture network	Impermeable core. Breccias and gouges	2
Ras ir Raheb & Victoria Lines fault zones, Malta	Haines et al., 2016	Normal	Carbonates	11,7m & 100m	Cemented - Low porosity	Fluid flow conduit	Breccias and cataclasites. Very low permeability values (0,001-0,0001mD)	2
Faults of Applecross Cambrian formation	Laubach et al., 2014	Strike-slip	Sandstones	<10m	Very low to no porosity $\Phi < 1\%$	Isolated but mostly open	Indurated fault rock (gouge). Barrier	2
Faults of Eriboll Cambrian formation	Laubach et al., 2014	Strike-slip	Sandstones	<10m	Very low to no porosity $\Phi < 1\%$	Quartz-sealed fractures	Cemented breccias but cavities >0,04mm. Porous	3
Faults of Barreiras Formation, NE Brazil Stage 4	Balsamo et al., 2010	Normal	Sandstones	>30m	Intergranular fractures and dilation bands. Strong increase of macroporosity and pore connectivity		Macroporosity reduced by mechanical compaction	5
D19 fault zone Provence, SE France	Aubert et al., 2019	Strike-slip	Carbonates	undefined	cemented matrix $\Phi < 5\%$	Barren fracture network	Partly cemented	6
Faults of Favignata site	Tondi et al., 2016	Strike-slip	Carbonates	10 to >200cm	Compacted grainzone and calcite precipitation. $\Phi < 7\%$	Ø	Zone of grain and porosity reduction. $\Phi < 1\%$	8