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# FRACTURE CLEAVAGE AND HOST-ROCK COMPETENCY CONTRIBUTIONS TO PERMEABILITY

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# Contents

# What sponsored this document?

This document was sponsored by some free time I have found in my calendar through no planning of my own. The backstory is that a potential client was seemingly keen for me to undertake a job for them, based on discussions that commenced in January 2024. Several weeks before the job was to be undertaken, which was 6 months later and after I had juggled my calendar several times to match their changing dates of mooted fieldwork, and during which time I rejected other jobs in favour of them, the potential client cancelled the job. The reasoning was that they wanted to get someone else from the same company that had undertaken their resource estimation. Their comment after their efforts was 'hope this makes sense'.

Anyway, backstory aside, I have been thinking about putting pen to paper regarding the contribution of fracture cleavages to permeability networks for a while. So, given my enforced spare time, I have attempted to put my meandering thoughts in this post.

## Key points

- Fracture cleavage is an important but commonly unappreciated component of the structural-permeability architecture of hydrothermal mineral deposits.
- Fracture cleavage, as defined here, is not the same as a disjunctive cleavage and is commonly continuous with relatively more ductile fabrics.
- Fracture cleavages commonly manifest as brittle and/or open structures within the relatively more competent units of a rock mass.
- There is overlap in the manifestation in morphology fracture cleavages and pervasive joint sets.
- The main thesis of the post is not to argue the merits or otherwise of cleavage nomenclature. Rather, it is to highlight the interaction of brittle fracture systems with those that also develop ductile fabrics, with both playing a critical role in host-rock permeability.
- Examples are given here of fracture cleavage control of hydrothermal mineralization in orogenic gold deposits, intrusion-related gold±copper deposits, and carbonate-hosted base metal deposits.

## Background

Fracture networks are well-documented with respect to their influence on permeability of many hydrocarbon and groundwater reservoirs. For example, Molly Turko recently showed great examples of bitumen-filled factures from the Woodford Shale in Texas in a LinkedIn post (https://www.linkedin.com/feed/update/urn:li:activity:7222639591235706880/) and Li (2023) discussed fractures in shale gas reservoirs from the Sichuan Basin, China. Similarly, fracture networks comprising fault damage zones are recognised for their roles in permeability, controlling both the passage of fluids and the deposition of hydrothermal minerals. In these cases, there is typically variability in orientation and distribution of the fractures, ranging from domainal occurrences (e.g. adjacent to particular segments of a fault) and their orientation e.g. forming stockworks with two or more orientations.

In this post, I want to concentrate on fracture cleavages, which differ somewhat in that they are commonly widely distributed, and they typically show much less diversity of orientation than fracture stock-/networks. They can also form in relatively higher metamorphic grade environments than those typically associated with reservoir systems, and can be intimately associated with coeval ductile cleavages. As will be seen, there is overlap between fracture cleavage and joint systems. Harking back to Molly's post, you can see similarity in morphology to some of the photos I show here. However, I think fracture cleavages are commonly distinctive enough to be viewed as important contributors to permeability systems in their own right, especially in the context of host-rock competency and common continuity with ductile fabrics.

As structural-economic geologists we recognise the critical importance of brittle-ductile deformation. This typically manifests as deformation that partitions into zones of strong ductile deformation in the form typically of phyllosilicate-bearing shear zones that occur in conjunction with relatively more competent lithologies that undergo brittle deformation. In the latter case, these are the zones that typically host domains of hydrothermal mineral deposition in the form of veins.

The photo below is from a brittle-ductile shear zone exposed on the coast northwest of Port Aux Basques, Newfoundland. Intense, fine-grained ductile shears wrap the relatively coarser-grained and more brittle competent lozenges that have localised quartz veining and chlorite alteration.

*Brittle-ductile shear zone exposed on the coast northwest of Port Aux Basques, Newfoundland.*

Inherent in the picture that we see in our minds of the brittle-ductile deformation environment is the formation of ductile cleavages and brittle fractures that are relatively domainal. We typically see the cleavages as anastomosing features that have accommodated variable amounts of slip and strain-enhanced dissolution. In my experience, it is rare to see discussion of the contribution of tectonic cleavages that have a strongly brittle character to them, such as fracture cleavages, in the context of hydrothermal mineral deposits.

The example below is from the Jaguar open pit at Southern Cross, Western Australia. The metasedimentary units host a well-developed fracture cleavage that cross-cuts them at a high angle. The open space is largely a product of the dissolution of carbonate veins that occupied the permeability presented by the fracture cleavage.

*Fracture cleavage cross-cutting lithological layering. Jaguar open pit, Southern Cross, Western Australia.*

In low metamorphic grade rocks and those without abundant phyllosilicate content, fracture cleavages are commonly extensively developed throughout the relatively competent rock masses. This is in part due to the lack of ability to grow or recrystallise phyllosilicates that will then interact with deformation to form ductile fabrics. This extensive fracture cleavage development can provide a similarly extensive permeability network that allows for both the passage of fluids and the deposition of hydrothermal minerals.

The example below is from the Eastern Desert southwest of Ras Gharib in Egypt and shows a pervasive fracture cleavage network. The fracture cleavage is developed in very low metamorphic grade rocks where recrystallisation and growth of metamorphic minerals has been largely precluded.


*Pervasive fracture cleavage, Eastern Desert, Egypt.*

When taken in conjunction with other structures that contribute to the permeability mesh, the role of fracture cleavages during both their formation and their reactivation is something that should be, but commonly isn't, appreciated when considering the formation of hydrothermal mineral deposits. Once again, in my experience, many geologists look at fracture cleavages as non-contributors to the economic inventory of a deposit. The cleavages are typically interpreted as forming late and being 'dry' i.e. not having played a role in either the passage of fluids or the deposition of minerals from them. To be fair, this is commonly the case. However, there are many examples where it is not.

In this relatively photo-heavy post, I give examples of fracture cleavages from several environments, including intrusion-related and orogenic gold deposits and low metamorphic grade domains that host veins. The post also gives examples of fracture cleavage permeability networks that host volumes of rock where the deposition of hydrothermal minerals has been controlled by this cleavage.

## What is a fracture cleavage?

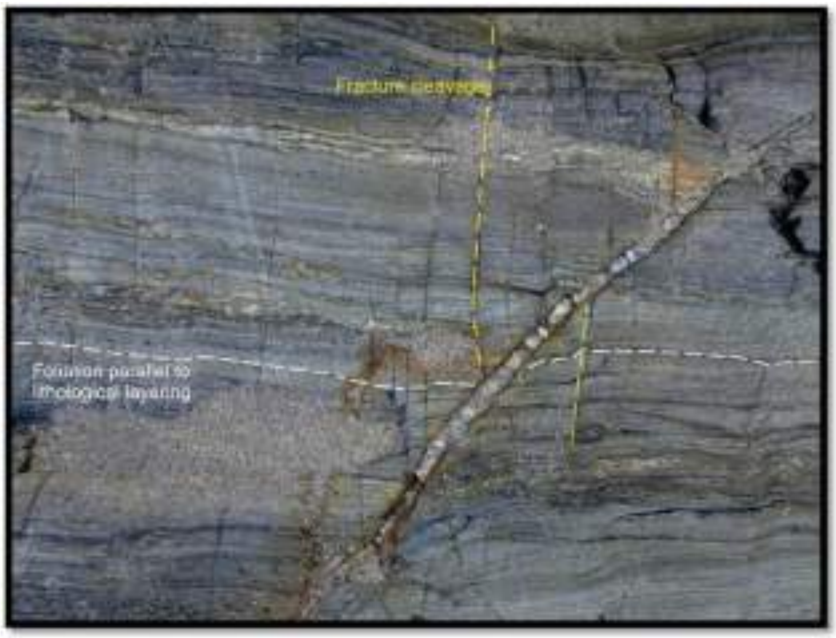
So, this is my view of the world and how I characterise fracture cleavage:

- Manifestation as a deformation product that forms a pervasive set of similarly oriented to acutely cross-cutting planes due to brittle-ductile deformation. As the term suggests, the cleavage manifests as fractures and commonly develop at high structural levels in lithologies where ductile deformation is precluded.
- General lack of domainal mineral development. For example, no separation into phyllosilicate-rich and phyllosilicate-poor domains due to general lack of growth or recrystallisation of minerals.
- Manifestation of the brittle aspect of the deformation is relatively more important in competent, relatively phyllosilicate-poor layers, producing a cleavage that comprises individual closely-spaced planar fracture planes separated by uncleaved volumes of rock. As such, the fracture cleavage may be continuous with relatively more ductile cleavages in zones that are more phyllosilicate-rich.
- Formation of cleavages may be irregularly spaced and discontinuous, resulting in variable stepping of the layer boundaries that the cleavage crosses, commonly on the scale of millimetres to centimetres.
- Fracture cleavage is commonly confined to rocks which are virtually unmetamorphosed, or which show a low-grade of metamorphism only. These low metamorphic grade environments are not permissive for the growth or recrystallization of ductile cleavage-forming minerals, particularly phyllosilicates.
- Fracture cleavage is commonly associated with the folding of layers, but can also develop in the vicinity of fault- or thrust-zones.
- Fracture cleavage development is locally associated with kink-style folding, which is typically a phenomenon that develops late in the structural history.
- The interaction of fracture cleavages with lithological layering can produce pencil cleavage.
- Fracture cleavages can have the appearance of, and manifest as, joint sets. However, as noted above, they are commonly associated with folds. In combination with spacing from millimetres to centimetres, plus pervasive development, they can be justifiably divided into cleavage populations. There is undoubtedly overlap in populations of structures defined as closely spaced joints and fracture cleavages.

I will add a relevant digression here. I do not consider fracture cleavage to be a disjunctive cleavage *per se*, which refers to a spaced cleavage that has formed by directed compressive stress that results in pressure solution e.g. stylolite formation or the alignment of phyllosilicates (e.g. Twiss & Moore (1992) and Passchier & Trouw (1996)). That said, as noted above, fracture cleavages in competent zones are commonly continuous with relatively more ductile fabrics in adjacent rock-types. As such, there is a grey area in terminology, and this is partly due to the scale of observation. It is also not uncommon to see fracture cleavages that have developed in rocks that also host stylolites. In this case, it is important to assess the overprinting relationships to assess relative timing of formation, because the fracture cleavage commonly post-dates stylolitisation. The grey area in classification is also evident in very good books by authors such as (Blenkinsop, 2000), where the descriptions and photo of a disjunctive cleavage is different to what I have defined as a fracture cleavage.

## Examples of fracture cleavages

The fracture cleavage in the photo below shows variable development across the host-rock. Interestingly, it is best developed adjacent to the vein, suggesting that the vein has influenced strain localisation. This outcrop was exposed on a beach in Asturias, Spain.

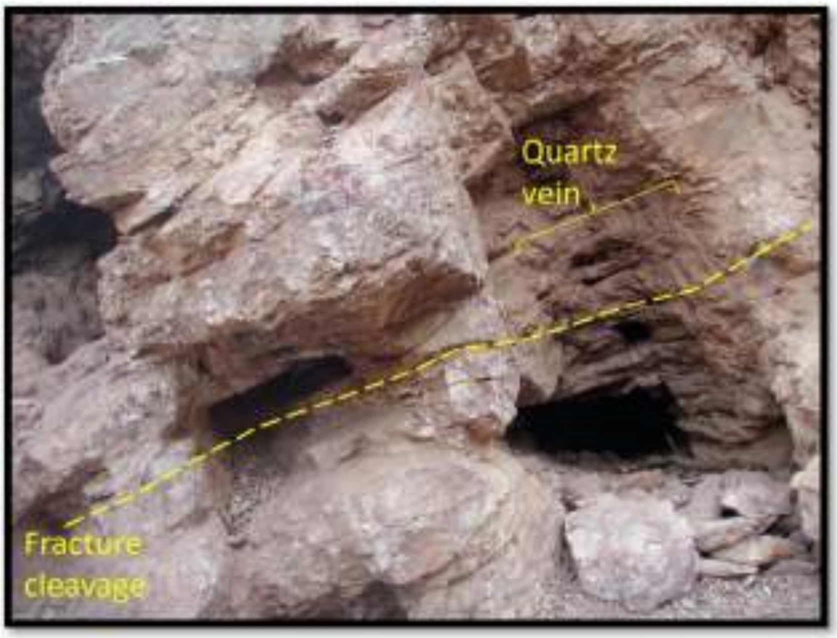



*Composite fabric defined by compositional layering and foliation, cross-cut at a high angle by fracture cleavage. Asturias, Spain.*

In this example below, there is a relationship between spaced fracture and intervening weak flexures/kinks. As such, the subvertical structures are interpreted as a fracture cleavage, and also manifest as a joint set. This outcrop is from northern Eritrea.


*Composite fracture cleavage/joint structures cross-cutting foliation and manifesting as the axial plane to weak flexures/kinks*

In the example below, a granodiorite host-rock has been traversed by quartz veins comprising the Zara intrusion-related gold deposit in northern Eritrea. A fracture cleavage is developed that shows variability in spacing that is dependent on rock-type, being relatively more closely spaced in the quartz veins. The cavities are from artisanal mining.

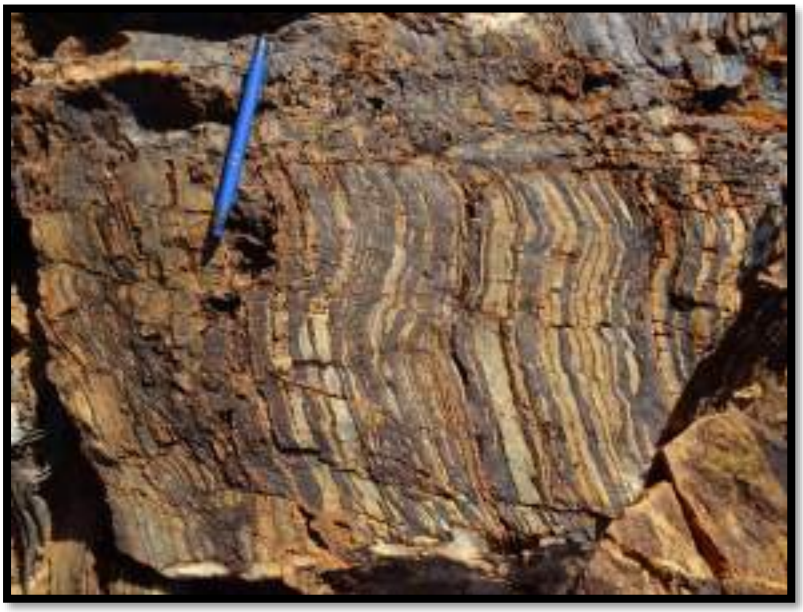



*Variability in fracture cleavage development between granodiorite host and gold-bearing quartz veins. Zara gold deposit, northern Eritrea.*

In the example below, which is from near the Zara intrusion-related gold deposit in northern Eritrea, a fracture cleavage has a joint-like appearance. This cleavage is axial plane to broad flexures in the competent host-rocks.

*Composite fracture cleavage/joint structures cross-cutting foliation and manifesting as the axial plane to weak flexures. Northern Eritrea.*

In the example below, the fracture cleavage cuts the host-rock at a high angle to metasedimentary layering. Locally, the cleavage is continuous with a relatively more ductile fabric, such as below the pen on the left of the photo. The fractures are axial planar to folds. The outcrop is near Sandstone in Western Australia.



*Variable manifestation of fracture cleavage in BIF from Sandstone, Western Australia.*

The photo below is another example from near Sandstone, Western Australia, showing a folded BIF with a fracture cleavage as the axial plane. Note that the cleavage is best developed in the relatively lower-strain upper portion of the sample, with virtually no development in the high-strain portion of the sample where the lithologies have been rotated into parallelism with the cleavage. Here, the slip accommodated by the layers and the finer-grained units has over-ridden the necessity to develop a fracture cleavage.

*Variable development of fracture cleavage as a function of strain and the orientation of layering that it has overprinted. From Sandstone, Western Australia.*

The photo below is also from a BIF sequence. This one is part of the Brockman Formation in the Pilbara region of Western Australia and shows a fanning fracture cleavage associated with mesoscale folding. Relatively wider spacing of the cleavage is apparent in the thicker, relatively more competent layers.

*Axial planar fracture cleavage in BIF from the Brockman Formation in the Pilbara, Western Australia.*

In the photo below, a well-developed fracture cleavage is developed at an acute angle to gold±copper-bearing quartz veins. The cleavage and the veins are interpreted as part of the same orogenic event affecting dioritic host-rocks in the Eastern Desert of Egypt. Ancient workings have exploited the veins.


*Subparallelism of gold±copper-bearing quartz veins and fracture cleavage. Eastern Desert, Egypt.*

The example below is from the Koongie Park copper-gold project in the Halls Creek Mobile Belt, Western Australia. The deposit hosts a well-developed pencil cleavage that is the product of the intersection of two fracture cleavages.

*Contribution of fracture cleavage to pencil cleavage development. Koongie Park copper-gold project, Halls Creek Mobile Belt, Western Australia.*

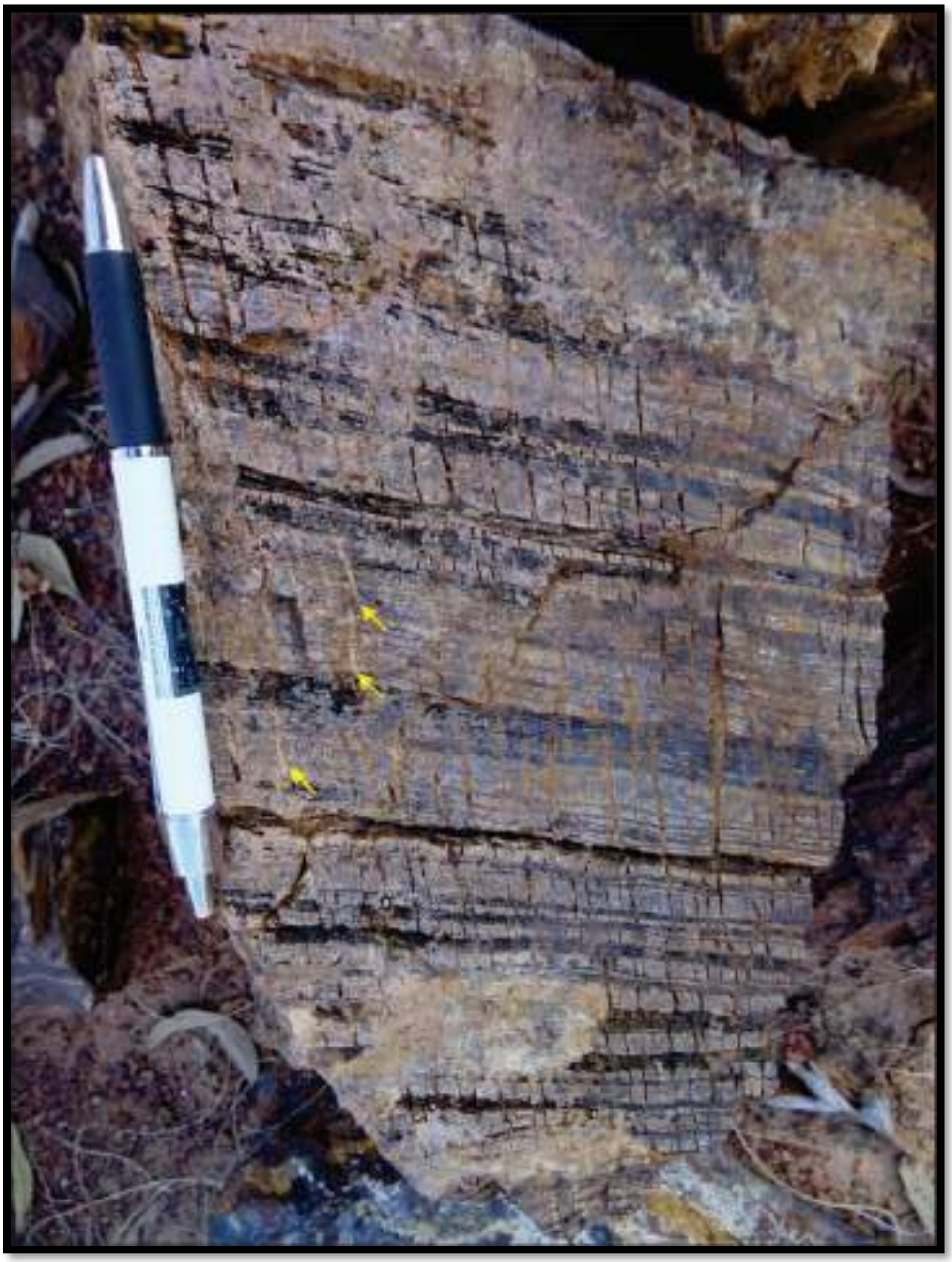
The photo below shows a good example of the transition between fracture cleavages and anastomosing ductile foliations. The cleavage has a distinctly brittle character to it but shows anastomosing geometries as it passes across layers of differing composition. Iron oxides have been preferentially deposited along the cleavage. The sample is from the Mt Olympus orogenic gold deposit in the Pilbara, Western Australia.

*Fracture cleavage with morphology that is transitional toward that of a ductile foliation. Mt Olympus orogenic gold deposit in the Pilbara, Western Australia.*

## Examples of hydrothermal mineral deposition controlled by fracture cleavage

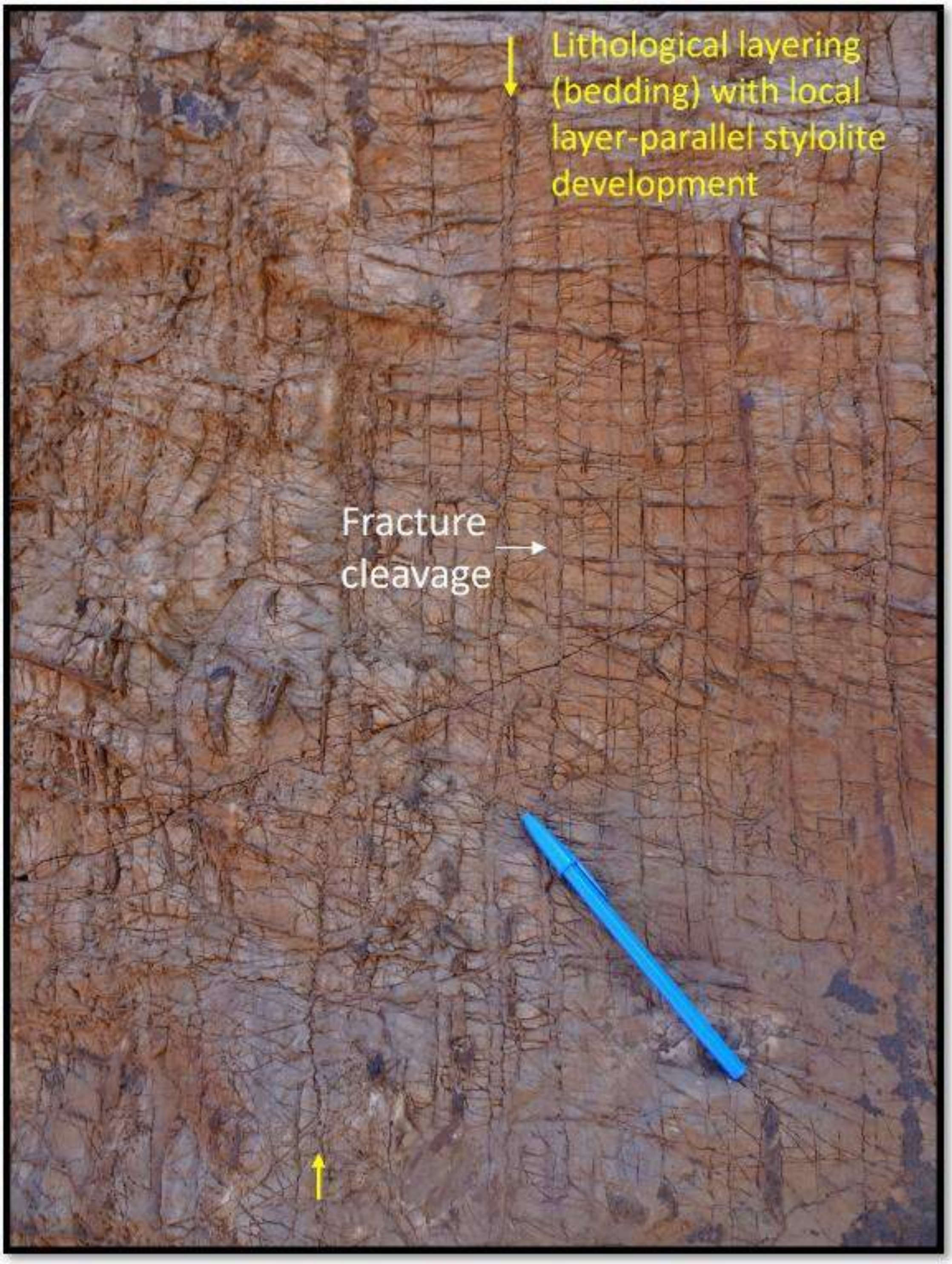
Fracture cleavages can make significant contributions to the permeability networks that develop in the deformed volume. In some cases, the permeability is reactivated e.g. the cleavage may have originally hosted a network of carbonate veinlets that are then dissolved during successive fluid events, 'reopening' the fracture cleavage.

The example below is from the open pit on the Jaguar orogenic gold deposit at Southern Cross, Western Australia. A well-developed fracture cleavage is evident at a high angle to lithological layering and manifests as open fractures due to the dissolution of carbonate veins. The yellow arrows show examples of veins that have not been dissolved.



*Fracture cleavage hosting remnant products of hydrothermal mineral deposition in the form of carbonate veins. Jaguar orogenic gold deposit, Southern Cross, Western Australia.*

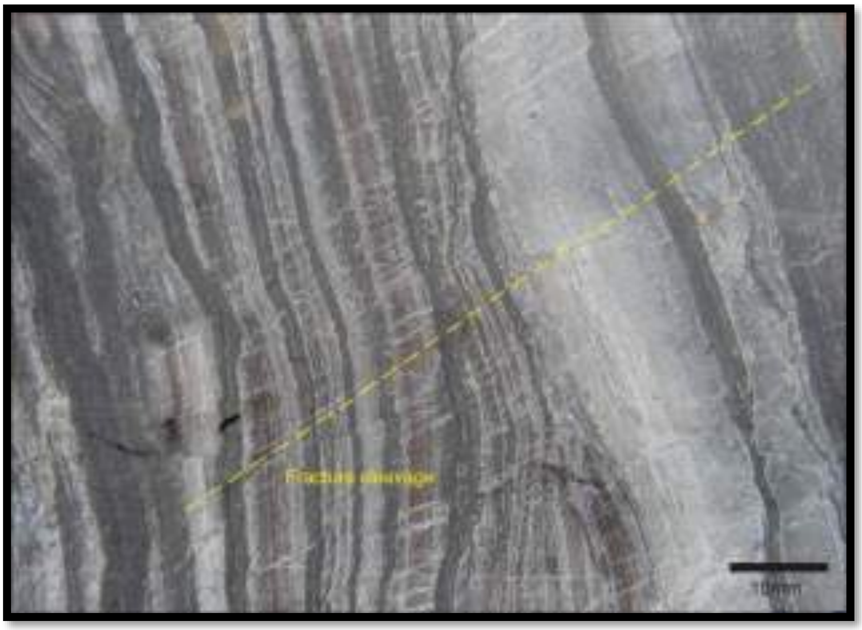
The outcrop below is from the Mt Olympus orogenic gold deposit in the Pilbara, Western Australia. The fracture cleavage in the carbonate-rich rocks has accommodated hydrothermal fluid movement and mineral deposition, resulting in sheeted, millimetre-width silica veinlets. Lithological layering and stylolites are contributors to the permeability network and have also localised silica deposition.




*Fracture cleavage control of silica ingress and deposition manifesting as sheeted quartz vein array. Mt Olympus orogenic gold deposit, Pilbara, Western Australia.*

The following three photos are from the same orogenic gold deposit and show a progression from non-sulphide bearing fracture cleavages peripheral to gold-mineralised zones through to zones where the fracture cleavage has provided permeability for the passage of mineralising fluids and deposition of gold-sulphide mineralisation. These examples are from Sandstone in Western Australia.

The first photo shows some quartz-carbonate veining occupying the fracture cleavage.

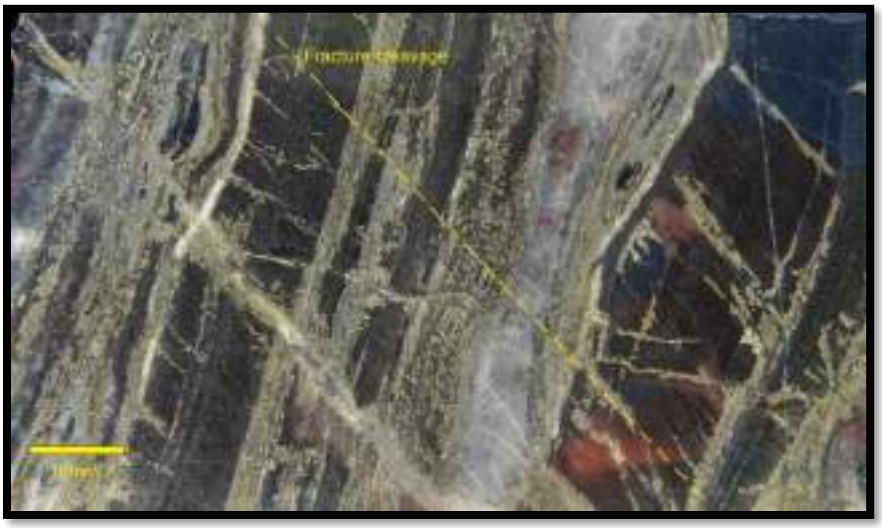



*Fracture-controlled quartz-carbonate veining. Orogenic gold deposit, Sandstone, Western Australia.*

In the example below the quartz-carbonate veins are apparent and marginally thicker than in the previous photo. Sulphides are present dominantly as sulphidation products of BIF layers, with minor ingress along the fracture cleavage.

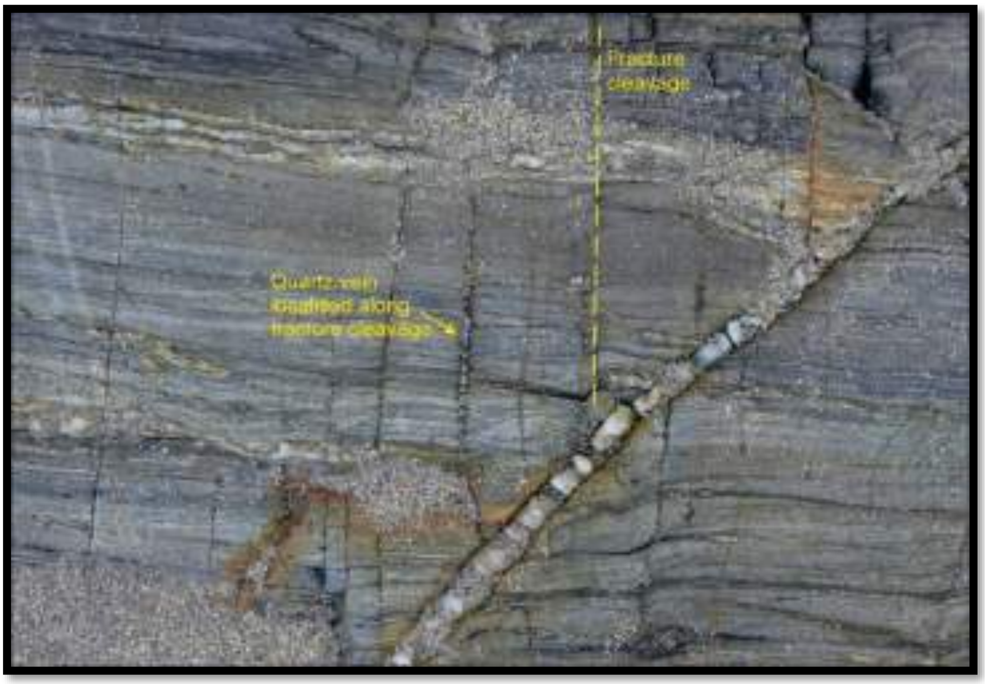

*From the same drill hole as the previous photo and showing a progression to relatively wider, fracture-controlled quartz-carbonate veins and appearance of sulphides.*

In the example below the fracture cleavage has become an integral part of the permeability network, hosting sulphides that are associated with gold. In combination with the lithological layering, this has produced an efficient permeability mesh.



*From the same drill hole as the previous two photos but closer to the principal mineralised zone. Strong fracture cleavage control to sulphide localisation is evident.*

The photo below has been windowed out of one from the start of the post and shows the fracture cleavage at a high angle to the host-rock foliation and being preferentially developed adjacent to the vein. The fracture cleavage permeability has also localised millimetre-scale quartz veinlets.

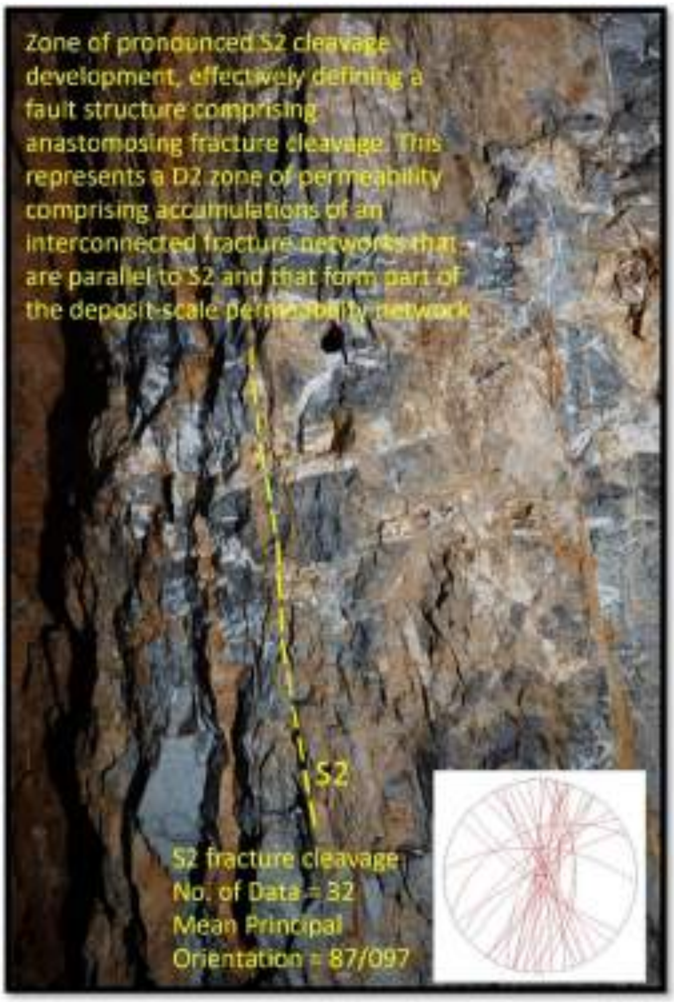


*Fracture cleavage control of the localisation of millimetre-scale quartz veins. Asturias, Spain.*

The piece of drill core in the example below is approximately 6cm wide. Chlorite alteration has been localised along the fracture cleavage that cross-cuts lithological layering at a high angle.

*Fracture cleavage control of chlorite.*

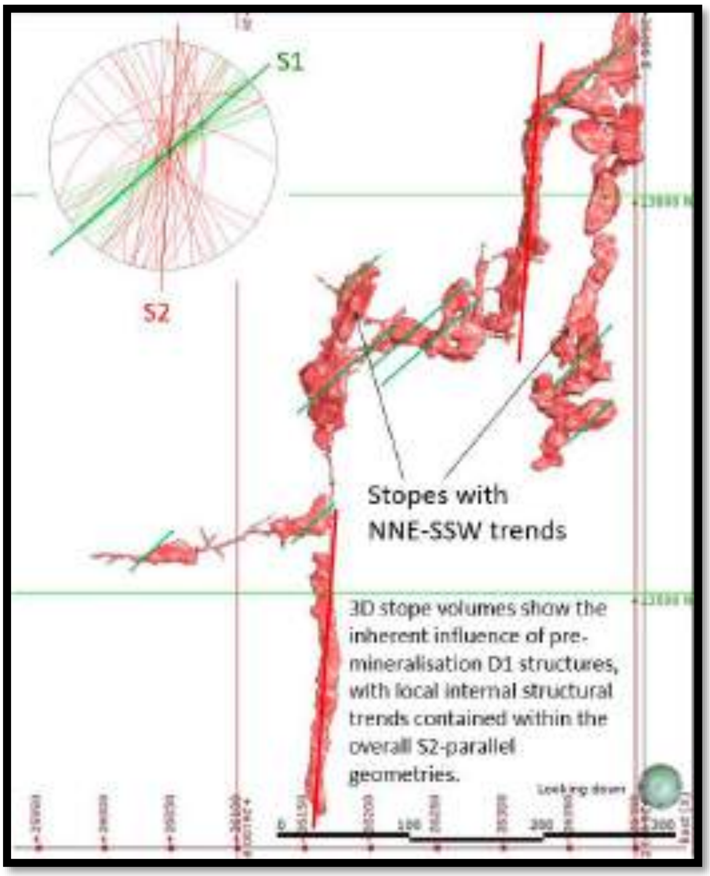
The next two photos are from the carbonate-hosted Novales zinc project in Cantabria, Spain. Here, the fracture cleavage is a manifestation of the deposit-scale structural controls to zinc accumulations in the dolomitic host-rock and parallels the zones of historical exploitation. This is an example of permeability associated with contributions from fracture-cleavage development on a massive scale.




*Fracture cleavage in the Novales carbonate-hosted zinc deposit, Spain*

*Fracture cleavage in the Novales carbonate-hosted zinc deposit, Spain*

The image below shows the exploited volumes within the Novales zinc mine. The S2 fracture cleavage effectively defines the orientation of the principal zones of exploitation. More detail on the structural controls to mineralisation in this deposit are given in the LinkedIn post: https://www.linkedin.com/feed/update/urn:li:activity:7197463402024214528/




*Historical zinc exploitation volumes strongly controlled by facture cleavage. Novales zinc deposit, Spain.*

## Some concluding comments

Establishing overprinting relationships is critical to understanding hydrothermal mineral systems. For example, it may turn out that fracture cleavages originally considered relatively late, and not associated with mineralisation, are in fact of the same age as mineralisation, or have been reactivated in a subsequent stage of fluid ingress. In both cases, the fracture cleavage is an inherent part of the permeability network and a fundamental contributor to the mineralisation budget.

Rock type plays a critical role in the formation of fracture cleavages in terms of spacing, intensity and the volume of rock over which it is developed. Equally critical within this is the relative competency of the different rock types, with those that are relatively more phyllosilicate-poor being more likely to develop the fracture cleavages and being more likely to sustain open space permeability networks for the deposition of hydrothermal mineralization including veins.

There is overlap and grey areas in the definition of fracture cleavage, and I've given my own definition herein. It will undoubtedly conflict with that of others, due in no small part to the diversity of styles of fracturing in upper crustal and/or low metamorphic grade and/or competent rock types. This diversity of cleavage style has been discussed over the decades by other authors and is not a new topic (e.g. Crook (1964); Engelder, 1987). However, the main thesis of the post is not to argue the merits or otherwise of cleavage nomenclature. Rather, it is to highlight the interaction of brittle fracture systems with those that also develop ductile fabrics, with both playing a critical role in host-rock permeability. As such, the important focus of this post is to emphasise that all structures should be documented, placed in temporal context, and measured accordingly.

A fundamental part of interrogating a hydrothermal mineral system is to establish the overprinting relationships and from this, the geological history. This allows subdivision of structures into different populations for comparison and allows their relative ages to be established with regard to mineralisation. Incorporation of the structural history is a key part to this, and comments that I've heard such as '*the structural part remains to be integrated, though I am strongly of the opinion that we can't let that unnecessarily complicate the deposit and exploration model*' represent blinkered thinking and a narrow-minded approach to orebody analysis. At the end of the day, we should be establishing all the different populations of structures, gathering orientation populations, and from this resolving informed models for the structural influence on the formation of permeability networks and hydrothermal mineral deposits.

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