# HOW TO CONNECT ROCK OBSERVATIONS AND GEOCHEMISTRY TO UNDERSTAND LARGE HYDROTHERMAL ORE SYSTEMS

## Part 3: An introduction to the principles of structural controls on veins and mineralization


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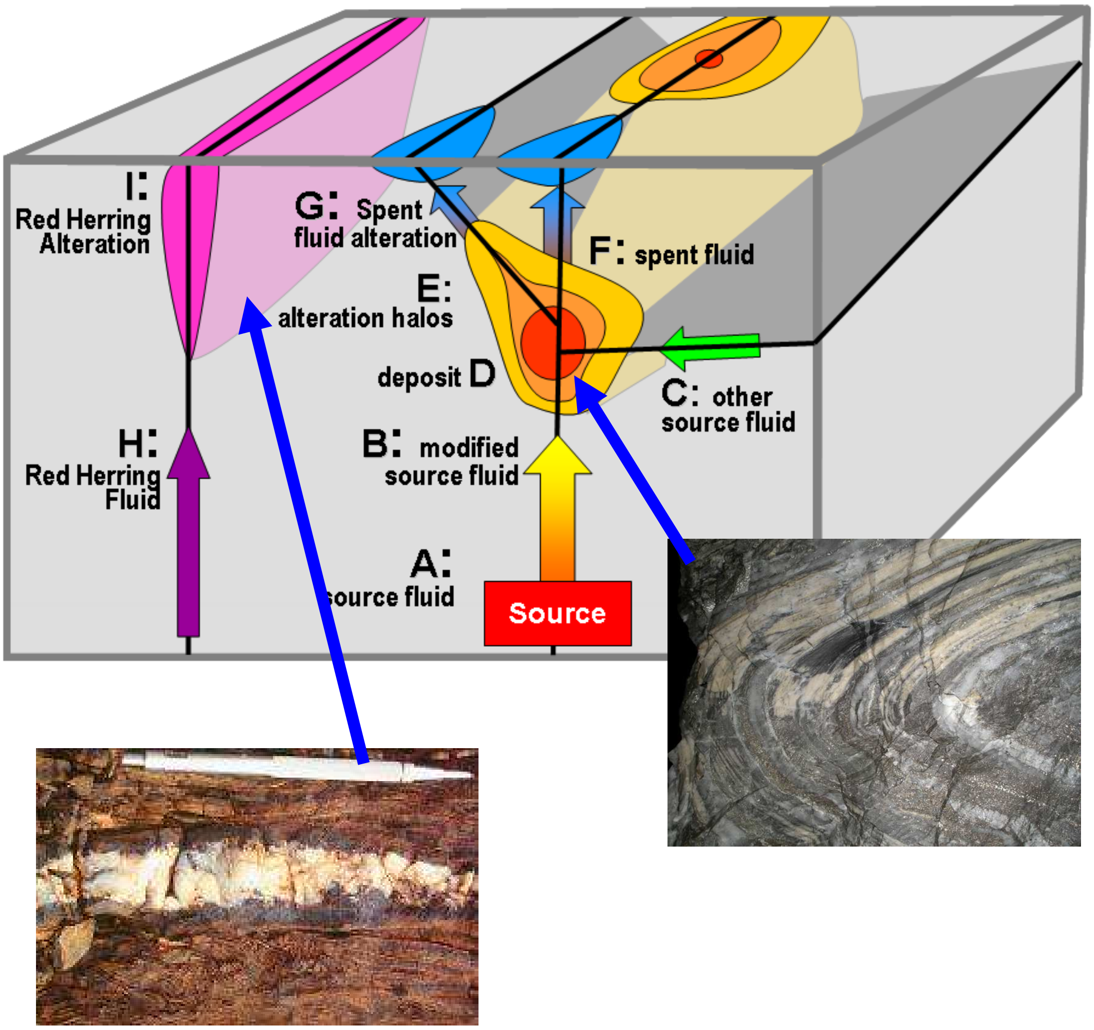
This module forms part of a series on use of veins, alteration, geochemistry and structures to identify which features can be used to recognise 'vectors' to potential sites of mineralization. The principles were developed through field- and laboratory observations and short course development for undergraduate & postgraduate students at several Australian Universities, as well as open-audience and site-specific industry workshops. The principles are most suited to alteration and vein recognition in deformed, metamorphic rocks, but have application elsewhere. Thanks here in particular to conversations and structural principles discussed with Stephen Cox, Rick Sibson, Tom Blenkinsop and Rick Valenta.



## Contents

## INTRODUCTION

This part of the course is designed to assist you with analysis of fractures, faults and veins in terms of identifying key characteristics that relate to fluid flow and mineralization. In addition, there is a component of basic mechanics useful for any geologist who has forgotten, or was never taught, how to deal with brittle structures.

Chemical depositional mechanisms in hydrothermal, epigenetic ores that relate directly or indirectly to deformation processes include

- pressure-dependent speciation changes, especially those triggered by boiling or immiscibility
- fluid/rock interaction around and through fractures
- fluid/rock interaction in ductile and ductile/brittle shear zones

Hence, there is a need to appreciate what processes allowed fluid to move to the particular sites to permit this chemical change. The key mechanical factors influencing ore deposition are

- pressure changes due to dilation,
- permeability enhancement due to deformation, and
- the mechanics of fracture in brittle or brittle-ductile rock.

To be predictive with this type of structural geology, you need to know:

- The timing of different structures relative to mineralization
- The distribution of known deposits or hydrothermal alteration relative to the structures
- An understanding of the kinematics and mechanics of the controlling structures
- An ability to recognise the controlling stress field at the time of mineralization

This information can be gathered by

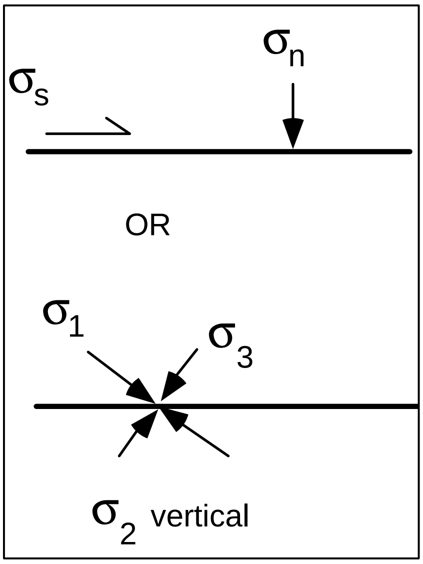
- Developing a structural paragenesis
- Measuring the orientation and internal features of veins
- Determining the correlation of different structures, and parts of structures, with known mineral deposits
- Applying the above information to regional datasets or near-mine prospects to rank potential new sites of mineralization

The first two of these cannot be done on a computer – they require field mapping and/or oriented core logging and detailed observations of the type presented here. The latter two can be done with the aid of spatial and statistical approaches (particularly in a GIS framework) but cannot be done in the absence of understanding and measuring the structural paragenesis and the orientation and internal features of veins.

So, this part of the course focuses on the sorts of practical, field- and core-based information you should collect if you are trying to determine when and how fractures formed that allowed the transmission of potentially ore-forming fluids, and/or the precipitation of ore minerals in veins.

## BASIC PRINCIPLES

Flow through channels or fractures has been simulated by various rock failure theories (e.g. Griffith, Anderson, Riedel, Mohr-Coulomb), as well as fluid flow solutions in open channels (much engineering literature). The basic principles most geologists use are those relating to Mohr-Coulomb materials, with basic definitions of stress for geoscientists first being rigorously applied by Jaeger (1969).




Unlike for most ductile structures, it is possible to glean information about the orientation and evolution of stress fields from brittle features, based on geometric arguments, textures in fault and vein-zones, and first principles.

Rules:

1. Stress at point: can be resolved into a cartesian coordinate scheme, hence $\sigma_1$, $\sigma_2$, $\sigma_3$, the principle stresses.

2. Stress on a plane: can be resolved into shear stress (the component of stress acting along the plane), and normal stress (the component of stress acting across the plane).

$\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_s$ & $\sigma_n$ are all interrelated. For fractures and faults, stress can be specified either as $\sigma_1$, $\sigma_2$, & $\sigma_3$, or as $\sigma_s$ & $\sigma_n$. This can be shown diagramatically (as at left) or by a Mohr Circle approach (see below).

3. The law of effective stress: $\sigma_{eff} = \sigma_n - P_f$

where $\sigma_{eff}$ is the effective normal stress acting on a plane, $\sigma_n$ is the normal stress, and $P_f$ is the fluid pressure. This simply means that stresses are effectively decreased if fluid is present, and this can be formally expressed by Mohr Circle analysis (see below).

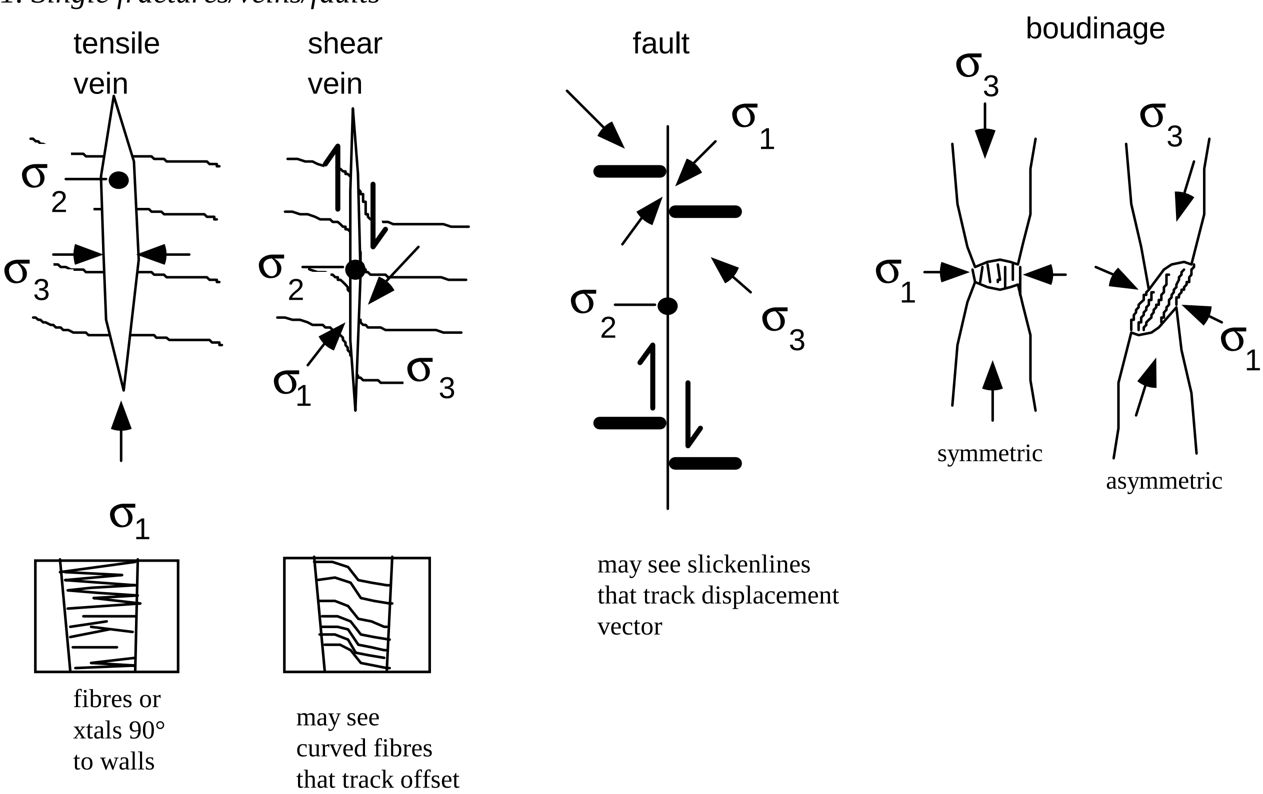
4. The condition for tensile failure at high fluid pressures: $P_f \geq \sigma_3 + T$

where $\sigma_3$ is the minimum compressive stress and T is the tensile strength of the rock. This means that if the fluid pressure exceeds the tensile strength of the rock (the resistance against being pulled apart, measurable in a laboratory) plus an amount equal to the smallest stress acting on the rock, then fracture will occur, and the geometry of fracture will relate to the stress field.

**Determining stress fields from geometric considerations**

This technique is important to identify places within and around a fault zone that are most likely to be in a favourable orientation for dilation and hence fluid flow, alteration, and mineralization. For the dominant orientation of the fault array, then $\sigma_1$, the maximum principal compressive stress (that essentially "drives" fault movement), will be oriented at a moderate angle to the fault plane, with a sense that is compatible with the determined movement vector on the fault. Note, however, that complex stress reorientation can be expected at fault tips, intersections, and bridges, and that the local stress field may exert the predominant controlling influence on the construction of mineralization sites. There is considerable literature on the pitfalls of applying these procedures without considering complex interaction between local and regional stress fields. Some of this is touched on below but in any case here we go:

*1. Single fractures/veins/faults*




*2. Simple vein or fracture arrays*

<u>a) En échelon vein arrays</u>

En-echelon arrays of tensile veins are caused by coupling of shear strain with dilation, and are a very common feature in and around structurally-controlled ore deposits, and indeed in most terrains that have undergone brittle-ductile deformation.

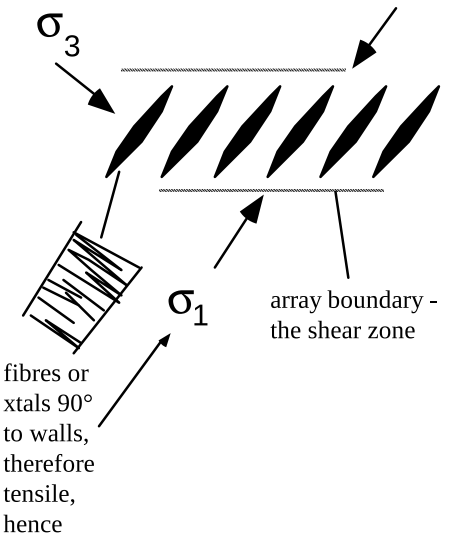
*Characteristic features*

- lines drawn connecting the outer tips of the tensile veins define the en échelon vein array; these lines are characteristically parallel to the master shear/fault

- individual veins are typically tapered, with tapering away from the master shear/fault

- individual veins are commonly sigmoidal (curved)
- the angle of the component veins in the array, and the asymmetry of curved veins, relative to the master shear/fault, can be used to infer the movement sense on that shear/fault

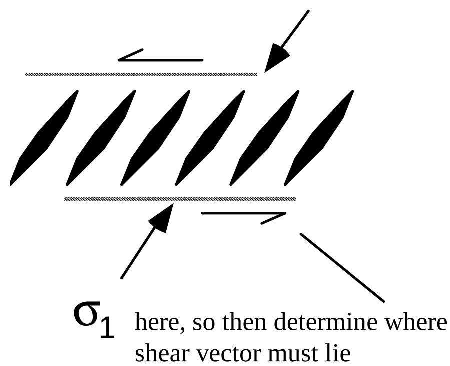
*Procedure*



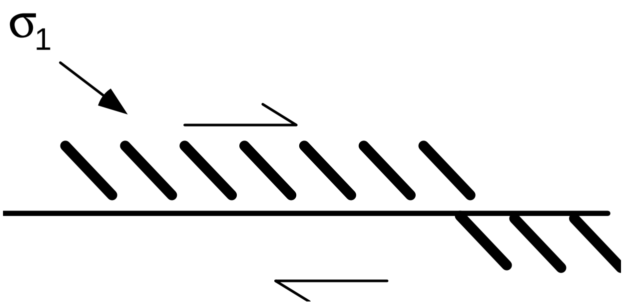

- Identify the vein array - look for the staggered, offset veins. Draw lines that bound the vein array - this is the bulk orientation of the shear/fault zone
- If the individual veins are not curved (as shown at left), check to see either displacement across the veins, or fibre orientations, to make sure they're tensile

If so, you can define $\sigma_1$ assuming that individual veins are tensile.

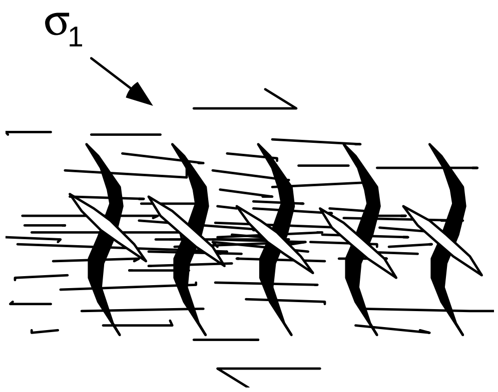
Once you have identified $\sigma_1$, then you use the principles of stress orientation around a fault to determine the movement sense



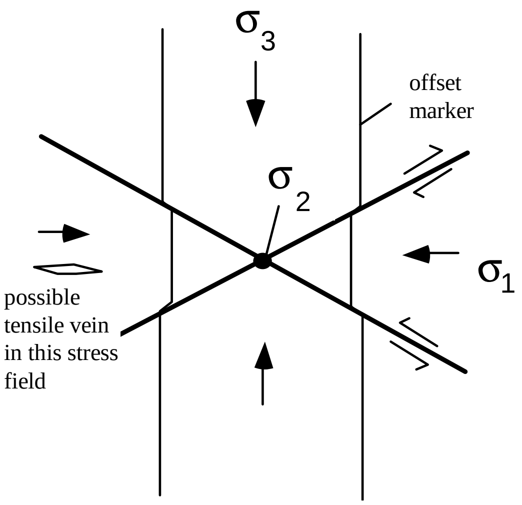

*3. Variations on the theme*




- En échelon veins adjacent to a fault: same principle, but in this case the recognition process should identify that the boundaries of the vein array are parallel to the fault, and therefore related to the fault, even if the veins are not connected to the fault



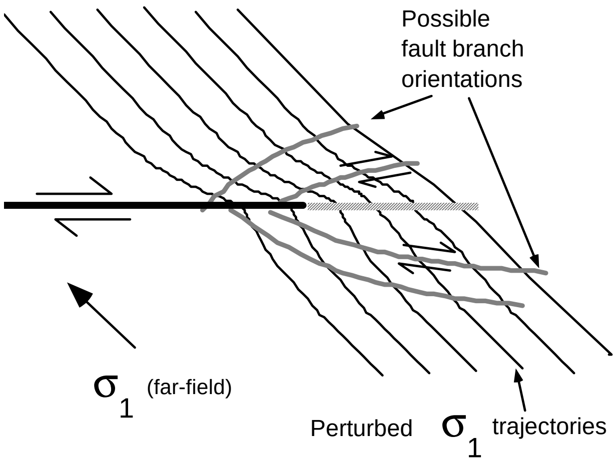

- Veins in shear zones: because shear strains are commonly highest in the core of shear zones, veins forming early in the shear zone history will be "caught" in the high ductile shear strain (black veins here), resulting in asymmetric curvature that tells you the shear sense. By close inspection you would detect ductile deformation features in the middle of these veins, e.g. recrystallized original quartz fibres or a polygonal mass of foam-textured grains. Later veins may overprint these as shown.




- Conjugate fractures

**Note:** $\sigma_1$ is typically 25° to 30° to shear planes, $\sigma_3$ is c. 60° to shear plane, and $\sigma_2$ lies along the intersection of the conjugate faults/fractures. This is the model for Anderson-type conjugate fractures. To identify these, look in particular for 120/60° angles between fault planes, opposing movement senses on faults (as per the diagram), and other evidence such as tensile veins etc that may also confirm the stress field.

*4. Fault bends, terminations & links*
*(figure modifed from Mandl 1988)*




At the tip of any propagating fracture or fault, the stress field is different to that on the rest of the fracture. In 3D, a fault or fracture is essentially like an ellipsoidal disk, and high shear strains near the middle of the fault must be accomodated by changes in the stress field at the tips of the fault.

This causes a number of things:

1. It allows the fracture to propagate: the difference in the stress field between the core and tip of a fracture can assist fracture propagation, particularly if fluid pressures are high (Griffith crack theory notes that microstructural damage at crack tips can prepare the rock for further fracture; Sibson *et al.* (1975) has referred to this in another way as "pre-failure dilatancy" prior to seismic pumping episodes)

2. Conversely, such a difference can force fracture termination - the change in stress field at the tip, for example, can be taken up by terminating fault splays or ductile deformation that will “pin” the fault tip.
3. If two fractures are “passing” each other, the perturbed stress field at the fracture tip often causes capture of the other fracture, leading to linking or jog structures: these may be dilatant or antidilatant and can assist in intrepreting fault movement and fluid flow.

**Fault orientations, irregularities and ore deposition**

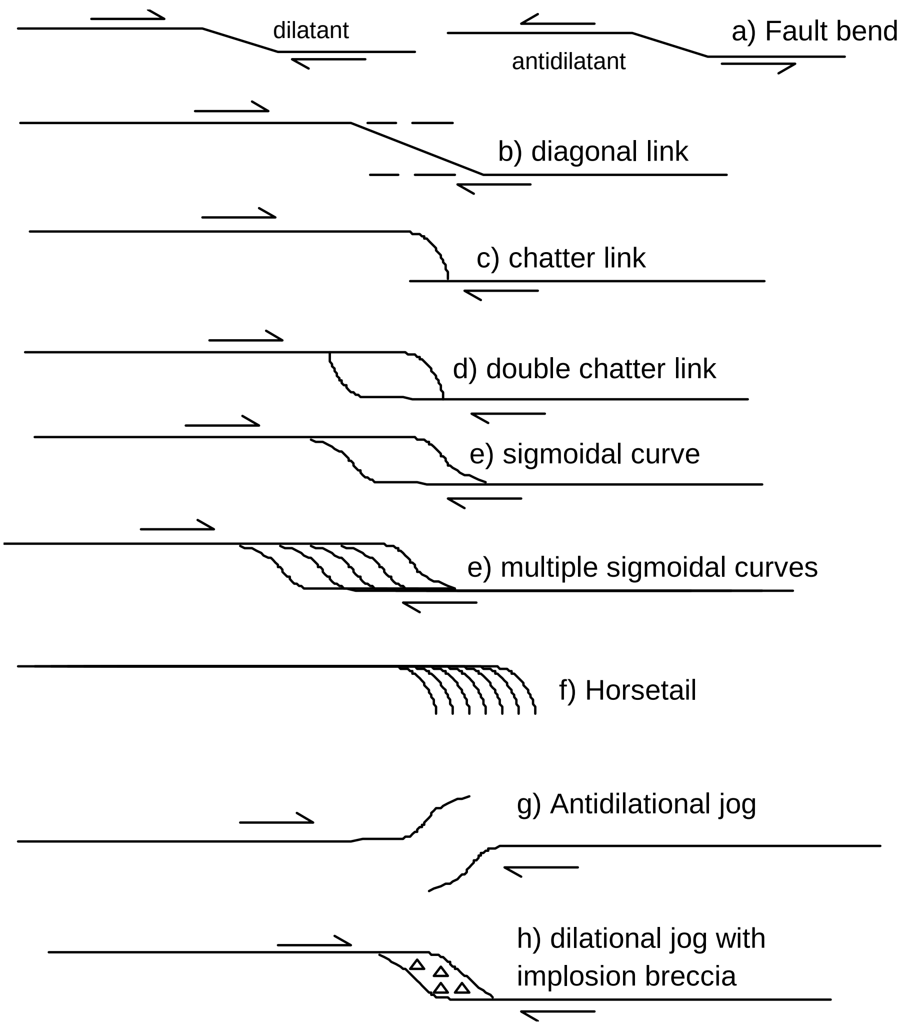
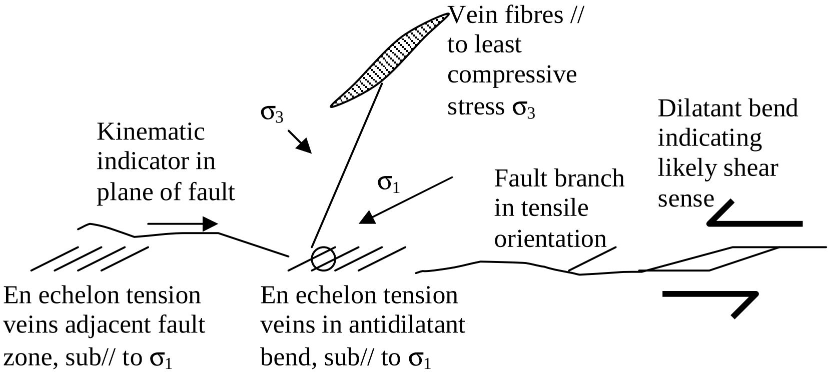



*Figure: Types of irregularities of single faults in which changes in stress states at the irregularities can lead to substantial dilation and fluid focussing. Adapted from Mandl (1988), Sibson (1981, 1985, 1988), & Oliver, Laing & Rubenach (Advanced Field Training course notes, JCU/EGRU 1999)*

Dilatant fault segments or branches are the most common site for mineralization. They commonly do not act as major channelways for fluid, but indeed may act as traps, which in turn allows mineralization to accumulate. Fault dilation can occur as a consequence of local perturbations in the stress field (i.e. due to fault irregularities), or to changes in the stress field leading to opening on previously "closed" faults or fault segments. i.e. dilation can occur during an individual faulting episode on one or more faults, but also by the action of different deformation phases or events (with different stress arrays) on pre-existing fault arrays. More on this later.

**Summary**

Simple geometric analysis of veins in relation to faults, shear zones, bends etc. can provide movement vectors, stress configurations, and a basis for determining which parts of the total array are most likely to channel fluid or act as fluid (or ore) traps.




Because of the law of effective stress (equation above), it should be clear that fracture permeability is a function of the orientation of a plane relative to the applied stresses. If fluid is added to the situation (required in most crustal settings, especially those involving ore deposition), then the most permeable faults/fractures will be those which are oriented at a low angle relative to the maximum compressive stress direction. This brings us to a point whereby we can apply this principle to the analysis of complex fracture arrays.

## ANALYSIS OF COMPLEX OR OVERPRINTING FRACTURE NETWORKS

### Fracture analysis principles

In complex brittle settings, the relationship of individual fault branches or segments to the inferred far-field stresses is most important. The key structural condition for ore formation in any fault-related mineralized region is the linking up of fracture networks. In this case, relatively connected faults will form long-distance fluid channelways. Ore deposition may occur at specific structural sites such as terminal fault branches, faults in particular orientations, and smaller faults that connect larger faults.

Fracture analysis in the field is complex but commonly rewarding. Your analysis should attempt to include the following steps:

4. <u>Identification of possible movement vectors along the fault or fault zone.</u> *Caution* - apparent offsets in 2D will commonly not reflect the true slip vector - seek independant kinematic indicators (en échelon vein arrays, slickensides, curvature of foliations into fault plane, 3D fault solutions).

5. <u>Identification of the history of movement along a fault or fault zone</u>. *Caution* - fault reactivation with opposing movement sense is common.

6. <u>Identification of the geometric characteristics of fault segments most amenable to dilation</u> (component of opening at high angle to fault plane). *Caution* - these will change depending on which orientation of far field stresses you choose.

7. <u>Identification of structures related to fault termination or branching.</u> *Caution* - you need to separate out fault branching/termination during one episode from overprinting in two or more episodes

8. <u>Identification of alteration and veining features related to the fault</u>. *Caution* - it is possible for two different alteration types to develop on different fracture sets at the same time, because if each fracture has different permeability/Pf/stress arrangements, these can influence the chemistry/mineralogy of infill and alteration.

*Real versus apparent offsets*

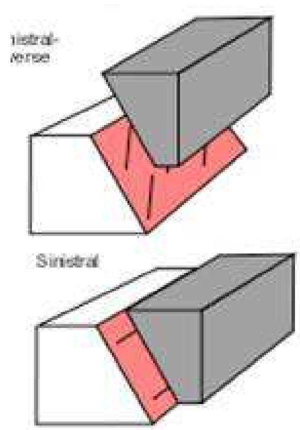


Image courtesy T Blenkinsop

A full appraisal of this issue is beyond the scope of this workshop, but most good modern structural geology texts cover this. The most important point is that apparent offsets on maps or sections need not bear a relationship with the actual movement vector on a fault. Two sets of data are ideally required:

- the apparent offset of markers across the fault (from maps, outcrops etc.)
- an independent indicator of the likely slip vector

A full fault solution (vector and distance of movement on the fault for a single displacement) is possible when two planar markers of different orientation to each other and the fault are transected by the fault. As this situation is relatively uncommon, however, it is more routine to combine apparent fault displacement with an independent kinematic indicator, see example at left.

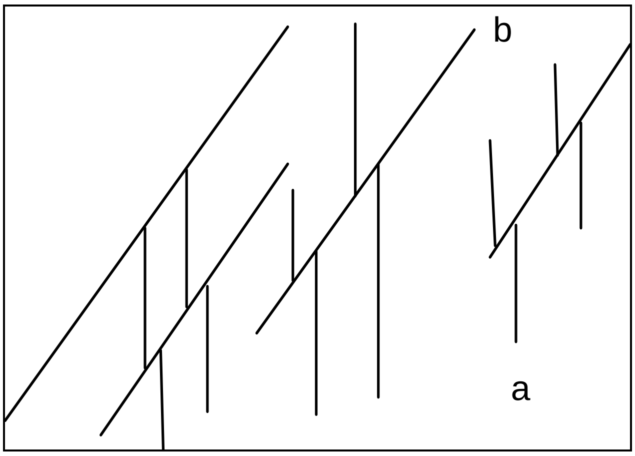
<u>Independent mesoscopic kinematic indicators:</u>

- curvature of foliation or other planar feature (e.g. bedding, early vein, dyke) into ductile shear zone, along with knowledge of shear vector (from lineations)

- arrangement of en échelon tensile vein arrays adjacent to fault zone (see below)
- orientation and asymmetry of slickensides and gouges developed on fault surface
- orientation and asymmetry of slickenfibres developed in vein infill on fault surface

**Paragenesis**

The main problem with analysis of fracture sets is trying to determine which fractures relate to each other and which do not. For example, consider a scenario as follows:




a) a single planar mineralized fracture set develops during one brittle deformation event
b) It is then overprinted by another planar fracture set forming an angle of approximately 30° with the first set. This set appears to be unmineralized.

*Problem:* How would you go about determining what to do here?

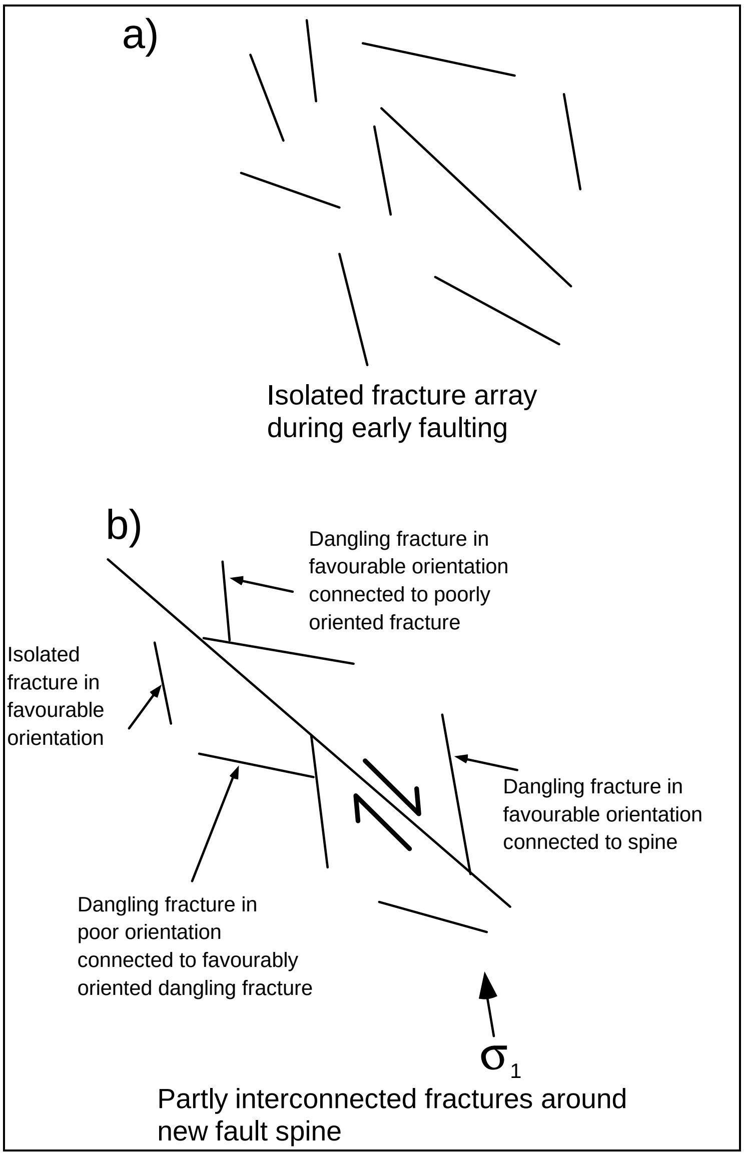
- Determine the overprinting relationships - you need to know that set b is younger, otherwise you might assume they were conjugates (but that wouldn't really explain why one set was mineralized and the other not)
- Determine the stress field for the youngest set - so you need to work out whether they are tensile veins or shear veins from field relations - lets argue that a fractures look like tensile veins (no offset across vein boundaries)
- Now you have two choices as to when the mineralization occurred - it could have occurred during the formation of set a, or it could have occurred along a during the formation of set b, with set a being highly dilatant and permeable at the time of operation of faults b. Using a Mohr Circle approach, or by inspection, determine whether the stress field operational during b would be suitable for a high degree of dilation on a.
- After you've done this, provide suggestions as to how you would resolve whether mineralization on a occurred during time a or time b.

**Fault linking and connectivity**

Linked fault systems provide real rock permeability and potential for major ore accumulation. However, real-time (syn-faulting) connectivity between faults or fault segments is difficult to prove from field relations. You should search for

- commonality of alteration styles and mineralization
- similar inferred P-T conditions
- lack of clear textural or map-related overprinting (although this may be misleading for complex fault movement histories)
- geometric relations consistent with synchronous movement

Despite the difficulites of firmly establishing real-time connectivity from field relationships, it is possible to make preliminary estimates of the degree of fault interconnectivity on a complex fault array. A favourably oriented fault segment that is linked to other faults is more likely to be able to transmit fluid considerable distance than one that is isolated in 3D. This forms the basis of "percolation theory" (see below), which states that fracture arrays commonly start as series of isolated fracture segments, and with time coalesce to produce spines (major flow-through channels) and dangling segments, the latter of which may be important fluid and ore traps.




By analyzing both the orientation and connectivity of fault segments, hypotheses can be constructed for field testing and ground truthing of prospective sites. *Take care* however, because you must go through the routine of establishing real movement vectors on as many faults as possible to determine the 3D fault movement solutions and hence be able to infer stress orientations and favourably oriented fracture arrays.

*Procedure*

*Beware:* each one of these steps is fraught with difficulty: you are constructing a speculative hypothesis for testing!

- Determine real movement vectors for as many as possible of the faults in your array
- determine the sequence of faulting so you can decide which faults do and don't "belong" to the fault array
- use knowledge of the geometry of the largest faults to infer the far-field orientation of the stress field causing the faulting
- determine which of the fault segments are in favourable orientations for dilation relative to the inferred far-field stress array
- determine the hierarchy of fracture/fault connectivity, whether spines, dangling or isolated
- identify favourably mis-oriented (dilatant) parts of the main spines
- combine the results of 4, 5 and 6 to prioritize targets for gound truthing and follow-up mapping
- reassess, after mapping, the potential for different outcomes if the far field stress orientation was different, and/or the sequence of faulting inferred was different

What is missing from this analysis? There is a vast amount of information that can be gathered from textural and alteration patterning around the fracture segments. The prioritization used in points 4, 5 & 6, and the subsequent iteration, can be improved by ranking different fractures or segments according to the inferred nature of fluid-rock interaction that occurred through and around the fracture. For example (Figure below):

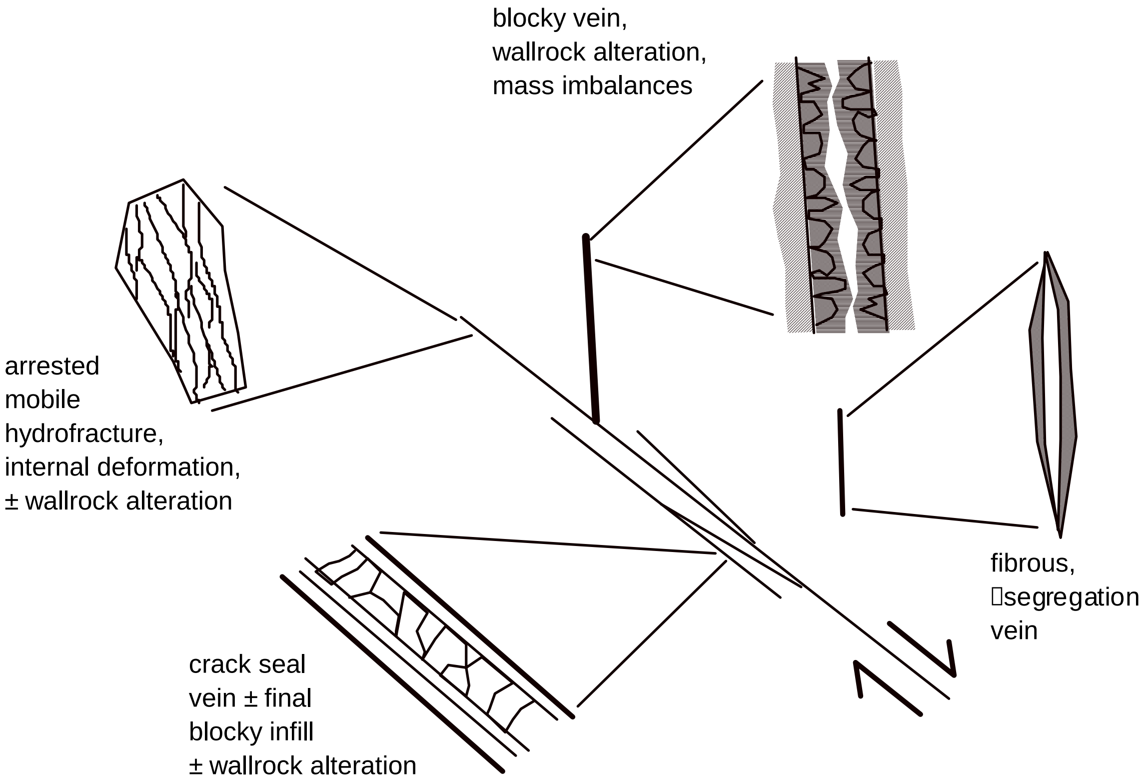
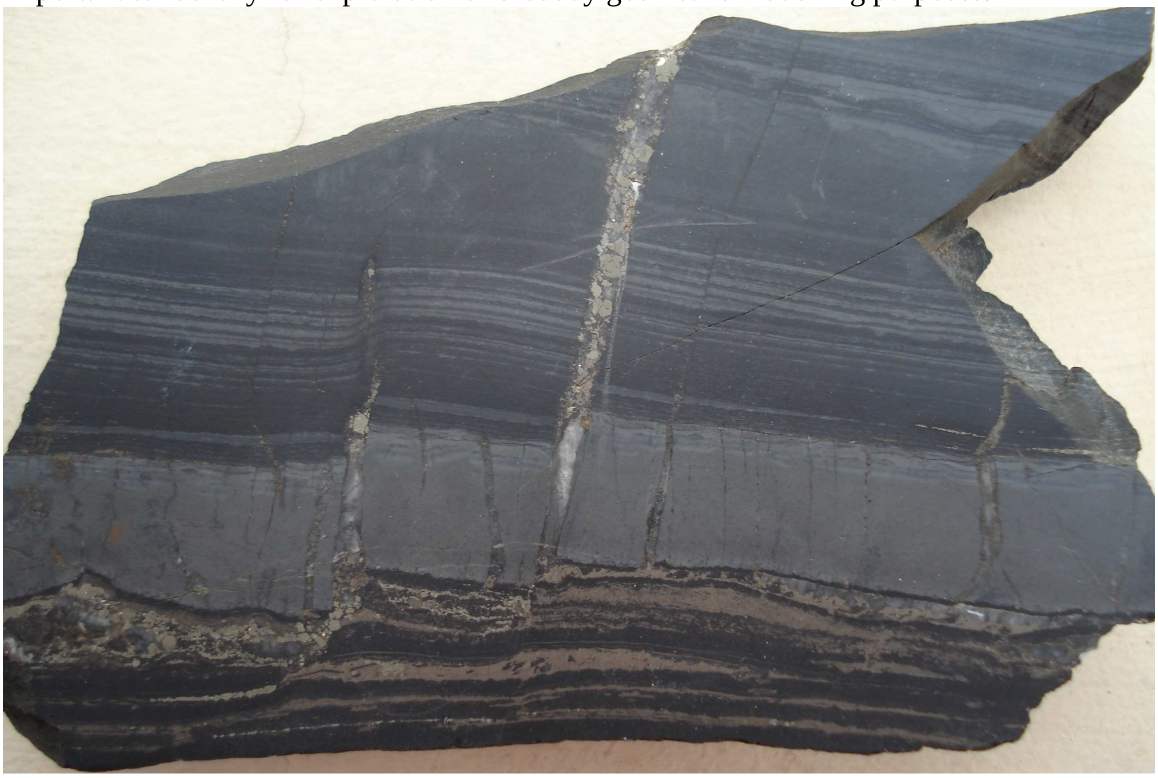



*Figure: Adding value to a fracture analysis is possible by determining the type of fluid-rock interaction revealed by internal vein textures and surrounding wallrock alteration patterns. By using the vein classification presented in Section 2, you can refine the outcomes of a basic prospectivity analysis built largely on structural principles.*

## ROCK-BASED PRACTICAL EXERCISE

This is ideally done interactively, with rocks you have found/logged yourself, in a workshop environment. These examples might give you a bit of an idea about how to approach the complexity of multiple vein and fracture sets, knowing that one or more of them could be important to identify for exploration or orebody geometric modelling purposes.



**Q1: Using the above image** (from the Mount Isa copper deposit)**, do the following:**

a) clearly mark in the edges of the observed veins, and trace them down into the dark layers
b) mark the apparent offsets on the veins
**c)** using the notes provided, determine what the likely stress field was for the main part of the veins, with the assumption that this field of view in 2D is looking orthogonal to the slip vector along the edge of the veins.
**d)** Classify the veins in terms of where they would sit on a Mohr Circle diagram (tensile vein, extensional shear, compressive shear, or intact rock)
**e)** Establish where the assumptions of a consistent stress field (as inferred for the main quartz-rich part of the veins) is probably inadequate
**f)** Noting the distribution of sulphides and quartz in the veins, speculate on the depositional mechanism of minerals in the veins

**Q2 Two intersecting structures** (from central Finland, Tampere Schist Belt)
a) determine the paragenesis of the features shown
b) looking at the black vein (tourmaline), discuss whether you think the apparent offset is a faulted vein, or a single vein with a jog
c) with the assumption it is a jog, determine the possible stress field operating during formation of the jog (again assuming that this 2D view is optimal in 3D)
d) are there any other features in the rock that are consistent with this stress field?

**Q3 Complex veins and shears** (from the Overlander Fault Zone, central Mount Isa Block)

a) with a sheet of tracing paper, draw the key features in
b) determine the paragenesis
c) for each vein/fault set, determine possible models of opening/faulting and stress fields
d) describe a possible stress history for these veins