THE VEINING BIBLE

The roles, textures and geometries of veins in a deformed rock volume

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2023

Contents

PREAMBLE

If you haven't seen my LinkedIn posts, or attended my structural geology training course, you may be wondering what this document is. Basically, I have put my thoughts from my LinkedIn posts into a single entity, represented here by this figure-laden document that I have somewhat arrogantly termed The Veining Bible.

The Veining Bible is a collation of my vein-related LinkedIn posts over the last couple of years, where I initially discussed the roles of veins in a deforming rock mass. Links to these posts are given at the end of the document. After that I continued to add to this document, compiling information of vein overprinting relationships, composite veins and defining the structural ages of veins. There is no need to chase the LinkedIn posts in terms of content because it is identical to that contained herein. However, you may wish to review the comments to the articles.

The long answer as to what this document represents, is that it is a distillation of some of my thoughts on veins that have developed over my career as a structural geologist who has been a researcher, a mine geologist, an exploration geologist, and a discovery geologist – basically as an interested structural geologist. More correctly, it represents a portion of my musings on veins and vein system analysis. The decision to collate some of this was prompted by the spare time imposed on me during two periods of COVID lockdown. Before this period of consulting inactivity, I spent a lot of time in a lot of places looking at veins in a lot of geological systems, from epithermal and porphyry deposits to sediment-hosted base metal deposits to orogenic gold deposits, plus many others in between.

Vein System Analysis is a critical component of Mineral System Analysis, which entails bringing all elements of geology together to understand the environment that can potentially host a world-class mineral deposit. Veins play many roles in the structure-fluid evolution of a deposit and my collated posts address the principal ones. The Parts pertaining to vein roles presented here are numbered one to six. These are followed by sections that include a brief discussion on variation of vein morphology, followed by a section on Composite Veins, and then a how-to section on how to undertake a vein overprinting analysis.

The Veining Bible shows how veins represent a record of the fluid evolution of a deposit, how they form and control part of the structural architecture of a deposit, how their orientations provide information on the geometry of a deposit, how their distribution is a function of the permeability of the rock encountered by mineralising fluids, how they provide structural time-lines for correlation, how they impact rock quality, and how their geochemistry provides insight into the fluid compositions over times. Most importantly for miners and explorers, and the shareholder, they are commonly the host to mineralisation.

The other thing that prompted me to post these articles was constant reinforcement of the unfortunate fact that much of the information that veins can provide goes begging. This is either because it is not captured, the vein systems are not interrogated in detail due to inexperience, the people in control of exploration and mining simply don't think it is important, or all of the above. Simple fact - at the end of the day, the complete understanding of a deposit with veins cannot be achieved if the veins are not studied. Conversely, a detailed study of the veins can identify the ones that aren't part of the fluid-mineralisation signature, avoiding an ongoing waste of time and money sampling, measuring etc veins that won't change the resource bottom line or the exploration/mining strategy.

The Veining Bible is a freely downloadable document available from Olinda Gold Pty Ltd. Olinda Gold is my structural geological consulting company, and you are reading just a portion of material I have compiled on veins. It is unlikely that I will freely divulge all the other material on veins soon, or the many other structural geological topics I cover, because I need to retain some money-earning intellectual property. Regardless, I hope the following chapters from the bible are both useful and inspiring. It's not a document that has been commissioned, so there is no great manner of formatting, no list of figures etc. If that is a problem – too bad. If not, move on dear reader and enjoy!

Contact details for Olinda Gold are given below. We provide many more services than Vein System Analysis, working globally as structural geology consultants to the minerals exploration and mining industry.

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THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 1: FLUID PATHWAYS

When reviewing the geological history of a volume of deformed rock we very commonly encounter veins. The veins can be divided into populations based on many criteria, most of which are initially visual e.g. drill core axis to vein angles, mineralogy, preferred host-rock, alteration selvedge, overprinting relationships relative to other veins and other geological features, geometry/morphology, colour etc. This is done regardless of the depth of formation, whether we are looking at epithermal veins close to the earth's surface or veins in a mesothermal gold deposit that formed at 10km depth.

When it comes to the thought processes around what the vein signifies, we commonly err toward it being a record of fluid passage and mineral deposition. And then we commonly home in on the vein population that we think contains the stuff we want to explore for and mine.

However, veins are more than just fluid pathways and points of hydrothermal deposition. I would suggest there are many roles, which can be broken down into the following:

Fluid pathways.

Veins represent the conduits accessed by hydrothermal fluids. We all accept this (or at least I hope we do!).

Depositional sites.

Hydrothermal minerals comprising a vein represent the point at which the chemical components in the fluid could no longer stay in solution. The sites may be multi-phase in terms of the different minerals. Even monomineralic veins can be sites that represent hundreds or thousands of stages of deposition. Most of us are aware of crack-seal increments in this regard.

Volume compensators.

Veins are commonly formed in zones where open space has been created. Breccia veins and veins comprising hydrothermal breccia infill are examples of space infill.

Fluid barriers.

Veins contain interlocked crystals that are commonly overprinted and cemented by subsequent episodes of hydrothermal mineral deposition. Such structures can then impede the flow of subsequent packages of fluids and serve to compartmentalise later alteration and mineralisation.

Strain localisers.

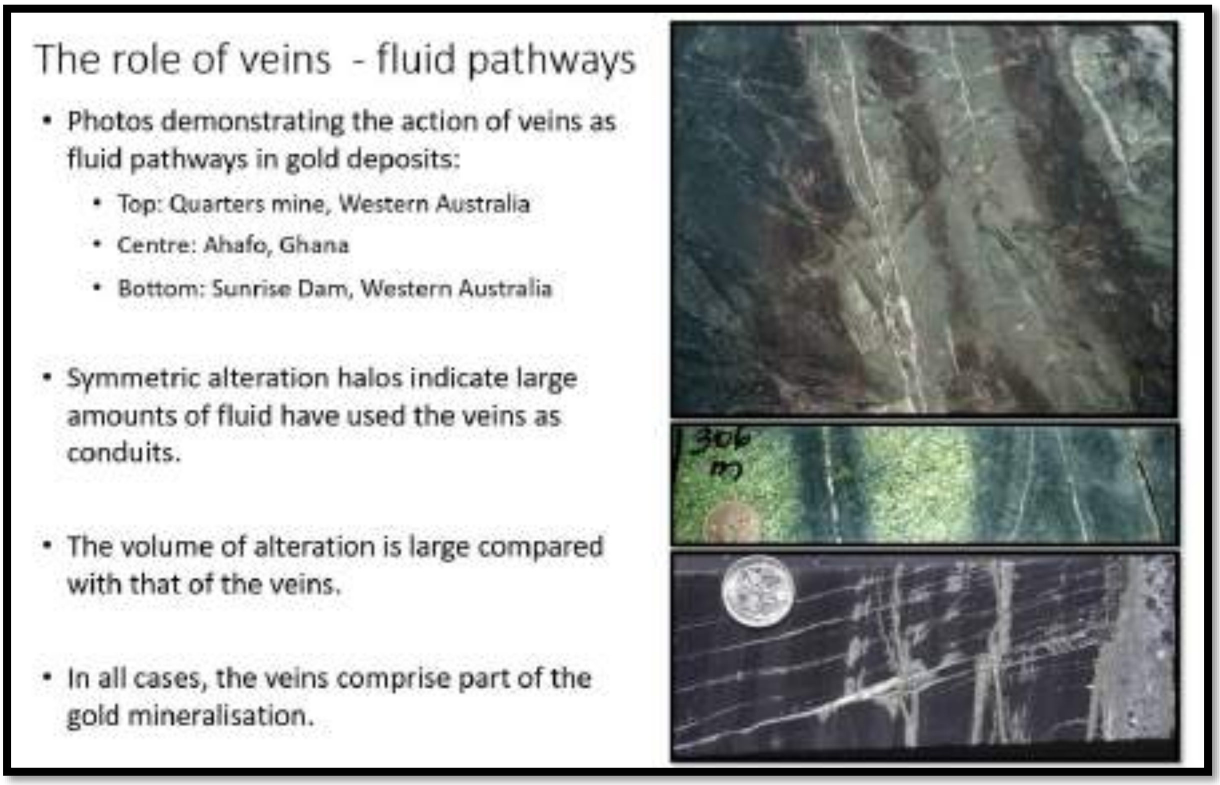
Veins vary significantly in geometry, width, length, composition, and grain size, leading to the accumulation of strain at the margins of the veins. In turn, this can localise subsequent deformation in the vicinity of previous zones of fluid flow. Thick, coarse-grained veins are particularly important in this respect, especially if they contain minerals such as feldspar that are difficult to deform.

Movement accommodators.

Veins are structures that move when opening. The action of opening can accommodate displacement of one vein wall relative to another. Coeval and overprinting deformation can utilise the veins as structures to accommodate significant movement.

Although this may seem a simplistic list, and some people will want to split or combine them (or even add their own definitions to the list), I would suggest that this encompasses most of the things that veins represent in rocks comprising hydrothermal mineralisation. In this short introductory section, I share some examples of veins that have acted as fluid pathways. I will give examples of veins that obviously acted as fluid conduits and then address the other topics in subsequent sections.

One thing to note is the size of the veins versus the volume of alteration adjacent to them. Commonly the volume of altered rock is extensive compared with the width of the fluid pathway. This demonstrates both the favourable composition and permeability network existing in the wall-rocks.

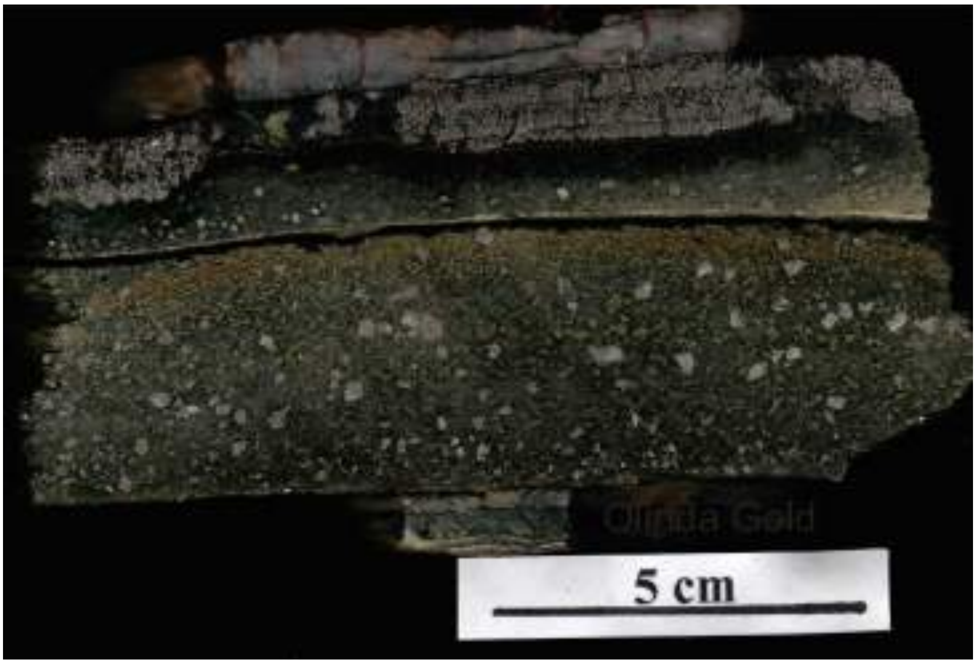


In the figure below there has been extensive wall-rock alteration with brown biotite(?)-altered wall-rock still present. Note the strong zoning of the alteration selvedge around the very narrow veins that host quartz and pyrite.

In this example there are at least two significantly different fluid events. An earlier stockwork of narrow white veinlets is overprinted by a sulphide-carbonate vein that has a visually different stage of alteration. The earlier permeability network set up by the white vein stockwork has not been exploited by the second stage of fluid, which is restricted to an irregularly shaped overprinting alteration selvedge. The textures in the sulphide-carbonate vein indicate brecciation processes at the left-hand end of the sample, and shear-induced lamination in the centre.

Alternatively, we commonly see veins that have narrow selvedges relative to vein width, such as in the next photo. This can be due to a number of factors, including 1) low permeability wall-rock, 2) unfavourable wall-rock composition, 3) fluid passage toward the core of the vein that cannot effectively pass through the impermeable vein margins, 4) low fluid volumes during the alteration-producing stage(s) of vein evolution.

In the case where fluid passage toward the core of the vein that cannot effectively pass through the impermeable vein margins, we may see discontinuous alteration selvedges or variations in mineral concentration along the vein. The photo below may be an example of this. Here, most of the alteration mineralogies are evenly represented along the vein except for the arsenopyrite immediately adjacent to the vein, which shows local gaps in continuity.



Two vein-fluid phases are shown in the next example below. The earlier stage of sheeted veins has brown alteration that has exploited a regularly oriented wall-rock fracture system. This has produced strong alteration adjacent to the veins that changes to fracture-controlled alteration linking the veins. The proximity of veins and their ability to use linked permeability is critically important for attaining economic volumes of mineralised rock.

The white breccia vein stage has likely exploited the same country-rock fracture system during deposition. However, alteration is limited. This may be a function of several factors, including unfavourable wall-rock composition, and the wall-rock permeability being subparallel to the orientation of the vein, rather than emanating from it.

In the example below the green-grey alteration forms a pseudo-botryoidal geometry (remember – veins can be narrow, but they are three-dimensional planar structures) next to the causative vein. The smooth outer margin of the alteration suggests that the fluids have pervaded the wall-rock along limited grain-scale permeability rather than by interlinked fractures e.g. as in the previous image.

If fractures are lacking but grain-scale permeability is high, and the host-rock has a favourable composition for reaction with vein fluids, we can get wide diffuse alteration haloes as shown in the example below.

At this point I will make the following comment - these are my thoughts based on looking at lots of rocks, being confused by them, and ultimately trying to reconcile my observations and data. So, they are interpretations and I'm not going to get bitter and twisted if people offer alternatives, so long as they can back them up.

THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 2: DEPOSITIONAL SITES

I stated in Part 1 that veins play several roles apart from the obvious ones of providing conduits for mineralising fluids and repositories for hydrothermal mineralisation. I will reiterate these roles here for the benefit of people who were too pre-occupied to read the previous Part. I will then go on to discuss the role of veins as depositional sites.

My list of the contributions that veins make to a deformed rock volume is:

Fluid pathways

Depositional sites

Volume compensators

Fluid barriers

Strain localisers

Movement accommodators

When considering veins as depositional sites we are looking at the hydrothermal minerals that comprise the vein. These minerals represent the point at which the chemical components in the fluid could no longer stay in solution. The sites may be multi-phase in terms of the different minerals. As an example, most of us are familiar with quartz-carbonate veins that commonly comprise large volumes of the veining in mineral deposits (and in deformed rocks in general). Even monomineralic veins, such as quartz-only veins, can be sites that represent hundreds or thousands of stages of deposition. Most of us are aware of crack-seal increments in this regard. For example, check out the first photo in Part 6 of this collation. In conjunction with the hydrothermal minerals comprising the alteration selvedges to veins, these represent the volume of rock that has had enough permeability to allow ingress of fluid and deposition of vein-associated minerals.

As with all the Parts in this collation, this one is photo-laden because every vein represents an example of hydrothermal mineral deposition. As such, there is an incredible number of textures to choose from. I will start off with extension veins, which used to be termed tension veins. Extension veins commonly contain minerals that are undeformed and that have grown at a high angle to the vein margins. They may also preserve crack-seal textures.

In the first example from Mallee Bull in the Cobar Basin, Australia, the quartz fibres are at a high angle to the vein walls. Chalcopyrite is intergrown with the quartz and shows similar elongate geometries parallel to the quartz fibres. These textures indicate syn-tectonic coeval deposition of the sulphides and quartz.

In the example shown below the extension veins shown symmetric colour banding reflecting compositional/mineralogical zoning. Note that locally the final white stage of infill cuts across the earlier grey vein margins. Intergrowth of the chalcopyrite occurs dominantly with the white carbonate suggesting coeval growth. Chalcopyrite in the grey portions of the veins is likely an overprint of the earliest carbonate vein stage. This example is from the Kinsevere copper deposit in the Democratic Republic of Congo.

The example below is also from Kinsevere, showing extension veins comprising thin carbonate margins and monomineralic centres comprised of chalcopyrite. Extensional spurs are attached to the vein left-hand vein but show progressive separation down to the left. The veins are subparallel to lithological layering, which shows grain coarsening in the right-hand side of the sample due to carbonate grain growth.

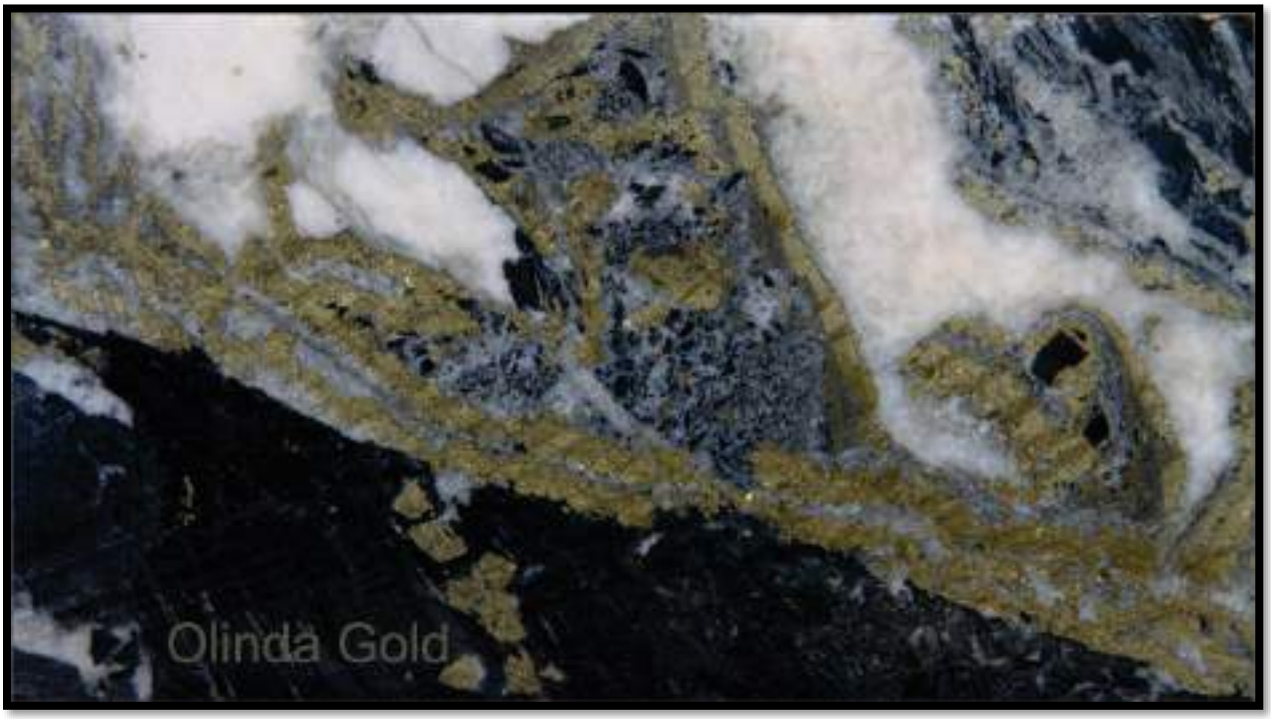
Asymmetric zoning of the vein below indicates several stages of mineral deposition that were localised along fractures at the contact between the early vein stages and host-rock, rather than successive opening occurring along the centre of the vein (as in the previous examples). Elongate pyrite-quartz grains on the lower side of the vein indicate coeval growth into open space, as do locally euhedral quartz crystal terminations (arrowed).

Sheeted extension veins in the two examples below have formed in competent silicified mylonitic hoist-rocks that preferentially fractured. These veins contain base metals and are from the Balaria deposit in Rajasthan, India. The early stages of vein formation involved brittle fracture exploitation as shown in the second photo.

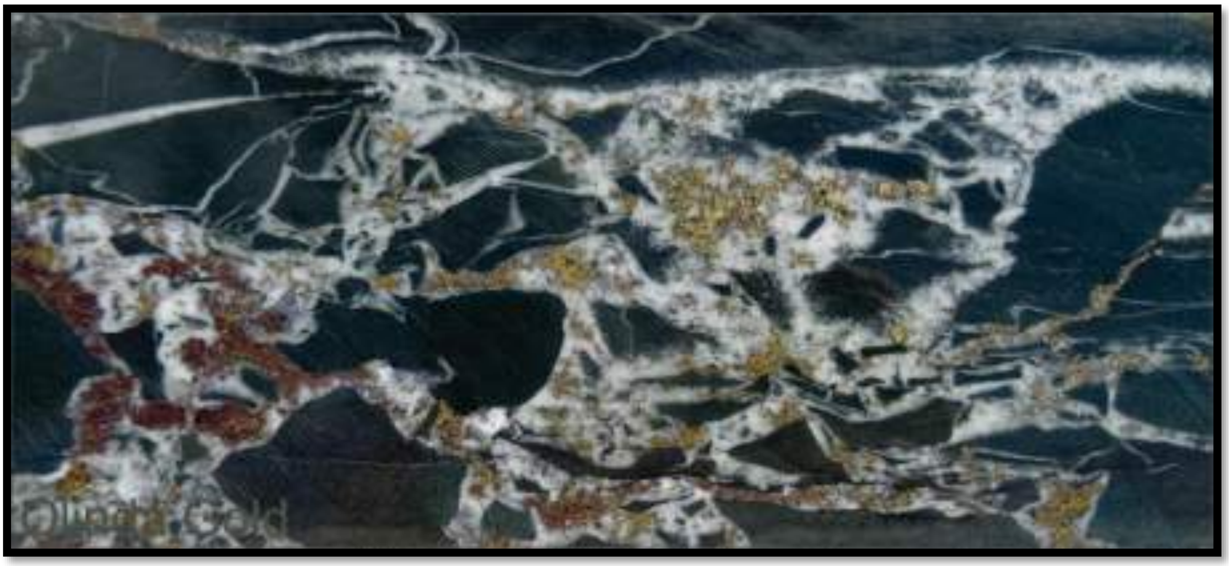
The scale of veining can be extremely variable. The impressive sheeted vein suite in the photo below is from the Mulgarrie gold deposit northeast of Kalgoorlie in Western Australia. If you look closely, there is a geologist in the photo.

In the example below the pyrite veins form a stockwork that has overprinted the pre-existing quartz extension vein. Pyrite crystals define veins that track across the quartz and that also rim wall-rock breccia fragments produced during formation of the pre-cursor quartz vein. This is from Twangiza in the Democratic Republic of Congo.

The next photo shows multistage vein opening and mineral deposition stages as indicated by an early breccia vein stage that has been in turn brecciated. The second breccia stage has involved deposition of white quartz, grey carbonate, and rimming of clasts by sulphide. This example is from the Inata gold mine in Burkina Faso.



Veins can form mosaics that comprise stockworks. Commonly, the distinction between stockworks, breccias, and breccia veins becomes subjective. This supports the existence of a transition between the different vein geometry styles. It also reinforces the importance of taking vein scale into account. For example, at the core-scale a series of irregularly oriented veins may comprise a stockwork at the development-scale. The quartz veins in the next two samples from Mallee Bull below bound chlorite-altered wall-rock and comprise a stockwork. In the second photo the final stage of vein deposition comprises sulphides that manifest as brown sphalerite and brassy chalcopyrite.

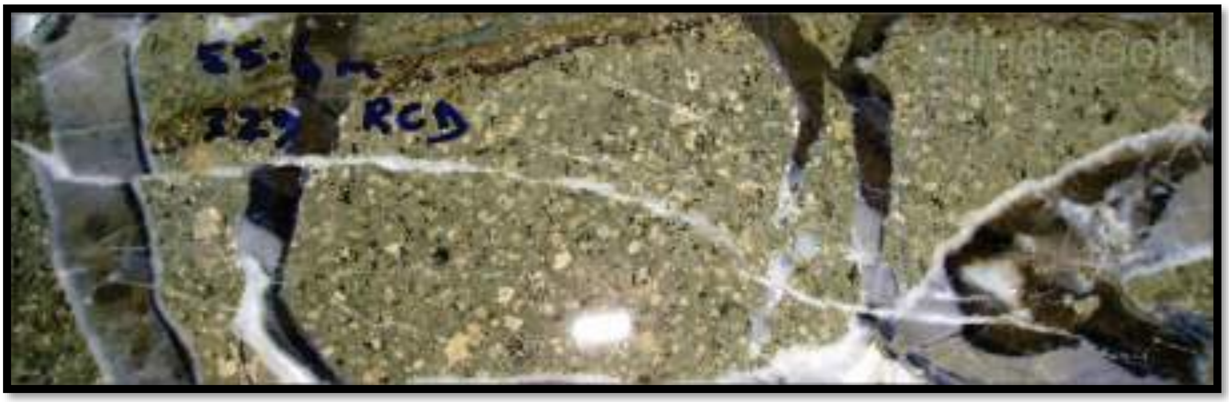


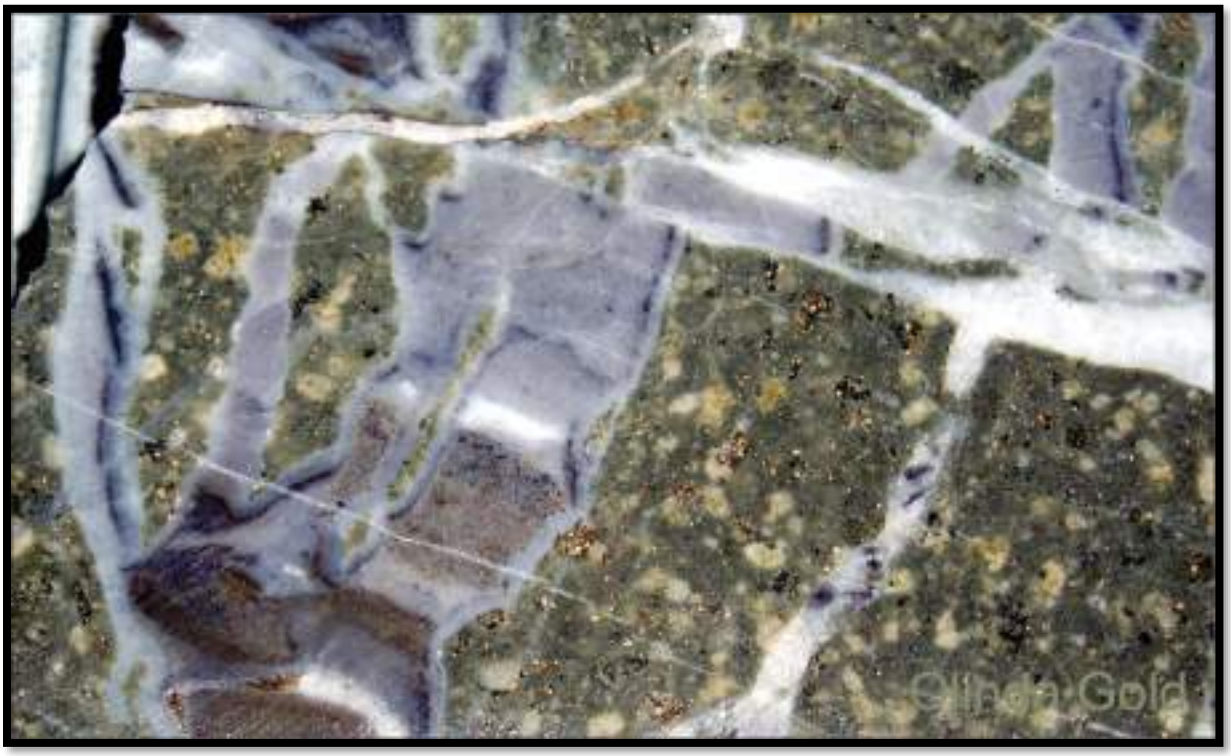
Vein stockworks can form at the deposit-scale, as shown in the Serajun open pit at Mt Muro. Here, two principal extension vein orientations on the right-hand side intersect obliquely to form a stockwork adjacent to the causative brown fault on the left-hand side.

Given the above geometry, it would be remiss of me not to mention veins that form infill of extensional sites on faults. The best known of these are extensional jogs, which can occur in veins at the core-scale (shown below) through to the scale of whole deposits.

As shown for the Serajun orebody above, epithermal vein systems are classic examples of open-space infill. In the example below, the zone of bright spots immediately below the coarse-grained white quartz band is free gold.

In some spectacular cases, such as the examples from Chatree gold mine in Thailand below, the open space has been connected to the surface and infill is represented by sediments that show layering that is locally continuous from vein to vein. The black material in the sediments is carbonised plant material.

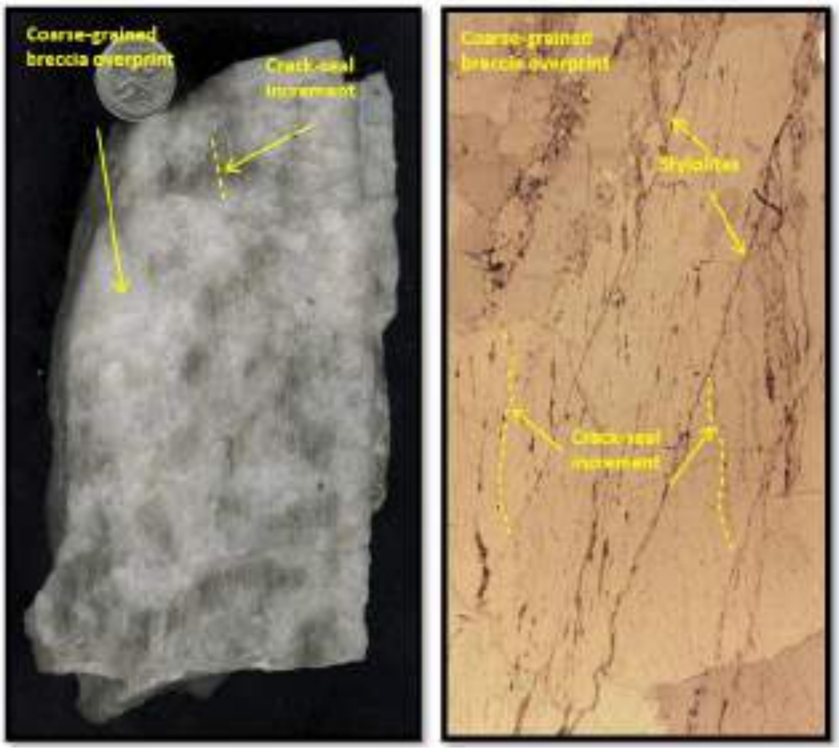




Veins commonly show examples of extension-related mineral infill and vein material that has been subsequently sheared. The typical way to form a vein to produce open space into which hydrothermal minerals can be deposited. There are veins that form via replacement only, but they are less common. The open-space veins can then progress to shear veins as they are overprinted by ongoing deformation processes. The next two figures are from the Brucejack deposit in Canada. The first shows a mosaic of gold that overprints the symmetrically zoned quartz vein. The second example shows anastomosing gold-electrum bands that mimic the textures in the host shear vein.

The example below is from the Curraghinault gold deposit in Northern Ireland. Extension vein banding is still preserved in the upper central portion of the vein. However, elsewhere sulphides obliquely overprint the banding. Toward the margins the quartz shows shear-induced lamination due to strain accumulation and shearing at the vein margins.

In the example below, the vein as we see it now has had a protracted history of formation. Initial vein formation occurred via thousands of sub-millimetre increments due to seismic swarm activity at the Quarters orogenic gold deposit in the Eastern Goldfields of Western Australia. The crack-seal increments are preserved in grey-brown clasts of original vein material that has been overprinted by relatively later quartz. Negligible jostling of clasts has occurred, as noted by the consistent orientation of the earlier-formed crack-seal increments from clast to clast.



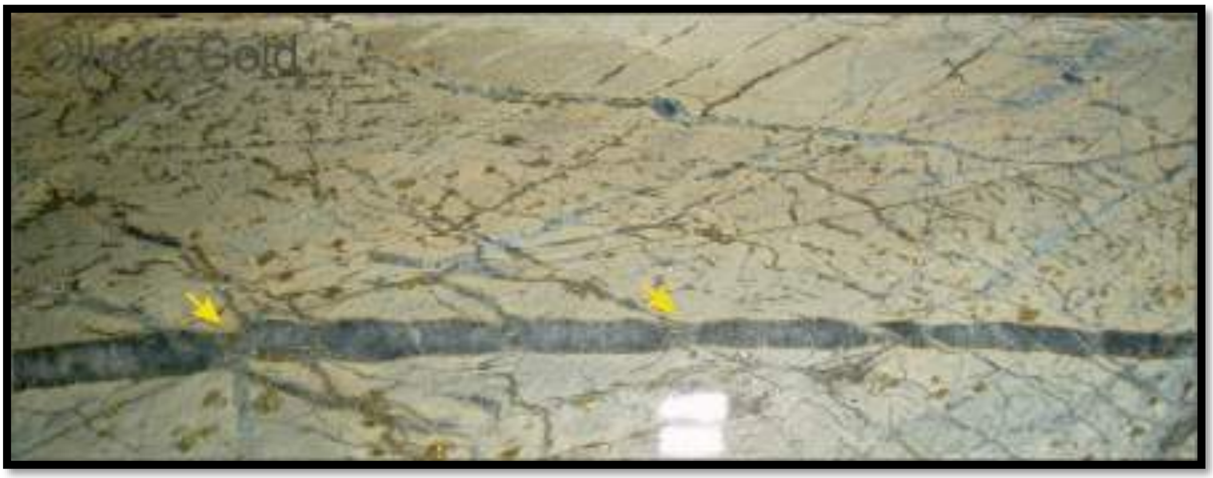
Shear induced lamination and stylolite formation overprinted the breccia stage in the sample above. This was in turn overprinted by crackle brecciation that was exploited by gold, as shown in the photo below. The dendritic gold-filled fractures cut across all other features and represent one of the last stages of mineral deposition.

As a digression, the specimen from Quarters shown here was presented to me as a trophy with a plaque saying, 'for finding the lost orebody'. Development and drilling had failed to locate the reef in one major stage of underground development. I worked out that this was due to the action of two faults, the intersection of which was exposed in development. The exposure allowed me to determine that the first had accommodated dip-slip displacement of the orebody. This had been overprinted by a second intersecting fault that displaced the already dislocated orebody with strike-slip motion. The key to resolving this was understanding overprinting relationships and being able to resolve the kinematics. In doing so, I located the displaced lode and contributed significant resources to the mining inventory. It also stopped any further expensive development in barren rock and removed the need for ongoing exploratory drilling.

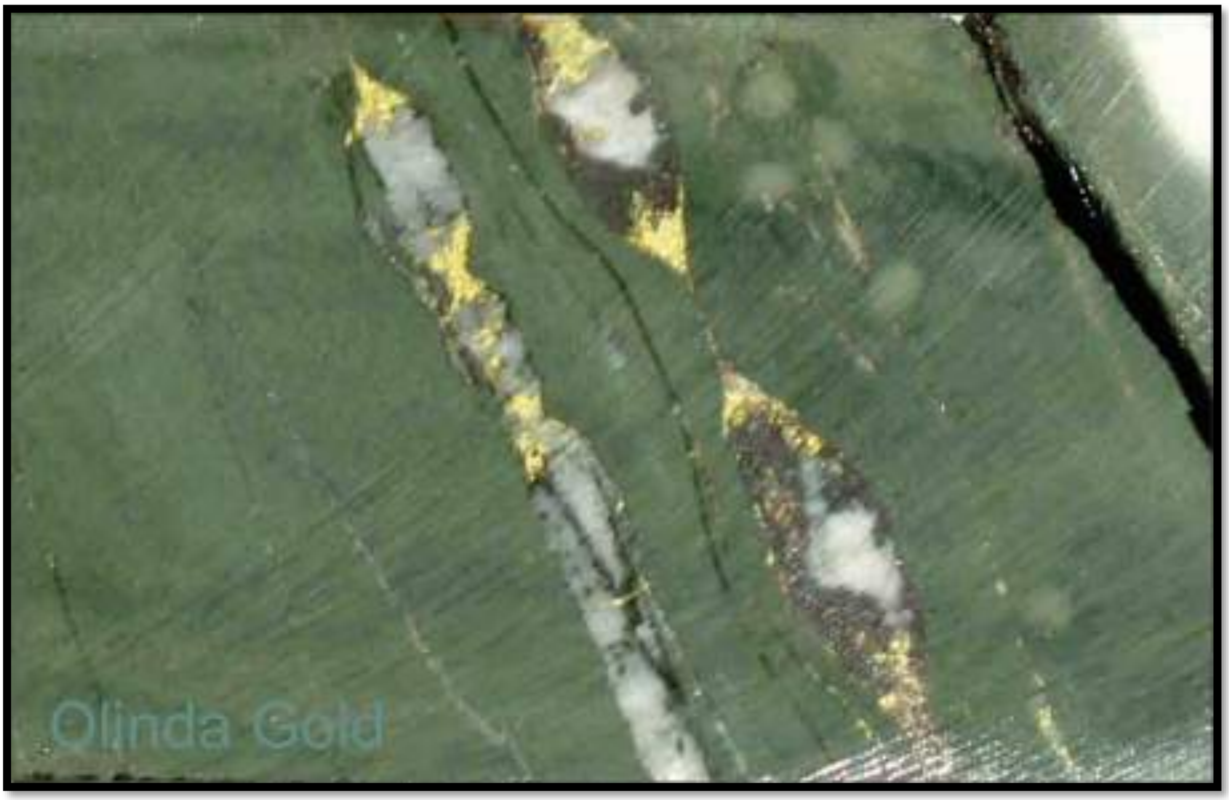
Permeability is the key to moving fluids at all scales. If permeability in the vein wall-rocks is high there this can lead to abundant alteration and economic mineralisation occupying the host-rocks to the veins. Commonly, it will be lower grade than the veins (which can contain bonanza grades in gold deposits) but it can occupy a volume much greater than that defined by the veins. The following two photos show gold-mineralised pyritisation of banded iron formation from a deposit at Sandstone in Western Australia.

As vein systems evolve, they are commonly overprinted by deformation. This can be brittle, ductile, or both and is a function of many things, including competency contrasts between veins and wall-rocks, the amount of strain, the strain rate, the presence or absence of subsequent fluid phases, subsequent alteration that changes the strain conditions, uplift over time passing from brittle through to ductile conditions, subsequent metamorphism etc.

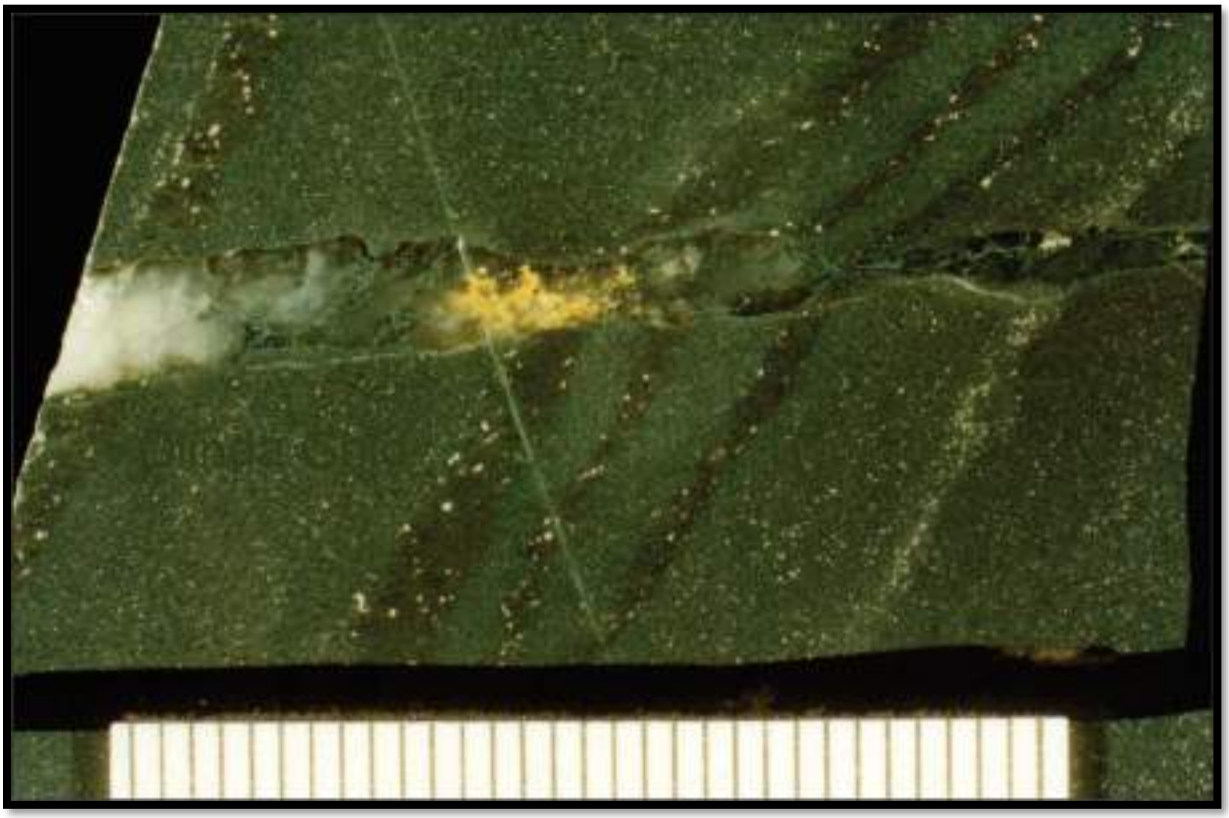
I'll start by showing some veins that have undergone ductile deformation. This is an incredibly important process during the evolution of a mineral system because early unmineralized veins can control deformation such that they deform and focus subsequent mineralisation. In the first example below, an early grey quartz vein has undergone boudinage. Deposition of carbonate and sulphides is localised to the boudin necks and into wall-rock fracture-filling veins. This is from the Salman prospect in southern Ghana.



In the example below from the Cobar basin, boudinage of the veins has controlled sulphide deposition, with chalcopyrite and pyrrhotite being focussed into the boudin neck and into extensional fractures in the boudins.

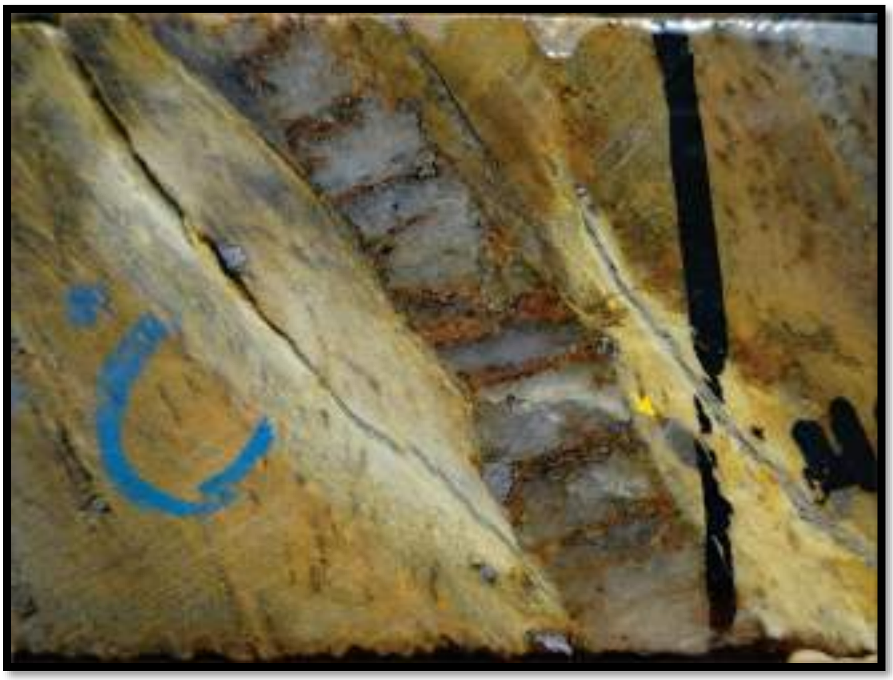


The fantastic example below is from the Callie gold deposit in the Tanami Desert in the Northern Territory, Australia. Here, vein deformation has caused vein attenuation and gold has been localised into the developing boudin neck. Extensional fractures occur to the left of the gold and have been infilled by chlorite.

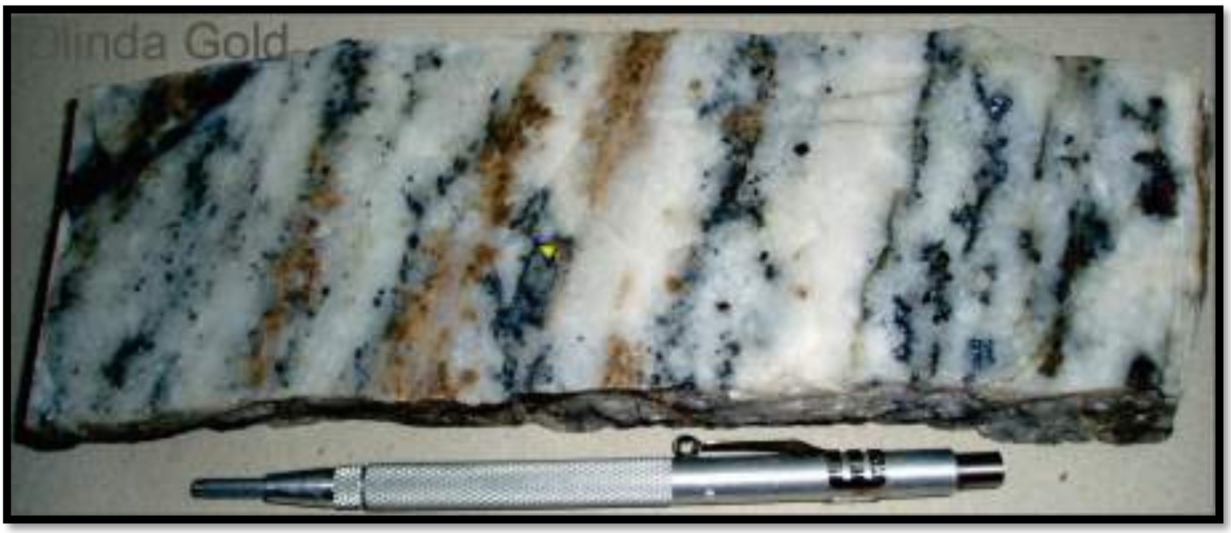


The example below shows a boudinaged quartz veins from the Kalabar deposit in Rajasthan, India. The strongly foliated wall rocks have accommodated strong ductile shear, causing boudinage of the quartz vein. Pyrite has infilled the boudin neck and also occupies an extensional fracture across the centre of the right-hand boudin. If you look carefully, you’ll see the fracture actually joins embayments in the quartz vein where it is starting to boudinage.

As we move into the brittle-ductile regime and through to the brittle spectrum of deformation, we see that veins are still important for hosting deposition of hydrothermal minerals. The example below is from the Lagushwa deposit in eastern Democratic Republic of Congo. Ductile deformation has been accommodated by the schistose wall rocks. However, the competent quartz vein has sponsored brittle deformation as a series of spaced fractures that have infilled with iron-carbonate and gold-bearing arsenopyrite. Note that deformation has continued after arsenopyrite deposition and is indicated by strain shadows at the ends of the preferentially aligned crystals in the wall-rock.



The example below is similar to that shown for Quarters above. This vein sample is from Kundana in Western Australia, and the vein has been overprinted by shear-induced lamination, stylolite formation, and crackle brecciation. The shear laminar are occupied by gold, base metals and scheelite (light brown). The subsequent stylolites and crackle brecciation are occupied by base metals (dominantly galena) and gold, indicating they continued to be deposited after cessation of scheelite deposition.



The example below shows shear a shear laminated quartz vein. Some of the features are actually sub-millimetre scale cataclasite zones defined by brittle deformation dominating over ductile deformation. These deformation zones have hosted deposition of chalcopyrite.

The final example below is from Twangiza in eastern Democratic Republic of Congo. The quartz vein has been strongly overprinted by pyrite-bearing shears that have in turn locally developed to cataclasite. The shears have been conduits for the fluids that deposited pyrite and deposition has been promoted by the competency contrast between the veins and host-rocks. Favourable pre-cursor chemistry of the early veins was likely also important.

So, that’s it for Part 2. The thrill of Part 3 awaits on the next page!

THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 3: VOLUME COMPENSATORS

This is the third item in the list of contributions veins make to a deformed rock volume, which I repeat below. So far, I have discussed veins as fluid pathways and depositional sites in Parts 1 and 2 of this series. In this Part I discuss, largely by way of illustration, the third item in the list below, namely the role of veins as volume compensators in hydrothermal mineral systems.

Fluid pathways

Depositional sites

Volume compensators

Fluid barriers

Strain localisers

Movement accommodators

The formation of veins entails the deposition of hydrothermal minerals into open space due to physical and/or chemical conditions. As the hydrothermal system evolves the veins can change many of their features, including morphology, size, mineralogy, and location in space in the hydrothermal system (e.g. due to changes in position of the main fluid conduit).

In an actively deforming rock mass, open spaces can act as stress localisors. Infill of the open spaces can thus change the local stress and strain conditions of the rock mass. In fluid overpressured systems, and in conjunction with fluid-assisted seismic swarm activity, hydrothermal mineral deposition is ongoing so long as fluid is available. The veins typically build up progressively but, if fluid access is interrupted, such as by a decrease in permeability, open space can be preserved.

The following photos show how deformed rocks accommodate changes in volume produced when open space is formed. This is directly related to the role of veins as depositional sites discussed in Part 2 where I discussed the role of veins as depositional sites.

The photo below shows a tennantite-chalcopyrite-carbonate vein that has filled open space in the Chelopech high-sulphidation deposit in Bulgaria. The second photo is also from Chelopech and shows well-banded pyrite-tennantite-chalcopyrite open space infill.

Extension veins show abundant evidence for accommodation of volume changes via infill of voids. mineralogical banding is well developed, and euhedral crystal terminations are common. The first example below is in a foliated granite that shows evidence for at least two deformations because the strong wall-rock foliation is openly crenulated. The vein is likely a response to later, higher-level, relatively more brittle deformation.

The example below is from the same area as the previous photo and shows remaining open space. Although some of the space is likely due to dissolution of vein minerals such as carbonate, a certain amount of open space was probably also present due to insufficient fluid to account for infill of spaces created during the volume change.

In the example below there has been insufficient fluid to fill the void created, leaving open space lined with euhedral crystals.

The example below shows fibrous vein material at the bottom of the photo that will have formed via crack-seal increments that kept pace with vein opening. The final stages have seen a volume change that could not be accommodated by complete infill, resulting in incomplete euhedral crystal infill of the vein void. This sample is from the top of Mt Read in western Tasmania, Australia.

Veins such as those shown above give indications of episodic fluid flow and deposition in the form of mineralogical banding. Commonly these veins comprise parts of sheeted vein arrays, meaning that the volume change the veins have accommodated can commonly be very large.

The sheeted veins below are from the Silver Star deposit in the MacArthur Basin in northern Queensland, Australia.

The sheeted quartz-chalcopyrite veins below are from the Cadia deposit in New South Wales, Australia.

The impressive sheeted vein array in the photo below shows the manifestation of the Drysdale Shoot in the Super Pit in Kalgoorlie, Western Australia.

The herring-bone style of sheeted veining below is a product of volume increase during brittle-ductile chevron folding. This has resulted in thicker discontinuous veins propagating along the brittlely ruptured hinge zone, with parting of layers on the limbs to form the sheeted array. This example is from the Curraghinault gold deposit in Northern Ireland.

As we approach the main causative faults that are repeatedly reactivated during seismic swarm activity, we see an increase in veining and a transition from individual planar veins to sheeted vein arrays to stockworks and then into the chaos of breccia veins. The amount of displacement during each seismic reactivation of the faults is minor but the fluid budget can be great, as can the cumulative volume changes that the veins account for.

The example below shows a sheeted vein array on the left that has intersected a stockwork of gold-bearing quartz veins that flare upward from a quartz breccia zone close to the main fluid conduit. This is from the Mulgarrie deposit in Western Australia.

The examples below show stockwork development, which need not be products of the same veining event. They simply represent geometries where veins of more than one orientation intersect. In examples such as that below, the veins are almost orthogonal. This is likely due to transient flipping of the stress axes, resulting in extension in one orientation swapping to extension in an orthogonal orientation as fluid pressures cyclically build up, deposit vein material, and drop.

The stockwork below was photographed in the region around Brucejack Mine in British Columbia, Canada.

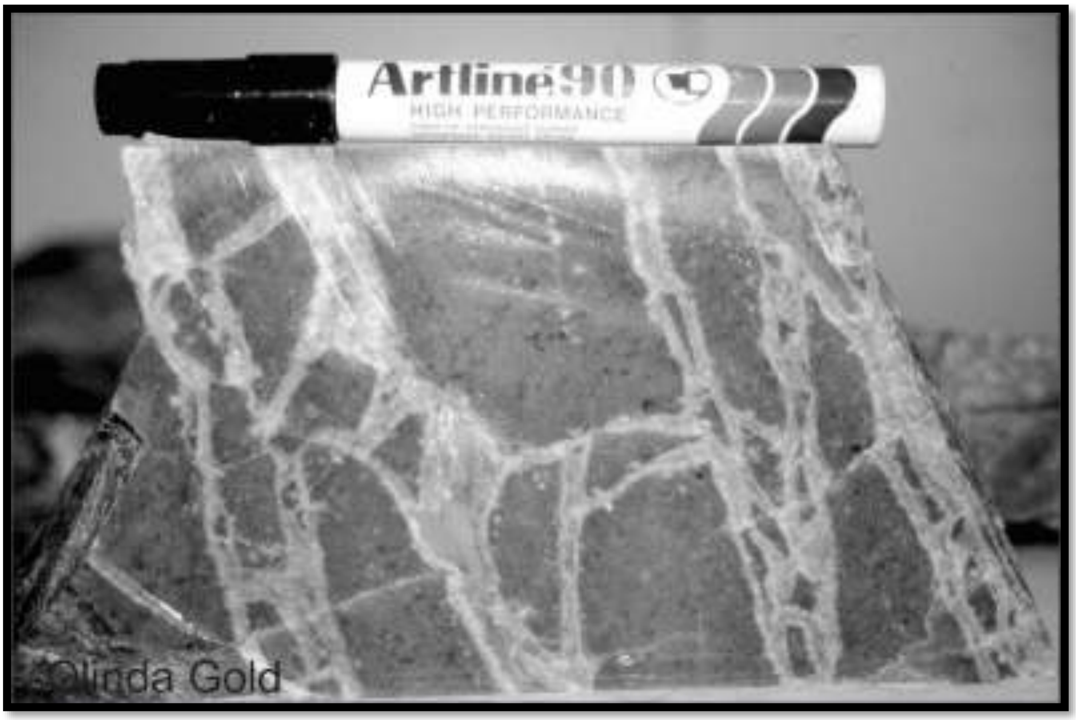
Some stockworks can be amazingly polygonal, especially if the host-rock is fairly homogeneous, as seen in the photo below from the Mulgarrie gold mine in Western Australia.

The hand-specimen below shows partial potassic alteration of host-rocks to the vein stockwork from the Comstock lode in Nevada. Locally incomplete infill is evident and, in conjunction with matrix-supported breccia, attests to the presence of volume increase that the veins attempted to fill.

Breccia veins are classic examples of the formation of open space and attempts by the deforming rock mass to accommodate the local change in volume.

The next set of photos show vein geometries produced as they transition from sheeted arrays and stockwork geometries to breccia veins. In the first example, the veins form a sheeted array, but the relatively larger ones have evolved to breccias with 'floating' clasts, indicating increase in open space.

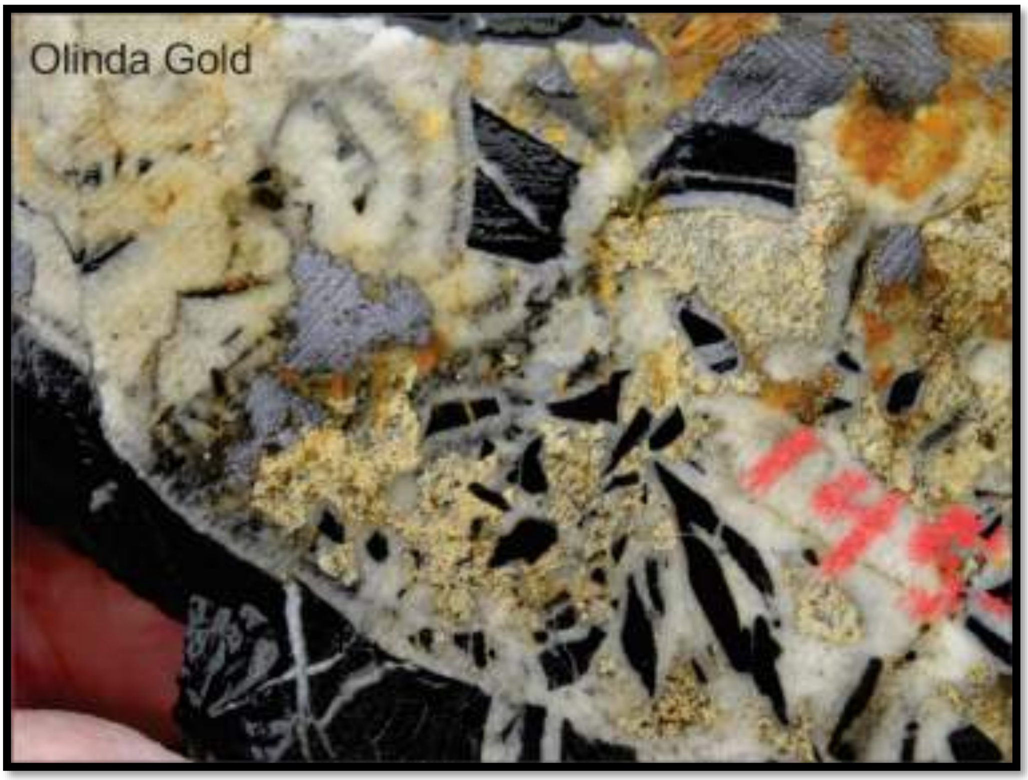
Similar geometries are shown by breccia veins from the Kanowna Belle orogenic gold deposit in Western Australia.



The example below is from the Black Flag Fault as it was exposed in the Woolshed open pit. The sheeted veins on the left are transitioning to stockworks and breccias on the right as the Black Flag Fault is approached.

The example below is from Watson's Lode, a base-metal mineral occurrence in the MacArthur Basin in northern Queensland, Australia. Creation of open space is indicated by mineralogically zoned extension vein and breccia veins.

As the principal fault is approached the veins in the above photo transition to relatively chaotic mineralised breccia zone with sphalerite and galena infill.

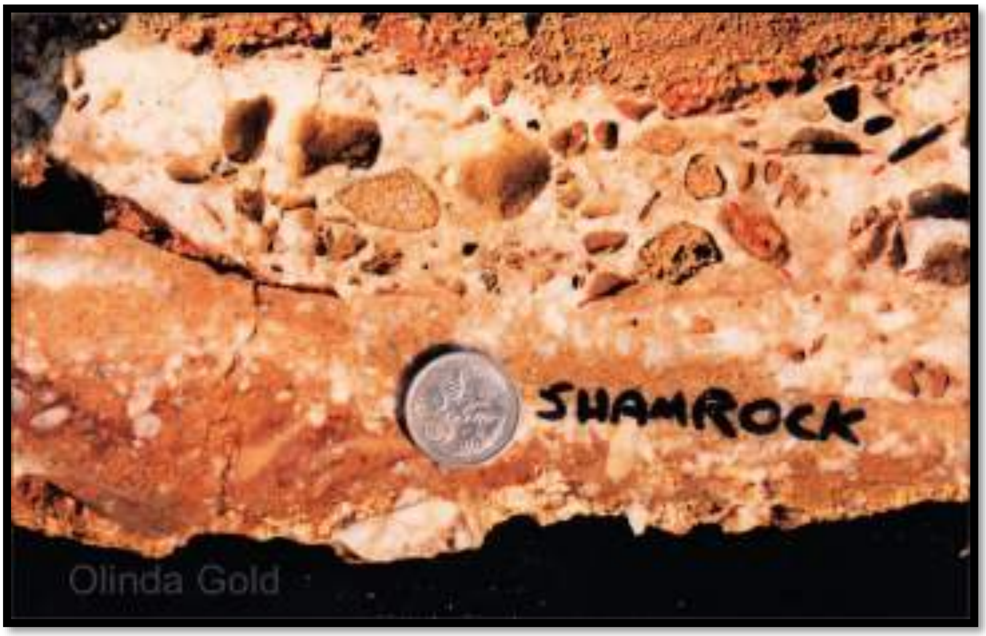


The example below is a development-scale exposure that demonstrates the dynamic nature of deformation, volume change, and massive fluid budget. The crustiform carbonate veins show evidence for abundant open-space crystal growth. Ongoing deformation has folded these, and the fold has then been overprinted by a carbonate breccia as seen in the upper middle-right of the photo. This vein system was developed against the Fitzroy Fault fluid pathway in the Kanowna Belle gold deposit.

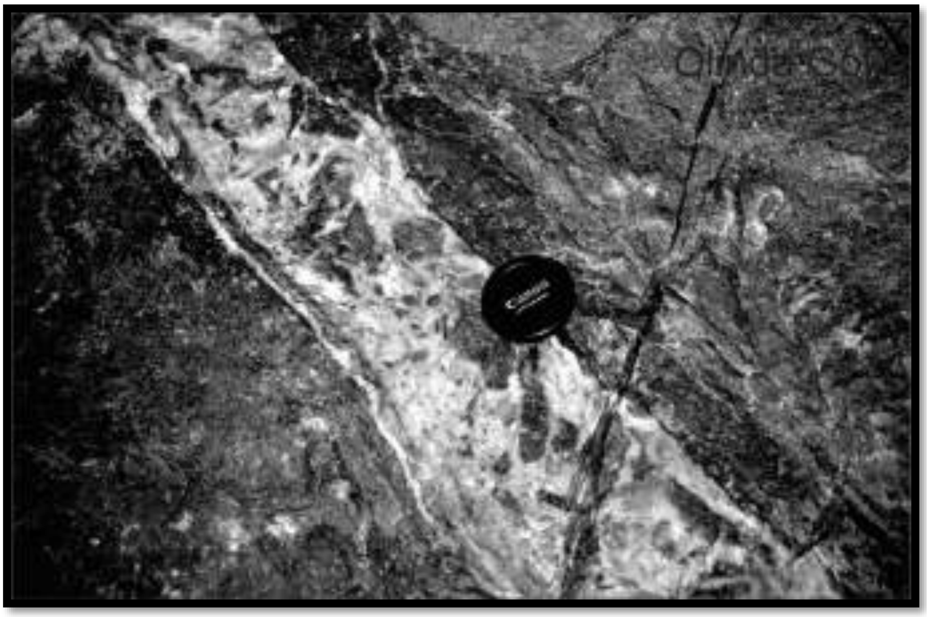
The next two photos are from the Tick Hill iron-oxide copper gold deposit in the Mt Isa Inlier, northwest Queensland, Australia.

My apologies but I don’t remember where the next two photos of breccia veins are from.

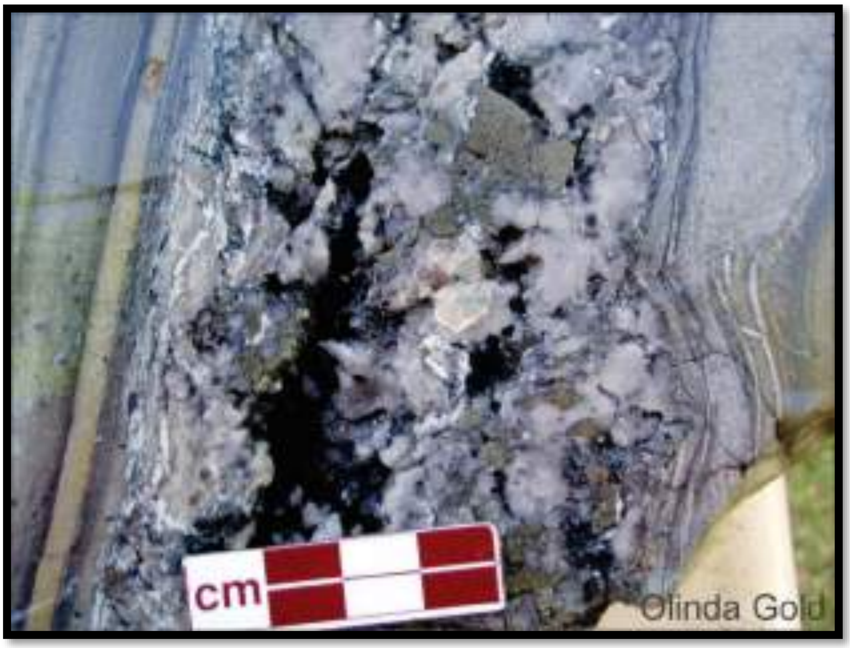
The multiphase breccia vein below is from the Shamrock trend, which is a gold-bearing quartz vein system northeast of Kalgoorlie in Western Australia. Volume change via creation and infill of open space is indicted by quartz matrix supported country-rock clasts that have rotated, as indicated by variable orientations of the host-rock foliation (red lines) in them. Note also the early-formed euhedral quartz crystals, such as blow the letter A, which also indicate open space growth. This deposit was one of many I reviewed around the Scotia-Kanowna dome. I have published a paper on many of these deposits in conjunction with Richard Blewett, my tireless colleague from Geoscience Australia. The paper was under review five years. When I got the paper back so much time had elapsed that my drafting package wouldn't open the diagrams and I had to re-draft them all. The very unprofessional journal editor then asked for even more changes, so I told him to retract the paper. I then published in a different journal.



In the image below, we can see a mineralised breccia vein from the Kanowna Belle gold mine in Western Australia.



The example below is from the Telfer gold deposit in Western Australia.



In cases where faults have been operative but permeability or fluid budget has been insufficient for complete infill, there may be preservation of voids linked by veins that have infilled the relatively lower volume voids.

Another obvious site of volume creation is the extensional jog. Jog infill is typically multi-stage, matching incremental fault movement, and containing extension veins.

Sigmoidal extension vein arrays are analogous in this respect, showing infill of progressively open voids developed under brittle-ductile to brittle conditions, with development in competent host-rocks. The sigmoidal extension veins below show fibrous carbonate infill and are from the Brucejack area in Canada.

The spectacular example below is from the Jundee orogenic gold mine in Western Australia and shows infill of extensional spurs by free gold.

The photo below shows transitions and overlap in geometries of sheeted vein arrays, sigmoidal extension vein arrays, stockworks, and breccia veins that have all developed in an attempt to accommodate the space produced during brittle deformation. This is a polished slab on the exterior of a shop in Stockland plaza in Rockhampton, central Queensland, Australia.

Fault terminations are sites where volume problems occur, depending on whether we are looking at contractional or extensional sites. One way for faults to terminate is to transfer movement to a series of smaller structures that accommodate components of the displacement, effectively leading to volume increase or decrease at a number of linked sites. In cross-section we commonly see positive and negative flower structures. The example below shows horse-tailing of veins at the end of a structures where veins have infilled the space created by incremental movement on the principal structure. This is from near Brucejack mine in Canada.

One of the prime controllers on the development of open space and volume change is the difference in physical properties of rock-types. Competency contrasts are particularly important in this regard, with relatively more competent units failing in brittle-ductile to brittle fashion.

The example below is from Adriatic Metal's Rupice base metal deposit in Bosnia and Herzegovina. The relatively more competent siltstone and fine-grained sandstone layers have fractured, with infill of the space produced by carbonate veins.

The example below is from near the Ada Tepe epithermal deposit in Bulgaria. Different layers host differing volumes of vein development due to the varying layer competencies.

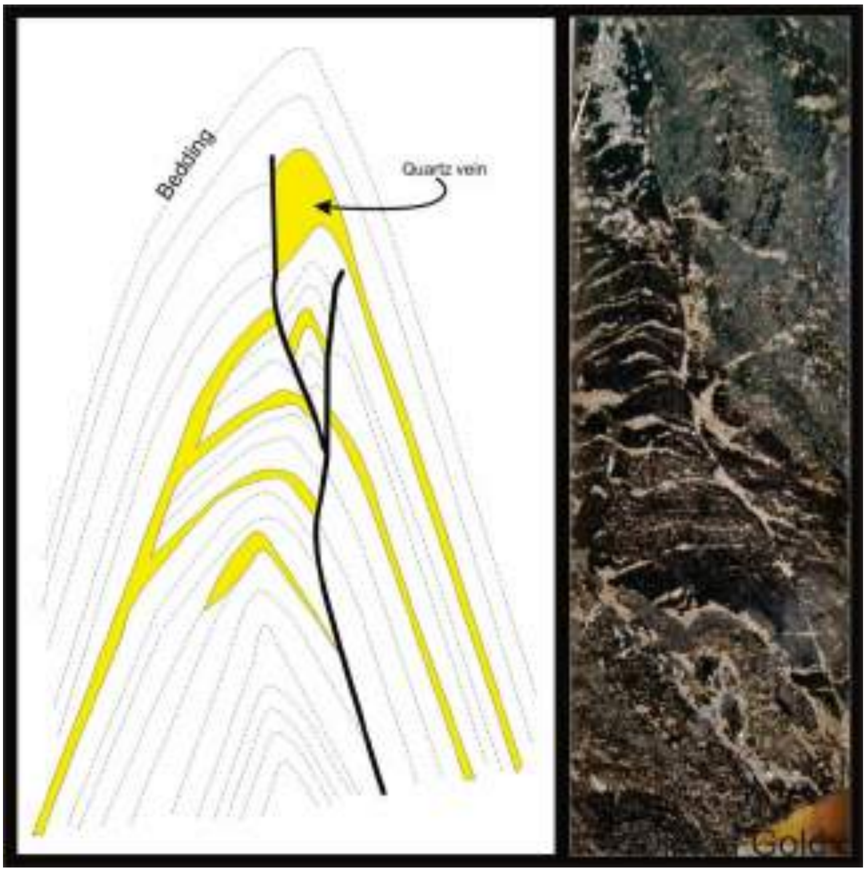
The example below shows silicified clasts that were original part of a continuous layer. The white silicified unit has been attenuated and dislocated, with extensional fractures infilled with pyritic veinlets. This is from the Buritica deposit in Colombia.

In rocks that have undergone boudinage, the boudin necks are low mean stress sites and fluid flow is focussed toward them. In rocks have minor compositional differences the relatively more competent units will undergo pinch-and-swell while the surrounding ductile units will accommodate the volume change by infilling the neck regions. If the ductile units can't fill the voids created, the volume created will be infilled by vein material. The example below is from the Hammad Kier prospect in northern Eritrea and shows extension vein infill of the neck regions of a basalt layer. Extensional fractures are developed in the boudins and have also been infilled by quartz extension veins.

The final examples I will show are those of saddle reefs. Deformation processes that produce folds, especially via flexural slip processes, can create space in fold hinge regions. Fluid flow can be focussed along the fold axis or via relatively narrower veins and faults that develop between layers down the fold limbs. Fluid flow along the fold hinges is probably the minor contributor to fluid flow, especially where folds have low plunges or have undulating hinge lines. Faults on limbs are typically much more extensive volumetrically and commonly have steep orientations, allowing them to be relatively more effective hosts to fluid movement.

The first example shows deposition of vein material in the fold hinges, suggesting an important component of fluid movement along the fold axis. My apologies for the poor photography but you can see hinge infill above and below the flash reflection.

The final image below is a schematic diagram showing linkage of hinge regions via veins along the fold limbs. This is akin to the saddle reefs developed at Bendigo in Victoria, Australia. The photo on the right is from the Lancefield orogenic gold deposit in Western Australia.



Thanks very much if you have managed to read this far!

THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 4: FLUID BARRIERS

So far, I have discussed veins as fluid pathways and depositional sites in Parts 1 and 2 of this series. I followed this with Part 3 on veins as volume compensators, documenting how they infill space that is created during host-rock deformation.

In this Part I discuss, again largely by way of illustration, the fourth item in the list below, namely the role of veins as fluid barriers in hydrothermal mineral systems.

Fluid pathways

Depositional sites

Volume compensators

Fluid barriers

Strain localisers

Movement accommodators

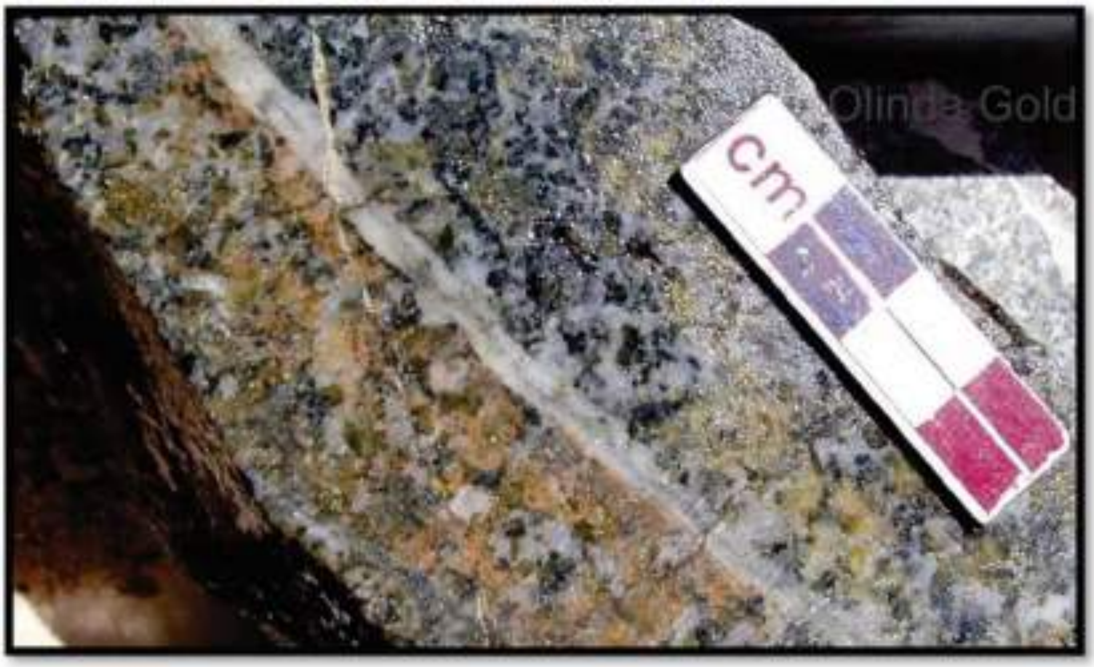
Parts 1, 2 and 3 have highlighted the formation of veins via the deposition of hydrothermal minerals into open space due to physical and/or chemical conditions. As the hydrothermal system evolves, the veins can change many of their features, including morphology, size, mineralogy, and location in space in the hydrothermal system (e.g. due to changes in position of the main fluid conduit). Further to this, the veins can then control the distribution of alteration in two main ways. Firstly, they produce an alteration selvedge, which is a change in adjacent wall-rock composition in response to fluids exiting the fluid pathway and reacting with the host-rocks. Typically, we think of alteration selvedges as forming on both sides of the veins, commonly as a symmetric distribution of minerals that can show zonation. This is shown in the figures below.

The first photo shows a quartz vein from the Callie gold mine open pit in the Tanami Desert of the Northern Territory, Australia. Weathering has accentuated the symmetric alteration selvedge, with the brown colour being due principally to iron-bearing carbonate.

The example below shows symmetric alteration in the form of silica-pyrite bounding millimetre-scale quartz-carbonate veins from Cardinal Resources' Namdini orogenic gold deposit in Ghana. Note that linking of alteration selvedges occurs if the veins are close enough and the permeability is sufficient. Linkage of alteration has also been facilitated by the thin bridging vein (arrowed) between the two veins in the middle of the photo.

In the photo below, both the vein and its alteration selvedge have been folded. This is also from Namdini, which has a complex vein-structure-alteration history. Note the zonation of the alteration, with the fine-grained pyrite being hosted in the outer portion of the selvedge (arrowed).

The other way that veins control the distribution of fluids is by acting as impermeable barriers to subsequent fluid packages. Veins contain interlocked crystals that are commonly overprinted and cemented by subsequent episodes of hydrothermal mineral deposition. Such structures can then impede the flow of subsequent packages of fluids and serve to compartmentalise later alteration and mineralisation. The following figures show examples of this. The first figure shows a granite cut by a quartz extension vein. Haematitic alteration is restricted to the left-hand side of the vein.



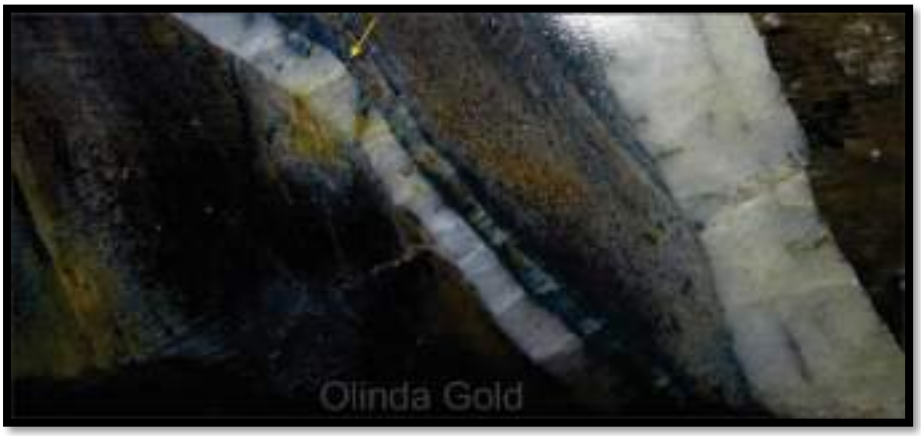
In the example below a vein has cut a BIF unit. Pyritisation of the BIF occurs dominantly on the upper side of the vein. Some pyritisation also occurs below the vein adjacent to locations where the fluids have managed to breach the vein. Compare this with the figure after the one below.

The figure below shows similar relationships to the one above. Pyritisation of layers with favourable compositions occurs dominantly on the upper side of the veins, despite the favourable layers being continuous and occurring on both sides of the vein.

For the above relationships to form, there must be more than one fluid event contributing to formation of the vein. The first stage is not responsible for the alteration, but instead forms a locus for emplacement of the next vein phase. The succeeding vein phase exploits the contact between the vein and the wall-rock, emplacing along it to form a composite vein. It is this later stage of vein emplacement that is responsible for the alteration, with the older vein phase impeding fluid flow.

Composite veins are commonly not recognised but are remarkably common. Their widespread development is a function of successive vein phases exploiting the weakness along older vein contacts. A separate section in this document is devoted to composite veins. Below are a couple of examples of composite veins, which comprise mineral assemblages deposited during separate events.

The image below is from Namoya in the Democratic Republic of Congo, a deposit I worked on with Peter Flindell and Banro exploration geologists. The photo shows a composite vein in the middle of the photo that comprises two quartz-dominant vein stages. In this case they are visually distinctive, and it is easy to discern the difference. Furthermore, the veins diverge at the top of the photo (arrowed).

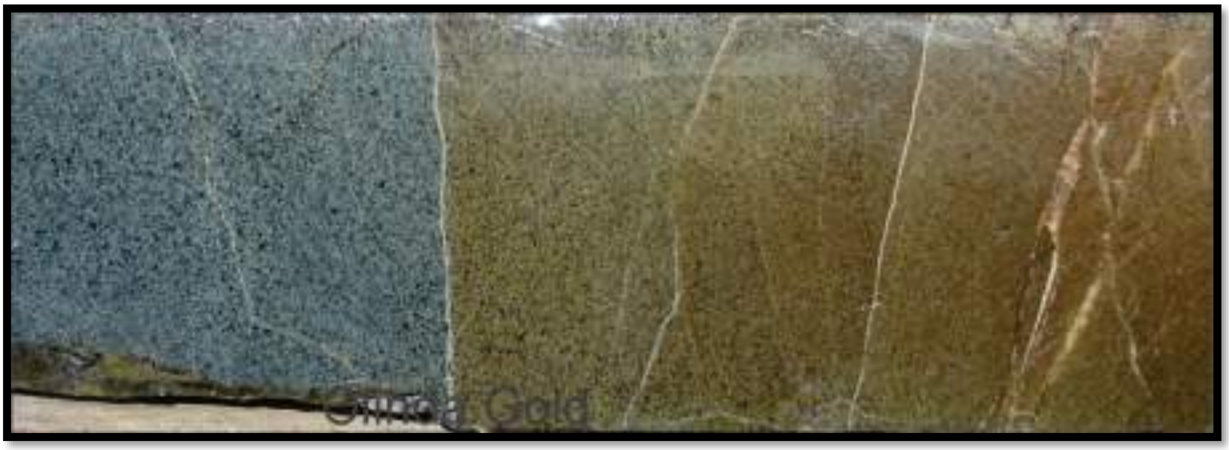


In the example below, the composite vein again comprises two visually distinctive phases, namely a quartz-rich one and pyrite-rich one. The composite nature of the vein is also confirmed by the varying location of the pyrite that tracks back and forth from the centre to the margin of the earlier quartz vein. In this case the pyrite overprints the quartz and has exploited vein-parallel weaknesses in the centre and margin of the earlier vein.

It is important to recognise composite veins for a number of reasons. Firstly, they commonly comprise an unmineralized vein population and a mineralised vein population that may have very different deposit-scale distributions and geometries. However, if logging fails to define them as two populations the database of orientation data used to constrain resource models may be incorrect, especially as it becomes increasing predictive toward areas of progressively less drilling/mapping information. Furthermore, failure to recognise two different populations, which can have markedly different ages and mineralisation inventories, will compromise mineral system analysis and the associated tasks of erecting a vein overprinting-paragenetic-structural history. It also has implications for metallurgy because the drill core may have only intersected a few composite veins that are not representative of the mineralised population.

Veins don't have to be thick to impede fluid migration. Conversely, thin veins are easily ruptured during subsequent fluid-deformation events. The following examples show veins that have impeded fluid migration despite being relatively thin.

The first example is from Toachi Mining's La Plata deposit in Ecuador and shows an abrupt termination of alteration against a sub-millimetre veinlet.



The next example shows a similar geometry from Galiano Gold's Asanko orogenic gold mine. Asanko Gold Mine is located in Asankrangwa Belt within the Kumasi Basin in Ghana and hosts some amazing vein-alteration-structure textures. The mine comprises two main deposits, Nkran and Esaase, and the example below is from Nkran. Termination of alteration occurs at a sub-millimetre width carbonate vein, producing visually distinctive colour differences.

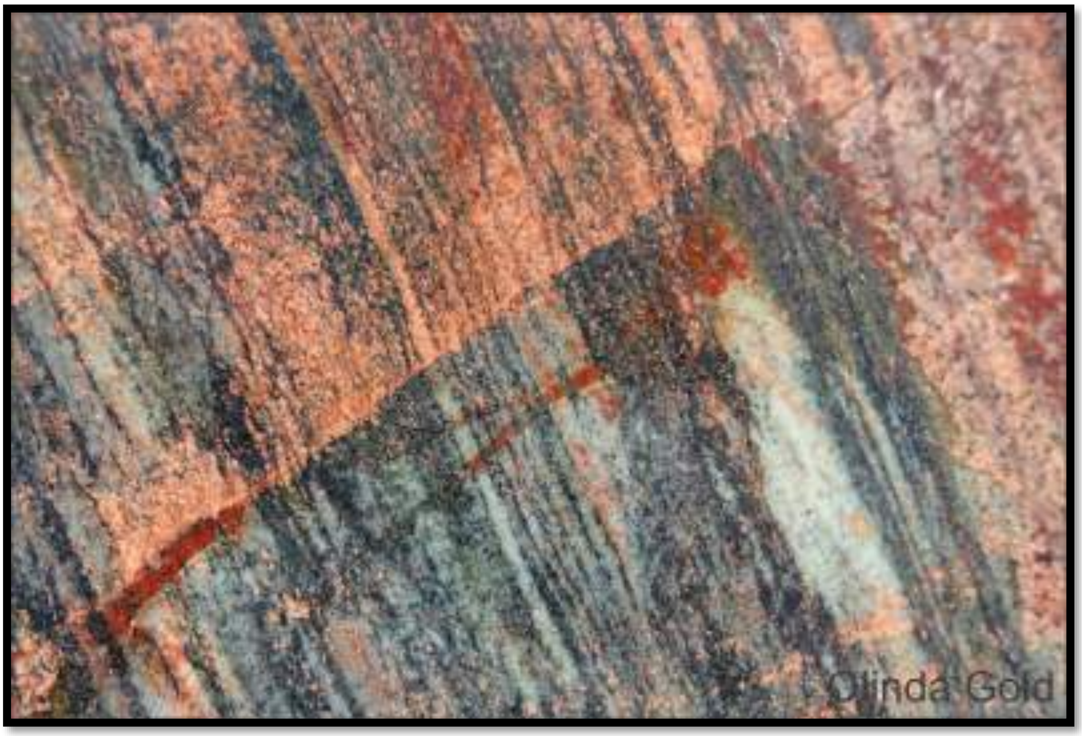
The example below is also from Nkran.

The photo below is from Newmont’s Ahafo orogenic gold mine. Buff-coloured sericite alteration terminates against a thin carbonate vein on the right-hand side of the photo. The vein has exploited a lithological difference marked by a variation in grain-size. As such, grain size, an impermeable barrier and a possible compositional difference have combined to impede alteration.

The image below shows a suite of granular quartz-carbonate veins that have been cut by another quartz-carbonate vein that shows extension-related mineralogical zonation. The second stage of veining has produced sericite alteration that is locally spatially controlled by the earlier vein suite, such as in the bottom left of the figure.

If the overprinting relationships and the alteration-structure geometries are not taken into consideration during logging, both vein sets will be documented in the database as quartz-carbonate veins. Consequently, there will be no indication of their relative ages or that only one stage is related to alteration and potentially to mineralisation. The problems will become compounded by the vein orientation data because of the markedly different orientations. Hence, modelling of the vein population can be compromised.

The next two photos are from the area hosting Carnaby Resources' Tick Hill iron oxide copper-gold deposit in the Mt Isa Inlier of northwest Queensland, Australia. Extremely fine-scale, mineralogically continuous silica veinlets have acted as barriers to haematitic alteration in the host tectonite. In the first photo this has served to compartmentalise a corridor of alteration across the photo. In the second example, the veinlet is a composite structure. The second stage of mineral deposition associated with alteration has been emplaced along the upper side of the vein.



The example below is from Continental Gold's Buritica deposit and shows alteration associated with a structure in the Veta Sur portion of the mine. As a digression, the geologists in the mine and exploration at this deposit were absolutely awesome to work with and I acknowledge them for the unfettered access they gave me. The most intense alteration is restricted to the zone between the two silica-pyrite shears. The shears are composite structures, comprising more than one stage of movement and veining. The distribution of alteration is a function of focussing of fluid movement in the later stages of structure development into the zone between the shears, with lesser external alteration occurring where permeability across the structures existed. An associated control on alteration has been the enhanced permeability in the linked damage zones between the structures.

The photo below is from MMG's Kinsevere copper mine in the Democratic Republic of Congo. Here we can see that chalcopyrite mineralisation located overwhelmingly on the upper side of the vein. There is very minor deposition of sulphide on the lower side of the vein despite the same lithologies existing on both sides of the structure. In detail, this is another example of a composite vein, which is subtly evident by slight textural and colour changes of the different component veins. The younger vein stage responsible for chalcopyrite mineralisation has exploited the upper contact between the older vein and the wall-rock.

Up until now, I have described examples where individual veins have been responsible for precluding, or markedly inhibiting, fluid movement. At bigger scales, however, these veins are likely members of sheeted populations or stockworks. In the following examples I will show examples of the effects vein stockworks can have on the permeability of the rock mass and demonstrate how this impacts the distribution of alteration.

The first example below is from the Mačkatica porphyry deposit, which is one of the largest molybdenum deposits in Serbia. Mineralisation occurs in the porphyry and in the foliated country-rocks, as in the image below that shows a stockwork of molybdenum-bearing veins overprinting the host metasedimentary rocks. Note that intense white alteration on the right-hand side of the core terminates abruptly at some of the stockwork veins despite precursor country-rock foliation being continuous from one side of the boundary to the other.

The next example is from the Black Flag Fault exposure in the Woolshed open pit. Here, a stockwork of quartz veins is exposed adjacent to two subparallel, relatively thicker quartz veins that locally show breccia development. Silica alteration associated with the stockwork has not affected the rocks above the central breccia vein. If the stockwork is associated with the breccia vein, the spatial relationships suggest silica wall-rock alteration after the emplacement of the first stages of laterally continuous breccia veining. Regardless, there is an abrupt change in silica alteration across the thick central breccia vein.

In the next stockwork example, which is from Nkran, the photo is dominated by two sheeted vein populations that have intersected to form a stockwork. Light grey-brown alteration emanates from, and is restricted to, the left-hand side of the left-hand vertical vein.

The example below was collected when doing regional reconnaissance mapping in the Tanami Desert in the Northern Territory, Australia. It shows a quartzite that hosts a quartz vein stockwork that has in turn compartmentalised alteration, as indicated by polygonal shapes of country-rocks with variable alteration colour.

I spend a lot of time traveling (or I used to before COVID-19 compromised the planet) and so I see a lot of airports and hotels. In doing so, I see some amazing examples of polished rock as floor and wall tiles. The following two examples are from the foyer of a hotel in Medellin in Colombia. In both cases they show a stockwork of veins that has compartmentalised alteration.

I've left the final three examples until last because I think they are visually and texturally stunning. All three examples are from Nkran and show the spatial distribution of strong buff- and yellow-coloured sericite alteration by populations of quartz veins.

So that's it for Part 4 of my missive on the roles of veins in deforming rock masses. Once again, thanks if you've made it this far.

Acknowledgements so far

Thanks to geologists Geoff Lowe and Tony Schrek for organising access to Callie. I spent time on site at Namdini reviewing the geology with Julian Barnes and Brett Gossage. The photos from Sunrise are a bit dated and are from a time when Malcolm Titley worked there and was incredibly generous with access to the deposit. Deposits reviewed along the Namoya-Twangiza gold belt were done in conjunction with Banro Corp mine and exploration geologists under the guidance and support of Peter Flindell and Brett Richards. In Ecuador I was toured through the geology with Phil Fox and had regular alcohol-infused conversations with Brian Wolfe and Julian Barnes. Benjamin Gelber was a fantastic geological host when reviewing the geology of Nkran in Ghana. Newmont geologists in Ghana provided access to Ahafo core to my colleague Julian Stephens and me. Carnaby Resources' MD Rob Watkins has provided access to Tick Hill and Paul Tan has been an enthusiastic sounding board for my wild-eyed theories and geological ravings. There are too many amazing geologists working at, or who have worked at, Buritica in Colombia. However, I will single out Carlos David Rios Restrepo, Andres Naranjo Sierra, David Reading, Juan Ricardo Sierra Largo, Marcelo Arango Trujillo, and Johany Castellanos Avila. Th geology of deposits in Serbia has been reviewed with many amazing geologists from Dundee Precious Metals, Avala Resources and Dunav Resources. However, I'll make a special mention of legendary geologists Justin van der Toorn and Dragana Davidovic. In the Congolese copper belt, I have been fortunate to share time on the core with Mike Northcott, Toby Dawborn and Herve Ilongo. Deposits in the Mt Pleasant area of the Eastern Goldfields of Western Australia have been visited with Gerard Tripp, Michele Spencer (nee Coutts), Steve Cox and Steve Mickelthwaite. Gary Snow was always a voice of reason during some of my crazier geological thought processes. Some of the projects mentioned in this and previous Part were reviewed when I worked with Jun Cowan at Orefind. Regardless, all mistakes and erroneous interpretations are my own.

THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 5: STRAIN LOCALISORS

So far, I have discussed veins as fluid pathways and depositional sites in Parts 1 and 2 of this series of posts. I followed this with a post (Part 3) on veins as volume compensators, documenting how they infill space that is created during host-rock deformation. In Part 4, I then documented the role of veins in controlling rock permeability and the distribution of alteration by impeding fluid movement.

In this Part I discuss, again largely by way of illustration, the fifth item in the list below, namely the role of veins as strain localisors in hydrothermal mineral systems.

Fluid pathways

Depositional sites

Volume compensators

Fluid barriers

Strain localisers

Movement accommodators

Before discussing the role of veins in a deforming rock mass it is necessary to understand the fundamentals of strain. The terminology used in this Part is explained initially, with some diagrams and examples that don't have veins. However, the analogies will become clear (I hope!) as I start discussing the geometries in the photos that contain veins.

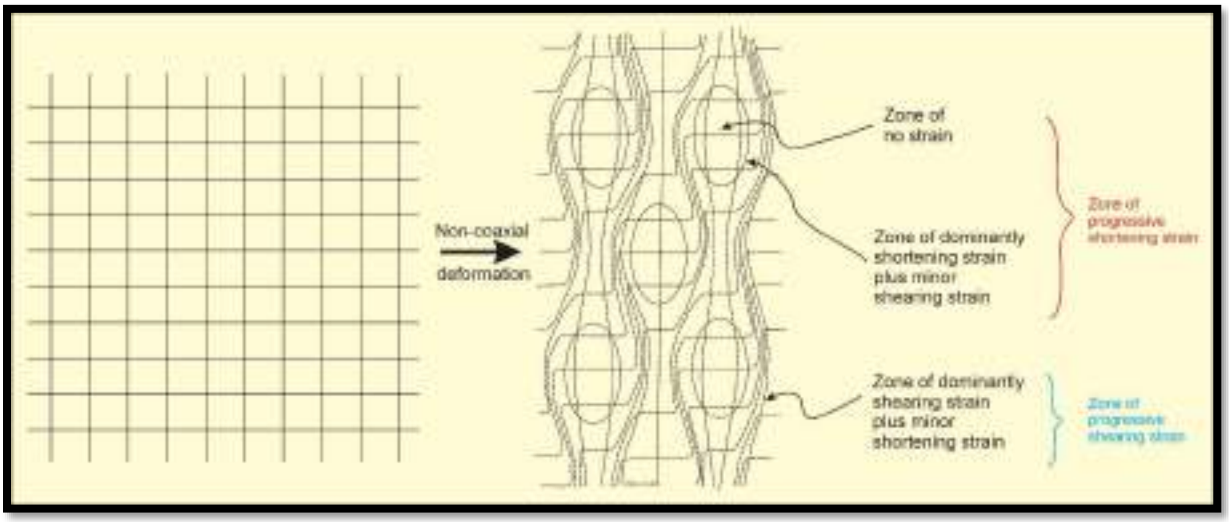
An important aspect of deformed rocks concerns the variable development of structures because of various factors, including:

- Difference in host-rock composition - some rock-types can accommodate strain more readily than others
- The presence of competent or rigid bodies (e.g. porphyroblasts, granite plutons) that can perturb stress trajectories
- Variations in crustal geotherm (hotter rocks promote ductile structure development better than in relatively colder rocks)
- Pre-existing structures that can be reactivated in preference to the formation of new structures.
- The amount of strain experienced by a rock
- The strain rate
- The presence or absence of fluids
- Grainsize
- Phyllosilicate content

Importantly, the strain experienced by a rock is never homogeneous, even at the grain-scale, and will partition into shearing strain and shortening strain. The following points are important for understanding how the introduction of veins into a deforming rock can change how the strain partitions:

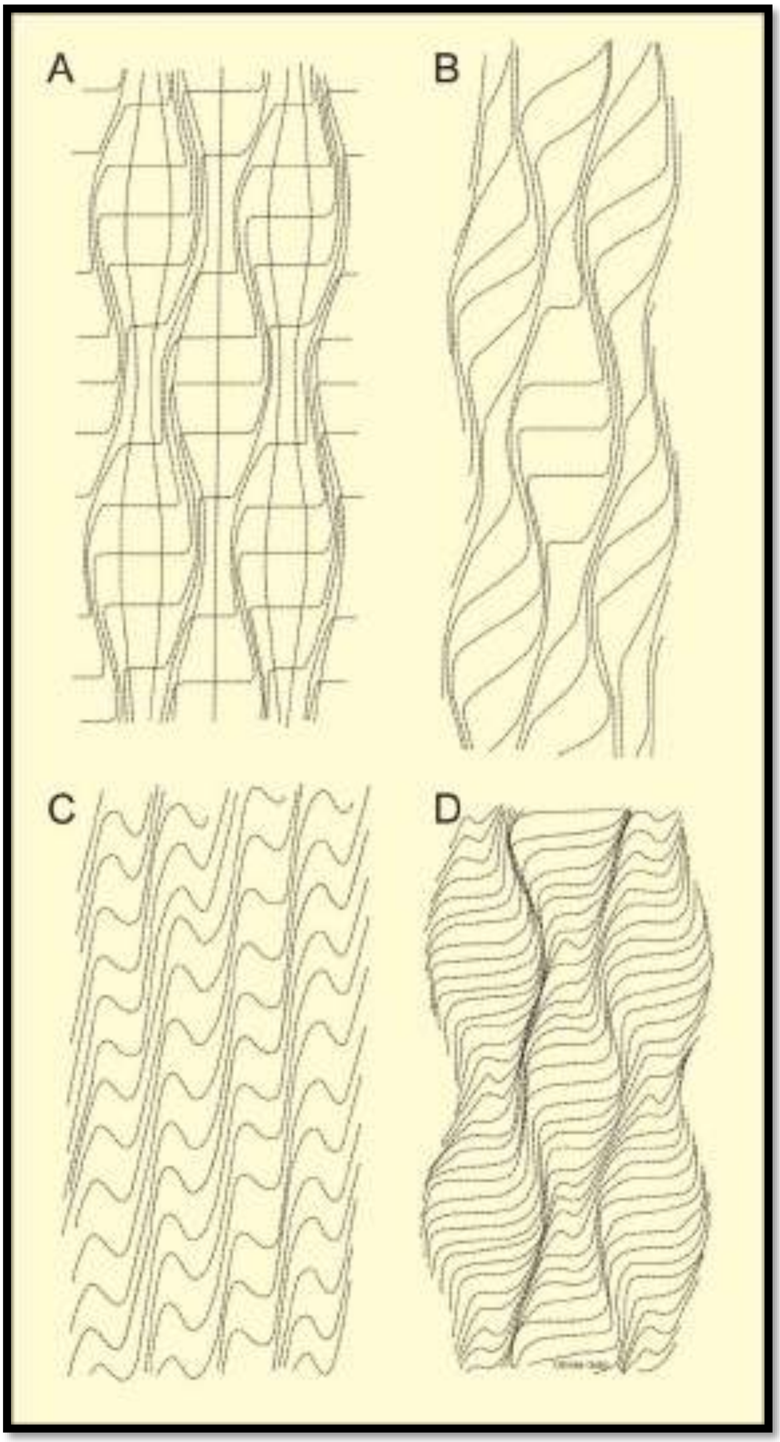
- Transitions occur from domains of shearing strain, which are typically represented by zones of displacement and dissolution (e.g. ductile shear zones) to those of shortening, which are represented by relatively more competent domains such as rigid bodies (e.g. plutons, porphyroblasts, boudins etc.).
- These transition zones accommodate variable proportions of shearing and shortening strain.

Perhaps the easiest way to understand this is to consider the deformation of a mesh comprising squares of uniform area, as in image below.

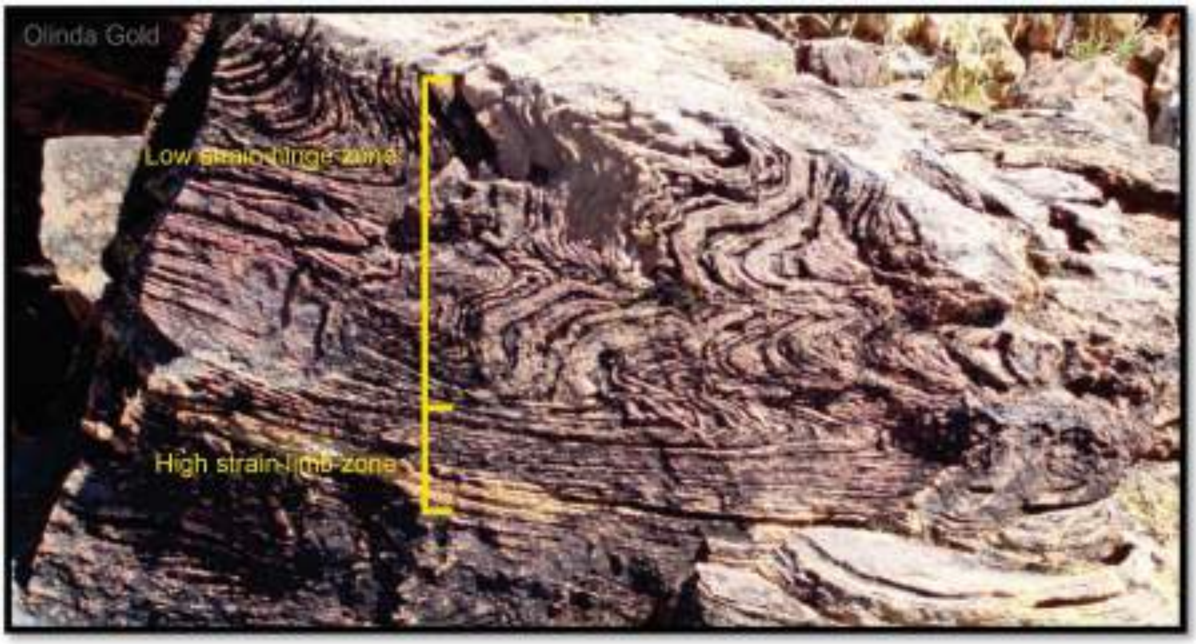


As deformation progressives, a myriad of geometries is possible. Common ones include the numerous fold geometries that we are familiar with in rocks that have undergone ductile deformation. Here, the anastomosing cleavages are represented by the subvertical structures in the meshes in the figure below and intensify on the fold limbs to produce zones of shearing strain. The hinges occur where the grid lines are subhorizontal and represent zones of dominantly shortening strain. The geometries in A, B, C, and D are all possible examples in rocks. For example, C is the same geometry as a differentiated crenulation cleavage.

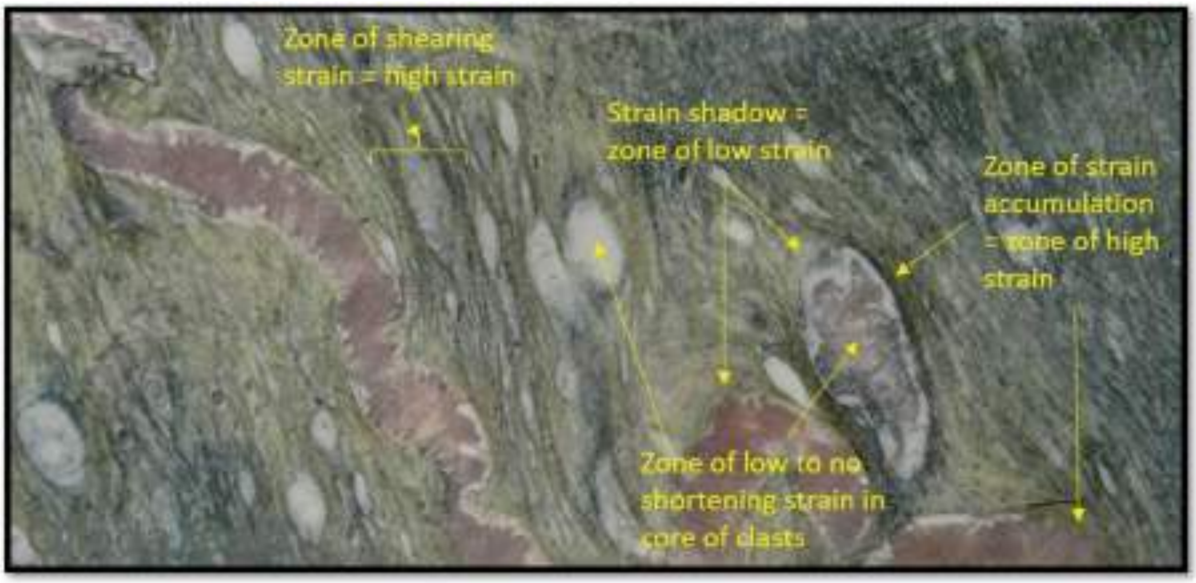
Note that zones of shearing strain must also contain a component of shortening strain because stress has to be transmitted across them – it doesn't magically stop at the shear zones.



In the figure below we can see high strain limbs and low strain hinges.



Zones of differing strain are highlighted in the schistose rock from the Namdini deposit in Ghana below. Here, the phyllosilicates have been critical for accommodating shearing strain. Phyllosilicate-poor lithologies, such as the veins, have accommodated shortening strain, which was also aided by their grainsize. This is because relatively coarser grained lithologies, even if they are the same composition, will be more resistant to deformation.



In the tectonised sulphide in the image below, we can see that the silicified clasts have resisted deformation and represent zones of no strain and shortening strain. The anastomosing, fine-grained lithologies, especially those comprising the brown sphalerite, have accommodated dominantly shearing strain. The pyrite-rich layers have accommodated shortening and shearing strain. Pyrite is one of the hardest sulphides to deform so it is more resistant to deformation and shear strain than the sphalerite. This example is from the Mallee Bull deposit in the Cobar Basin.

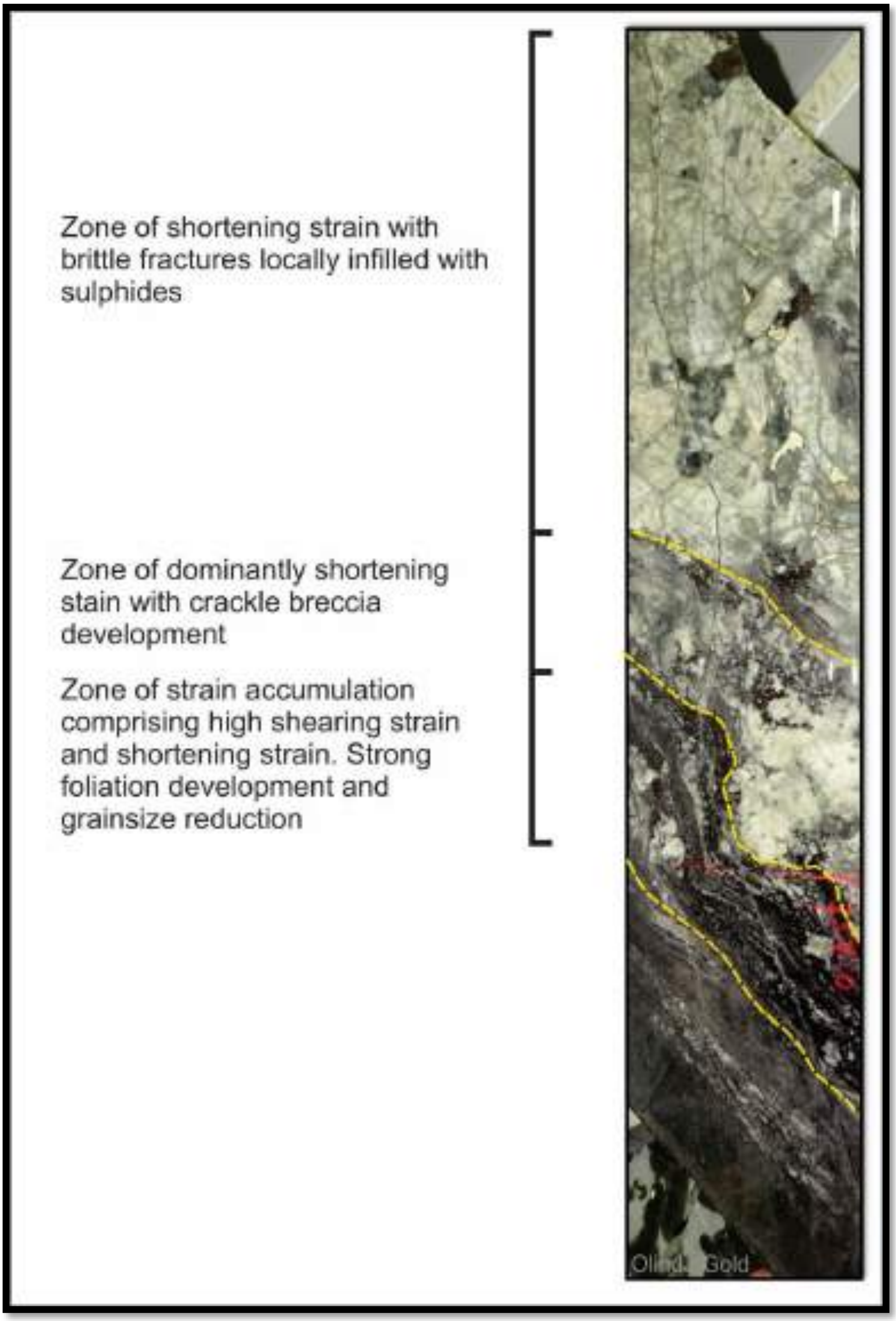
Now that the fundamentals of strain partitioning have been summarised, I will show examples of various vein geometries and how they have influenced the strain state of the rocks. Because I want to deal with both ductile and brittle deformation, I have precluded high-level vein systems such as in porphyry and epithermal systems where deformation is dominated by brittle processes.

In the first example, I have annotated the different strain domains in a rock containing a strongly boudinaged vein. Note that the areas that are phyllosilicate-poor and relatively coarser-grained tend to accommodate dominantly shortening strain and will tend to fail in a brittle manner rather than in a ductile fashion. This results in brittle extension fractures, crackle brecciation etc that can then become a locus for fluids and deposition of mineralisation. As shown previously, the neck regions of boudins can also become important sites of mineral deposition as the boudins separate.

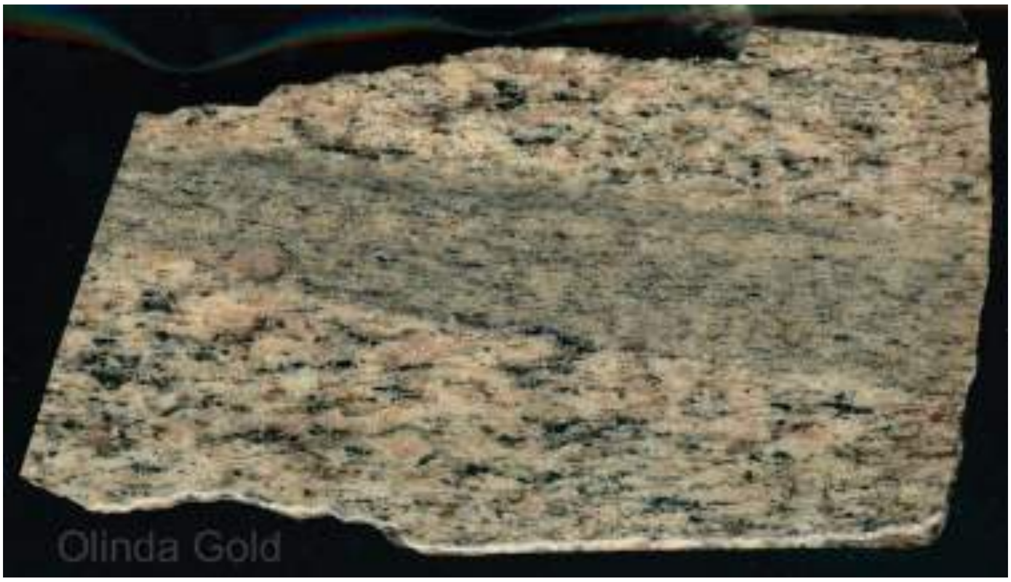
As mentioned earlier, another fundamental control on strain partitioning is grainsize. For example, if a fine-grained marble containing a coarse-grained calcite vein is deformed, the fine-grained host will preferentially strain even though both the vein and host have the same composition. Veins are very commonly much coarser-grained than their hosts, due largely to crystal growth into uninhibited open space. If we add the additional factor of vein minerals of variable strengths, we can commonly see pronounced deformation of the host adjacent to the vein contact. This zone of cumulative high strain at the contact of the wall-rock and the vein is called a zone of strain accumulation.

The next figure from Rajasthan, India, shows strong foliation development in the host quartzite adjacent to the boudinaged quartz-feldspar pegmatite vein e.g. under the pencil. The coarse grainsize has been instrumental in strain partitioning, as has the feldspar. Feldspar is an incredibly hard mineral to deform. We have all seen the feldspar-rich porphyroclasts in mylonitic rocks, which represent the portions of the protolith that has been most resistant to strain.

In the piece of core in the figure below we can see that the coarse-grained carbonate-rich vein has been resistant to deformation and has failed largely by brittle fracture. The vein will have been a zone of shortening with minor shearing strain near the contact, transitioning to a zone of low strain toward the core of the vein. In the wall-rock, a zone of strain accumulation has developed due to the combination of intense shearing and shortening strain. The zone of strain accumulation contains fragments of vein that have been entrained, reduced in size, and have geometries that are products of ductile and brittle deformation.



In the next example a granitoid contains a dyke of similar composition. However, the dyke is much more strongly deformed, having undergone mylonitic strain due to it having a relatively smaller grainsize and being deformed more easily.



In volumes of rock where brittle deformation dominates over ductile, veins commonly show strain as brittle fracture development with minor shear strain accumulation in the wall-rock. Part of this is a function of the wall-rock selvedge. If there is very little selvedge development, especially in the form of phyllosilicate-dominated alteration (e.g. sericite), the strain will commonly localise in the veins as networks of fractures.

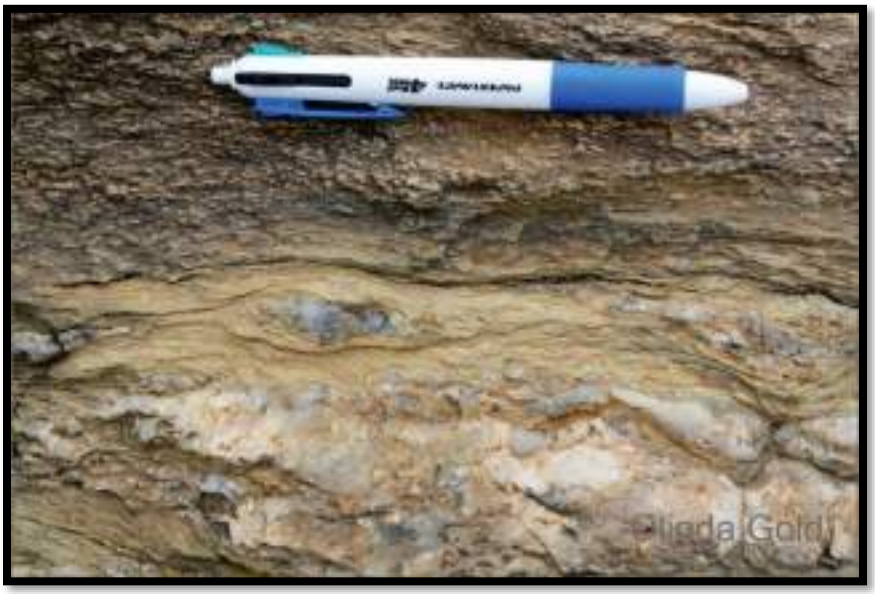
The next example shows a quartz vein from the Groundrush gold mine in the Tanami Desert of the Northern Territory, Australia. A very thin selvedge that has accommodated shearing strain is evident on the upper side of the sample. Within the vein, deformation is expressed as a brittle fractures that host sulphide.

The next two examples from the same vein in the Brucejack area in Canada show a quartz vein that has had minor shearing strain accumulation at the lower margin. Internally, the bulk of the vein hosts a network of brittle fractures. This can be seen in the figure following the one below, where the narrow zone of shearing strain is highlighted. A stockwork of brittle fractures dominates the bulk of the vein above this.

The example below is from the Zara deposit in northern Eritrea. Once more, we can see the strain localised on the vein margin as an anastomosing network of brittle fractures that track the vein margin even as it goes around a change in orientation of the contact. The adjacent host-rock is relatively much more phyllosilicate-rich and finer-grained, accommodating strong shearing strain.

As noted before, the wall-rock selvedge to veins marks a large contribution to how the strain is partitioned. Layered silicates are common contributors to wall-rock alteration assemblages e.g. sericite, biotite, chlorite. Layered silicates easily accommodate shearing strain due to their crystal structure. This results in the development of zones of strong strain accumulation in the wall-rocks at the vein contact, a very common phenomenon in orogenic gold deposits.

The example below, from northern Ethiopia, shows intense shear strain development at the margin of a quartz vein due to the development of a well-developed white mica alteration selvedge that has facilitated shearing. The host-rock is a foliated granitoid, but the alteration and shearing have been totally texturally destructive. Portions of marginal vein material have become entrained in the shear zone, resulting in discontinuous, elongate slivers of intensely strained vein rock.



If an example such as in the above figure continues to deform it can ultimately transform into spatially separated lenticular quartz boudins within an intense ductile shear zone. An example of this is shown in the next figure from the Koka gold deposit in northern Eritrea. In this case, intense ductile deformation has been accommodated by the micaceous alteration in the host structure. The original vein has been reduced to spatially separated lenses within a relatively much more foliated zone in the host-rock. Post-shearing vein emplacement has manifested as the subvertical cross-cutting quartz vein, which may be a late stage extensional product of the shortening that occurred during shear zone development.

The next example is from the Golden Age Reef, which comprises part of an orogenic gold system at Wiluna, Western Australia. Strong strain accumulation has been facilitated in the wall-rock alteration selvedge, which likely contains a large component of graphite that accommodated shear strain. Note that the zone of shear strain here has accommodated dextral movement as viewed.

The example below is from the Konate gold deposit in northern Eritrea. Here, an iron-stained strongly foliated zone on the right-hand vein hangingwall has accommodated significant shear in the vein. In this example and the ones following, deformation has been relatively more ductile than in some of the earlier examples. Note that the artisanal miners have removed much of the shear-laminated hangingwall because it contained gold mineralisation in preference to the relatively barren massive portions of the vein.

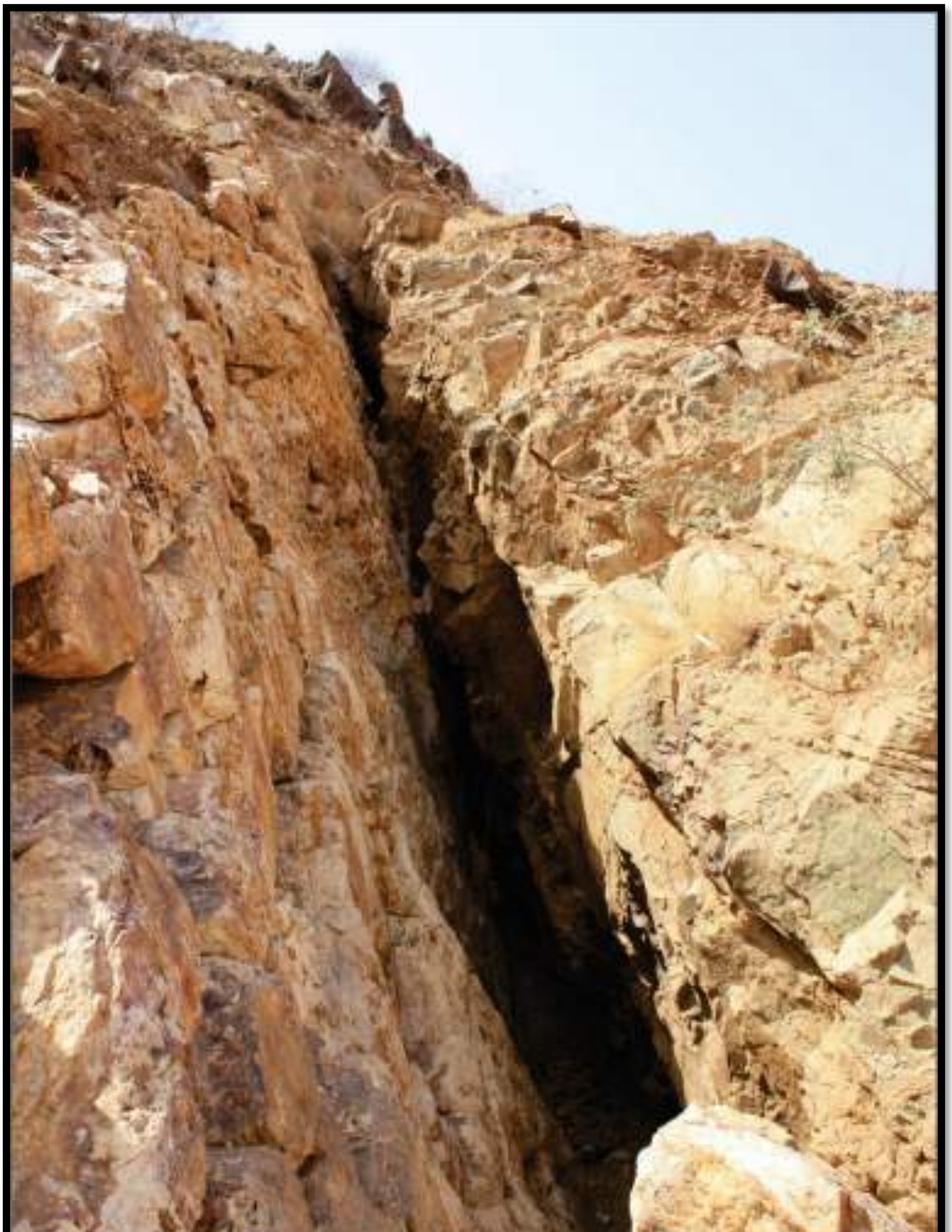
Strongly sheared vein margins are very common in orogenic-style gold deposits. They are commonly developed on one side of the vein only, and more commonly than not on the vein hangingwalls. This is likely due to easier deformation of the hangingwall rocks, with movement typically occurring by translation of hangingwall blocks. Once a zone of shearing starts to develop, ongoing deformation tends to exploit and intensify structure development at that margin rather than producing new structures.

Another important consideration when working with the shear-laminated veins is that the mineralisation may not be the same age as the vein. Commonly, it is introduced in the final stages of vein deformation or in subsequent deformation that has produced the overprinting shear lamination.

The example below shows development of a zone of strong ductile shear development along the hangingwall contact of the vein. This was one of the veins exposed in the Quarters basalt-hosted orogenic gold deposit in Western Australia.

The example below also shows partitioning of strong shearing strain into the hangingwall of a quartz reef in the Shamrock orogenic gold trend near Kanowna in Western Australia.

The next two examples are from the Debre-Tsaeda gold deposit in northern Eritrea. Here, strongly foliated zones are developed in the quartz vein hangingwalls. In both cases the gold mineralisation has been restricted to the shear-laminated hangingwall, which has been removed by artisanal miners. As a digression, a soldier from the Eritrean army was guarding this deposit, which is at the top of steep ridge. Five artisanal miners had entered the workings but had not exited, presumably suffocating due to the practice of using burning wood underground to break the rocks. The soldier's job was to prevent any more miners from entering.



In systems such as these, where the strain has been localised at the vein margins, kinematic indicators are commonly well developed. This is probably because many of these veins, although steeply dipping, are not orthogonal to the principal stress at the time of deformation. This induces non-coaxial strain in both section and plan. For example, in the next photo, the shear zone developed at the vein margin has accommodated a hangingwall-side-up sense of shear as viewed.

In the next example, from the Monty VHMS deposit in Western Australia, a shear zone has developed adjacent to a quartz vein intersected in drill core. Kinematic indicators are well developed and indicate a dextral sense of shear as viewed.

I have shown the next example previously. This vein is from the Curraghinault gold deposit in Northern Ireland. Both the vein margin and the adjacent wall-rock are strongly foliated in the hangingwall. A wall-rock sliver in the bottom portion of the vein is likewise strongly foliated. In both cases the foliation asymmetries are consistent with the accommodation of sinistral shear as viewed.

The example below shows the strongly foliated 040 vein from the Quarters gold deposit, Western Australia. In this case the massive basalt and lack of a strong alteration selvedge have resulted in much of the shearing strain being partitioned into the vein itself. At this location, the vein is structurally thickened due to the hangingwall portion being translated to the right along the structure that acutely passes through the vein from upper right down to the left where it exits at the blue pencil. This sense of displacement is also supported by the curvature on the steep 060 veins in the hangingwall and footwall. Gold mineralisation was localised along the shear laminae in the main vein.

The example below is from Inspiration Peak in the Tanami Desert. Strain accumulation at the lower margin has resulted in accommodation of these rocks moving to the right, as indicated by the curvature of the foliation.

In the example below, strong non-coaxial strain is developed in the hangingwall to this specimen from the White Feather Trend, a large quartz orogenic gold reef developed at Kanowna in Western Australia. Sense of shear is sinistral as viewed.

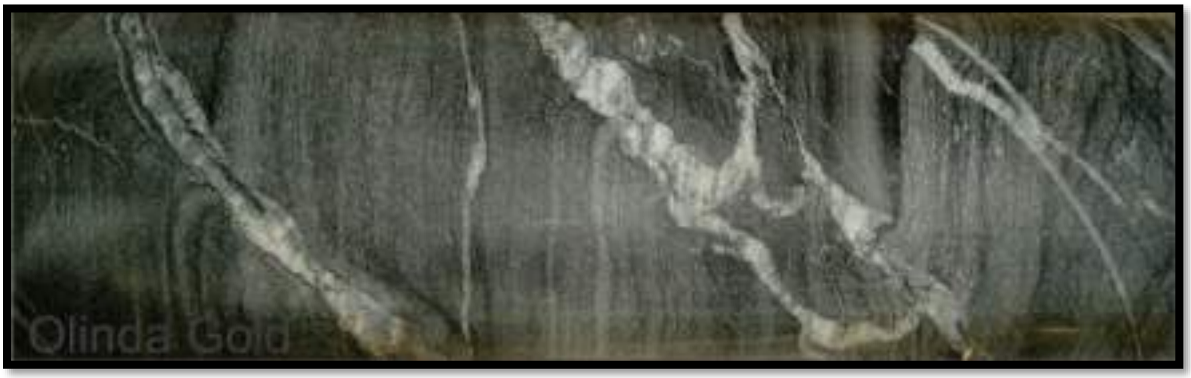
The previous examples have focussed on the development of zones of strong ductile shear at the vein margins. However, ductile strain accumulation also manifests as zones of shortening with very little shearing at vein contacts. Two of the main factors that influence a dominance of mainly shortening strain are the lack of an alteration selvedge to accommodate shear and the principal stress being at a high angle to the vein.

Development of shortening-dominated strain at vein margins manifests as folds and locally as cleavage formation. The first example is from the Mulgarrie orogenic gold mine in Western Australia. Here, the alteration is dominantly brown iron-bearing dolomite rather than phyllosilicates. The strain has resulted in boudinage of the quartz vein and development of tight folds at the vein contact.

The next example also shows development of tight folds due to shortening against a quartz vein. Sulphides have been deposited in the fold coeval with shortening and now define the axial plane cleavage.

The example below is from a pyritised BIF from a deposit near Sandstone in Western Australia. Pyrite forms part of the alteration selvedge to the veins and has a preferred alignment defining a cleavage associated with folding. These geometric and overprinting relationships demonstrate shortening strain accumulation at the vein margin coeval with mineralisation and cleavage development.

The example below is from the Tuapim gold deposit in Ghana. Shortening strain has caused boudinage of the quartz veins as well as strain localisation resulting in folds at the vein margins e.g. to the left of the left-hand vein. Axial planar cleavage development is also strongest adjacent to the veins.



I will finish with a few photos of structures that can potentially confuse the issue of strain localisation against veins. Commonly, pre-vein structures, or structures that have developed early in the deformation of the veins, can be preserved. This is because veins will also act as rigid bodies that produce strain shadows. Strain shadows are volumes of rock that have experienced relatively less deformation than that in the rest of the rock. A classic example are the zones that people commonly call pressure shadows at the ends of porphyroblasts.

In the example below, intense deformation has produced a strong foliation in the host rock and caused attenuation, boudinage and dislocation of the quartz vein. A relatively open fold is preserved in the strain shadow near the boudin neck and is highlighted with a dashed line. This fold is much more open than those in the rest of the host-rocks, representing a zone of lower strain rather than one of strain accumulation. This is from Hurum in northern Eritrea.

The example below is from the Tucano gold deposit in Brazil. Here, a pegmatite vein has preserved a fold adjacent to it, which is much more open than others in the surrounding rock. Shearing along the exposed vein margin is indicated by a well-developed, low-plunging lineation highlighted as a dashed line.

In the final example, from near Hurum in northern Eritrea, a quartz boudin relic of a strongly tectonically dismembered quartz vein has preserved open crenulation in the strain shadow embayments on its margin. This is shown in the detailed final photo of the lower margin. No crenulation preservation has occurred along the upper margin due to shearing along the vein contact.

THE ROLES OF VEINS IN A DEFORMED ROCK VOLUME – PART 6: MOVEMENT ACCOMMODATORS

So far, I have discussed veins as fluid pathways and depositional sites in Parts 1 and 2. I followed this with a Part 3 on veins as volume compensators, documenting how they infill space that is created during host-rock deformation. In Part 4, I then documented the role of veins in controlling rock permeability and the distribution of alteration by impeding fluid movement. Part 5 was a lengthy discourse on the roles of veins as strain localisors during deformation.

In this Part I discuss, again largely by way of illustration, the sixth item in the list below, namely the role of veins as movement accommodators in hydrothermal mineral systems.

Fluid pathways

Depositional sites

Volume compensators

Fluid barriers

Strain localisers

Movement accommodators

From Parts 1 to 5 it should be obvious that the vein walls must move relative to each other to make space for the deposition of vein material. The action of opening can accommodate this displacement of one vein wall relative to another both during vein deposition and during subsequent deformation i.e. coeval and overprinting deformation can utilise the veins as structures to accommodate significant movement.

The displacement associated with veins can be broken into two broad categories:

- Displacement of vein walls during opening with minor deformation of the vein material. The best examples are extension veins, especially crack-seal veins, that incrementally open, with the opening direction being orthogonal or oblique to the vein margins.
- Displacement of the vein walls during and after opening due to accommodation of movement along the structural weakness occupied by the veins. These examples manifest as vein filled faults that commonly represent products of hydrothermal mineral deposition as part of the fluid-sourcing process. In this case the host fluid pathway will be a structure with variable amounts of brittle and ductile deformation.

I will begin this Part with examples of veins that have formed via incremental opening with minor coeval or subsequent deformation. The first example shows fibrous quartz veins from an area of orogenic gold mineralisation in northern Ethiopia. The trajectory of vein opening can be traced by following the geometry of the fibres and it is obvious the vein is a product of many fluid cycles.

Overall, however, the hundreds to thousands of vein opening episodes have resulted in very little lateral displacement of the vein walls. This is an important point to keep in mind. Most vein deposits, in particular orogenic gold deposits, form on low-displacement structures. My colleague Steve Cox has done a phenomenal amount of work into these systems and it seems that lodes seldom occupy areas much greater than 1 km^2 of fault surfaces, and net slip accumulated during ore formation is typically less than 150 m. In particular, they indicate that swarm seismicity is the characteristic response to injection of large volumes of overpressured fluids into intrinsically low-permeability rock. Injection-driven swarm seismicity and related permeability enhancement involves repeated sequences of thousands of ruptures.

A variation on this theme can be seen where the zone of displacement comprises a sheeted vein array. Individual veins can each accommodate movement increments that cumulatively produce a zone of displacement.

Commonly, we see the effects of movement accommodation by veins because of the separations of other marker structures, including earlier veins. In many cases there is no obvious strain accumulation at the vein margins, suggesting all displacement has been accommodated during lateral translation of the vein walls during growth of the displacive vein. This is show in the next three images.

One of the things to appreciate from the next three images is that earlier veins are markers that give the direction of separation (it is not displacement because we don’t have a movement vector and hence the displacement may be apparent). The overprinting relationships are especially important as they contribute to our knowledge of the fluid evolution and geological history of the fluid system.

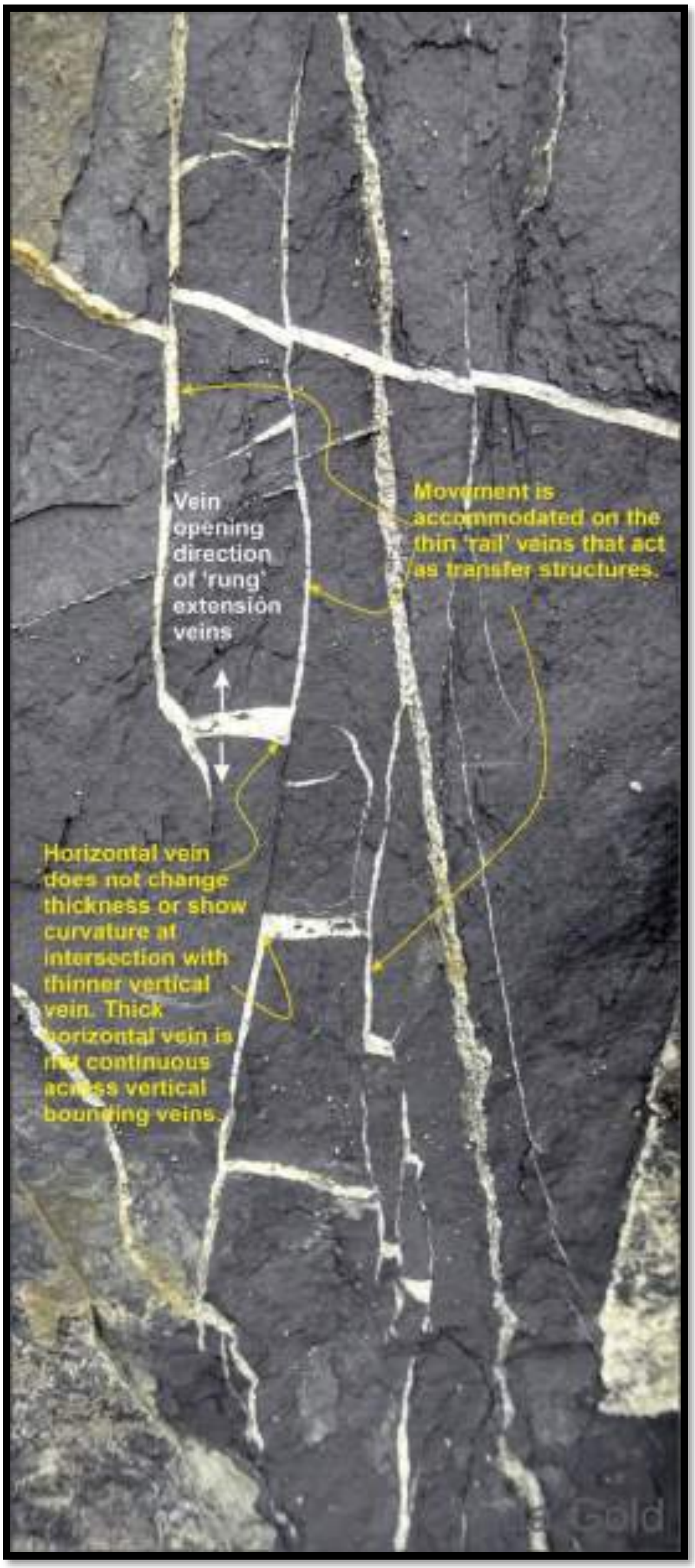
Stockwork vein systems are also movement accommodators, although overall there is generally minimal wall-rock translation at the scale of the vein populations. The exception is if one of the contributing populations is subparallel to the main fluid pathway and is preferentially reactivated relative to the others. If this does not happen, the main effect of vein opening is to increase the volume of veined rock. Differential transient opening on differently oriented veins will occur, depending on the stress state of the rock, rather than marked displacement in a preferred direction.

In the example below, the overall displacements on vein structures will have been minimal. A relatively greater amount of displacement may have been accommodated by the subhorizontal veins because there are more of them, but this will still have been minor.

In the example below, the subvertical veins have accommodated minor displacement, as indicated by the offsets of the other veins and their sense of curvature at the point of vein intersection. Note that the vertical veins are the oldest set and have been reactivated to deform the younger set.

Orthogonal vein sets, in particular ones that show ladder vein development, must necessarily have some movement parallel to at least one vein set. This is required to explain the lack of continuity of corresponding portions of veins that form the 'rungs' of the ladder veins across the veins that form the 'rails' of the ladder.

In the example below, the relatively thinner 'rails' of the ladder have effectively acted as transfer structures, accommodating movement at the vein boundary to compensate for opening of thicker 'rung' veins.



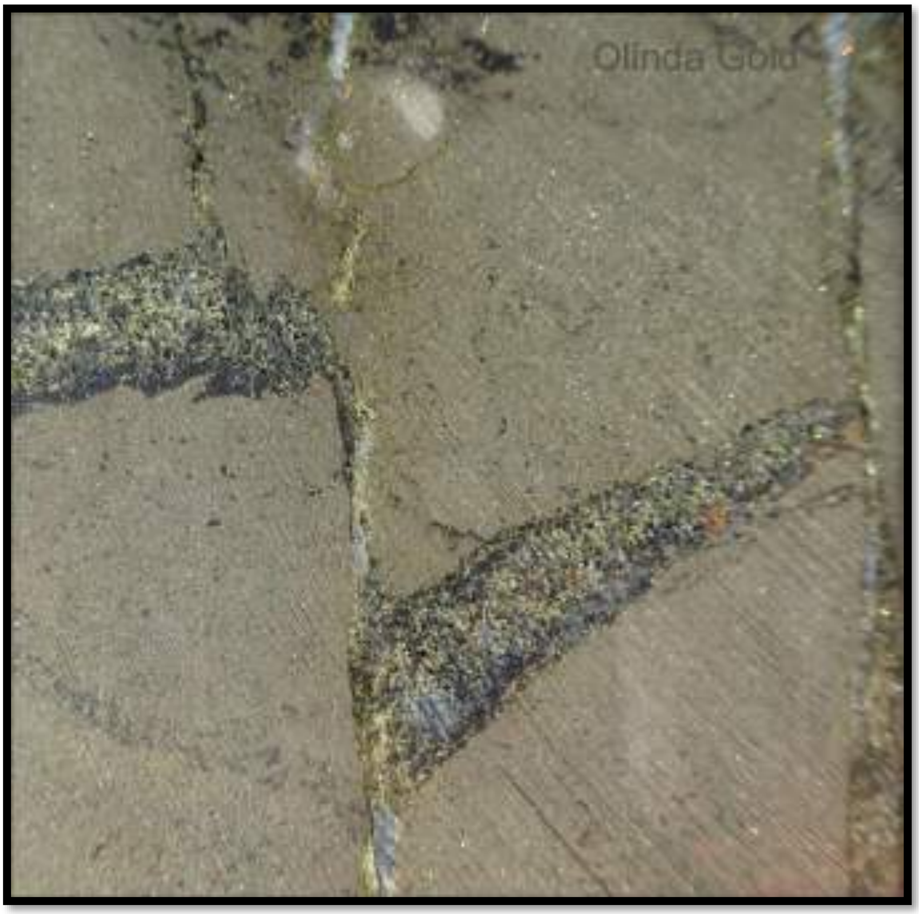
In brittle vein systems the displacive veins are commonly hosted by fractures and the veins appear discontinuous. Vein segments are commonly irregularly shaped and thicker sections can occupy extensional sites such as jogs.

In this example an earlier vein has been progressively steeped down to the right by fractures that host discontinuous veins. This example is from a quarry on the eastern side of Rockhampton, Queensland, Australia.

The vein segments can morph into breccia veins that also show displacement. This is common in epithermal systems, as shown in the central section of the core interval from Ada Tepe below where a breccia vein displaces the contact between banded silica and the host-rock.

In the example below the steeply dipping vein has been displaced by a composite vein. The youngest portion of the composite vein is evident as a thin white feature below the composite vein on the left but then traverses to the middle of the earlier vein portion before exiting at the lower side of the composite vein on the right.

In host-rocks that are relatively more ductile, discrete veins can displace country-rock structure and produce curvature of the displaced features at the vein contact. These geometries are important because they provide information on overprinting, fluid evolution and kinematics.



The geometries and continuity (or lack of) of displacive structures with veins in the adjacent wall rock can give information on the relative ages of the vein populations. In the example below, a narrow steeply dipping vein is a zone of displacement but becomes continuous with wall-rock veins in the bottom half of the photo. This indicates evolution of the structure coeval with vein deposition.

In the photo below, a fault zone manifests as an anastomosing network of sinuous, narrow, graphite-filled shears. These shears are also zones of strain enhanced dissolution. Most of the carbonate veins terminate against the shears and show geometries similar to ladder veins. However, some veins have also been emplaced along the shears and show continuity with veins in the wall-rock, indicating that a portion of the shear evolution overlapped that with vein deposition.

A similar relationship to the above photo can be seen in the next one. Here, a stockwork of quartz veins is developed in the footwall of a fault. Some of the stockwork veins are locally continuous with the sheared veins occupying the fault.

Shear veins are ductile movement accommodators that occupy structures that have hosted both deposition of vein material accompanied by coeval or subsequent displacement. The degree of ductile fabric development is a function of many things, including the vein mineralogy, the amount of strain, the strain rate, how much fluid was present, contrasts in host-rock composition, depth of displacement, geothermal gradient etc. The figure below shows a structure hosting shear veins with variable fabric development, which is due to the factors listed above plus the relative ages of the different deposition episodes. The youngest veins are least deformed and locally retain initial extension vein textures.

The example below shows displacement of a carbonate extension vein by a shear vein of variable thickness.

The last two examples show drill core of the same scale but with different manifestations of the shear veins. In the first example the structure is discrete, and the shear veins occupy about half of the structure. In the example shown after that, the zone of displacement is comprised entirely of shear vein material.

And so concludes the contributions veins make to a deformed rock volume. There are many other topics that are fundamental to understanding vein formation and deformation, but they are for another day. There is one more Section, which is a very short one on the variations on vein morphology.

However, at this point it is time to acknowledge people. I have spoken to many of the industry and academic experts on the transfer of fluids at all scales, the controls on the fluid movement and the history of this in the rock, structural geological processes, and how to understand the products that geologists search for and mine. In doing so, I find that there are too many people to name who have influenced my work. However, ones who immediately come to mind, who have made a remark or explained a texture that has sent me off on tangents of confusion and learning, include Tim Bell, Aidan Forde, Julian Stephens, Jon Hronsky, Dick Tosdal, Bill Laing, Roger Taylor, Ken Hickey, Nick Oliver, Steve Cox, Dave Craw, Giuseppe (Joe) Lo Grasso, Rick Sibson, Julian Barnes, Sean Hasson, Scott Halley, Alex Aaltonen, Greg Morrison, Joao Hippertt, Roger Taylor, Peter Pollard, Marcus Tomkinson, Pat Williams, Garry Davidson, Gerard Tripp, James Siddorn, Steve Mickelthwaite, Richard Lilly and Jun Cowan. I've no doubt forgotten people and for this I apologise. In the end, the thoughts and mad ramblings present in my articles, correct or otherwise, are my own and I have benefitted from the feedback so far.

VEIN SYSTEM ANALYSIS – SOME COMMENTS ON VEIN MORPHOLOGY

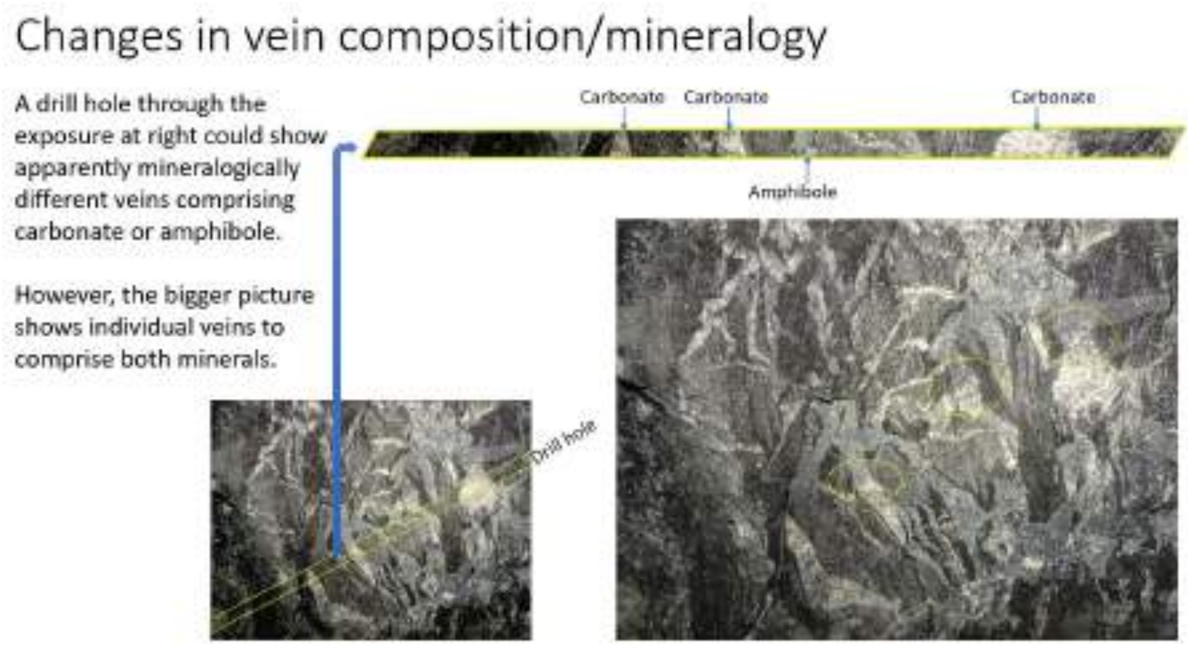
As exploration, mining and research geologists, we commonly deal with rocks that host multiple vein populations. Understanding the geometric and overprinting relationships are paramount to teasing apart the fluid history of mineral deposits. This means incorporating vein and wall-rock structures, vein morphologies, alteration assemblages and sulphide-precious metal assemblages into a consistent geological history.

Vein system analysis can vary from apparently very easy in the case of single vein populations, through to overwhelmingly complex in the case of stockworks and vein swarms comprising many different vein populations. Just to confuse the matter, I thought I would show several slides of vein populations from projects I have worked on. In some cases, I was able to see sizeable mining exposures that showed the vein relationships. I have taken photos of these and drawn imaginary drill hole intersections across them to illustrate how confusion could arise when interpreting the relationships at the scale of diamond core only. In others, there was sufficient drilling to track changes in vein morphology over distances of 10's of metres – distances that don't seem large but were sufficient for changes in alteration assemblages to change markedly.

The images are from one of my training courses on vein system analysis and illustrate just a few of the things we need to think about when compiling our deposit history. They also illustrate why we need to compile individual vein overprinting histories from different locations (drill holes, development areas, outcrops, open pits etc) and then compare them until we know the extent of the fluid systems.

The conclusion? There are many but two main ones are 1) that veins are really cool!, and 2) you have to take care, put them in context, and document them accordingly.

Enjoy the photos and apologies for repeating the title to each figure but they separate the individual images!



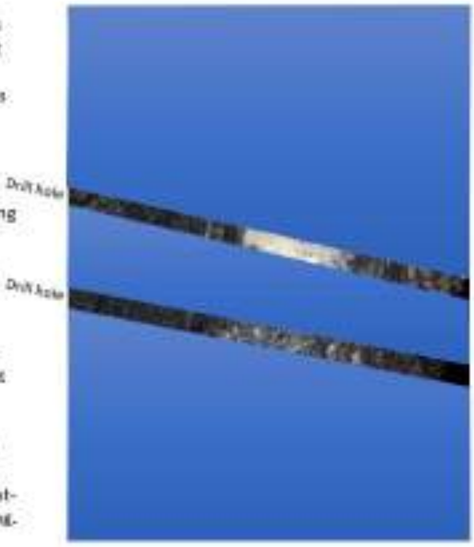
Changes in vein composition/mineralogy

Two closely spaced drill holes through the exposure at right could show apparently mineralogically different veins comprising quartz or amphibole.

However, the bigger picture shows a single vein comprising both minerals.

The amphibole is due to infill of a fracture mesh that was produced during a deformation-fluid flow event that post-dated emplacement of the quartz vein.

Competency contrasts of the quartz vein versus the fine-grained phyllosilicate-rich host-rock have controlled fracturing.



Changes in vein composition/mineralogy

Example of a vein from an orogenic gold mine in West Africa, showing variation in mineralogy and colour along the vein length.

Alteration intensity is also greatest adjacent to the white portion of the vein.

Variation in vein morphology

Variations in vein morphology, including host-rock alteration assemblage are a function of proximity to fluid source in the case of examples in the diagram at right.

In the example below, the white quartz veins show local infill by later carbonate that also cuts across them. The two vein mineralogies may be part of a progressive event, or they may be widely separated in time.

COMPOSITE VEINS

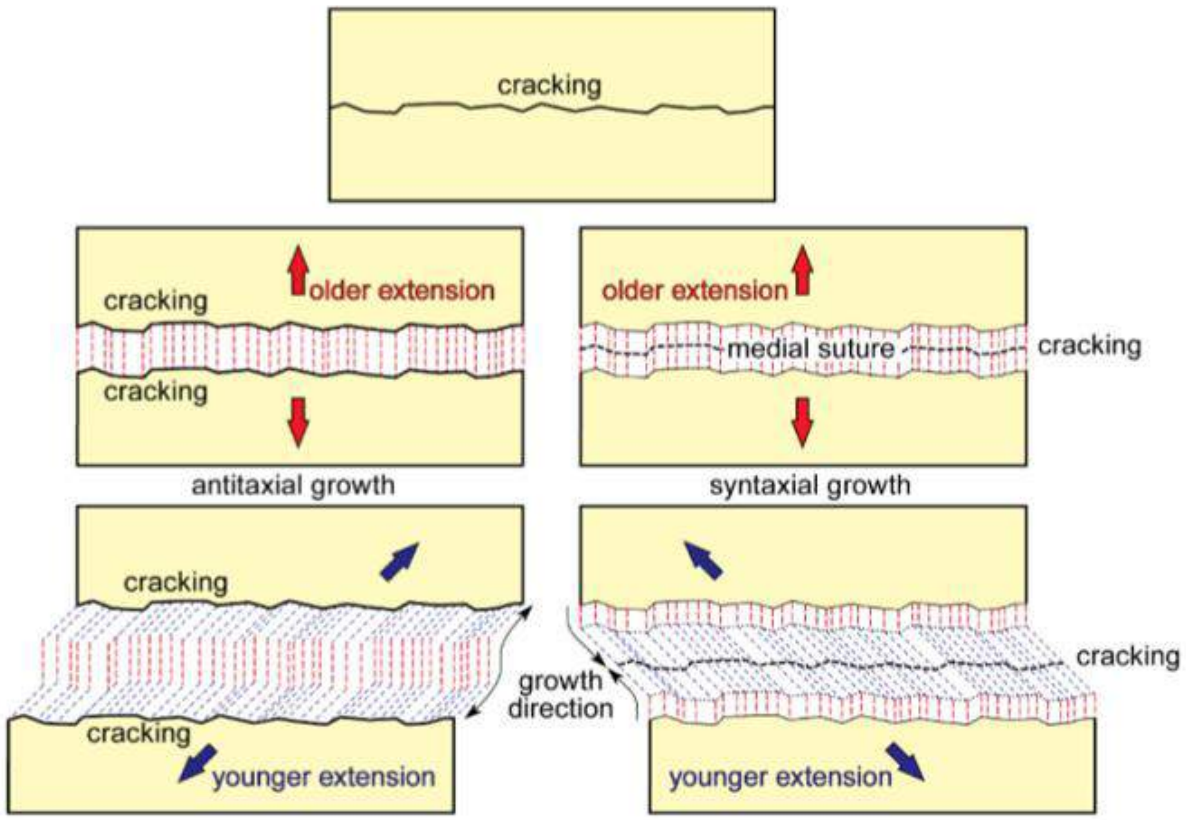
Composite veins are very common veining structures comprising structures that are the product of more than one vein-forming event. The term *composite vein*, and the definition of this structure, as used here, are my own and differ from some historical definitions for the same term.

Terminology

The definition of composite veins used herein fits the context of veins we observe in hydrothermal mineral deposits, and is, in my opinion, markedly more useful than that proposed historically. Much of the previous terminology centres around the definition of veins as *syntaxial* or *antitaxial*. In reality, the textural definition of *syntaxial* and *anititaxial*, which pertains to vein fibre growth, is never used when trying to resolve the context of the vein in an evolving mineral system. Furthermore, the historical terminology can only be applied to extension veins, severely limiting the usefulness of composite veins as proposed by previous workers. Importantly, their definition cannot be applied to shear veins, where the primary growth textures and history have been destroyed.

The term *composite vein* has been used by a couple of previous workers in the following contexts:

- Alex Strekeisen (https://www.alexstrekeisen.it/english/meta/veins.php) defined composite veins as '*veins in which an antitaxial vein segment is sandwiched between syntaxial vein rims. Such a vein has three median lines.'* Strekeisen's diagram is shown below because it is a very good one for summarizing antitaxial/syntaxial terminology.



- Paul Bons (Bons: The formation of veins and their microstructureshttps://www.tectonique.net › wdmrom_pdf › bons) used the same definition as Strekeisen for these morphologies, citing Durney and Ramsay (1973, In: Gravity and Tectonics (edited by K. A. De Jong & R. Scholten, pp 67-96), and further commenting that *'The term composite should be reserved for veins where both morphologies and minerals occupy similar proportions of the vein.'*
- The Free Dictionary https://encyclopedia2.thefreedictionary.com/composite+vein defines a composite vein as *'a large fracture zone composed of parallel ore-filled fissures and converging diagonals, whose walls and intervening country rock have been replaced to a certain degree'.*

My definition of composite veins, as used in this document, is as follows:

- Composite veins comprise the parallel to subparallel juxtaposition of two or more different veins that differ in terms of one or more factors, including mineralogy, age, morphology or conditions of formation.
- Veins commonly develop as composite structures when subsequent vein episodes exploit the weakness represented by pre-existing vein-wallrock contacts, or planar weaknesses internal to the veins (e.g. shear-induced laminations, mineralogical boundaries).
- In the case of exploitation of earlier-formed internal weaknesses, the younger veins will commonly track from one side of the vein to the other.

Recognition of composite veins

Composite veins can be recognised by:

- An asymmetric distribution of vein minerals
- The presence of two sets of minerals that have markedly different formation conditions e.g. lower greenschist-grade metamorphic minerals may comprise a vein that has adjacent bands of amphibolite-grade minerals
- An asymmetric distribution of alteration selvedges
- Cross-cutting relationships between the component veins that that are developed along strike/dip
- Differing overprinting/geometric relationships between the different vein fill minerals e.g. one set of vein minerals may be folded whereas others are not
- Differing morphology of the planar structures comprising the vein e.g. fibrous versus massive

Examples of composite veins

This section provides various examples and descriptions of composite veins from hydrothermal mineral deposits.

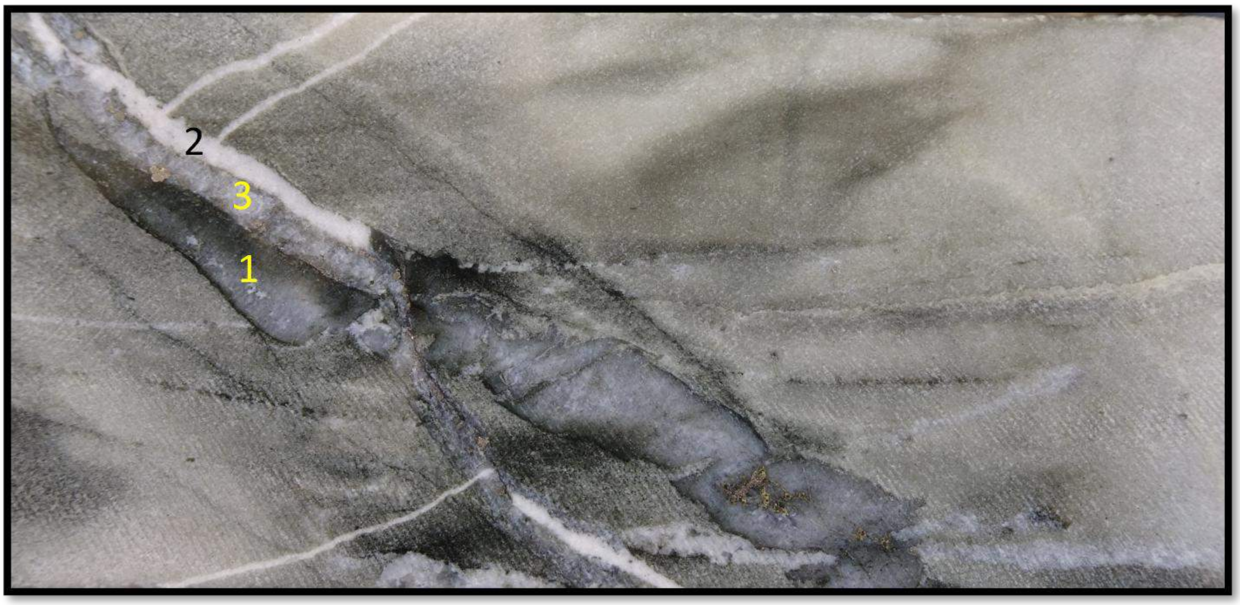
The first two photos are from the Homestead orogenic gold mine in Western Australia. The top photo shows a laminated quartz-carbonate vein that has been emplaced along the margin of a relatively massive quartz vein. Local cross-cutting relationships and divergence of the two veins provide information on relative ages. The lower photo shows a fibrous quartz extension vein that is juxtaposed against a relatively massive quartz extension vein. Relative ages are difficult to evaluate in this example.

The example below is from the Monty VHMS deposit in Western Australia shows a composite vein formed from the juxtaposition of an early carbonate extension vein against a later epidote-quartz breccia vein.

The next two photos show examples of composite veins displaying an asymmetric distribution of alteration selvedges. In both examples, fine-grained biotite alteration is preferentially developed on one side of the composite vein. In the photo immediately below, the two veins can be seen to diverge at the lower left of the image.

In the photo below, the alteration is associated with relatively thin quartz-carbonate veins that have been emplaced along the contact of the older carbonate-actinolite veins.

The figure below shows development of a composite vein in the upper left of the figure where three veins coalesce. Cross-cutting relationships show the order of emplacement of the veins, from 1 (oldest) to 3 (youngest).

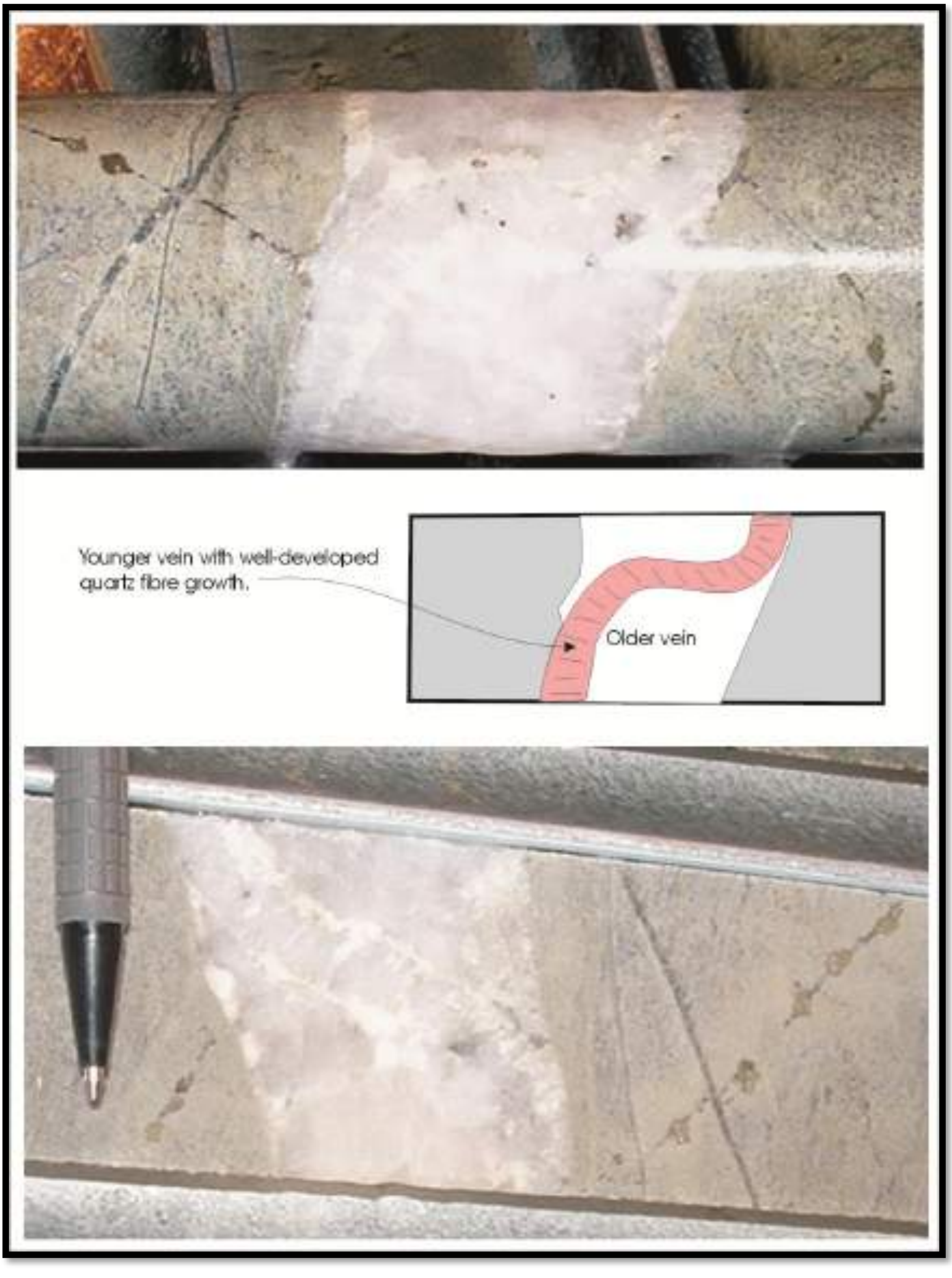


The next example shows a composite vein from the Chatree epithermal gold deposit in Thailand. The older grey quartz vein is overprinted by a subparallel pink laumontite vein that progressively cuts across the older vein along strike, varying in position from one side of the older vein to the other. The yellow inset is shown in detail in the photo following this one.

The detail of the inset from the previous photo shows the pink laumontite vein varying in position from one side of the host quartz vein to another. The occurrence of two distinct vein types is supported by a relatively thin laumontite-only vein below the composite vein.

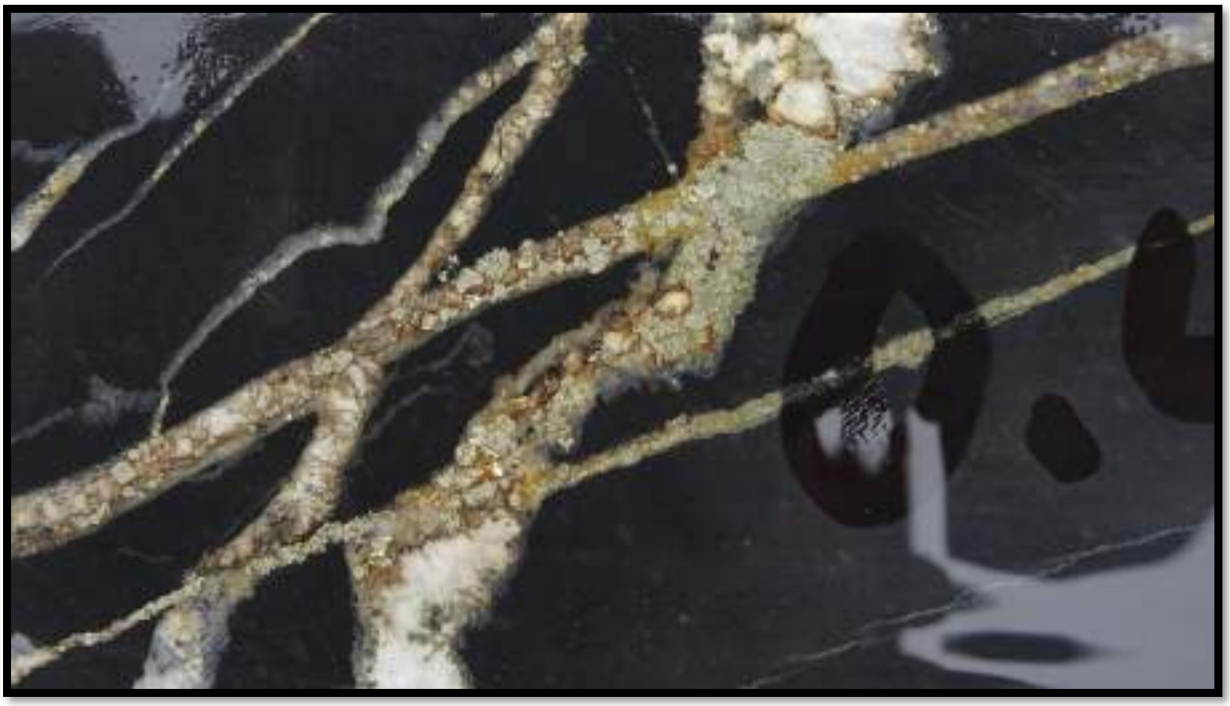
The photos plus line diagram in the figure below show a composite quartz vein viewed in both sides of diamond core from Quarters gold mine, Western Australia.

A younger quartz extension vein cross-cuts the older vein and then trends parallel to the contact of the older vein.

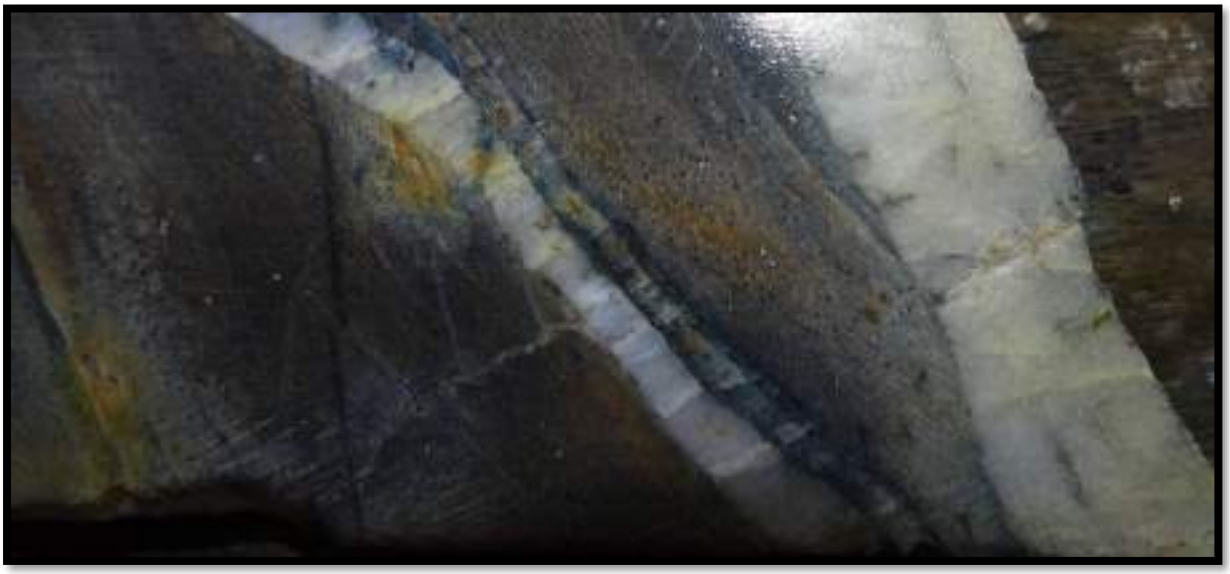


The example here is from the Twangiza orogenic gold deposit in the Democratic Republic of Congo.

The relatively more steeply dipping, older veins have a mineralogy that is the product of two veining events. The younger veins with a lower dip have cross-cut the older veins, causing deposition of pyrite in the older veins close to the vein intersections.



The photo below is also from the Twangiza orogenic gold deposit in the Democratic Republic of Congo and shows white quartz veins comprising the same population. The contact of the left-hand vein has been exploited by a younger quartz-sulphide vein with a graphite(?) or chlorite(?) alteration selvedge, forming a composite vein.



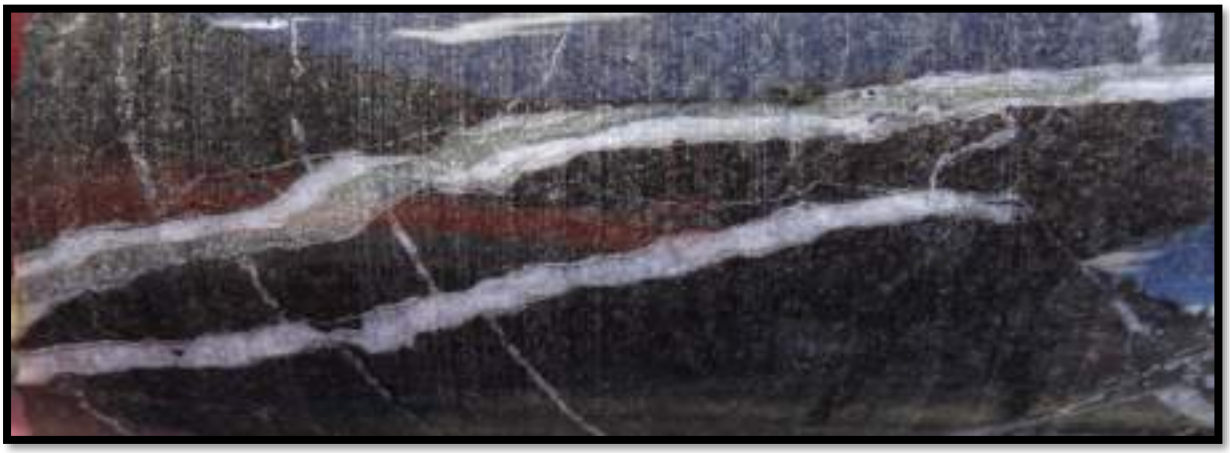
In the example below, two parallel, planar veins comprise a composite vein. The earlier vein is a khaki-grey colour and the younger vein is a white colour.

The younger vein can be seen to run parallel to the older vein until the centre of the photo where it swaps sides to the other margin.

The above example is similar to the one below, two parallel veins have different mineralogy and colour. The younger white carbonate vein can be seen to cut across the grey quartz-rich vein on the right-hand side of the image.

The following example shows a composite chalcopyrite-carbonate vein from the Kinsevere copper deposit, Democratic Republic of Congo. Note how the veins diverge on the left-hand side of the photo.

In the following example, the same vein in both sides of a core interval are shown. The images show a composite vein comprised of an older white carbonate vein and a younger quartz-carbonate vein that has overprinted it.



The photo below shows a relatively younger, thinner laminated, quartz extension vein that has been emplaced along the contact of the older, thicker relatively uniform, monomineralic quartz vein.

The next photo shows a black, chlorite-rich shear vein that has bifurcated. The younger carbonate veins have been emplaced dominantly along the contacts of the chlorite veins. However, local splays off the carbonate vein faithfully mimic the older asymmetric shear fabric and the continuous portion of the younger vein locally cuts across the chlorite veins.

The relatively thinner, younger vein in the photo below traverses country-rock and locally cuts across the older vein, producing a composite structure where they intersect.

In the photo below, the white quartz-carbonate vein is at a high angle to pre-existing quartz-carbonate-actinolite veins. However, it locally trends subparallel to the older vein set, forming a similarly local composite structure.

The relatively thinner, younger vein in the photo below traverses country-rock and locally cuts across the older vein, producing a composite structure where they intersect.

In the next photo, the two veins are subparallel, locally contacting to form a composite vein in the lower portion of the photo.

The photo below shows two veins comprising the composite vein are evident by their different colours, mineralogy, and texture. In detail, the thin younger vein is also a composite vein, with a white quartz vein overprinting the pink-brown carbonate-quartz vein.

This page contains several photos from the same piece of core.

The upper right photo shows a relatively symmetrically mineralogically zoned quartz-carbonate vein with chloritic margins.

The centre photo shows the quartz-carbonate vein cutting across the chlorite vein.

The lower photo shows the spatial context of the previous two photo as viewed from right to left.

The photos here show a composite quartz-chlorite vein in granodiorite from Meguet, Burkina Faso.

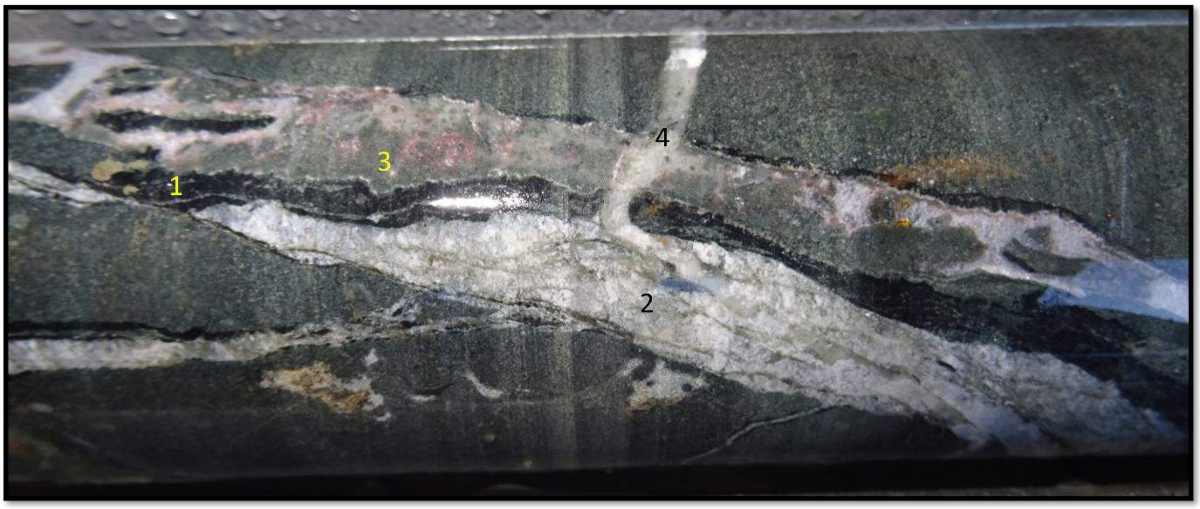
The composite nature of the vein is indicated by the asymmetric distribution of vein minerals

The lower photo overlaps the top one and shows separation of the composite vein into two discrete veins – a chlorite vein and a fibrous quartz vein.

The composite vein in the photo below can be identified by:

- Difference in mineralogy
- Difference in morphology (breccia veins vs shear veins)
- Cross-cutting relationships

Note that the black vein has been split by both the lower white vein and the upper carbonate breccia vein. Some of the black vein occurs as a remnant selvedge on the upper margin of the carbonate breccia vein and as clasts within it.



The photo below is from the Buritica deposit, Colombia, and shows a composite vein formed by a pyrite vein overprinting the host carbonate vein.

In the example below, also from the Buritica deposit, the younger vein has exploited a fracture (arrowed) that is at an acute angle to the host carbonate vein orientation. It is unlikely that the younger vein was part of the same structure-fluid event as the host vein because it has a white alteration selvedge that has overprinted the host carbonate.

The photo below shows a quartz vein that has been overprinted by a relatively thinner quartz-haematite vein to produce a composite vein.

The photo below shows a composite vein comprising veins of different thickness and colour. Note that a zone of pyrite mineralisation occurs along the contact of the two veins, possibly representing a reaction product between the two structures.

The photo below is from the Buritica deposit, Colombia. The host is a quartz-sphalerite vein with minor carbonate that has been overprinted by a thin carbonate extension vein to produce a composite vein.

In the lower photo the host is a pyrite-carbonate-quartz vein from the Curraghinalt orogenic gold deposit in Northern Ireland. Note that the younger thin carbonate vein has a grey alteration selvedge (fine-grained pyrite?) that overprints the host vein.

In the photo below, the younger white quartz-pyrite vein has exploited the grey quartz-carbonate vein.

In the photo below, the host is a quartz vein. It is cut by a quartz-pyrite vein that has exploited an acutely cross-cutting fracture.

Composite veins – limitations/conflicts

As with many textures, geometries and overprinting relationships in geology, there are grey areas of interpretation and application.

In the case of composite veins, the question arises as to whether mineralogically different layers in a vein are the products of markedly different prevailing conditions, or if they simply represent the evolution of vein growth under relatively similar conditions. This complexity is especially difficult if the mineralogy of the veins does not change markedly from layer to layer e.g. carbonate-quartz-sulphide bands next to carbonate-quartz bands.

In cases of mineralogical similarity, other vein attributes have to be compared, e.g. there may be extension vein fibres developed adjacent to shear vein textures. Generally, unequivocal cross-cutting relationships will define a vein as being a composite feature. Epithermal veins are the biggest exception in this case, commonly producing multiple cross-cutting relationships between similar mineralogy veins. Note that different features comprising a composite vein don't necessarily imply a large intervening time period. For example, breccia vein textures internal to chalcedonic layering in an epithermal vein may have formed over a very short time.

The following veins shown here could be defined as composite veins, based on variations in mineralogy and texture of adjacent compositional layering. However, there is enough uncertainty to suggest they may also be products of development of the same veining episode.

The vein below is from Kanowna Belle gold mine, Western Australia, comprises a white quartz vein on top of a quartz-sulphide vein that shows extension textures. However, there is no discernible cross-cutting relationship and the bulk mineralogy of the upper and lower portions of the vein differ only with respect to the presence of sulphide. As such, it is probably best to consider this as part of a single vein population in which the fluid composition has changed over the period of formation i.e. not a composite vein.

In the sample below from the Golden Grove VHMS deposit, Western Australia, there are compositional differences, and the lower fibrous, chlorite-bearing portion of the vein locally diverges from the white vein core. In this case the vein could be either a composite structure, or part of a single vein population in which the fluid composition has changed over the period of formation. This is a good example of the grey area in definition.

The vein below comprises several layers that vary in mineralogy, texture, and wall-rock clast content. Overall, however, the vein is largely quartz, with variations in graphite content. The breccia texture may simply be a product of relatively more explosive opening of the structure but with infill of essentially the same fluids that formed the white, monomineralic layers. As such, this is probably not a composite vein.

The significance of recognizing composite veins

Composite veins, as defined herein, are products of separate veining episodes. Commonly, the mineralogy of the component veins is very similar. It is critically important to recognize the different vein populations because a failure to do so will render the interpreted geological history for a deposit incomplete and/or incorrect.

Establishing a geological history is one of the most important things to do when trying to understand a hydrothermal mineral deposit. It allows recognition of all of the geological entities and identifies the mineralizing structures in time and space. This then allows collection of orientation data for different populations. Critically, it mitigates against the mixing of data populations.

If a composite vein is not recognized, the component veins will be rendered the same in terms of geological age and orientation. This can impact drill program design, correlation of geological bodies, and the shape of resource models.

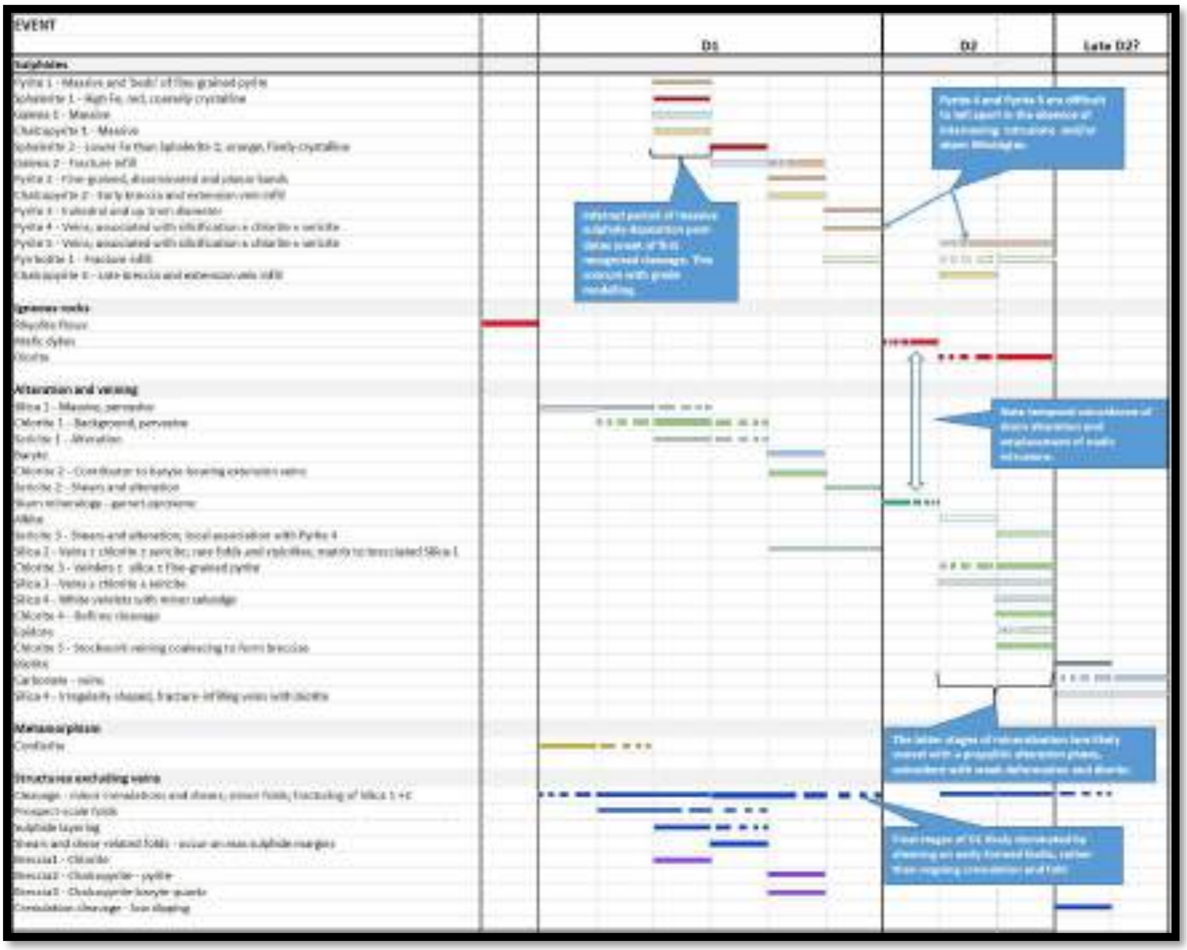
ESTABLISHING A VEIN OVERPRINTING HISTORY

The importance of geological history

One of the most important tasks to do when trying to understand a deposit is to establish a geological history, not just the veining history or just the structural history. The structural history comprises the sequence of deformation events and the various structures that have formed in response to this. Similarly, the veining history comprises a sequence of hydrothermal deposition events that produce successive (mostly) vein formation events.

The veining history is a subset of the geological history! The ultimate goal of the geologist should be formulation of a complete geological history that can be used as an exploration tool and for understanding orebodies such that they can be economically mined. Limitation to a subset (e.g. just the veining history or deformation history) of the geological history will blinker and bias you, and will blind you to exploration and discovery opportunities.

The figure below is an example of a geological history that incorporates the veining and structural history. This provides a snapshot of deposit evolution, placing veins and structures in a temporal context.



A fact that cannot be denied is that the task of establishing a geological history and auditing the confidence level of core orientation must be undertaken before a quality 3D model with geometric/orientation constraints can be produced. Establishing the temporal context of the veins within the overall geological history is fundamental to this. **Undertaking the task of establishing a geological history is not a waste of time and is not a purely academic exercise.**

Basically, there are 2 things that encompass structural geology, which includes veins. These are **geometry** and **over-printing.**

The geometry of veins:

- Refers to their shapes and volumes in 2D and 3D
- Is important because understanding geometric relationships such as the asymmetric shapes of veins, polygonal outlines, repeated shapes etc enables us to understand the processes involved in developing these geometries.
- Enables prediction of favourable locations of mineralisation, resolution of kinematics, and construction of realistic geological and resource models.

The overprinting of veins:

- Refers to the cross-cutting relationships between veins
- Can control the geometry of features
- Gives us the relative ages of structures that enable us to pinpoint which ones have been important for localising mineralisation.

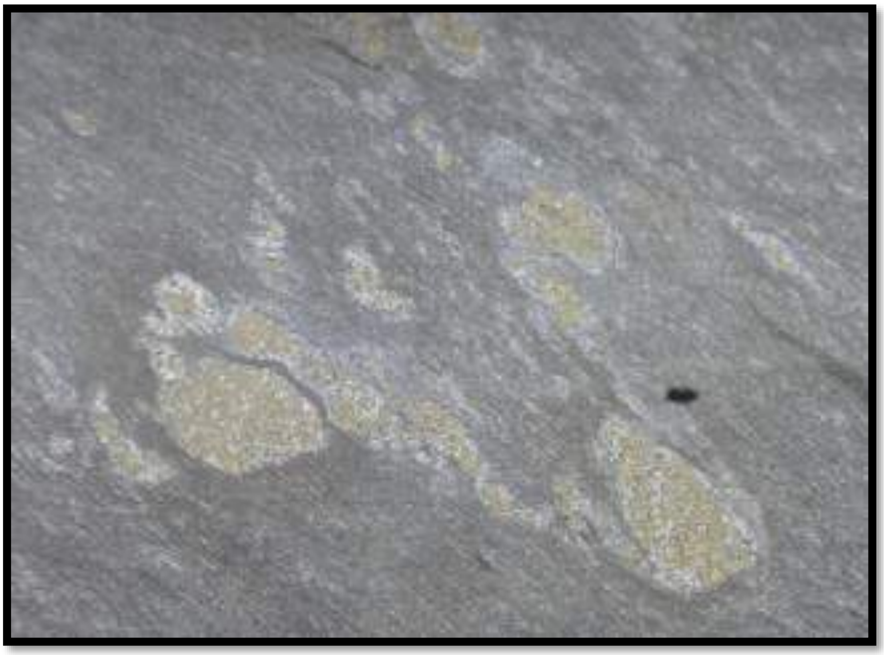
The cost of ignorance – comments and an example

The repercussions of not understanding the geological history can be expensive:

- If the mineralising structures, such as a particular vein population, are not identified then orientation constraints cannot be resolved. This commonly happens when several groups of veins, only one of which contains mineralisation, are grouped together.
- Because temporally and spatially associated structures, such as veins and faults that have acted as conduits for mineralising fluids, may be overlooked.
- Because incorrect drilling orientations may be suggested and employed. Unfortunately, the ultimate result may simply be a waste of time and money.
- This can be very embarrassing if subsequent exploration by another company discovers an economic deposit because they took the time to understand the geological history and orientation constraints to mineralisation.

Basically, we are trying to establish the cross-cutting/overprinting relationships between all vein populations. To do this we need to describe all of the textural, geometric and cross-cutting relationships between different vein populations. As an example of problems that can arise from failure to establish a vein overprinting history, consider the example below from an orogenic gold mine in the Democratic Republic of Congo.

The images below are all from the Twangiza gold mine, and display the complexity of vein geometries, the diversity of textures, and give an indication of the many vein populations present. In the first image we can see a carbonate-pyrite vein defining a fold with a well-developed country-rock foliation.



In the photo below, one vein is comprised of a steep quartz-carbonate-pyrite vein with a pyritic selvedge. This has been overprinted by a white quartz vein with no selvedge. The quartz-carbonate-pyrite vein has then localised a fracture, which is now filled with iron oxide, to produce a composite feature.

In the example below there is local composite vein formation where the steep carbonate veins combine with the brown low-dipping pyrite. The margins of the older veins are pyritized at the points of intersection.

The photo below shows a yellow carbonate-rich vein population overprinting white quartz-only veins.

The next two photos show laminated shear veins cross-cutting white quart-pyrite veins.

Having looked at the preceding six photos, it is obvious that there is more than one population of veins. Furthermore, the vein populations commonly have orientations at high angles to each other.

The image below is a map of the Twangiza gold mine. The dark symbols are bedding, and the red symbols are veins. It is obvious that this map of a portion of the deposit is wrong because the vein geometries on the map do not reflect the overprinting relationships seen in the outcrop or core.

The definition of resource volumes, drill hole planning, in-mine exploration etc will all be compromised in this situation.

Establishing a vein paragenetic history

This section gives the process that I follow to establish a veining paragenetic/overprinting history. The process is given for veins encountered in diamond drill core, but the procedure is basically the same if dealing with outcrops, and/or mining development.

The initial steps comprise selection of core intervals to gain an overall assessment of the rock and vein types, the complexity of geology etc:

- The entire hole, or significant portions of holes, should be laid out and a 'walk-through' of the geology done.

- Sticks of core are highlighted that contain the following information:

  - Examples of each different (or apparently different) vein set

  - Any pieces displaying vein cross-cutting relationships

  - All pieces showing structural relationships to veins and cleavages (e.g. folded veins, alteration controlled by foliation etc.)

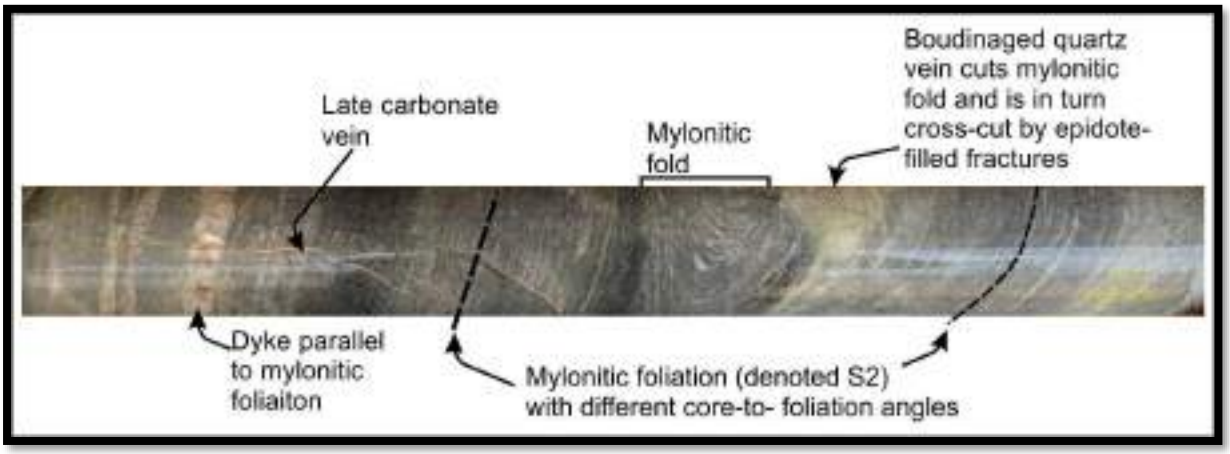
  - Pieces of core with alteration associated with structures

  - Any other features such as intrusions, metamorphic minerals etc

The simplest way to highlight intervals of interest is to lift them up in the tray. Initially there will be many pieces but, as the process of identifying the different features progresses, these will distil down into a manageable number of core intervals and features to describe.

The next step is to identify the different geological features in terms of geometry and overprinting relationships. Remember, the vein history is a subset of the geological history, so we need to work out the overprinting relationships between all geological features.

The figure below shows examples of some of these relationships in the New Liberty orogenic gold deposit from Liberia, West Africa.



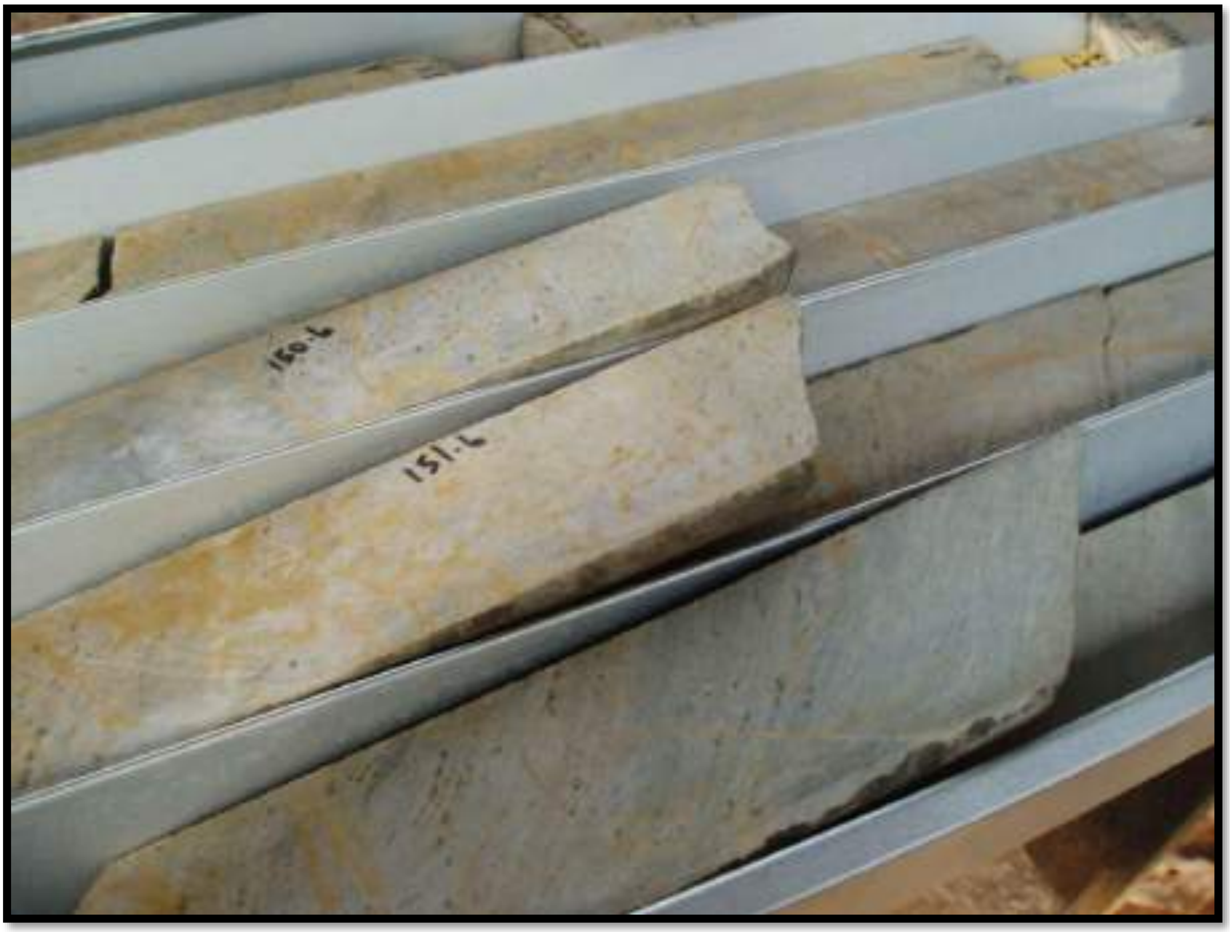
With respect to establishing the veining history, we need to identify the different vein sets and alteration styles by:

- Highlighting sticks of core that have examples of each different (or apparently different) vein set

- Identifying any pieces displaying vein cross-cutting relationships

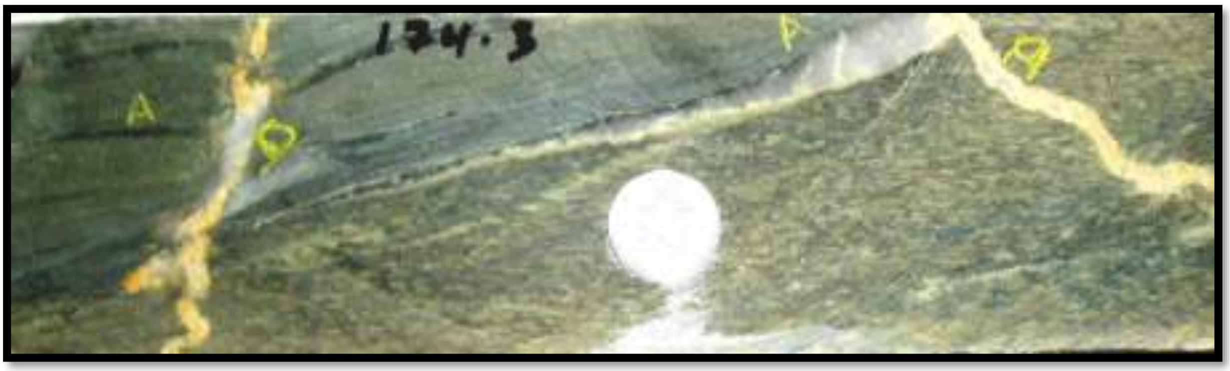
- Identifying pieces showing structural relationships to veins and cleavages (e.g. folded veins, alteration controlled by foliation etc.)

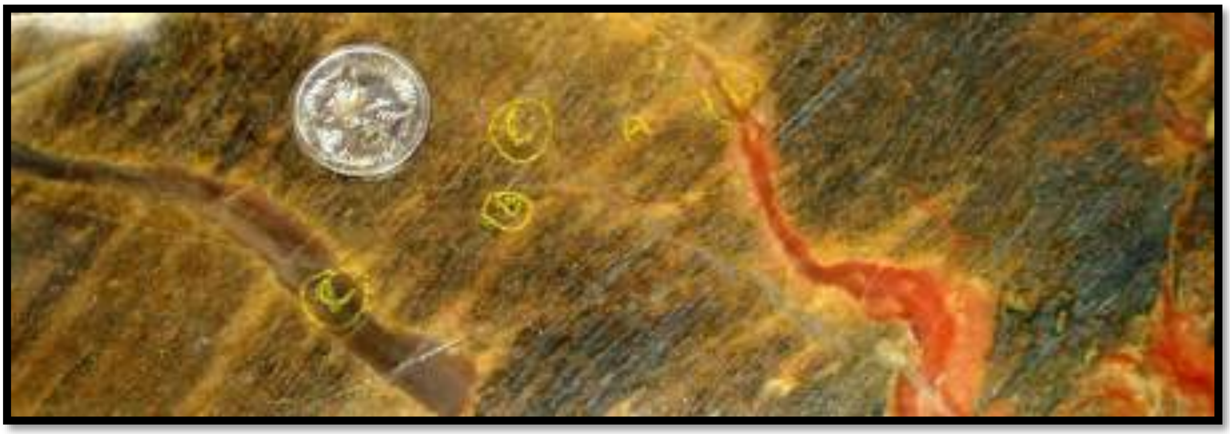
It is also critically important to mark the core intervals with their depth in the hole so that any relationships in them can be correctly documented and easily checked later, if necessary. It also helps when putting core back in the correct location!



Each apparently different vein set needs to be characterised. This can be done on the core by giving each apparently different vein set its own unique identifier e.g. using letters of the alphabet. Be careful if using numbers because the tendency to put the veining events in the same order as the identifier numbers can lead to incorrect overprinting relationships. I also like to write down descriptions of each vein set so that I can compare vein characteristics from different portions of the hole, or between holes.

In the core in the following two photos below, the vein populations have been given letter identifiers so that they can be compared.





The veins need to be described veins in terms of:

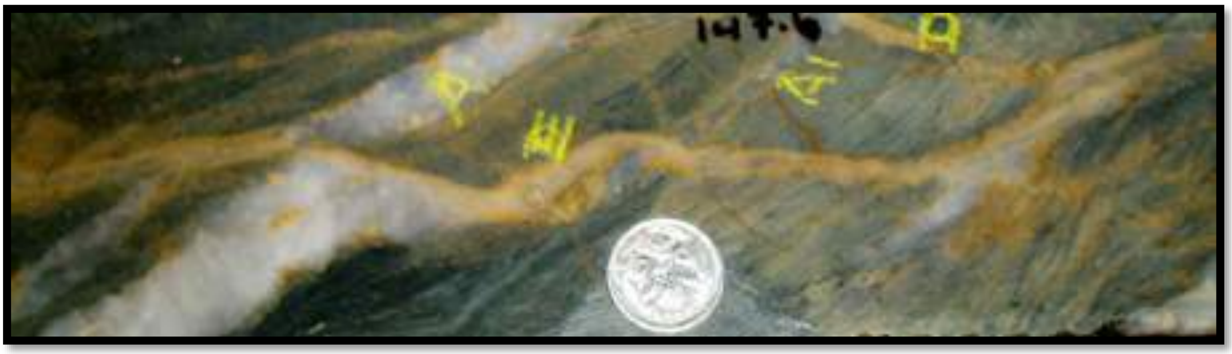
- Mineralogy
- Morphology
  - e.g. crack-seal, breccia, laminated, fine-grained, infill, colour, thickness etc.
- Cross-cutting relationships with other veins and structures
- Geometry
  - e.g. planar, boudinaged, folded etc.
- Orientation
  - e.g. are the veins at a low or high angle to the core, or both
- Alteration selvedges

To reiterate:

- Give each apparently different set of veins an identifier:
  - A, B, C etc. is good as it doesn't indicate the chronology of vein formation

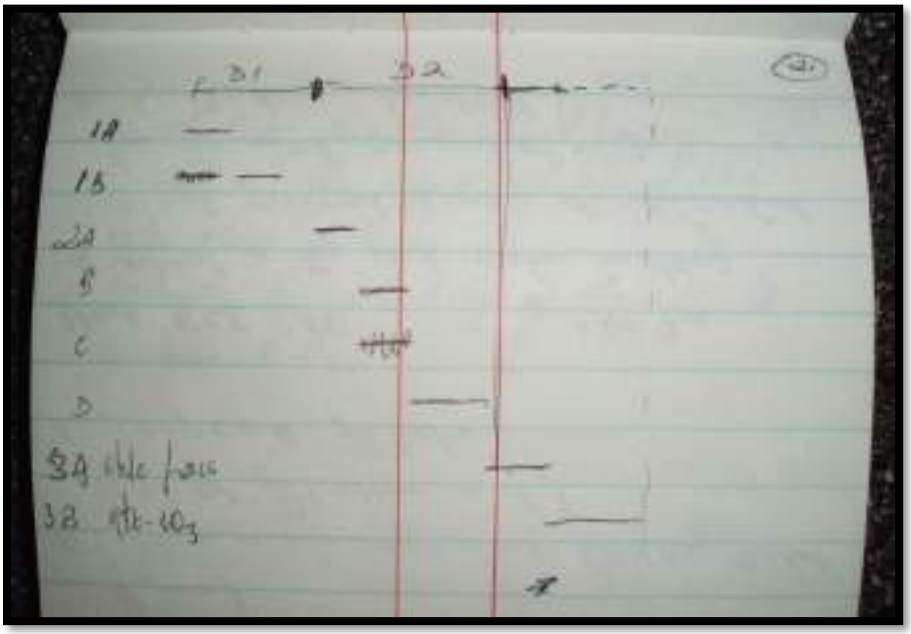
- Once you've described a vein, write the letter for that vein type next to it on the core
  - This lets you refer back to the piece when deciding if, for example, Vein E is the same as Vein A or not

- Expect to scribble and erase your markings on the core, at least initially:
  - Chinagraph pencils do not leave a permanent record of your scribblings



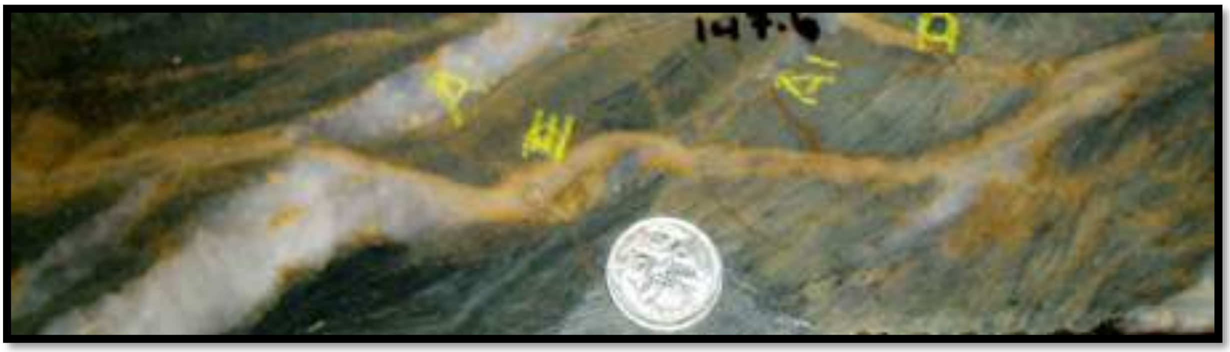
The next step is to start putting together a rough chronology. The best way is to tabulate this because it will be progressively amended. Ongoing amendment will result in development of an overall geological history, rather than a series of disjointed relationships. I initially do this in my notebook, but it is sometimes better to involve everyone working on the project and to build up the history on a whiteboard in the core-shed (e.g. see below).

The following photo shows a first-pass history in a notebook, where I have listed the different vein groups vertically, and their interpreted relative ages given across the page.

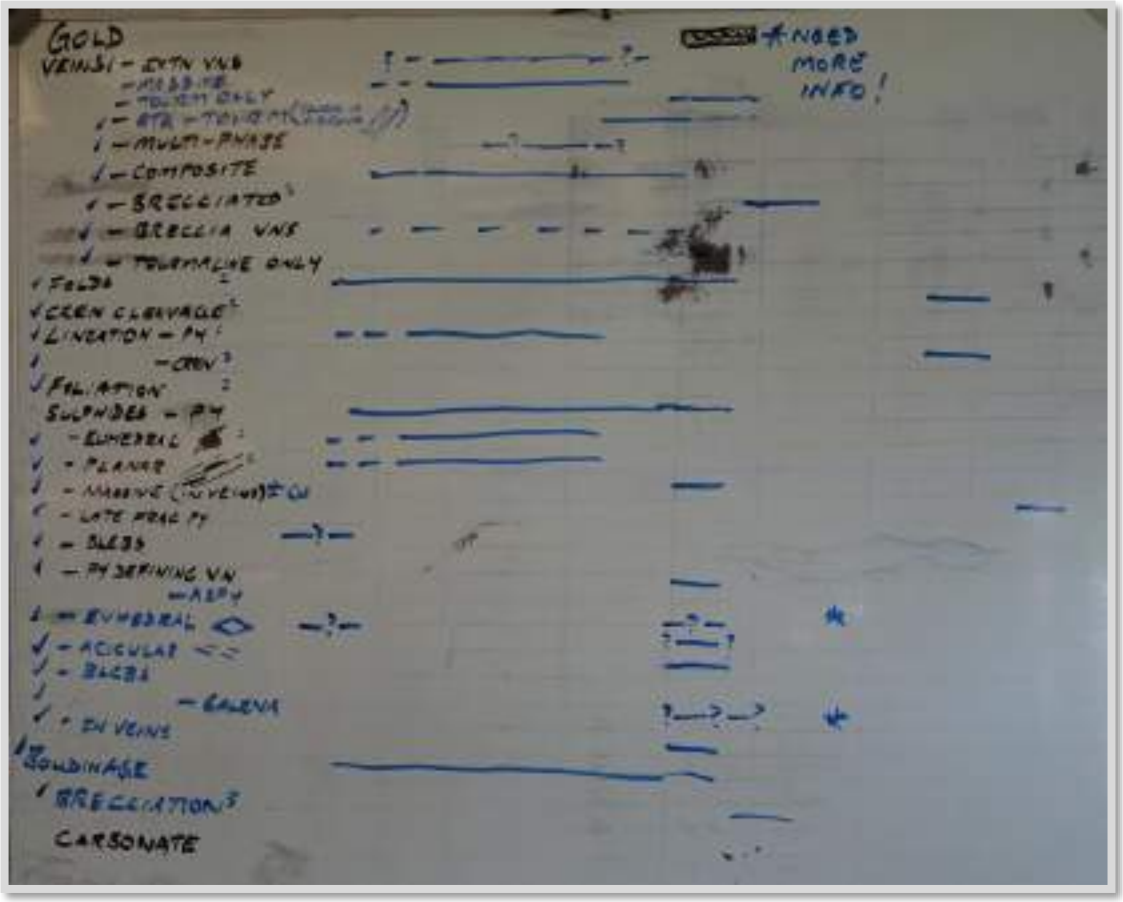


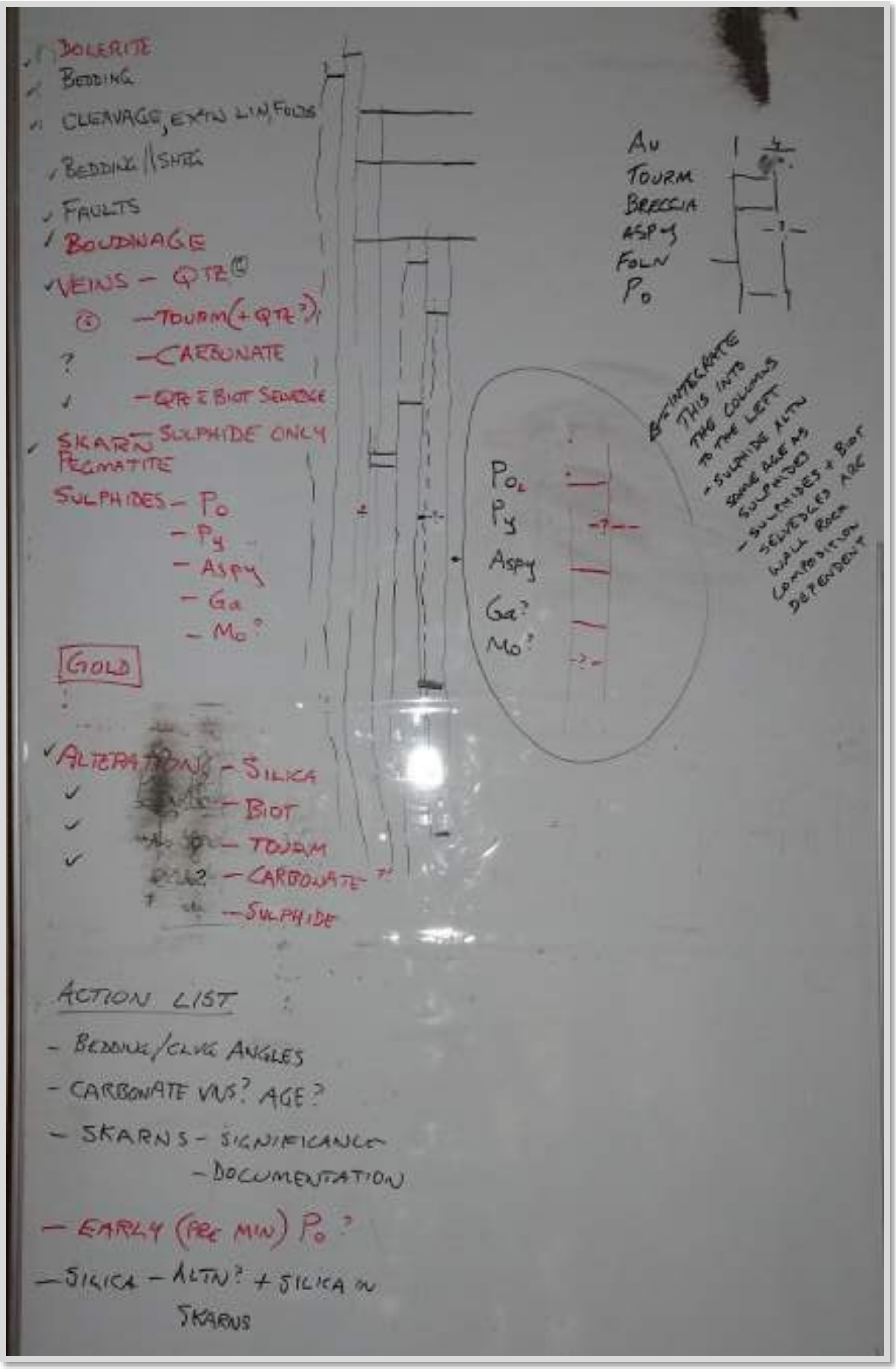
One thing that will become apparent is that you will initially have many different vein populations and other structure types. However, when overprinting relationships and correlations of apparently different vein populations are made, the number of structures will distil down to a manageable quantity.

If you look at the image below, which is repeated from earlier in this section, you will see that some vein identifiers have been over-written by new ones. This has been done as the different vein populations have been correlated, reducing the final number of vein groups.



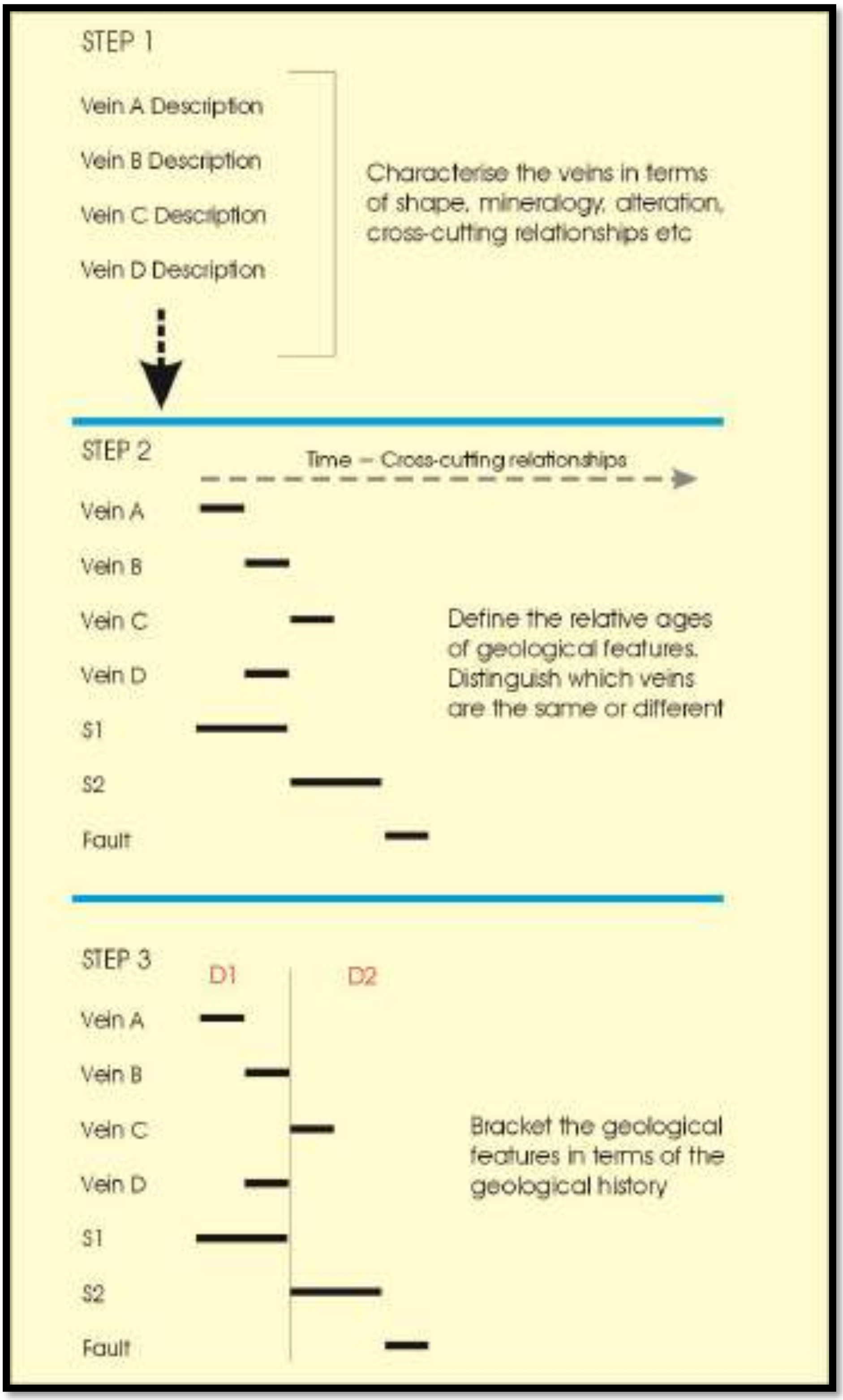
Compiling the geological history on a whiteboard or in a spreadsheet allows easy modification of the geological history when new information, such as overprinting relationships, is gathered. The whiteboard histories shown here were compiled in the space of less than a day each. They correspond to two of the orogenic gold deposits on the Namoya-Twangiza gold belt trend in the Democratic Republic of Congo.


GOLD
VEINS
NEED MORE INFO!
MULTI-PHASE
COMPOSITE
BRECCIATED
BRECCIA VNS
TOURMALINE ONLY
FOLDS
CREN CLEAVAGE
LINEATION – PY
FOLIATION
SULPHIDES – PY
EUHEDRAL
PLANAR
BLEBS
PY DEFINING VN
ASPY
EUHEDRAL
ACICULAR
BLEBS
GALENA
IN VEINS
BOUDINAGE
BRECCIATION
CARBONATE



DOLERITE
BEDDING
CLEAVAGE, EXTN LIN, FOLDS
BEDDING || SHTG
FAULTS
BOUDINAGE
VEINS – QTZ
– TOURM (+ QTZ?)
– CARBONATE
– QTZ ± BIOT SELVEDGE
SULPHIDE ONLY
SKARN
PEGMATITE
SULPHIDES – Po
– Py
– Aspy
– Ga
– Mo?
GOLD
ALTERATIONS – SILICA
– BIOT
– TOURM
– CARBONATE
– SULPHIDE
Au
TOURM
BRECCIA
ASPY
FOLN
Po
Po
Py
Aspy
Ga?
Mo?
RE-INTEGRATE THIS INTO THE COLUMNS TO THE LEFT
– SULPHIDE ALTN SAME AGE AS SULPHIDES
– SULPHIDES + BIOT SELVEDGES ARE WALL ROCK COMPOSITION DEPENDENT
ACTION LIST
– BEDDING/CLVG ANGLES
– CARBONATE VNS? AGE?
– SKARNS – SIGNIFICANCE
– DOCUMENTATION
– EARLY (PRE MIN) Po?
– SILICA – ALTN? + SILICA IN SKARNS

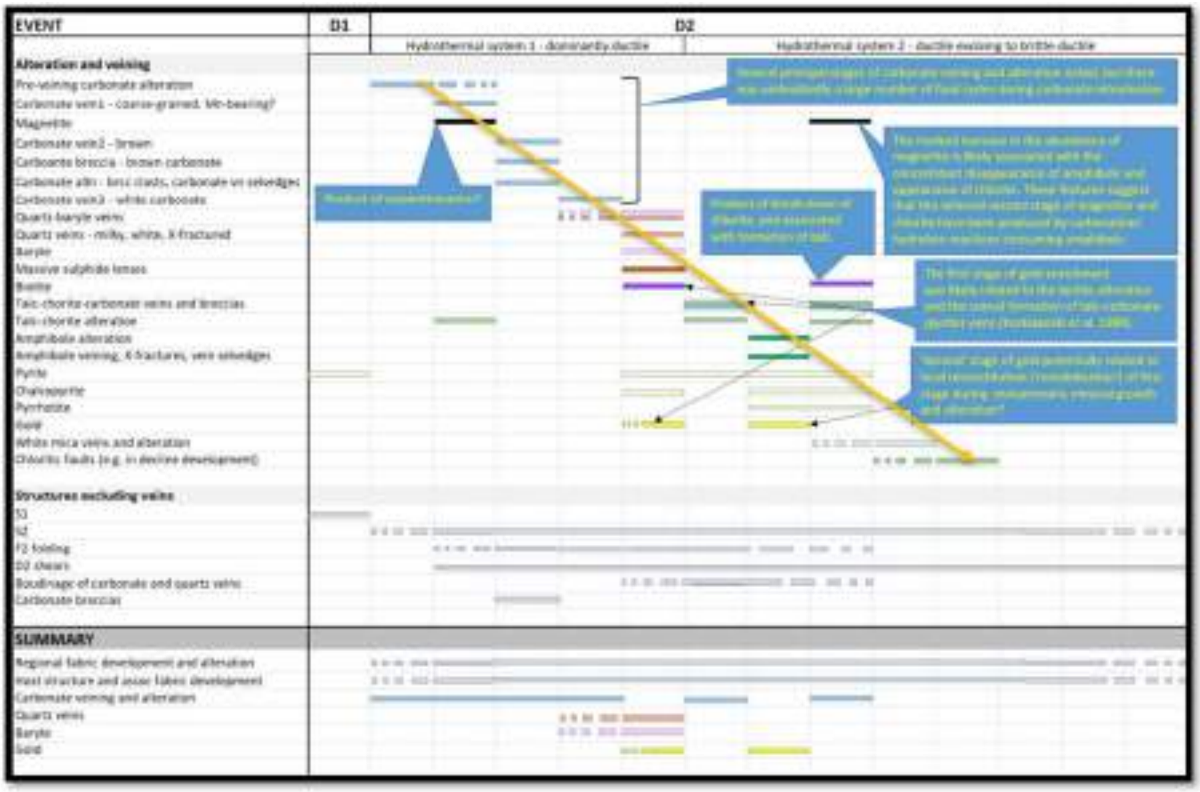
So, to reiterate and summarise - the figure below shows the process of establishing a vein overprinting history for incorporation into the geological history.



That really is as hard as it gets!

Once my geological history has been established, I compile it in a spreadsheet. Columns and rows can be inserted or deleted as necessary. The beauty of this is that it makes the geological history a living beast because it is easy to account for ongoing updates when additional information is obtained or the interpretation changes.

I like to colour code my veins. That way I can see at a glance the different types e.g. green for chlorite, orange for quartz etc. This then allows for easy construction of a geological history summary at the base of the table, which shows the duration of different hydrothermal events combined with structure. The other thing I like to do is to cascade the different features down the table from left to right. This is shown by the orange arrow, and it gives a visual representation of how the system evolved.



Once again – not a difficult exercise but it provides a snapshot of the evolution of the hydrothermal system and places the mineralisation in temporal context with the structures that have controlled mineral deposition. This is a powerful, pragmatic, visual display of the understanding of the deposit.

DETERMINING THE STRUCTURAL AGES OF VEINS

It is abundantly clear that veins in many deposits commonly comprise several different populations. The previous section dealt with establishing the overprinting relationships between the different vein types in order to resolve a vein paragenesis that can be incorporated into a geological history. The geological history also includes deformation elements, such as lineations, folds, and different types of planar features, such as cleavages and faults. Deposits also commonly show evidence for one or more stages of deformation, which can manifest in several main ways:

- As a foliation that can be recognised at various scales from regional (e.g. across a fold belt or tectonic terrane) to local (e.g. as a halo to large ductile shear zones)
- As dislocations varying from brittle faults through to ductile shear zones
- As pervasive veining and fracture sets

It is possible to get several generations/populations of all of these features in a single deposit. When dealing with deposits containing multiple deformation features, it is critical to establish the timing of emplacement of each vein set relative to the deformation types; i.e. the structural ages of the veins must be resolved.

The confident determination of the structural timing of veins in hydrothermal mineral deposits is critical but challenging. Failure to establish a correct history and structural timing can lead to different interpretations for the evolution of the same deposit, and severely impact exploration and project generation programs.

The terms pre-tectonic, syn-tectonic and post-tectonic are used to describe the ages of veins relative to the same structure. Most commonly, this will be with respect to a foliation.

Note: Veins may be pre-tectonic with respect to one cleavage (e.g. S2), but post-tectonic with respect to another (e.g. S1).

The structure that the veins are timed relative to must be described fully.

Pre-tectonic veins

Criteria to support the interpretation of vein emplacement as pre-tectonic include:

- The presence of post-vein dykes (or a later vein set) that is also deformed.
- A transition from well-preserved vein relationships (e.g. stockworks) outside a shear zone that show a transition to strongly deformed geometries within the shear zone. Note that this is not unequivocal because shear zones can have protracted lives that are typically longer than that of the veins.
- The presence of at least two deformation events affecting the vein. Although the relative timing of the vein and the first-formed fabric may be equivocal, this relationship indicates that the vein pre-dates the second deformation.
- The geometric arrangement of a suite of en echelon veins (e.g. EVAs) or multiple vein sets may be incompatible with the kinematics of high strain zones in the same

rock (e.g. steeply-dipping sigmoidal extension veins may be overprinted by a penetrative foliation with a down-dip extension lineation).

The photo below is an example of pre-tectonic carbonate veins from the Mulgarrie gold deposit in Western Australia. The following observations and interpretation can be made:

- There is open to close folding of the carbonate veins.
- The carbonate veins are parallel to S1 and do not appear to be deformed by it, suggesting that they were emplaced along S1 at the end of D1.
- Both S1 and the veins are folded by F2 folds, making the veins pre-tectonic relative to D2.

The example below is from the Sunrise Dam deposit in Western Australia. The tightly folded vein to the right of the pen contains chloritic shear laminations at a low angle to the vein margins, and both the vein and the shear laminations are folded. This indicates a pre-folding stage of deformation has affected the vein and the vein is, therefore, pre-tectonic with respect to the folding event.

The photo below was taken underground at the Prestea gold mine in Ghana. As background to this photo, I visited the mine when the upper levels to the largely flooded mine were still accessible. At the time I took this photo, the cage stopped at Level 6 and we were knee-deep in water and the cage was freely swinging because the shaft supports had been rusted out. Subsequent to this, the illegal miners blasted the shaft pillar, and the Mines Inspector closed the underground operation because there was no second means of egress.

The photo shows open folding of a shear-laminated quartz reef. The vein has shear lamination parallel to the country-rock fabric. This suggests that the vein was emplaced parallel to the intense tectonic foliation and that deformation associated with the tectonic foliation outlasted vein emplacement.

Both the tectonic fabric and the vein have been folded and are pre-tectonic with respect to the folding event.

The photo below is also from the Prestea gold deposit. The vein geometry defines open folding of the shear-laminated vein, which has been boudinaged prior to folding.

The vein is pre-tectonic relative to the late open folding event.

The photo below is from the Wassa gold deposit in Ghana and shows deformation of a vein population that was boudinaged prior to folding. The quartz-carbonate veins display attenuation and boudinage within the folded fabric, which is S1. As such, the boudinage is interpreted as a syn-D1 feature. The boudinaged veins and S1 have been folded by D3 to produce a recumbent F3 fold.

The veins are pre-tectonic relative to D3.

In the photo below, also from Prestea, the veins have been boudinaged prior to folding. The quartz veins display attenuation and boudinage within the folded fabric. Boudinage is interpreted as occurring during development of the foliation (S2) that has been subsequently folded during D3.

The boudinaged veins and the foliation are pre-tectonic relative to D3.

Note that the structural timing of the steeply dipping vein just to the right of the dashed line is less equivocal. It cross-cuts the folded veins and is subparallel to the axial planar fabric, S3. This suggests emplacement into the axial planar fabric (S3), with ongoing deformation then causing boudinage. That is, this vein is likely to be syntectonic with respect to D3. This photo shows how complex vein-deformation overprinting relationships can be developed for different vein populations of different age but similar composition in the same rock volume.

The photo below is from the Penjom gold mine in Malaysia and shows folded fibrous carbonate extension veins.

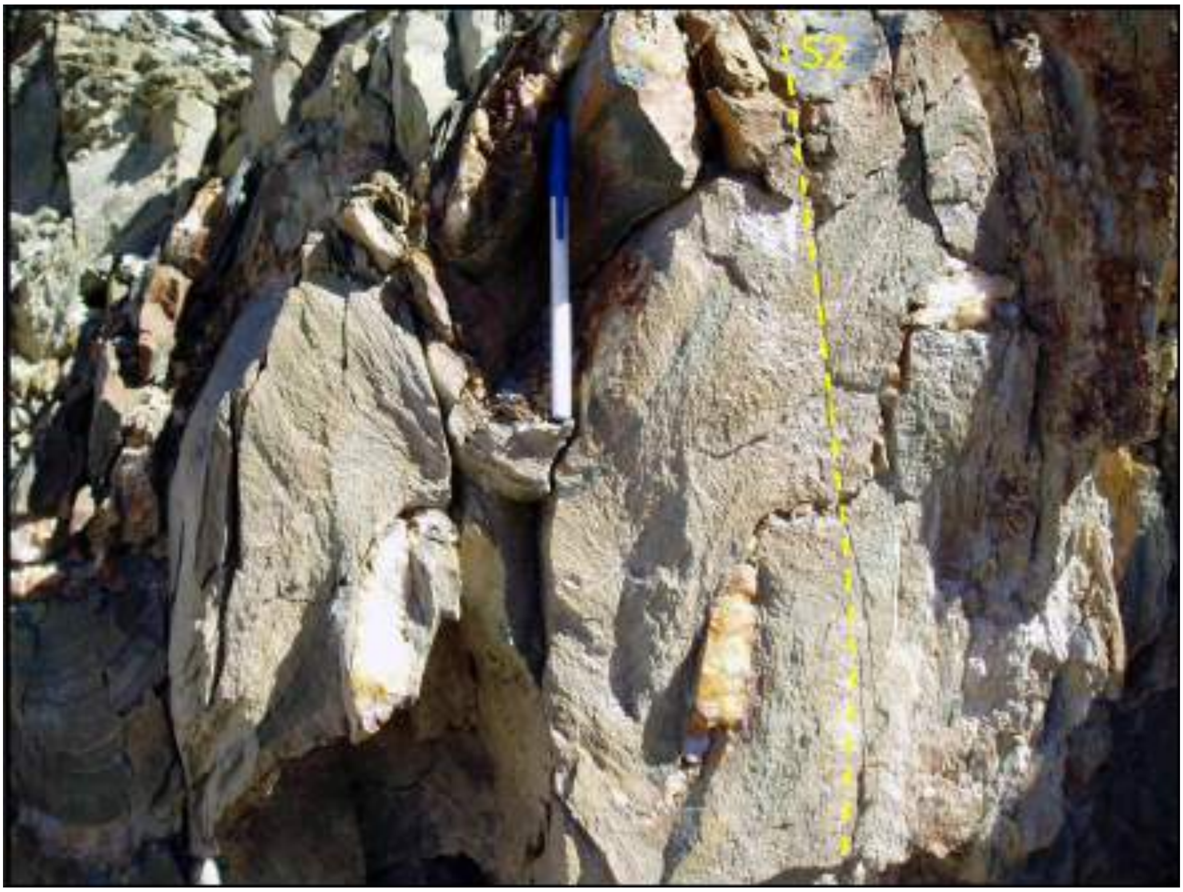
The photo below shows a similar example of fibrous quartz-carbonate extension veins that have been folded.

In both photos above, the veins are pre-tectonic relative to the folding, as indicated by variation in fibre orientation around the folds.

The photo below shows boudinaged veins from the Fortnum goldfield, Western Australia, that pre-date folding.

- The quartz veins display attenuation and boudinage within the folded fabric, which is S1.
- Boudinage is interpreted as a syn-D1 feature.
- The boudinaged veins and S1 have been folded by D2 to produce an upright F2 fold.

The veins are pre-tectonic relative to D2.



Syn-tectonic veins

The following relationships are characteristic of syntectonic veins, and these are illustrated in the figure on the next page:

- The overall vein configuration and geometry will be compatible with the kinematics of the host shear zone that has provided permeability. For example, the line of intersection between shear and extension veins is expected to be at a high angle to the slip direction along the host shear.

- Vein-vein intersections will be sub-parallel to the intersection between conjugate shears and subparallel to the intersection between S- and C-planes in the shear.

- Planar extension veins will cut the penetrative foliation and develop at a high angle to the foliation and extension lineation in the shear zone or strained host rocks.

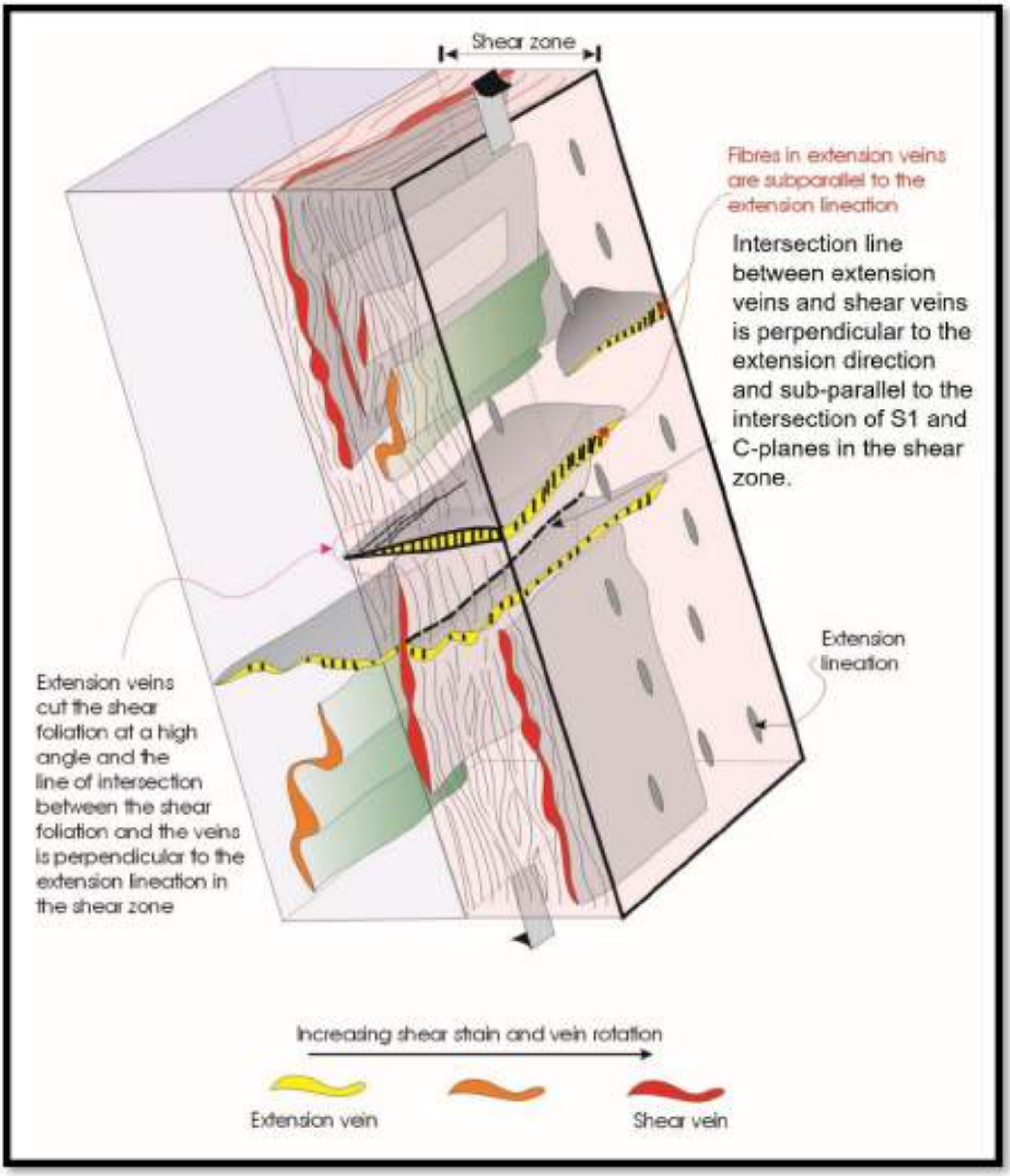
- The line of extension between the veins and the foliation will lie nearly perpendicular to the extension lineation.

- Mineral fibres within the veins will also be subparallel to the extension lineation.

- If extension veins are folded by progressive shortening during evolution of the shear zone, the enveloping surface of the vein remains at a high angle to the shear zone's extension lineation unless the shear strain is very high.

- The internal geometry of extensional vein arrays is compatible with the sense of shear determined for the synchronously forming host shear zone.

- Striations on slip surfaces within shear veins, and especially those defined by hydrothermal minerals present in the veins, will be subparallel to the elongation in the host foliated rocks.


Shear zone
Fibres in extension veins are subparallel to the extension lineation
Intersection line between extension veins and shear veins is perpendicular to the extension direction and sub-parallel to the intersection of S1 and C-planes in the shear zone.
Extension lineation
Extension veins cut the shear foliation at a high angle and the line of intersection between the shear foliation and the veins is perpendicular to the extension lineation in the shear zone
Increasing shear strain and vein rotation
Extension vein
Shear vein

The syntectonic structural age of a vein can be determined where different degrees of folding of the vein have occurred relative to other structures being folded.

The example below is from the Sunrise Dam deposit, Western Australia, and shows a well-developed fold of pyritic banded ironstone formation that has been cut by a carbonate vein. The carbonate vein shows the same fold geometry, but it is much less developed. This is interpreted as a product of carbonate vein emplacement in the final stages of fold formation. Thus, the vein is syn-tectonic with respect to the deformation that has produced the folding.

The drill core in the photo below is from Bogoso in Ghana, and shows syn-deformational veins. The following observations and interpretations can be made:

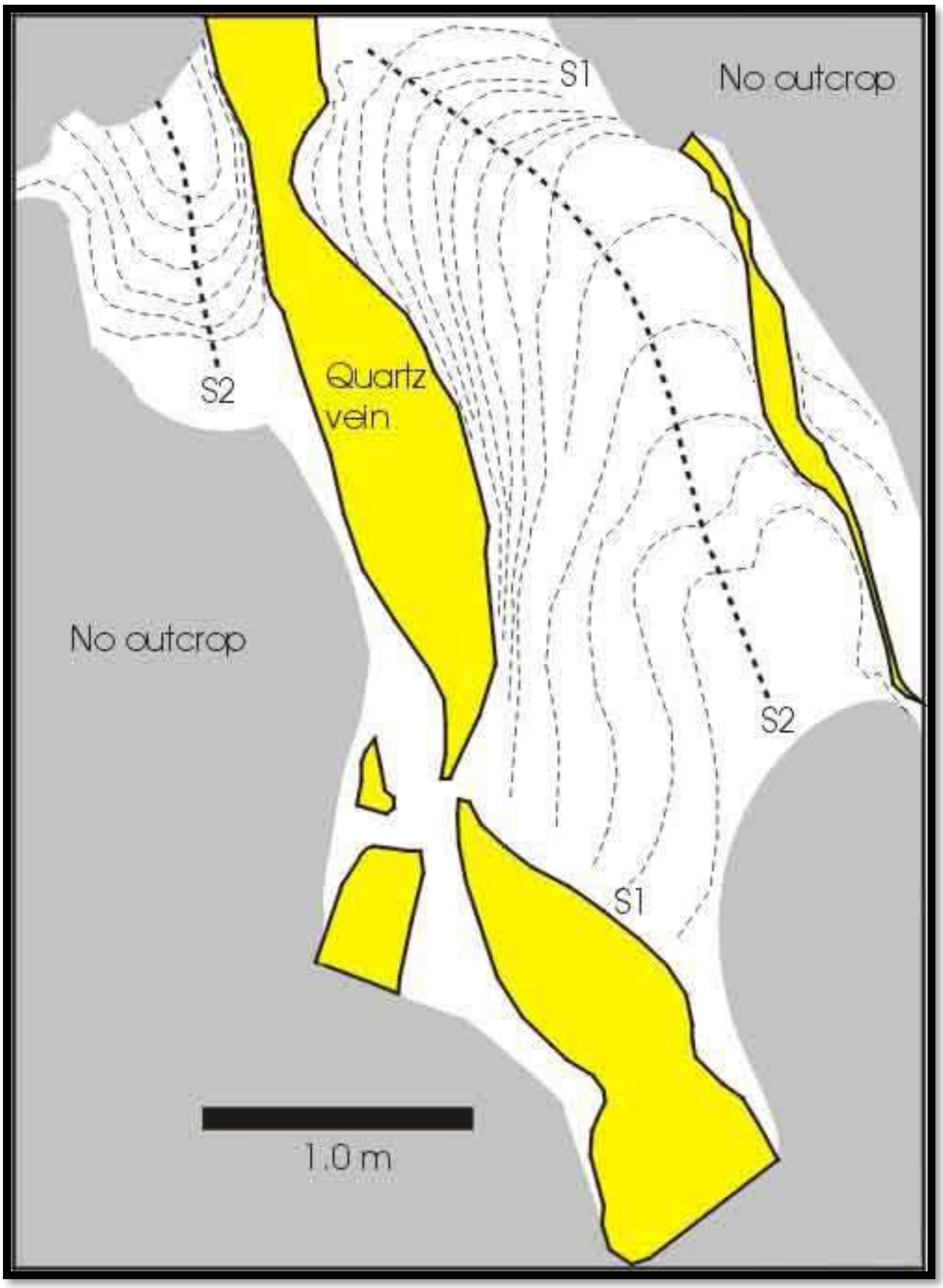
- Weak folding and cleavage development has affected the metasedimentary host rock.
- Veins have been emplaced subparallel to the cleavage suggesting a syn-cleavage timing of vein formation.
- The cleavage is best-developed adjacent to the veins due to ongoing deformation and strain accumulation at the vein margin.
- This indicates that deformation outlasted vein emplacement.

The veins are interpreted as syn-tectonic with respect to the fold- and cleavage-forming event.

In the photo below from the Prestea gold mine, Ghana, the laminated vein has been emplaced parallel to the intense country-rock foliation. Margin-parallel stylolites in the vein developed during shortening that was normal to the vein margin and a product of the deformation that produced the cleavage. Weak pinch-and-swell of the vein is evident and would be expected to have been much more intense if the vein had been emplaced early in the development of the cleavage. Consequently, this vein is interpreted as syntectonic with respect to the country-rock foliation.

The sketch of vein and foliation geometries below is from the Adamus prospect, southern Ghana. The veins are interpreted as syn-tectonic relative to the D2 folding event because of the following geometric relationships:

- S1 trendlines define open to tight F2 folds.
- Veins have been emplaced parallel to S2 and subsequently boudinaged by D2, indicating syn-tectonic emplacement relative to D2.
- The cleavage intensifies adjacent to the veins due to strain accumulation during progressive D2.



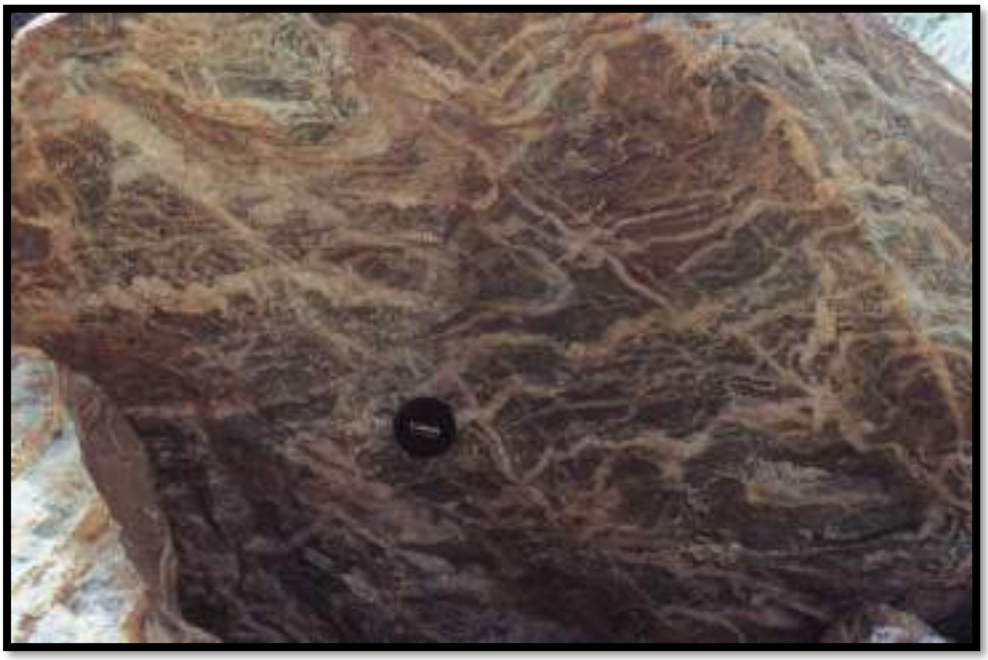
The photograph below is a hand-specimen showing vein-structure relations in a sample from the Mulgarrie mine, Eastern Goldfields, Western Australia. The following observations and interpretations can be made.

- S1 is defined by an intense foliation that is folded. Carbonate veins have been emplaced parallel to S1 and are attenuated and boudinaged in S1.
- Both S1 and the carbonate veins are folded and define F2 folds.
- F2 folds are developed adjacent to the quartz-carbonate vein due to progressive accumulation of D2 shortening strain at the vein margin.
- The quartz-carbonate vein has been emplaced parallel to S2 and has then undergone D2 boudinage due to ongoing D2 shortening that outlasted vein emplacement.
- The carbonate veins in the country-rock are interpreted as syn-D1 and thus pre-tectonic with respect to D2.
- The large quartz-carbonate vein is interpreted as syn-tectonic with respect to D2.

Both photos below are from the Ballarat-Last Chance gold mine east of Kalgoorlie, Western Australia. The photos show vein arrays comprised of two sets of synchronously deformed veins.

The steeply dipping, relatively thinner veins are subparallel to S2. These veins have a restricted thickness due to ongoing progressive shortening at a high angle to them.

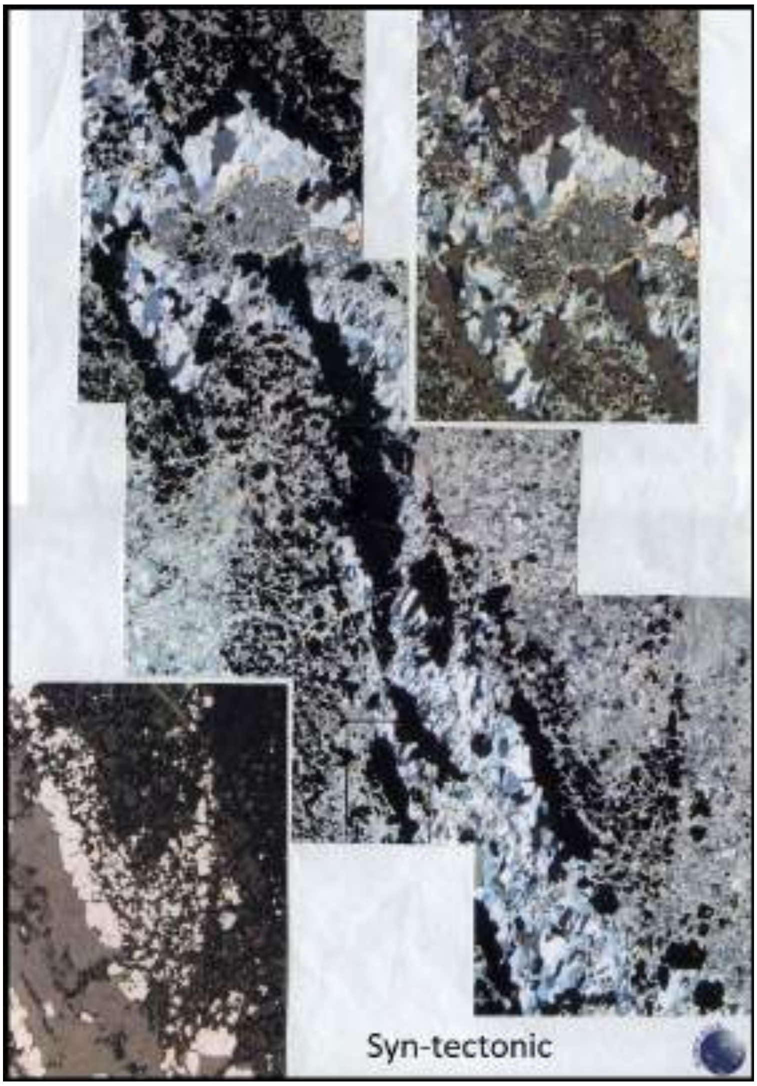
During D2 shortening, the thicker subhorizontal veins (subparallel to the long edge of the photos) opened as extensional structures and incremental opening has produced the characteristic extension vein banding in them. Ongoing shortening after vein deposition has produced open of the relatively thicker extension veins.



The photo below shows a syntectonic, D2, mineralised vein from the Kanowna Belle Deposit, Western Australia. The images have been taken under polarised and reflected light. The dark material is arsenian pyrite, which hosts the refractory component of the orebody in the form of gold bound in the lattice of oscillatory growth-zones.

The vein has opened in response to D2 shortening and the quartz fibres have grown parallel to S2, which is parallel to the long edge of the figure. Note that the fibres maintain an axial planar orientation around the fold hinge i.e. they don't splay as seen in pre-tectonic veins. Compare this with the pre-tectonic vein in the photo below this one, where the fibres radiate around the fold hinges.

Progressive shortening has caused open folding of the vein from Kanowna Belle. Ongoing vein growth during D2 included introduction of auriferous pyrite, which forms an alteration selvedge that locally extends away from the vein along synchronously-formed S2 (bottom right-hand inset).



In the photo below, two sets of synchronously deformed veins cross-cut a turbiditic unit from near Prestea, Ghana. The following observations and interpretations can be made:

- The less common planar veins that trend at a high angle to the long edge of the photo separate the less continuous, folded extension veins.

- The population of extension veins subparallel to the long edge of the photo formed by incremental extension during D2.

- The early-formed veins have then been crenulated by the same progressive deformation.

Post-tectonic veins

The example below is from the Sunrise Dam deposit, Western Australia, and shows a breccia veins comprising a stockwork that contains numerous clasts of foliated country-rock that have been variably rotated during vein formation.

The same foliation is present in the host-rock and the intensity of cleavage development is the same in both the wall-rocks and the clasts.

The foliation orientation is misaligned from clast to clast within the vein, indicating that the clasts have been rotated during breccia vein formation that post-dates formation of the foliation. Hence, this breccia vein stockwork is post-tectonic with respect to the foliation.

The example below is also from the Sunrise Dam deposit.

The white quartz vein that is at a high angle to the core axis has a pyritic alteration that has emanated along the cleavage to produce a well-developed selvedge.

The vein cuts the cleavage and there is no intensification of strain at the vein margin.

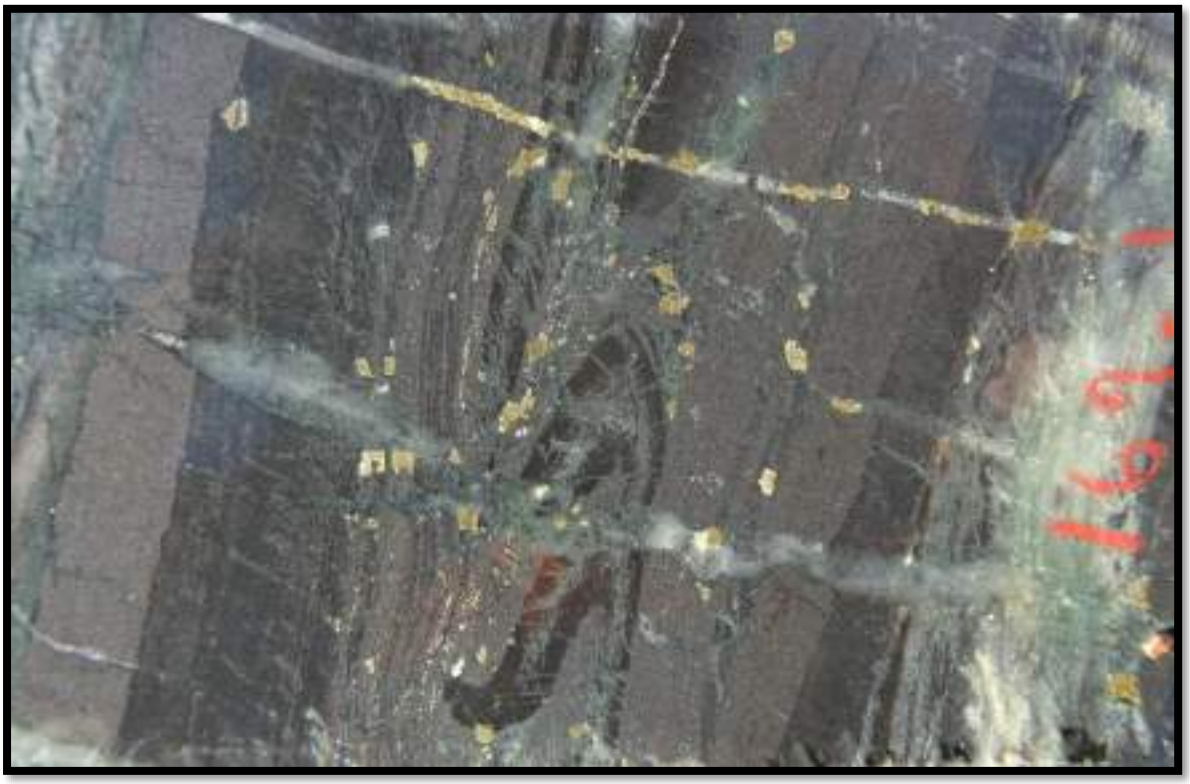
These relationships indicate that the vein post-dates the country-rock cleavage.

Note that the upper quartz vein at a moderate angle to the core axis has no alteration selvedge because it is part of a separate population, not a splay off the one with the pyritic halo.

In the example below a recumbent fold has been overprinted by a sheeted quartz extension vein array. The fold is outlined with yellow dashes. The veins are post-tectonic with respect to the fold. This example is from the Dog Shit Creek area in north Queensland (God's Own Country), Australia. I did my doctorate in this area and know that the folds are F3 structures, and the veins formed during D4, which produced upright folds.

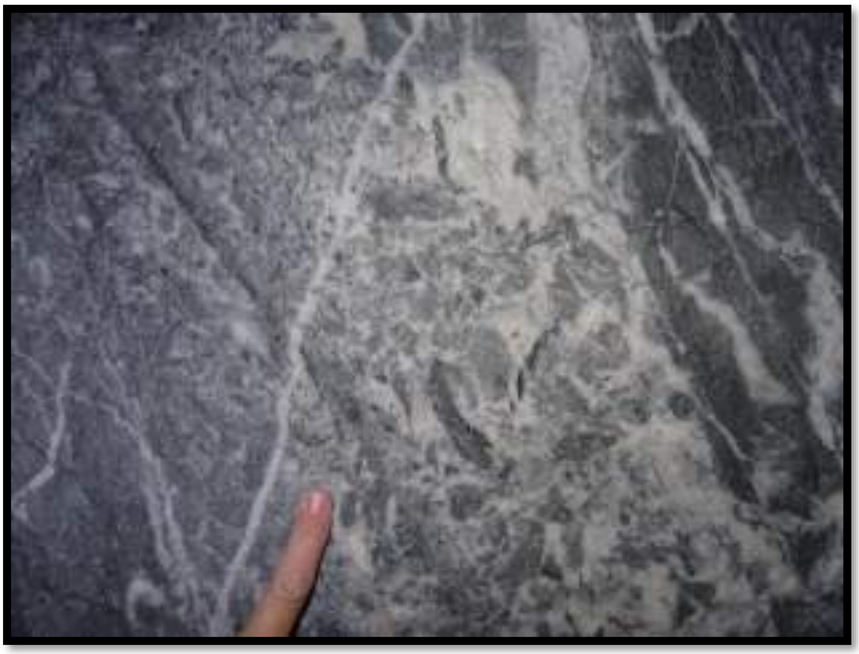
In the example below a narrow post-tectonic quartz-pyrite vein of relatively uniform width has overprinted open folds in a banded iron formation from the Sandstone area in Western Australia.

The example below is also from Sandstone, Western Australia. Isoclinal folds are developed in the banded iron formation and planar post-tectonic quartz-sulphide-chlorite veins associated with gold mineralisation have overprinted them.



The photo below is from the Sunrise Dam gold deposit and shows a fibrous quartz extension vein of uniform width cutting a breccia. The quartz vein is post-tectonic with respect to the breccia.

In the example below, the same overprinting relationship as in the previous phot can be seen. A carbonate vein of uniform width cuts a breccia unit, indicating the vein is post-tectonic with respect to the breccia.



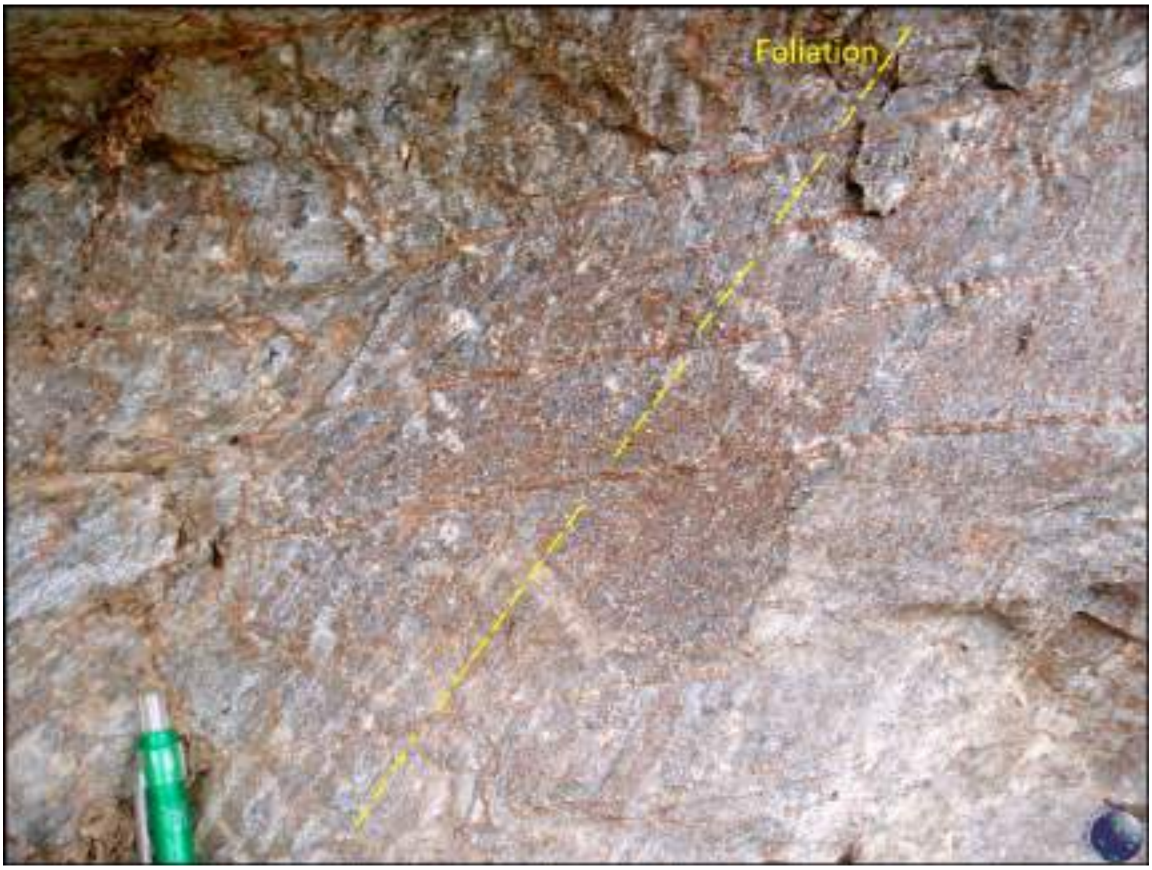
The photo below is from the Prestea gold deposit in Ghana, and shows cross-cutting vein-vein and vein-cleavage relationships.

Two stages of veining are present. The large vein is a splay off the main Prestea reef, and the wall-rocks are intensely cleaved. The cleavage has affected the large vein, which locally contains foliated clasts (e.g., under the pen and extending down to the left) and shows pinch-and-swell geometry.

The subhorizontal vein cuts across the country-rock cleavage and, although it is difficult to see, extends into the larger vein. The smaller vein is not deformed and is post-tectonic with respect to the intense wall-rock fabric.

The photo below shows sub-horizontal, sheeted, millimetre-scale, Fe-carbonate veins cross-cutting the penetrative foliation at the Wassa gold mine, Ghana.

These veins are undeformed and are post-tectonic relative to the wall-rock foliation.



In the photo below, a structurally-late, planar, fault-fill vein cross-cuts the country-rock cleavage in the Aykem gold deposit, Ghana.

Quartz-carbonate veining has been intersected along the length of the core interval and is at a low angle to the core axis. The veining is associated with a thin shear zone that cross-cuts all other veins and wall-rock structures.

This relationship, combined with the overall planarity of the vein, indicates that it is post-tectonic with respect to the wall-rock structures but syn-tectonic with respect to the shear. Note that there is minor deflection of the wall-rock foliation at the vein margin. This is due to post-foliation movement on the fault that hosts the vein.

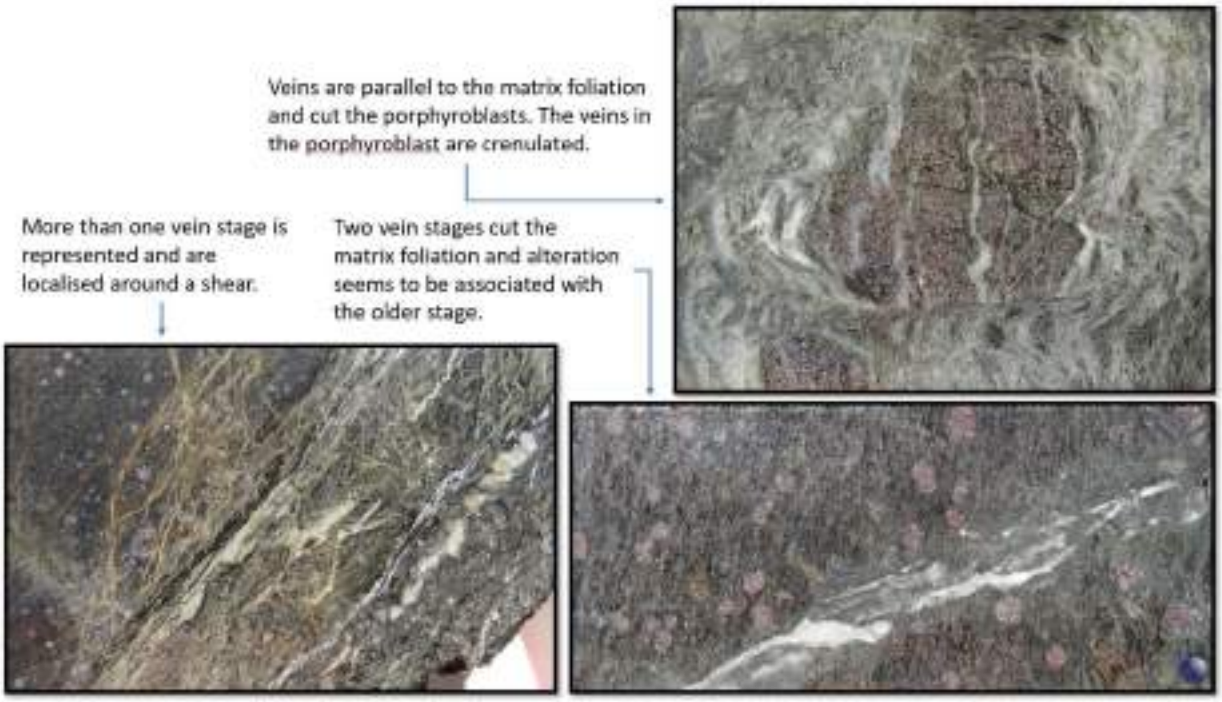
Caution – there is more than one vein type present in the shear, which combine to form a composite vein that is identifiable by different compositions.

Compiling the geological history

I have emphasized many times in this document about taking the time and effort to compile the best geological history possible, because this is critical for understanding how a rock volume evolved.

Compiling the history requires identification of all of the overprinting relationships. As has been shown many many many times in this document, commonly there will be more than one vein population and more than one age of structures. A geological history must be compiled that puts all of the elements together in terms of relative ages.

The three images below are all from the same drillhole and give examples of some of the overprinting relationships that can be determined using vein geometries.

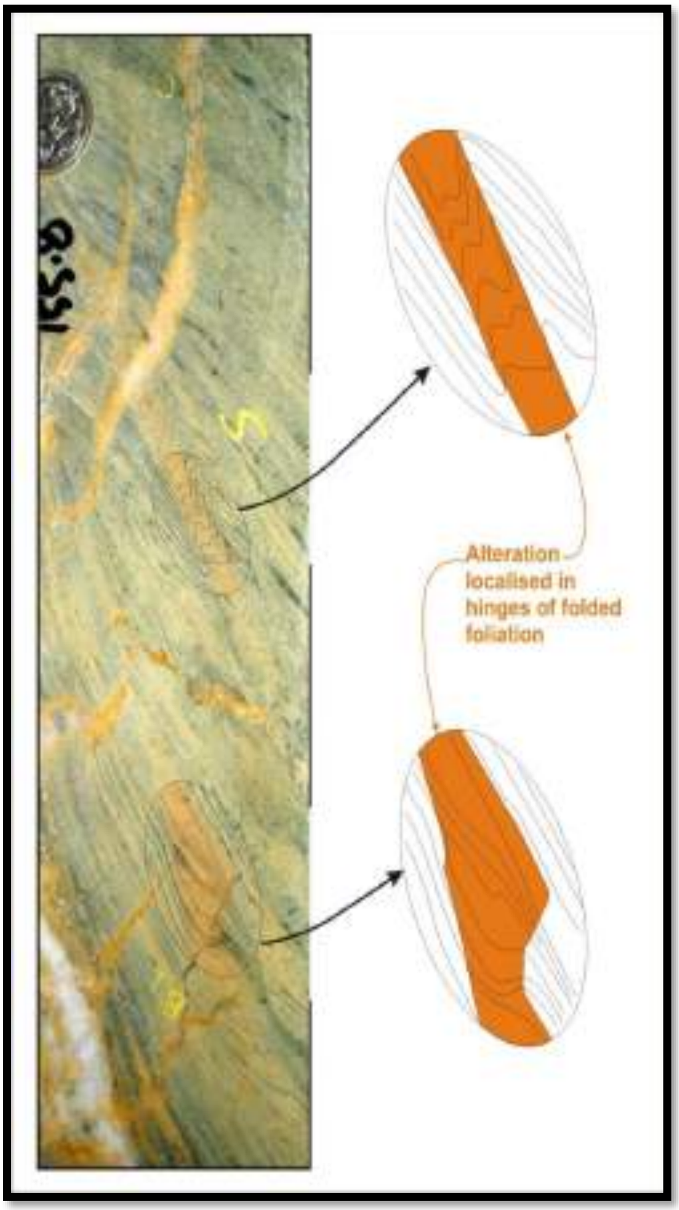


Structural ages of veins – Information from alteration

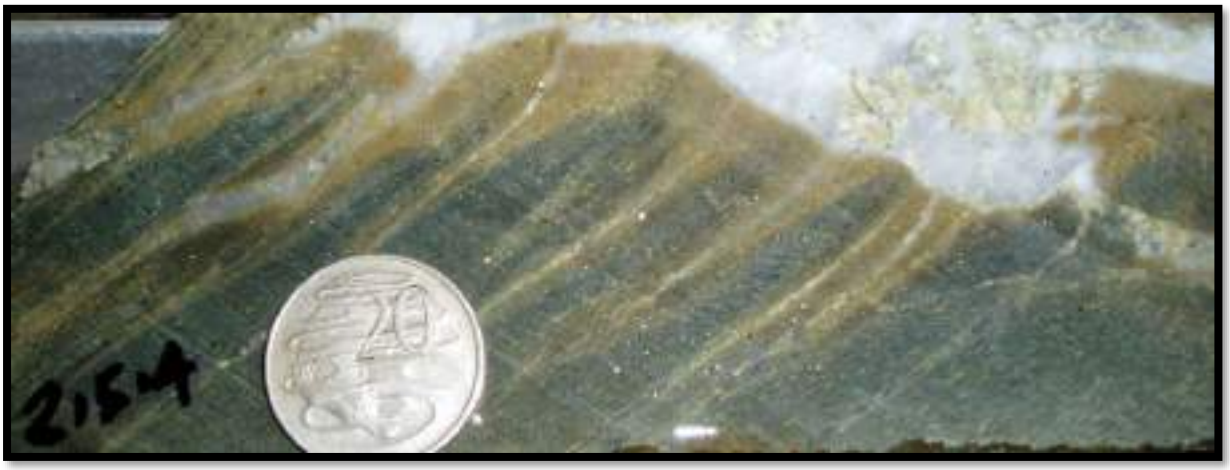
Alteration can be a very powerful tool when trying to establish a geological history.

- Veins commonly have well-developed alteration selvages.
- The distribution of alteration to be controlled by the wall-rock structure.
- Resolving the structural timing of the alteration can also provide the structural age of the veins it is associated with.

In the example below, from the Aykem gold deposit, Ghana, light brown Fe-carbonate alteration is associated with quartz-Fe-carbonate veins. The alteration is also localised in fold hinges, suggesting that it has been introduced at the time of folding. A much more pervasive distribution of the alteration would be expected if it post-dated the folds i.e., it would not be expected to be localised in the fold hinges.



The photo below is also from the Aykem deposit and shows carbonate alteration adjacent to a quartz-carbonate vein. The carbonate alteration extends out along the wall-rock cleavage, indicating the alteration, and hence the vein, are of the same age or younger than the wall-rock cleavage.



The image below shows several generations of alteration and veining cross-cutting a sample of Gardiner Sandstone from the Tanami region in central northern Australia.

Note that the orange alteration locally stops against some of the millimetre-scale quartz veins i.e., it is present on one side of the vein but not the other. This indicates that the vein was emplaced prior to the alteration and is not related to it and formed a barrier to subsequent alteration fluids.

The photos below have been taken underground in the Quarters gold deposit, Western Australia. Well-developed alteration haloes in basaltic host-rock around auriferous veins in the Quarters deposit, Western Australia. This alteration is clearly related to the veins so structural timing of the alteration also gives an indication of the structural age of the veins.

The next image shows an extension vein cross-cutting a sample of granite from the Hyperion prospect in the Tanami region in central northern Australia. Note that the orange haematitic alteration locally stops against the extension vein i.e., it is present on one side of the vein but not the other. This indicates that the vein was emplaced prior to the alteration and is not related to it and formed a barrier to subsequent alteration fluids.

FINAL COMMENTS (SO FAR)

The mad ramblings I have presented in this document have all been posted on LinkedIn and the links to these are below. Although the content of my posts is the same as presented here, people may find it interesting to read the comments that were posted in response to my articles.

The roles of veins in a deformed rock volume – Part 1

- This discussed veins as fluid pathways.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-brett-davis/

The roles of veins in a deformed rock volume – Part 2

- This discussed veins as depositional sites.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-part-2-brett-davis/

The roles of veins in a deformed rock volume – Part 3

- This discussed veins as volume compensators, infilling space as the rock undergoes deformation.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-part-3-brett-davis/

The roles of veins in a deformed rock volume – Part 4

- This documented the role of veins in controlling rock permeability and the distribution of alteration by impeding fluid movement.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-part-4-brett-davis/

The roles of veins in a deformed rock volume – Part 5

- This discussed the role of veins as strain localisors in hydrothermal mineral systems.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-part-5-brett-davis/

The roles of veins in a deformed rock volume – Part 6

- This discussed the role of veins as movement accomodators in hydrothermal mineral systems.
- https://www.linkedin.com/pulse/roles-veins-deformed-rock-volume-part-6-brett-davis/

Vein system analysis – some comments on vein morphology

- This discussed some of the variations in vein morphology we need to be aware of in order to make informed interpretations on geology at all scales.
- https://www.linkedin.com/pulse/vein-system-analysis-some-comments-morphology-brett-davis/

Composite veins

- This discussed the formation of vein structures as products of more than one veining episode, and gives examples of criteria for recognition, including many examples.
- https://www.linkedin.com/feed/update/urn:li:activity:6880715783534714880/

Establishing a vein overprinting history

- This discussed how to construct a vein overprinting history that can be incorporated into the geological history of a deposit.
- https://www.linkedin.com/pulse/establishing-vein-overprinting-history-brett-davis