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

Part 1: Looking at rocks

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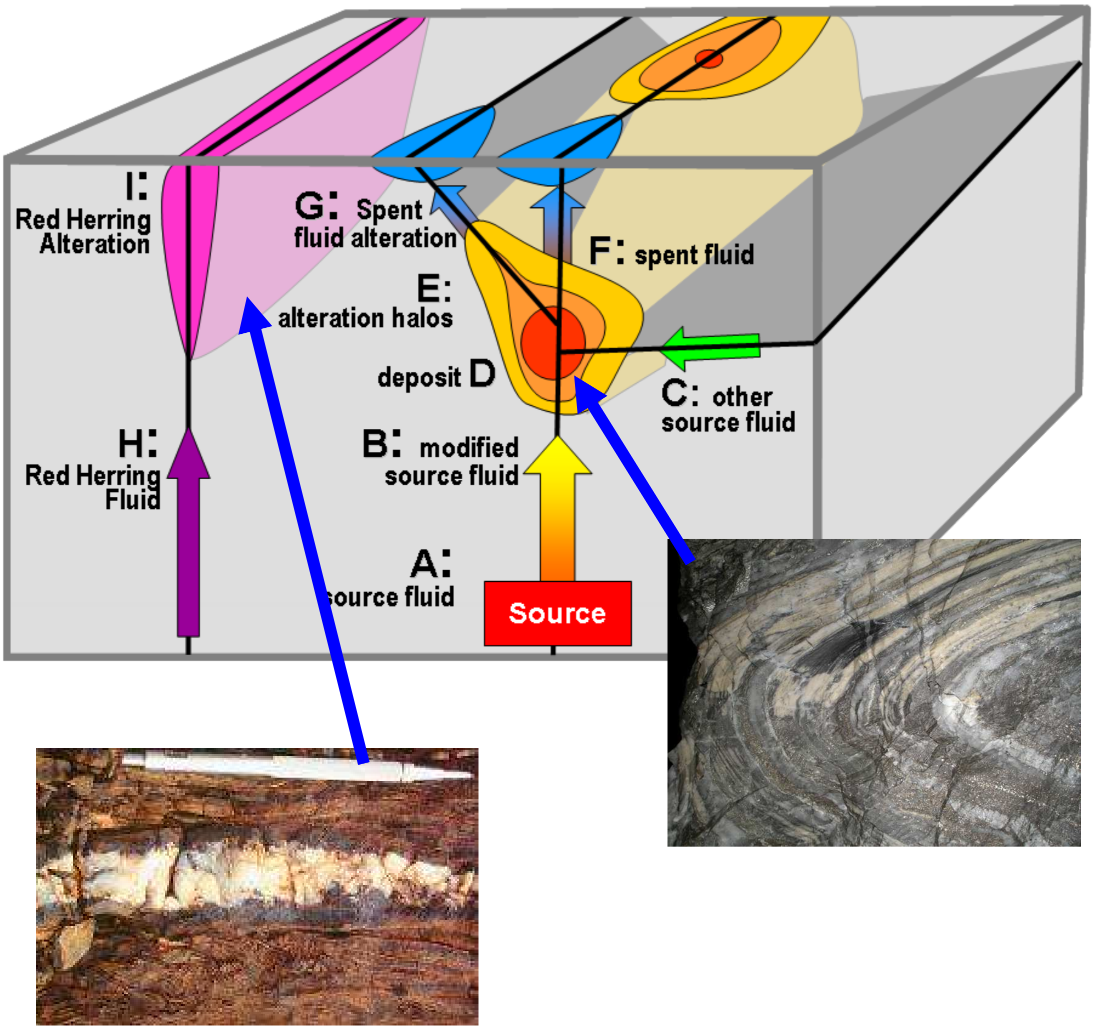
This module forms part of a series on use of veins, alteration, geochemistry and structures to identify which features can be used to recognise ‘vectors’ to potential sites of mineralization. The principles were developed through field- and laboratory observations and short course development for undergraduate & postgraduate students at several Australian Universities, as well as open-audience and site-specific industry workshops (e.g. Vancouver Roundup, PDAC, Predictive Mineral Discovery CRC, SEG workshops). The principles are most suited to alteration and vein recognition in deformed, metamorphic rocks, but have application elsewhere.



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Background: broad scale fluid flow in mineralized systems

Every hydrothermal ore deposit is surrounded by an alteration envelope (Fig. 1). Whether syngenetic or epigenetic, this alteration envelope is one of the key tracers to the deposit, and yet commonly forms uneconomic gangue to the main ore zone. This alteration envelope is also only a part of the broader hydrothermal system associated with the deposit, and it is possible to identify these different types of fluid flow systems by inspection of the rocks and structural environment in conjunction with mineralogical, petrological, isotopic and geochemical analyses. In the mid-crust, near-surface waters can only enter the system under special circumstances. In recognition of this, various authors have attempted to explain the apparent "extra" sources of fluids in some terrains in different ways (Fig. 2). Some of these involve recirculation of fluid, others involve exotic fluid, and others involve effects of deformation or thermal evolution. However, at this (regional) level, most researchers are yet to agree on the relative contributions of these sources, particularly considering the other, localized sources of fluid provided by crystallizing late-tectonic granitoids, or shear zones and faults that access upper-crustal fluid reservoirs.

Figure 1 (below): Cartoon depicting a total hydrothermal system (in this case for a mesothermal deposit), with the various types of associated fluid/rock interaction indicated. This type of model can be extended to include any hydrothermal system at any crustal level, including syngenetic varieties.

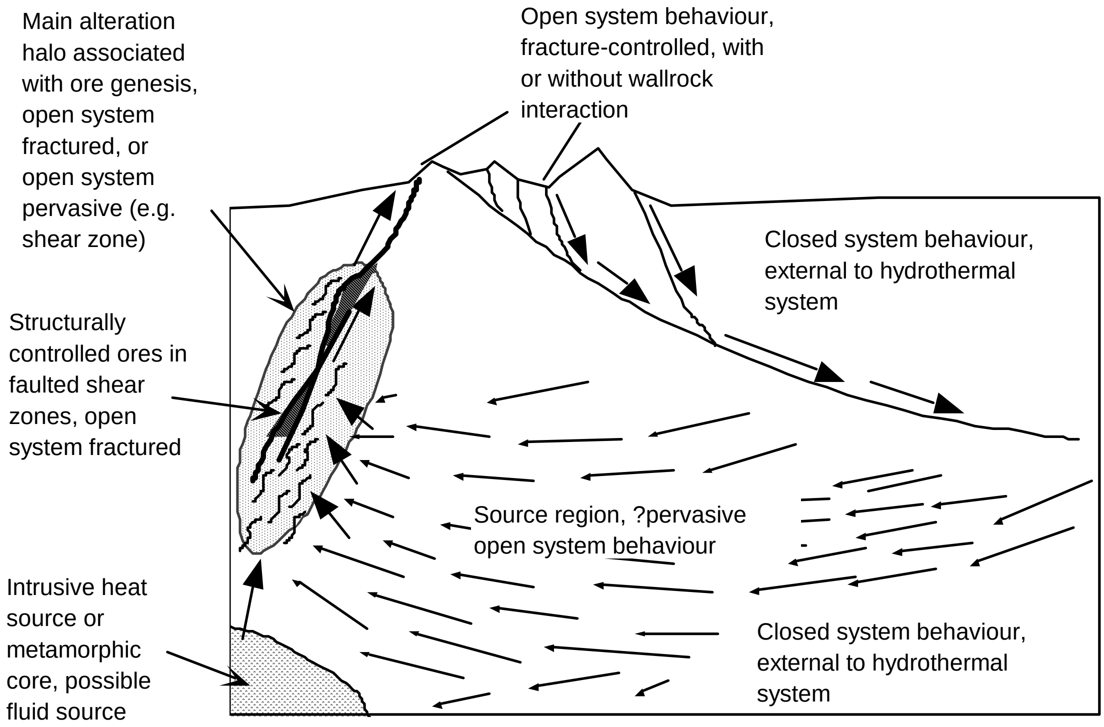
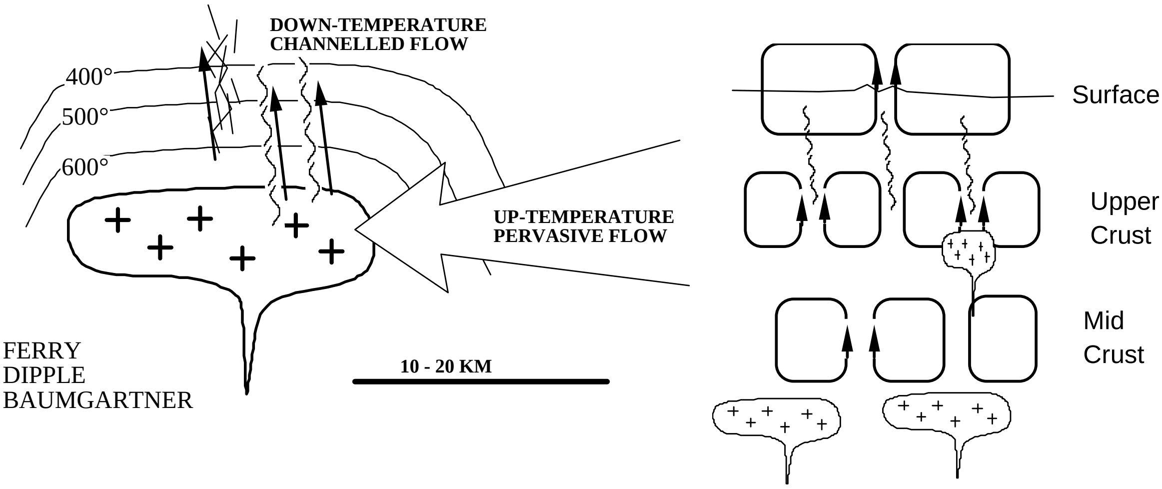
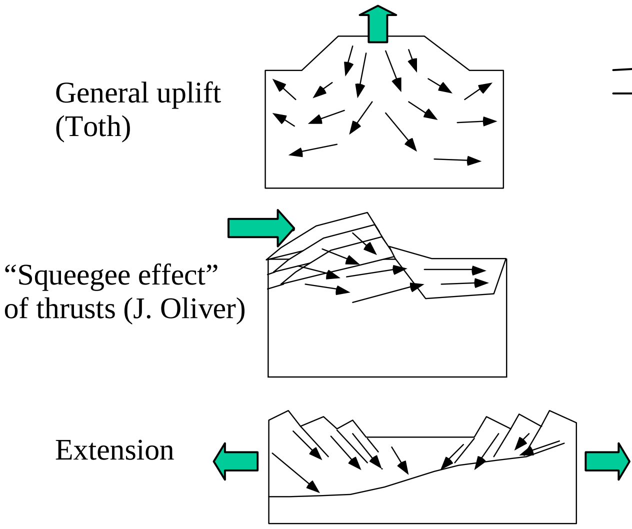
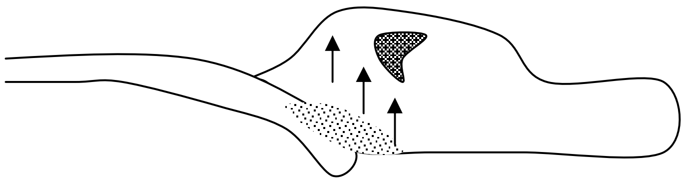


Figure 2 (below): Cartoon depicting various author's interpretation of reasons for large fluid fluxes



a) Thermal control: fluid buoyancy **b) thermal control: convection**





c) (Left): structural and topographic controls on rock dilation

d) (above): renewable fluid sources: e.g. dehydration above subducted slab (arcs)

The practical recognition of fluid pathways

At hand-specimen and outcrop scale, it is usually possible to infer the degree of interaction of fluid with the rocks by inspection of the distribution of visible fluid pathways, or by various isotopic or geochemical means.

An alteration system is one in which we can recognise that the original rock has been geochemically altered relative to its precursor. Normally this definition excludes the highly volatile components (e.g. H_2O, CO_2), because these phases may be released simply by heating, e.g. during metamorphism or burial. An alteration system is thus geochemically "open", as opposed to "closed" systems where it is possible to determine that no mass transfer (apart from some volatiles) has occurred. This definition is strongly scale dependent, as it depends on being able to recognise over what distance mass transfer has (or hasn't) occurred (Fig. 3). There are two or three components to a hand-specimen scale alteration (or open) system, and these components are also relevant to the definitions and interpretation of closed systems -

1) vein or infill (may be absent)
2) altered wallrock in rim of vein ("selvage")
3) precursor rock (less altered or unaltered)

<u>Types of open systems</u>

There are a few things to consider when determining whether fluid has passed through a rock and left some geochemical signature - a) scale, b) whether or not the fluid flow is associated with a fracture, and c) whether or not there is interaction between fluid in the fracture and the surrounding rock. As depicted in Figure 1, these different types of behaviour can correlate with different parts of hydrothermal systems.

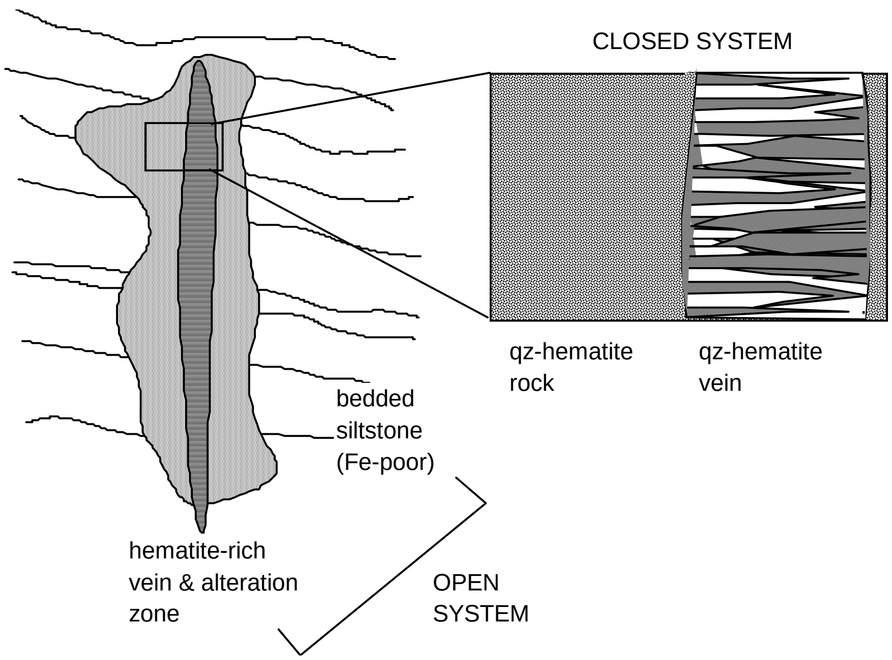


Figure 3: System definition can be scale dependent - note here how the apparent "closed system" on the right, with quartz-hematite vein in quartz-hematite rock, is actually part of a broader open system in which iron is added to the system.

(A) Channelized, fractured open system with closed-system wallrocks

In these systems, fluid flow is through visible fractures, but no observed chemical interaction occurs between the fracture-hosted fluid and the wallrock (Fig. 4). The veins are usually inferred to represent channelways for externally derived fluid, and the fluid may have come from up to several or 10's of kilometres away. Lack of chemical interaction of veins with the adjacent wallrock implies that migration of the fracture and fluid within it occurred rapidly, without fluid migrating or mass diffusing into the wallrocks. This type of behaviour is most common in the upper crust, particularly in fault zones. Although they are infrequently associated with mineralization in epithermal to mesothermal environments, they may be major conduits for ore-forming fluid - i.e. they can be major fluid pathways.

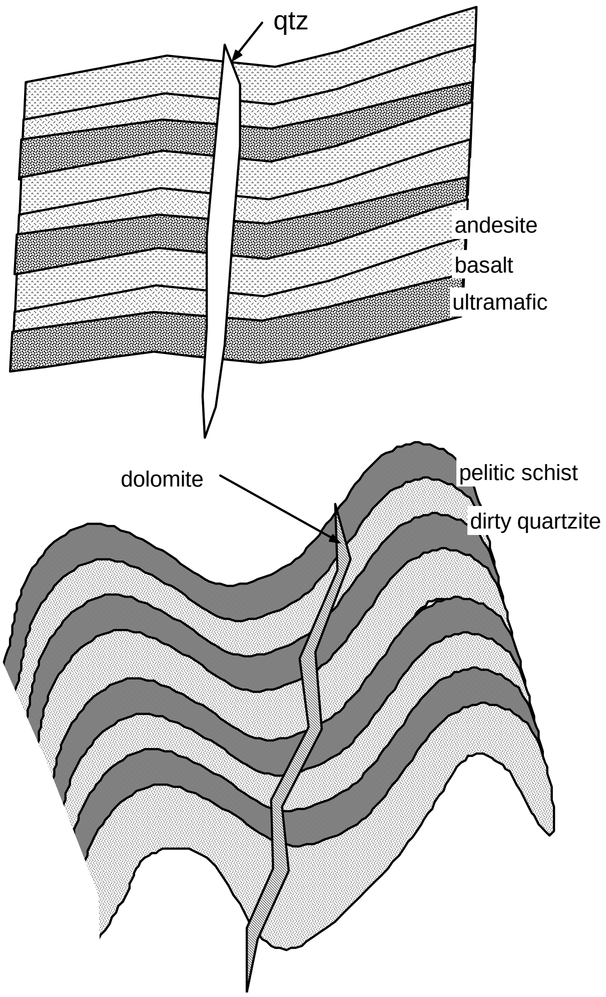


Figure 4: Some hypothetical examples of open system fracture-related fluid flow with no wallrock interaction. In order to determine this type, you also need to be able to recognise that the mineral(s) in the vein are most likely not in equilibrium with the surrounding rock. As shown in these examples, a quartz vein in a mafic-ultramafic sequence is unlikely to have derived its silica from the silica-poor surrounding rocks, i.e. it's come from elsewhere. Likewise, a classic turbidite sequence, metamorphosed to a schist/psammite sequence, typically won't contain much carbonate or Ca, so dolomite or calcite veins are unlikely to have been derived by local leaching of the surrounding rocks (in a closed system fashion).

You can occasionally see this pattern in hand specimen, but it is also common at map scale with large, late faults containing quartz infill and cutting a big variety of surrounding rocks without any visible chemical interaction with them.

How to recognise them in hand specimen and in the field:

- mineral(s) in vein are unrelated to those in the wallrock at hand-specimen scale, e.g. dolomite veins in a quartzite, quartz veins in a pure dolostone; plus

- no visible reaction rim between vein and wallrock; and

- no correlation between vein mineralogy and the different rock types cut by the vein (e.g quartz vein cutting sequence of mafic-ultramafic-carbonate)

(B) Channelized, fractured open system with reactive wallrocks

These systems are dominated by fracture flow, but with substantial infiltration of fluids into (and from) the local wallrocks, or significant diffusive transfer, typically resulting in veins that have isotopic or mineralogical selvages (Fig. 3). This type of behaviour is most commonly observed in the alteration zones of ore deposits (Fig. 1), but they have also been observed in many unmineralized rocks with well-developed regional alteration systems.

Interaction of externally derived and chemically reactive fluid with wallrocks or other fluids is a primary mechanism for deposition of vein-style or shear-hosted epigenetic ore minerals, either via direct wallrock reactions (e.g. redox), or by changes in the state, speciation or chemical composition of the fluid, e.g. immiscibility, boiling or mixing. The main reasons for chemical interaction with the wallrock include major chemical disequilibrium between the fracture-hosted fluids and the wallrocks, diffusion, and enhanced permeability in the wallrock due to fluid overpressuring in the fracture.

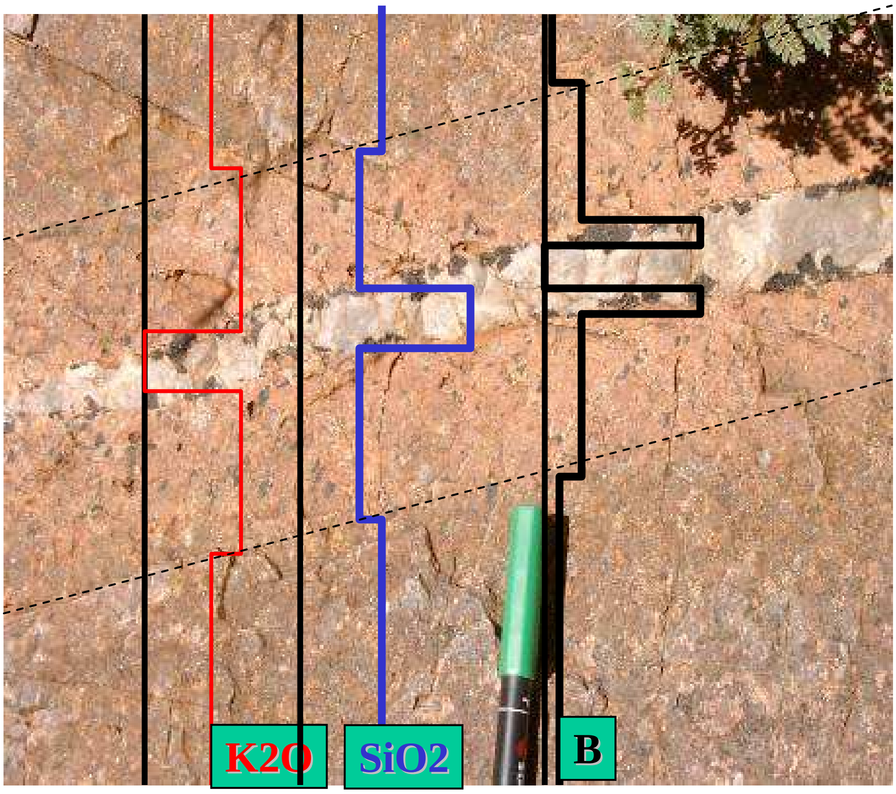


Figure 5: Open system with reactive wallrocks, showing schematic elemental abundance profiles: the Boron profile requires that B has been added to this system from outside. Note however, that the apparent potassic alteration zone could possibly be formed by removal of silica from the already potassic wallrocks to leave behind a relative K-enriched zone adjacent to a quartz vein (closed system behaviour).

How to recognise them in hand specimen and in the field:

- mineral(s) in vein are usually unrelated to those in the wallrock at hand-specimen scale, <u>plus</u>

- distinctive reaction zone(s) (selvages) surround the vein, <u>plus</u>

- at least one major chemical species found in the vein or the selvage cannot have been derived from the surrounding rocks (e.g., in Fig. 3, the amount of iron in the vein + selvage cannot have been derived from the surrounding siltstone at the scale of observation). The latter point requires that you need to be able to appraise the chemistry of the minerals (or rocks) concerned (Fig. 5). This may not be possible without geochemical analyses if the rocks or alteration zones are complex, but if I am presenting this course to you in a workshop environment with specimens (yours and/or mine), you will get the idea from the hand specimens. Importantly, this type of behaviour (veins plus selvages) can also develop in essentially closed systems, and there are a few relatively easy steps to distinguish between these.

(C) Open system shear zones

These are essentially a subset of (B) above, but the distribution of the alteration products is different. In altered shear zones, there is a close spatial association between shearing strains (e.g. shear-related foliation development, curvature of foliation into a shear plane, grainsize reduction), and the degree of alteration, with the most altered rocks characteristically occurring in the most strained (usually central) parts of the shear.

Micro cracking allows open-system behaviour along the zone (with or without associated meso-scale veins), so that an initially externally-derived fluid reacts with the shear-zone rocks and alters them. This can be a chicken-and-egg situation: in some cases fluid influx may trigger shearing (e.g. by changing the mineralogy and making the rock softer, thereby localizing the strain), in others shearing may trigger fluid influx (by dilatancy pumping), and combinations may occur during shear zone evolution.

How to recognise them in hand specimen and in the field:

- spatial correlation between intense foliation development and alteration
- decrease in grainsize associated with change in colour going towards a fault or shear zone
- change in weathering pattern or weathering-related staining going towards a shear zone

These are normally straight-forward to identify; again the critical thing to determine is that an actual chemical change has occurred, rather than just an addition or loss of water. For example, a muscovite-rich shear zone cutting a granite may not necessarily reflect an alteration process - it could just be due to hydration of K-feldspar. This will be addressed in the prac.

(D) Open system with pervasive fluid flow

This type of behaviour refers to macroscopic changes in chemical composition due to pervasive reaction with a fluid at grain scales. A large, and chemically reactive component of the fluid is inferred to flow along microcracks and grain-boundary porosity, rather than in larger cracks, and partial or complete equilibration occurs between fluid and rock at every point along the flow path.

Because mineral-fluid partition coefficients change with changing temperature and pressure, pervasive flow and equilibration of fluid along a thermal gradient can induce substantial alteration. For example, fluid in equilibrium with a granitoid at 500°C will be silica saturated. If this fluid is allowed to cool and continually re-equilibrate with granite, it will be come progress-ively oversaturated, be-cause less and less silica remains in solution in the cooling fluid (Fig. 6). As a consequence, the granite would become progressively silicified as it cooled. This type of pattern is common in retrograde shear zones (where the fluid is moving from hotter towards cooler temperatures).

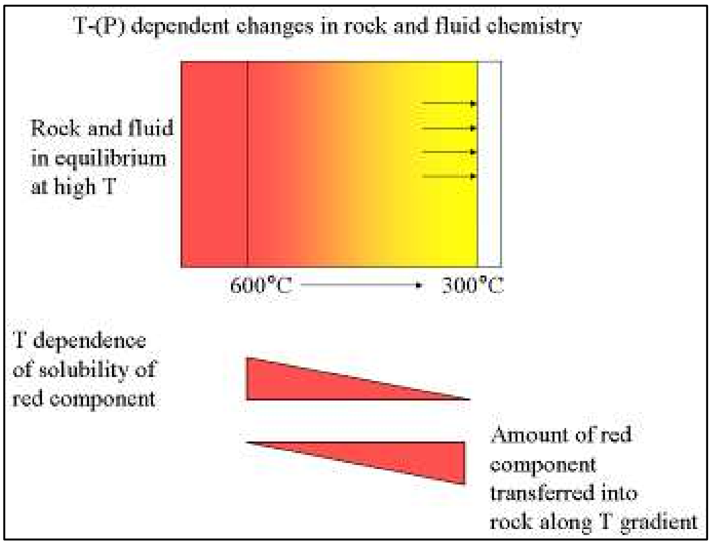


Figure 6: Schematic diagram showing the effect of allowing fluid to progressively equilibrate with a rock across a temperature (or pressure) gradient. E.g. down-temperature flow will cause silicification (yellow), up-temperature flow will cause silica dissolution. Such patterns can be recognised by regional sampling, and in some cases may correlate with the source-regions of major mineralized hydrothermal systems, although the links are very difficult to demonstrate.

How to recognise this in hand specimen and in the field:

• extremely difficult at hand specimen scale

• at map scale, you would need to see a geochemical change (in a given rock type) fairly gradually distributed across a thermal gradient - again very tricky, the main problem being how to distinguish primary variations form relatively subtle regional changes in rock composition

• not normally possible to determine without broad sampling program and thorough knowledge of thermal gradients in the area of interest

Types of closed systems

Relative to the general geometry of a hydrothermal, mineralized system, “closed systems” should dominate in the distal parts (Fig. 1). That is, the amount of fluids present outside the main hydrothermal system may be insufficient to develop into through-going plumbing systems. However, there are several problems with this general approach:

• the source regions of major hydrothermal ore deposits must have undergone significant dissolution and transport of potentially ore-forming materials, requiring substantial fluid flow. In this case, truly “closed systems”, in previously unaltered rocks, will only occur in regions that have absolutely nothing to do with the ore-forming hydrothermal system (Fig. 1)

• “closed system” behaviour can commonly superimpose on previous open system behaviour, or can even be inferred if the scale of sampling is inappropriate to the scale of the hydrothermal system (e.g. Fig. 3). It is normally possible to determine this by inspection, but the main point here is that just because you have a vein sitting in mineralized, altered rocks, you shouldn't automatically assume that the vein is part of a through-going open plumbing system involved in the mineralization process, i.e. it may be a red herring.

However, the latter scenario can normally be sorted out by making the necessary mineralogical observations at hand specimen scale (Fig. 3), and then comparing that with the broader scale features, i.e. if you have a "closed-system" vein in an obvious alteration zone, then the alteration is not related to the vein, and the vein has derived its internal components by dissolving and reprecipitating some of the previous alteration material.

(A) Closed system fractured with no reaction rims

These systems involve mesoscopic veins that are in chemical equilibrium with their immediate wallrocks. The most common vein variety is fibrous, and in extreme cases individual fibres may be connected to wallrock grains of corresponding composition, although this normally requires a microscope to check. They can form by growth along a very thin film, without a large crack ever appearing, although the final appearance may be of a decent-sized vein.

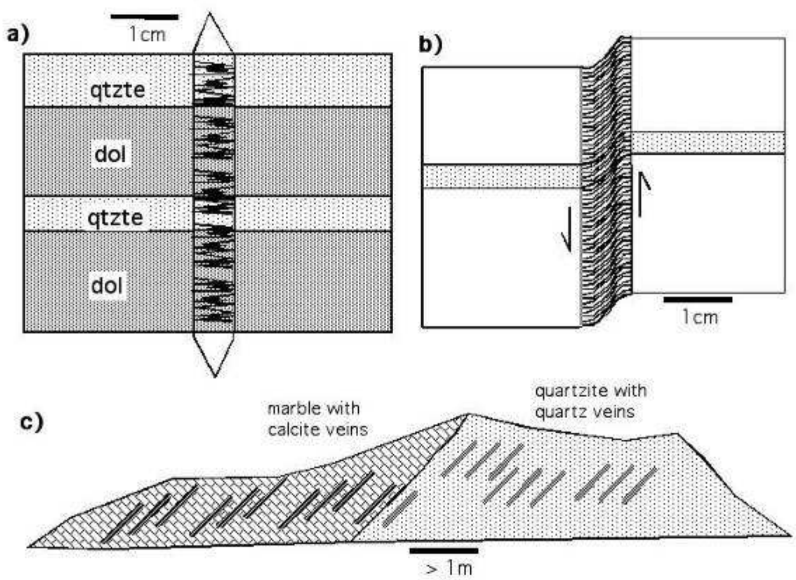


Figure 7: Diagrams showing typical closed system veining behaviour: a) hand-specimen scale mimicking of host rock type by vein fibres; b) fibrous veins with wallrock mimicry can sometimes reveal shear sense; c) outcrop scale pattern in which vein type varies as a direct function of host rock. Note however, that this pattern needs to be checked at hand-specimen scale too, because similar patterns can be caused if an externally infiltrating fluid is partly modified by wallrock interaction, i.e. you get different vein types but they show open-system reaction with the wallrocks.

Individual fibres can sometimes track the opening direction of the vein walls, and thus can be used as shear-sense indicators (Fig. 7b). In a fluid-saturated rock, a thin crack may appear, and this will then cause fluid to move towards the crack, and/or mass to diffuse towards the crack. Because the fluid is in equilibrium with the surrounding rock, the minerals precipitated will be very similar to those in the surrounds (however there is a solubility dependance here). If all the minerals in the rock are capable of dissolving at that P and T (i.e.

none are insoluble), then no reaction rim will be evident. The vein may, however, have a different appearance to the rock because of different grainsize or textures.

The most spectacular and convincing examples of this type of fluid flow occur where large primary gradients in rock composition are mirrored by large gradients in vein composition, even where the veins apparently form part of a consistently oriented fracture array (Fig. 7c, 8). Fracturing is probably rapid and transient (e.g. crack-seal veining), multiple veins being accumulated by many separate vein cycles, with very restricted interconnectivity between fractures at any one time. The distance of fluid flow associated with this type of veining is limited, and may even be non-existent, with the veins forming by diffusion through a static fluid.

How to recognise these in hand specimen and in the field:

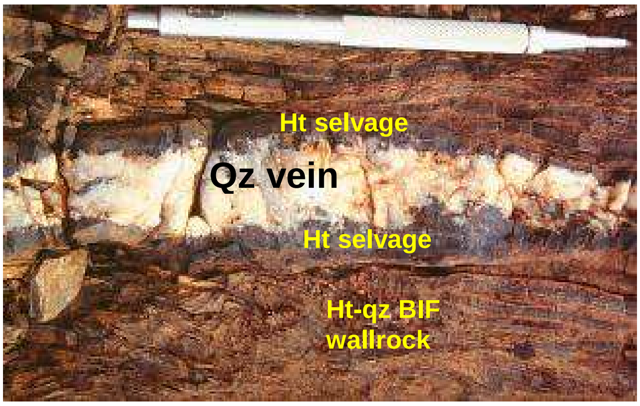
- mineralogy of vein and rock is very similar
- no reaction rim
- vein mineralogy may mimic wallrocks closely even when veins cross different layers
- different vein types associated with different lithologies, and vein types change composition in correspondence with lithological changes

Figure 8: Diagram showing different veining behaviour in one sample: a) below: vein of pyrrhotite and calcite mimics the position of sulphide and carbonate veins in the deformed ore in the rock – this is classic closed system behaviour. In addition, because the background rock is foliated whereas the vein has coarse grains and is not deformed, we can infer there is a substantial time gap between the two, thus supporting the indication that the vein must have formed by closed system diffusion from a previously banded, sulphide bearing rock. b) (top) thin pyrrhotite vein with local sulphidation of the surrounding rock, is not influenced by the composition of the local wallrock. Note the alteration halo (arrow). This vein is thus open system relative to the scale of the rock, but the sulphides may not have come from too far.

(B) Closed system fractured with reaction rim

These are similar to the above type of veins, but in this case there is a selvage associated with vein formation. However, for such a selvage to be produced in a closed system environment, requires that the vein material is produced by “local segregation”, i.e. components gained by the vein are mirrored exactly by components lost in the wallrock so that the selvage is in essence a depletion zone (Fig. 9). This is the mode of origin proposed for the development of some migmatites during partial melting, but has also been identified in aqueous systems. The difference with the above type of behaviour is probably because there is an open fracture rather than a very thin fluid-lined crack. This type may grade into the open system variety (with selvage) discussed above, depending on how much external fluid gets into the system, or how sensitive the chemical changes are. To be absolutely certain of how closed system such a scenario is would normally require careful geochemical analysis of the vein, selvage and wallrock (see below).

Figure 9: Closed system veins in which the mass gained in the vein (qz) exactly matches the mass lost from the wallrock. This is not easy to verify visually, and normally requires a geochemical check, because this can look very similar to open system veins with selvages, the difference being that the latter will involve some mass change to the total system. In the case shown, {Mass x composition$_{(selvage)}$} + {Mass x composition$_{(vein)}$} = composition$_{(wallrock)}$.

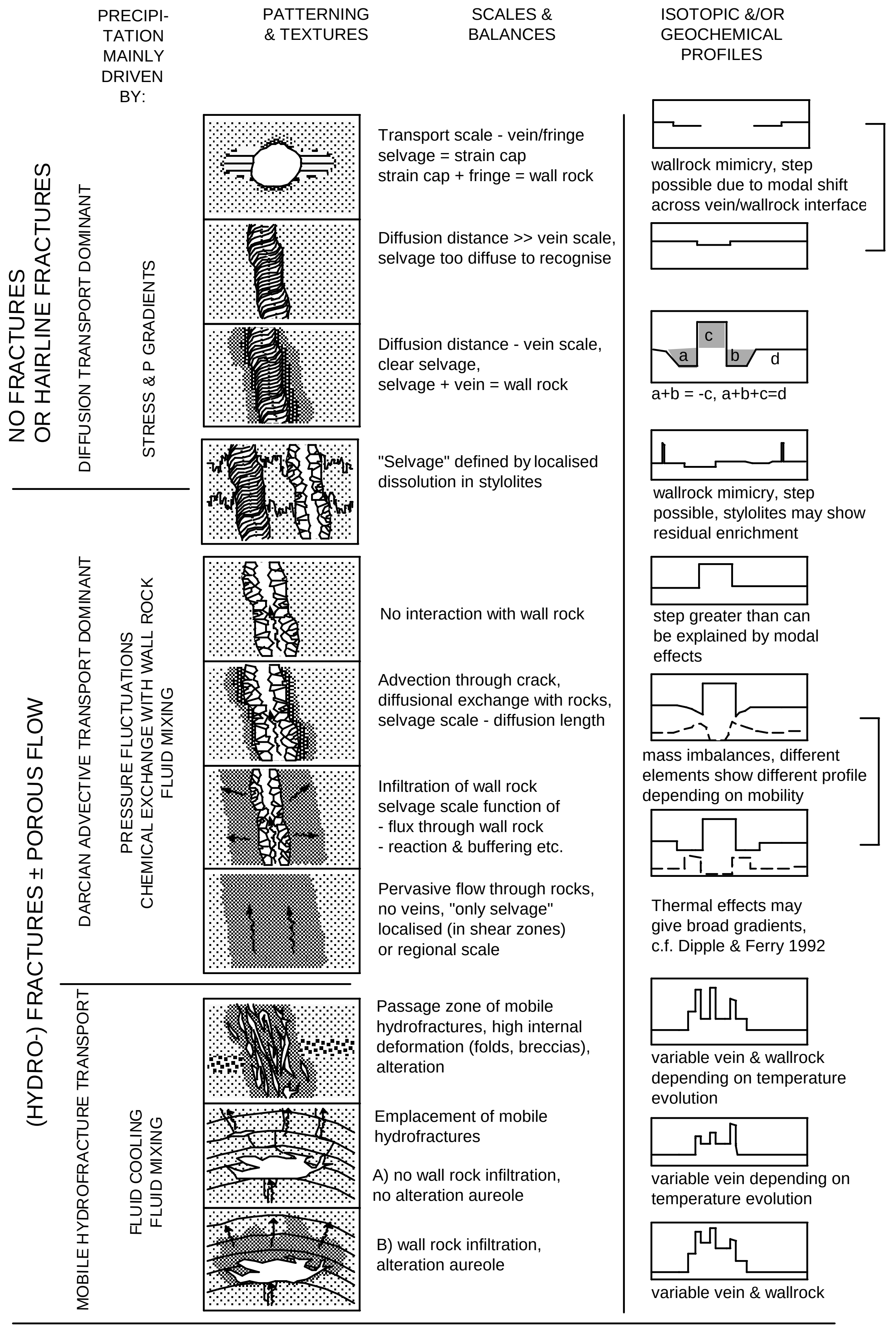


How to recognise this in hand specimen or the field:

- colour changes such that the mixture of selvage + vein would approximately equal the colour of the wallrock
- width-matching: the selvage width should correspond approximately to a half vein-width, depending on the components being transferred (if a low density mineral is in the vein, the selvage will be denser, so will be a little narrower than the vein half-width)
- mineralogy - the mineral(s) in the vein should be the one(s) missing from the wallrock

Note: For closed system behaviour to be demonstrated correctly, it is may be necessary to undertake comprehensive geochemical studies. This is because if there is a small volume of externally derived, infiltrating fluid, then mass transfer patterns may be dominated by the host rock, i.e. the fluid is "buffered" by the host rock. Some elements, particularly strongly mobile ones (see below), may show open system behaviour when all other elements apparently show closed system behaviour, and this type of pattern may indicate small amounts of external fluid were present. Another way of saying this is that some elements may show closed system behaviour while others show open system behaviour. If you can recognise this, it is a powerful tool for understanding the amount and composition of the externally derived fluid.

Fig. 10 (overleaf): From Oliver & Bons (2001): Classification of veain/wallrock patterns based on combined textural, mineralogic, isotopic and geochemical analysis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PROFILES
NO FRACTURES
OR HAIRLINE FRACTURES
DIFFUSION TRANSPORT DOMINANT
STRESS & P GRADIENTS
Transport scale - vein/fringe
selvage = strain cap
strain cap + fringe = wall rock
wallrock mimicry, step
possible due to modal shift
across vein/wallrock interface
Diffusion distance >> vein scale,
selvage too diffuse to recognise
Diffusion distance - vein scale,
clear selvage,
selvage + vein = wall rock
c
a
b
d
a+b = -c, a+b+c=d
"Selvage" defined by localised
dissolution in stylolites
wallrock mimicry, step
possible, stylolites may show
residual enrichment
(HYDRO-) FRACTURES ± POROUS FLOW
DARCIAN ADVECTIVE TRANSPORT DOMINANT
PRESSURE FLUCTUATIONS
CHEMICAL EXCHANGE WITH WALL ROCK
FLUID MIXING
No interaction with wall rock
step greater than can
be explained by modal
effects
Advection through crack,
diffusional exchange with rocks,
selvage scale - diffusion length
mass imbalances, different
elements show different profile
depending on mobility
Infiltration of wall rock
selvage scale function of
- flux through wall rock
- reaction & buffering etc.
Pervasive flow through rocks,
no veins, "only selvage"
localised (in shear zones)
or regional scale
Thermal effects may
give broad gradients,
c.f. Dipple & Ferry 1992
MOBILE HYDROFRACTURE TRANSPORT
FLUID COOLING
FLUID MIXING
Passage zone of mobile
hydrofractures, high internal
deformation (folds, breccias),
alteration
variable vein & wallrock
depending on temperature
evolution
Emplacement of mobile
hydrofractures
A) no wall rock infiltration,
no alteration aureole
variable vein depending on
temperature evolution
B) wall rock infiltration,
alteration aureole
variable vein & wallrock

TABLE 1 Summary of vein types according to nature of fluid-rock interaction

	Scale	texture	selvage present?	selvage mineralogy similar to vein?	visual/ chemical recognition of added component ?
Open system fracture + closed wallrocks	cm-km	blocky, random, or vuggy	No	n.a.	Yes, in vein material
Open system fracture + reactive wallrocks	cm-100m	blocky, random, euhedral, vuggy	Yes	No or Yes	Yes, in vein, selvage or both
Open system shear zone	cm-100m	finer grained than surrounds, strong foliation	n.a.	n.a.	Yes, correlate colour/mineral change with strain
Open system pervasive	100m-10km	not distinguishable from other rocks	No	n.a.	Cannot see visually, need regional samples
Closed system fractured + closed wallrocks	cm-m	mostly fibrous, sometimes blocky	No	n.a.	No, mineralogy mimics wallrock
Closed system fractured + reactive wallrocks	cm-10m	euhedral, blocky, intergrown	Yes	No, mineral(s) absent from selvage present in vein	Mass lost from selvage = mass gained in vein

Such assessments of the minimum mass transfer distances in open systems are almost always over-conservative, and a comprehensive appraisal of vein/wallrock patterns across a broad thermal gradient in rocks for which a detailed sampling program has been undertaken may reveal broad trends in mass losses or gains not revealed by analysis of individual veins (e.g. Ague, 1995; Oliver et al., 2004). Detailed appraisal of this type of open system mass balance over multiple scales ultimately may be used to constrain potential source or trap regions for large hydrothermal systems, such as those involved with genesis of large ore deposits (e.g. Heinrich et al., 1995; Oliver et al., 2004).

Key references

Ague J J (1995) Deep crustal growth of quartz, kyanite and garnet into large-aperture, fluid-filled fractures, north-eastern Connecticut, USA. *Journal of Metamorphic Geology* , **13**, 299-314.

Barnicoat A C (1988) The mechanism of veining and retrograde alteration of Alpine eclogites. *Journal of Metamorphic Geology*, **6**, 545-558.

Beach A (1977) Vein arrays, hydraulic fractures and pressure-solution structures in a deformed flysch sequence, S.W. England. *Tectonophysics*, **40**, 201-225.

Bons, P.D. (2001) The formation of large quartz veins by rapid ascent of fluids in mobile hydrofractures. *Tectonophysics* 336, 1-17.

Cartwright I, Power W L, Oliver N H S, Valenta R K & McLatchie G S (1994) Fluid migration and vein formation during deformation and greenschist-facies metamorphism at Ormiston Gorge, Central Australia. *Journal of Metamorphic Geology*, **12**, 373-386.

Cox S F, Etheridge M A. & Wall V J (1987) The role of fluids in syntectonic mass transport and the localisation of metamorphic vein-type ore deposits. Ore Geology Reviews, 2, 65-86.

Dipple G M & Ferry J M (1992) Metasomatism and fluid flow in ductile fault zones. *Contributions to Mineralogy and Petrology*, **112**, 149-164.

Durney D W (1972) Solution transfer; an important geological deformation mechanism. Nature, 235, 315-317.

Ferry J M (1992) Regional metamorphism of the Waits River Formation, Eastern Vermont: delineation of a new type of giant hydrothermal system. *Journal of Petrology*, **33**, 45-94.

Fisher D & Brantley S L (1992) Models of quartz overgrowth and vein formation: deformation and fluid flow in an ancient subduction zone. *Journal of Geophysical Research*, **97**, 20043-20061.

Heinrich, C.A., Bain, J.H.C., Mernagh, T.P., Wyborn, L.A.I., Andrew, A.S. and Waring, C.L. 1995, Fluid and mass transfer during metabasalt alteration and copper mineralization at Mount Isa, Australia, *Economic Geology*: v. 90, p. 705-730.

Knipe R J & McCaig A M (1994) Microstructural and microchemical consequences of fluid flow in deforming rocks. *Geological Society, London, Special Publications*, **78**, 99-111.

Oliver N H S (1996) Review and classification of structural controls on fluid flow during regional metamorphism. *Journal of Metamorphic Geology*, **14**, 477-492.

Oliver N H S, Dipple G M, Cartwright I & Schiller J C (1998) Fluid flow and metasomatism in the genesis of the amphibolite-facies, pelite-hosted Kanmantoo copper deposit, South Australia. *American Journal of Science*, **298**, 181-218.

Oliver, N. H. S. & Bons, P. D. (2001). Mechanisms of fluid flow and fluid–rock interaction in fossil metamorphic-hydrothermal systems inferred from vein–wallrock patterns, geometry, and microstructure. Geofluids, 1, 137-151.

Oliver, N.H.S., Mark, G., Cleverley, J.S., Pollard, P.J., Rubenach, M.J., Marshall, L.C., Bastrakov, E.N., Williams, P.J., Nemchin, A.A., & Baker, T. (2004). Modeling the role of sodic alteration in the genesis of iron oxide–copper–gold deposits;eastern Mount Isa Block, Australia. *Economic Geology*, 99, 1145-1176.

Ramsay J G (1980) The crack-seal mechanism of rock deformation. *Nature*, **284**, 135-139.

Robert F, Boullier A-M & Firdaous K (1995) Gold-quartz veins in metamorphic terranes and their bearing on the role of fluids in faulting. *Journal of Geophysical Research*, **100**, 12861-12879.

Robin P-Y F (1979) Theory of metamorphic segregation and related processes. *Geochimica et Cosmochimica Acta*, **43**, 1587-1600.

Urai J L, Williams P F & van Roermund H L M (1991) Kinematics of crystal growth in syntectonic fibrous veins. *Journal of Structural Geology*, **13**, 823-836.

Widmer T & Thompson A B (2001) Local origin of high pressure vein material in eclogite facies rocks of the Zermatt-Saas zone, Switzerland. *American Journal of Science.*

Yardley B W D & Bottrell S H (1992) Silica mobility and fluid movement during metamorphism of the Connemara schists, Ireland. *Journal of Metamorphic Geology*, **10**, 453-472.

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