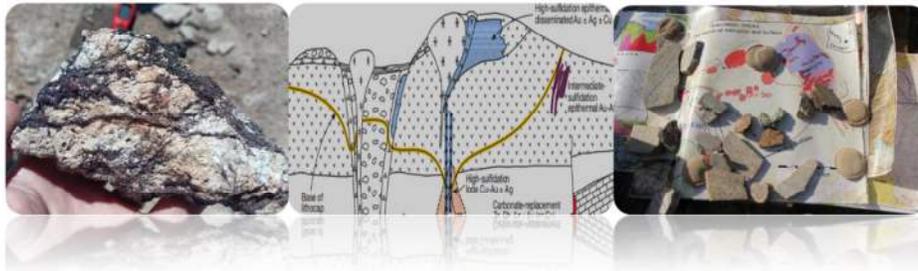


Porphyry Copper Deposits

Exploration Model v. Real World



TIM IRELAND & FEDE CERNUSCHI

PRINCIPAL EXPLORATION GEOLOGIST

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Real World v. Model

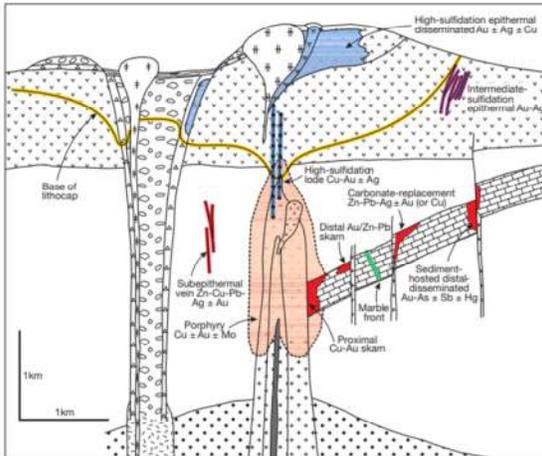


Overview of the standard “Sillitonian” porphyry model

Departures from that model:

- Early, high-T veins that introduce most Cu (Proffett 2009)
- Chemical pathfinders (eg. Halley 2015)
- Porphyries that make no ore (FQM in house)
- Lithocaps, and do all porphyries have them?

“Sillitonian” porphyry model



Seedorff et al., 2005, SEG 100th anniversary volume; Sillitoe, R. H., 2010, Economic Geology, v 105.

- Intrusions are porphyritic. Quenching. Sharp contacts. Diverse breccias.
- transition to epithermal environment; lithocaps
- Multiple related intrusions; intrusions host ore; earlier porphyries are richer than later.
- Fluids → dissociation to two types: brine and gas: brine = stockwork; gas = phyllic & lithocap
- Alteration → concentrically zoned; potassic internal to phyllic
- Grade → potassic alteration (kfs-bt-mt), grey saccharoidal quartz-sulfide veinlets (A-veinlets)

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Shallow crustal process

Intrusion is porphyritic (~50% crystals) because release of magmatic water causes quenching

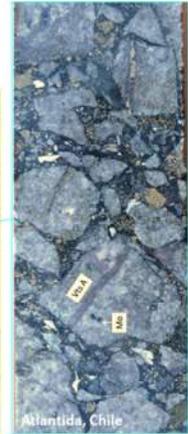
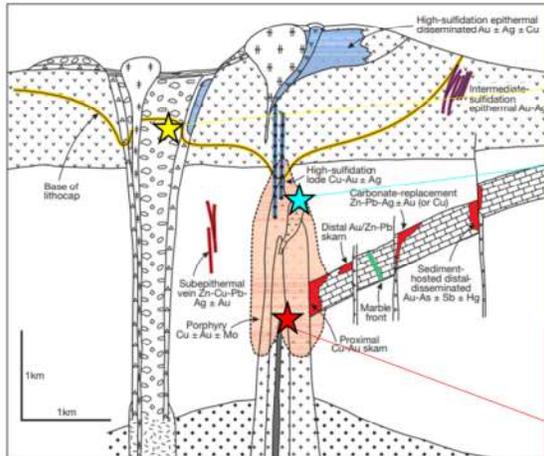
Multiple porphyritic intrusions derived from a parental magma chamber; earlier porphyries are better-mineralised than later.

Release of magmatic fluids causes rapid cooling and a change from ductile to brittle conditions

Veins and alteration are caused by two fluid types – the product of spontaneous dissociation of magmatic volatiles at the transition from lithostatic to hydrostatic pressure

Grade is mainly associated with potassic alteration (kfs-bt-mt) and a stockwork of distinctive grey saccharoidal quartz-sulfide veinlets (A-veinlets)

Sub-volcanic processes



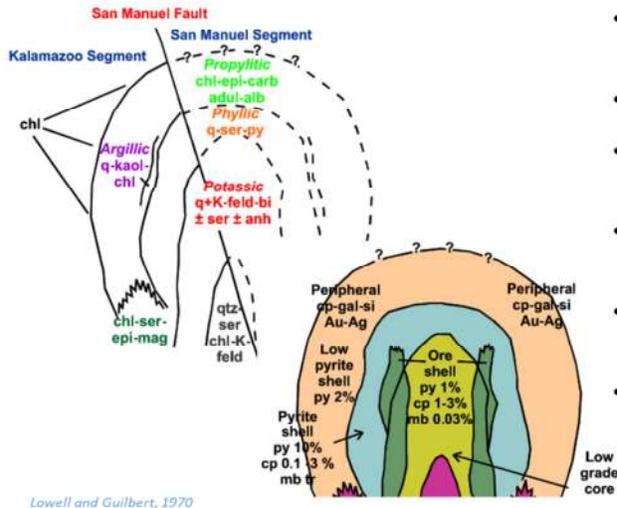
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Implied by the Sillitonian model is that shallow emplacement leads to batches of magma cooling quickly.

Cool wallrocks mean these rocks are brittle for subsequent events:

- New batches of magma incorporate fragments of porphyry that only just crystallised: a sequence of porphyry intrusion is easily defined (early-mineral, inter-mineral, and late-mineral porphyry) because fragments of each are common among the younger stages.
- Hydrothermal fluid pressure can drive wholesale brecciation and cementation with hydrothermal minerals, or
- Geothermal processes can pulverise the magma and create breccia columns with a rock flour matrix

Concentrically zoned alteration zones



Lowell and Guilbert, 1970

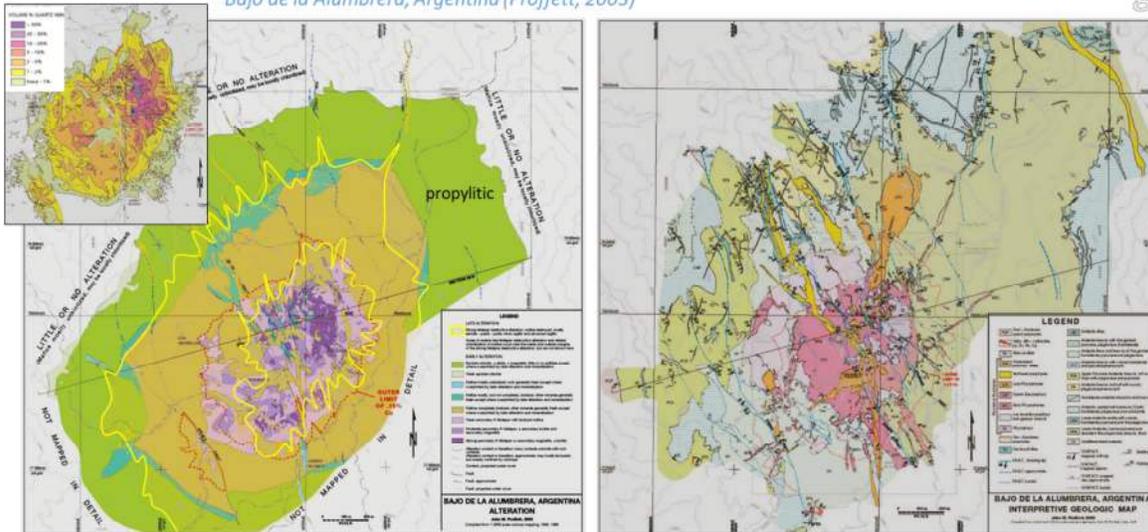
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Key aspect of the standard model is concentric zonation of alteration; initially presented as symmetric on sides or top, but generally now recognised as a feature of the upper central parts of the system, with variations at depth and above the main ore zone (transition to epithermal environment)

Concentrically zoned alteration; ore in the intrusions

Bajo de la Alumbraera, Argentina (Proffett, 2003)



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Here's perhaps the best real world, right way-up, mapped example of standard concentric facies distribution is Bajo de la Alumbraera: propylitic outboard of phyllic; phyllic outboard of potassic.

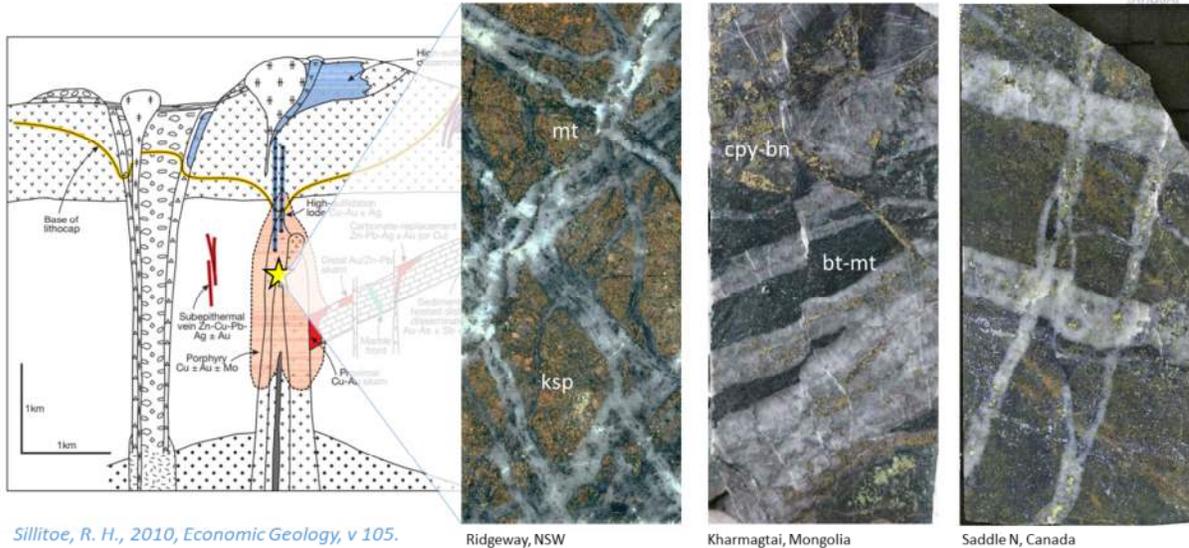
The yellow zone is chlorite after biotite, indicating how broad the early-mineral potassic zone was. Notably the potassic was broader than the intense stockwork (quartz vein density inset, top left), and the chlorite-after-biotite coincides in space with the phyllic (evidently this is what happens when the acid fluids responsible for the phyllic meets early potassic rocks, but at lower fluid:rock ratio. Note also that both phyllic and chlorite-on-potassic are almost perfectly antithetic with grade AND occur mostly outside the main causative porphyry intrusion. Either:

- acid alteration in these systems is generally barren and destructive of grade and/or
- Grade and intense quartz stockwork development are mainly restricted to the causative intrusion.

Ore-bearing grey quartz veins

"A & B veins"

Ti

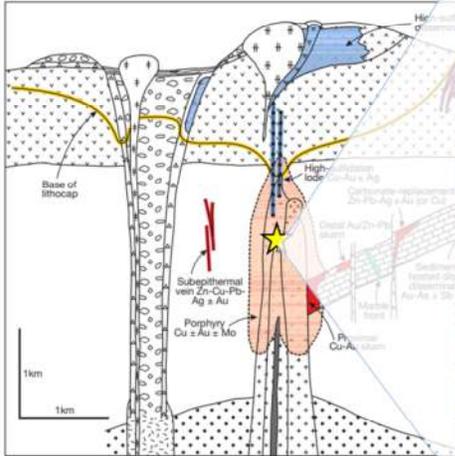


Some detail of what good A-veins (and AB veins) look like:

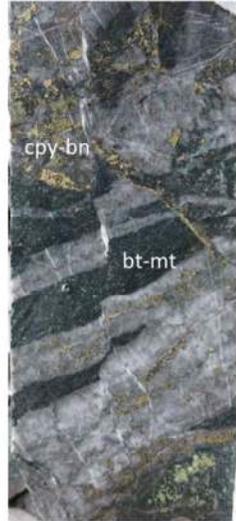
- Greyish saccharoidal quartz
- Irregular walls and variable, partial internal banding
- Potassic alteration in host, but generally not as perfect haloes
- Veins are mostly IN porphyritic intrusive rocks
- Fe-Cu assemblage includes bornite and magnetite (high fO₂)

Ore-bearing grey quartz veins

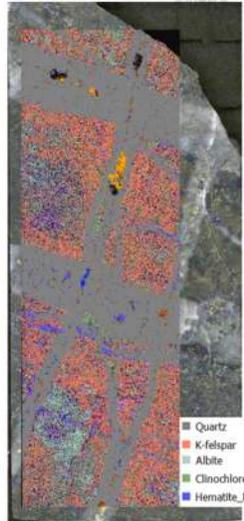
"A & B veins"



Ridgeway, NSW



Kharmagtai, Mongolia



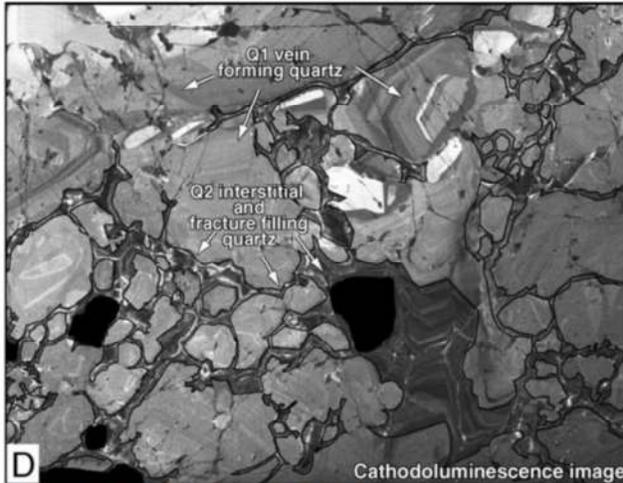
Saddle N, Canada

Sillitoe, R. H., 2010, *Economic Geology*, v 105.

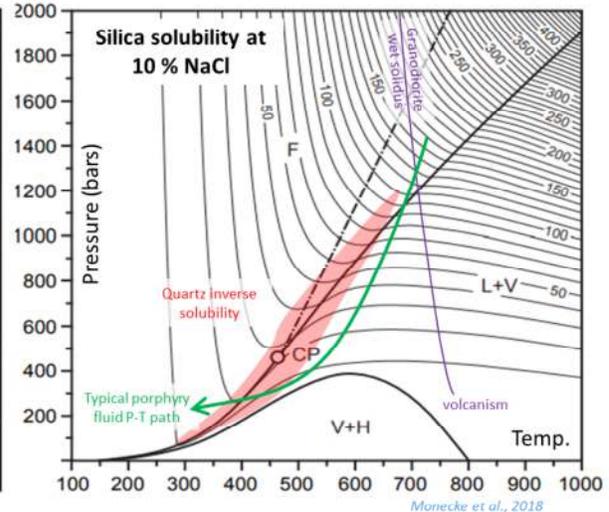
TIMA map showing extent of K-feldspar alteration in wallrocks

Ore-bearing grey quartz veins

“A veins”



Landtwing et al., 2005. See also: Cernuschi et al., 2023



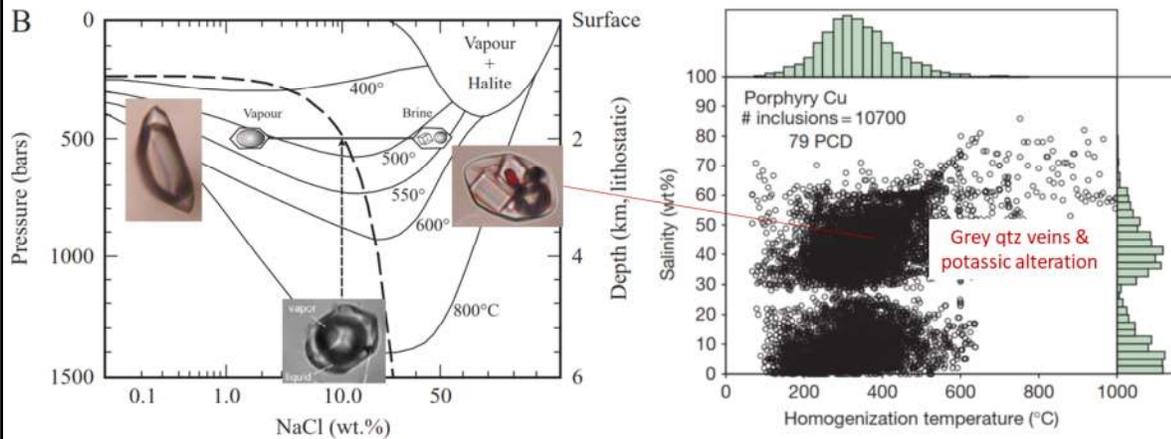
Monecke et al., 2018

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The saccharoidal texture and grey colour of A veins (cf glassier or white appearance of earlier or later quartz generations) is generally taken to be a function of their internal grain structure.

Fluid inclusion studies of these veins tend to homogenise in the range 500-300C, and at common porphyry emplacement depths cooling through this range means a period of weak retrograde solubility → so earlier formed CL-bright quartz is transiently dissolved along grain boundaries and then re-cemented by new CL dark quartz at lower temperatures.

Zoned alteration



Hedenquist et al 1998, after Shinohara 1994 and Bodnar et al., 1985

Bodnar et al., 2014

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Speaking of fluid conditions:

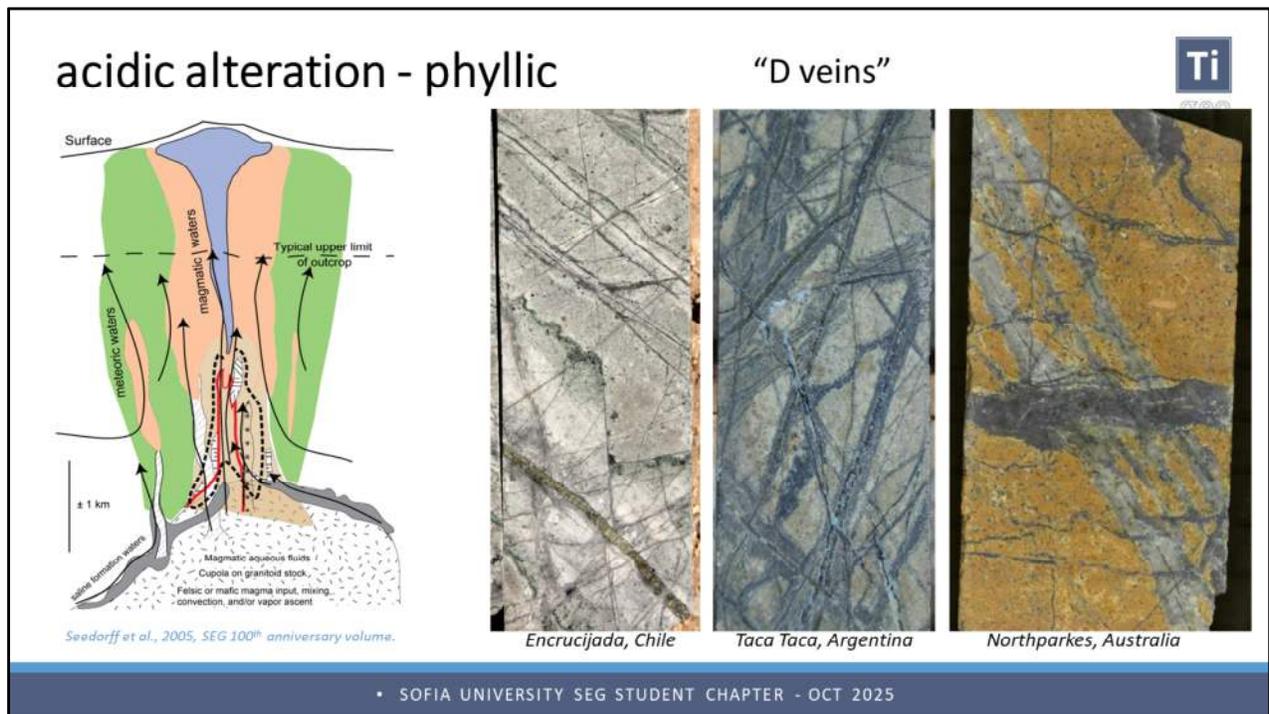
Fluids exsolving from a magma experience phase transitions depending on pressure and temperature.

These phase transitions – between salts, liquids, and gases – are key to many hydrothermal, and volcanologic processes.

For this story, the phase transition story matters because it explains why classical porphyries have such striking contrast in proximal and distal alteration styles

At low pressures (ie $< \sim 3.5$ km depth for fluid exsolving at 600C), the things exsolving from the magma don't all exsolve to a single fluid. Instead, at depths shallower than this limiting pressure, the exsolved contents spontaneously split into a high salinity liquid, and a low-salinity gas. We see this as the common co-occurrence of two types of inclusions in A-type quartz: defined most simply by pronounced bimodality of inclusion salinity for all porphyries (Bodnar, 2014)

This separation into two fluids with different characteristics means all the hydrothermally mobile elements partition between the phases, with a bias to the component in which they are more soluble: The brine component takes most of the silica, alkalis and base metals; whereas the vapour takes all the sulfur and toxic metalloids (As, Sb etc). The brine, therefore is responsible for the potassic alteration, the A-type quartz veins and the Cu precipitation in a stockwork ore zone.



On the other side of that ledger is the vapour.

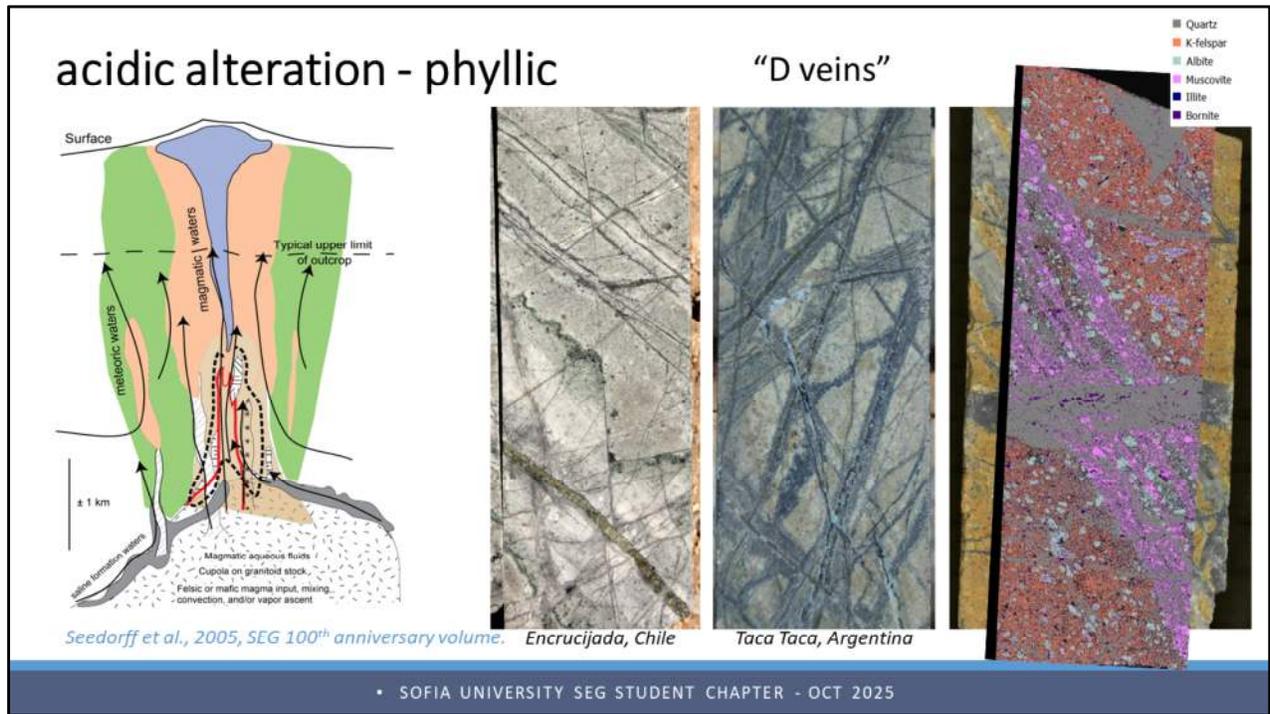
As it exists in stark density contrast to the material around it, the vapour rises toward the land surface. Upon ascent it cools, condenses, and hybridises with groundwater (as evidenced by the appearance of H and O isotopic components from meteoric sources).

At this point it is a hot dilute acid liquid that dissolves primary magmatic minerals and converts them to muscovite, or, at high Fe activity, chlorite. This alteration is destructive of grade. Once condensed from gas to liquid its movement is limited to fracture permeability and reprecipitation of dissolved Fe leads to formation of D veins.

D-veins are notable for their general character:

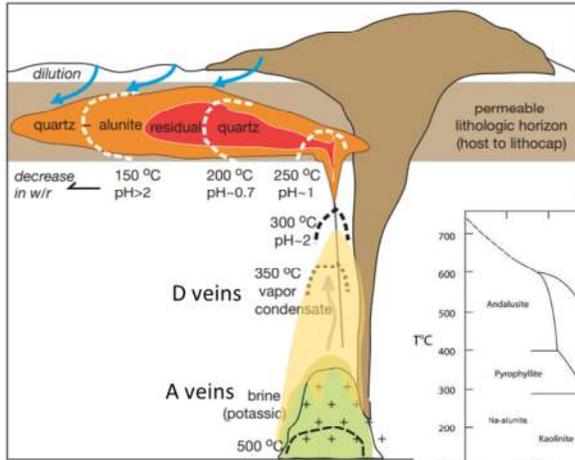
- Rectilinear form, commonly sheeted

- Pure sericite (generally, Al-rich, low w2200) halos that are 5-10x wider than the pyrite fill.
- Halos lack disseminated sulfides, and lack biotite or Kfs.

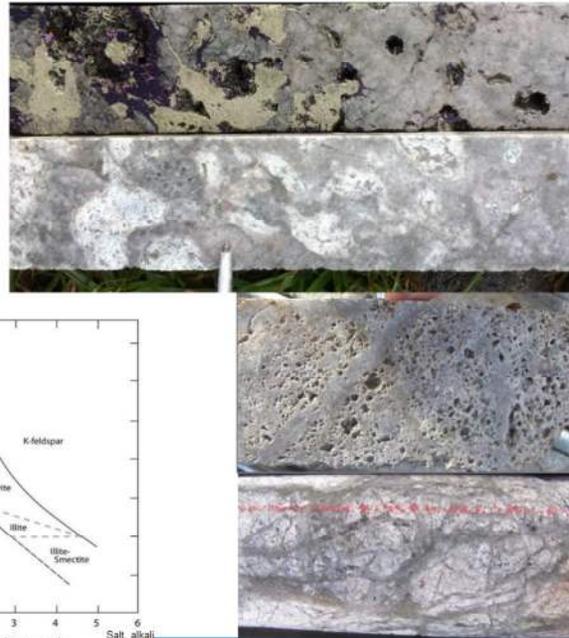
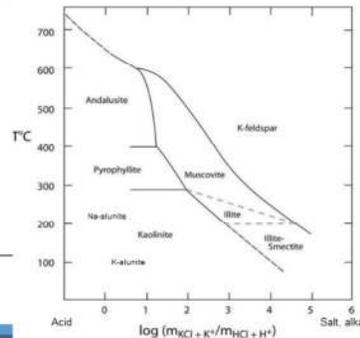


TIMA image showing clean muscovite composition of D vein haloes

acidic alteration - lithocaps



Hedenquist & Taran, 2013
 Seedorff et al., 2005
 Burrows, 2020



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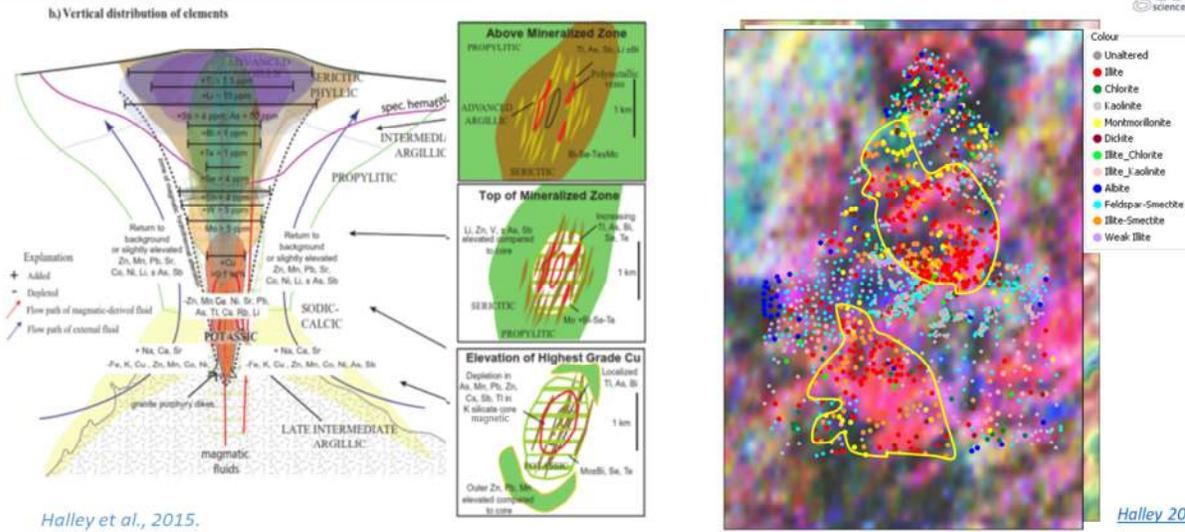
The process of acid alteration caused by ascending magmatic volatiles continues at yet shallower levels

The fluids cool further and hence become more acidic, leading to extreme leaching and stability of advanced argillic assemblages. Add some groundwater and we have the conditions for formation of a lithocap, or if the fluid fluxes allow groundwater to dominate and be acidified by magmatic vapour then a “steam-heated” blanket develops with typical acid volcanic hot springs and fumaroles.

There’s lots of complexity here, but the point is that the classic Sillitonian model envisages high sulfidation epithermal processes as the low-pressure part of the anatomy of the overall system; evolved from the fluids that caused the phyllic event and synchronous with it.

At best, this HS mineralisation can be overprinted on the A-vein stockwork

Alteration patterns & chemical distribution



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One way of mapping this process of ascent of magmatic volatiles is the zoned distribution of trace elements in the altered rocks.

Famously this was publicised by Scott Halley 10-15 years ago, relying on a change in analytical technology that lowered detection limits so these distribution of these trace element anomalies.

In the example shown, a porphyry camp in Romania, two alteration cells are marked by the presence of sericitic alteration at surface. The southern of them is a known outcropping porphyry deposit. In the Halley view of the world, that these are *both* marked by Bi anomalies (as well as Te, Se etc) implies the presence of blind porphyry mineralisation at depth. This was later proven at this prospect.

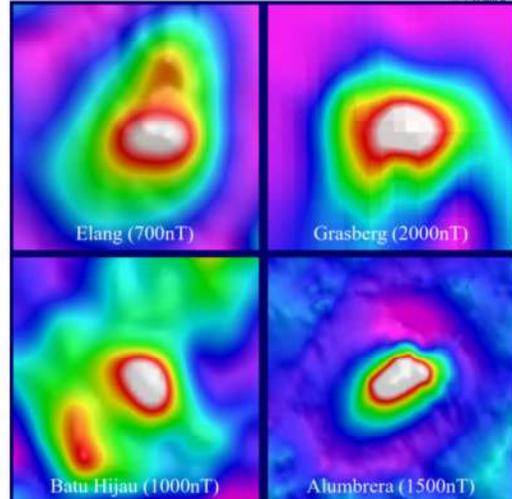
This has become part of the porphyry model as it is widely understood. Implied in this presentation of the model is that the existence of trace element anomalies above certain thresholds, coincident with the acid alteration assemblages, and arranged in the 'right' zonation, is evidence that the whole system exists → including a mineralised porphyry stockwork.

Alteration patterns & physical response

Ti



Halley et al., 2015.



Hoschke, 2011.

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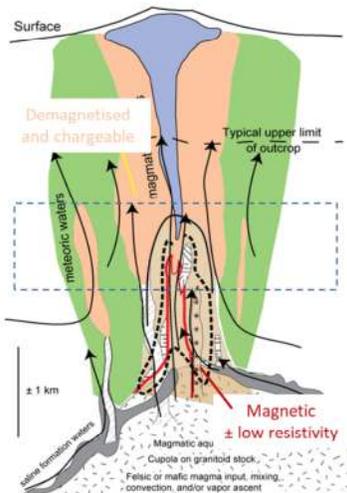
Another aspect of the standard model is the physical responses.

A vein stockworks, because they either contain magnetite, or are associated with potassic alteration that includes magnetite, tend to make significant magnetic anomalies.

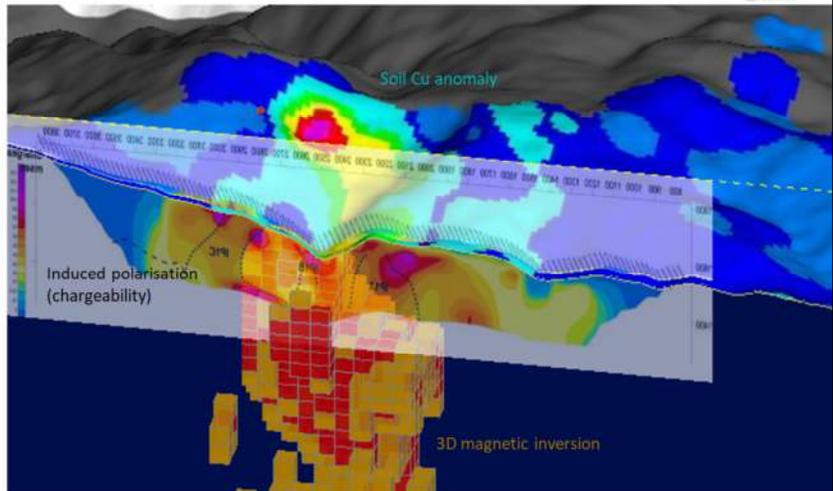
As the phyllic alteration is destructive of primary Fe minerals, the peripheral areas are commonly demagnetised.

In his book on porphyry geophysical signatures, Hoshcke shows the best, simplest examples. In real life, the phyllic tends to be somewhat asymmetric, and hence the geometric relationship of magnetisation and demagnetisation can be messy. However, the observation remains true that strong A-vein stockworks are generally magnetic if exposed or in the shallow subsurface: below ~250 m depth they become lost among the normal magnetic background of magmatic host rocks.

Alteration patterns & physical response



Seedorff et al., 2005, SEG 100th anniversary volume.



FQM, 2018

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The electrical response of the A vein stockwork and the phyllic/D vein zone is also notable.

The D veins and phyllic are marked by widespread disseminated or fine veinlet pyrite and these are typically chargeable. The A vein stockwork is also chargeable, but less intensely. Sometimes, the A vein stockwork can be a low-resistivity anomaly, owing to connected sulfide veins that post-date the A veins.

So a perfect A-vein type porphyry has a magnetic orebody stockwork, surrounded by a phyllic altered halo that is chargeable, as per this example.

“Sillitonian” porphyry model - summary



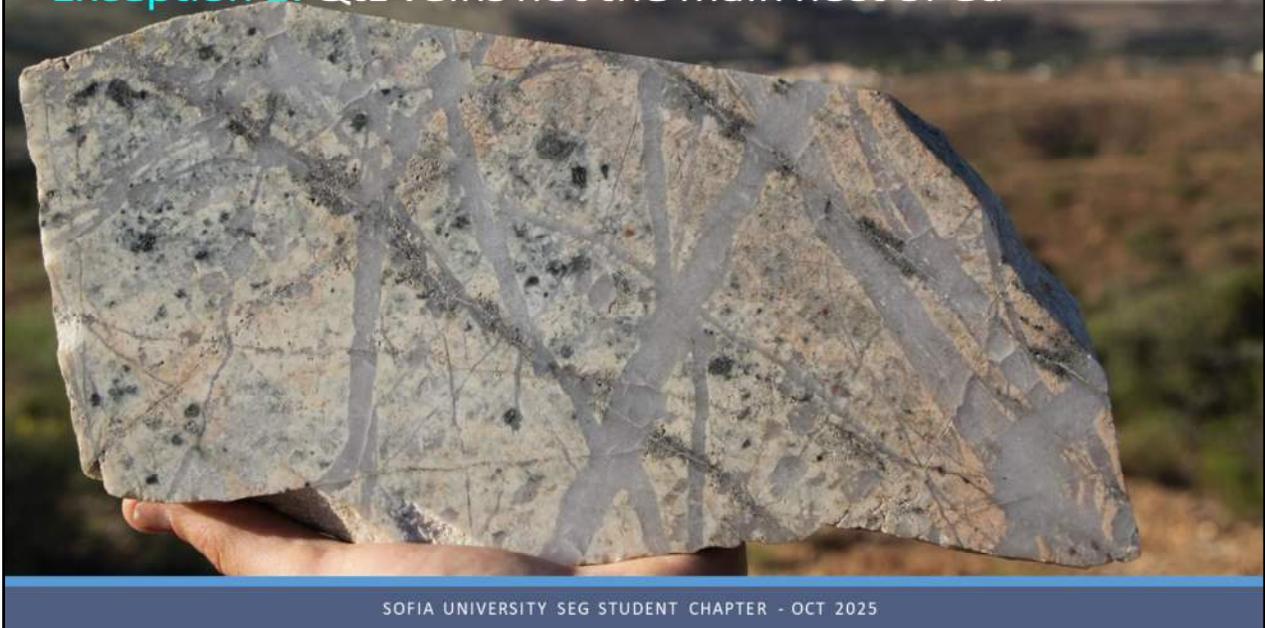
- Intrusions are porphyritic. Quenching. Sharp contacts. Diverse breccias.
- Multiple related intrusions; **intrusions host ore**; earlier porphyries are richer than later.
- Two fluids → two major vein & alteration groups:
 - A-vein stockwork; qtz-**mt**-kfs; cpy-**bn**;
 - target is magnetic, potassic
 - the qtz vein stockwork is the main mineralised volume
 - Peripheral gas condensates & mixes with external water = phyllic → argillic
 - Initially destroys grade
 - Creates strong chargeability around the
- Chemistry → pathfinder elements are systematically zoned with alteration
 - If the shallower parts of this zonation exist, there should be a porphyry below

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So here's a summary of all that.

To this point we've just laid out the standard porphyry model, as widely applied in the exploration industry.

Exception 1: Qtz veins not the main host of Cu



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So here's problem 1: you did your targeting, mapping etc and find a great stockwork...
but the quartz veins are barren.
What's going on?



In many such cases, outboard of those barren quartz veins we see veins like this:

- Straight
- Very narrow; vein itself may be discontinuous or not really obvious at all
- Broad halo (sometimes zoned)

... so kind of looking like D veins (and you'd expect D veins outside a quartz stockwork) but... in these case these "halo veins" are not destructive of grade. In fact the centreline contains cpy.



Not only the centreline: there is chalcopyrite disseminated IN the halo, and also disseminated in apparently unaltered wallrock
Note also the timing: these halos are old: Where A-type quartz veins exist they cut the halos. Ie, halos are early and pre-date A-type quartz. That's a defining criterion – they're early in the vein sequence. Generally later than aplite vein/dykes, but older than A veins.



Another example

Note the range of colours: these haloes can be dark green, dark brown, grey-green, grey-brown, grey... but generally not clean white or cream like the halos of D veins.

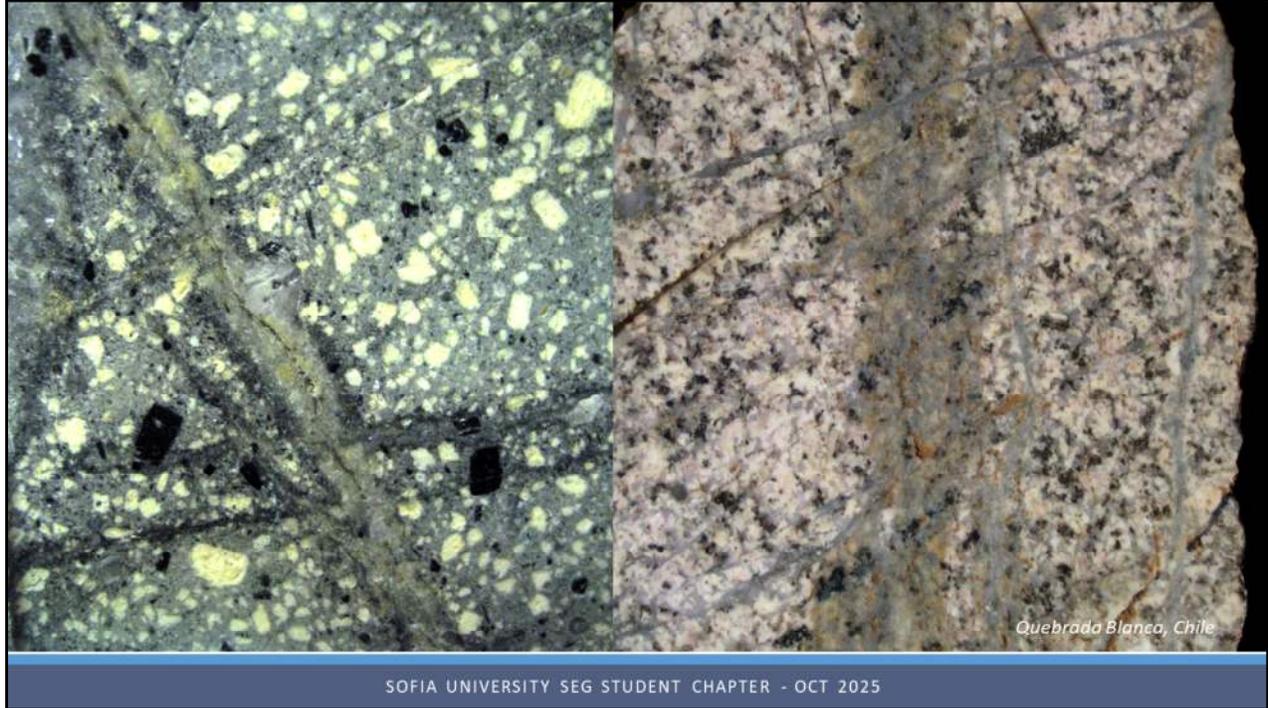
That colouration relates to the bulk FeMg composition of the host rock.

In detail here, note the chalcopyrite disseminated IN the halo

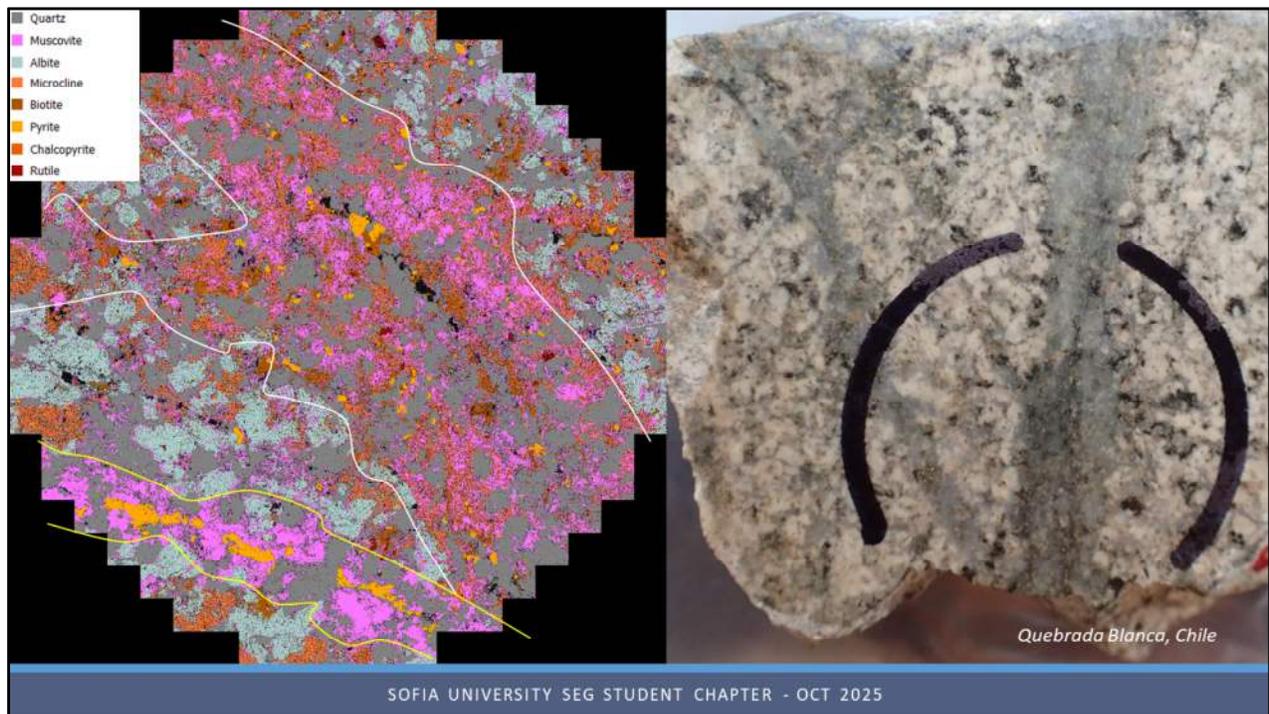
And also – less abundant but disseminated in apparently unaltered wallrock

Commonly, as here, these early halos can be re-opened by a quartz veinlet.

That's a defining criterion – they're early in the vein sequence



More examples, to hammer the point about how their colour corresponds to host rock. These are from the same deposit; just different intrusions (syn-mineral monzodiorite on left; premineral qtz-monzonite on right). Again, in the right hand example we see A-like quartz veinlets cutting the haloes.



So what are these halos? What are they made of?

The proportions can vary, but by definition they have muscovite AND a dark phyllosilicate (biotite/phlogopite or chlorite)

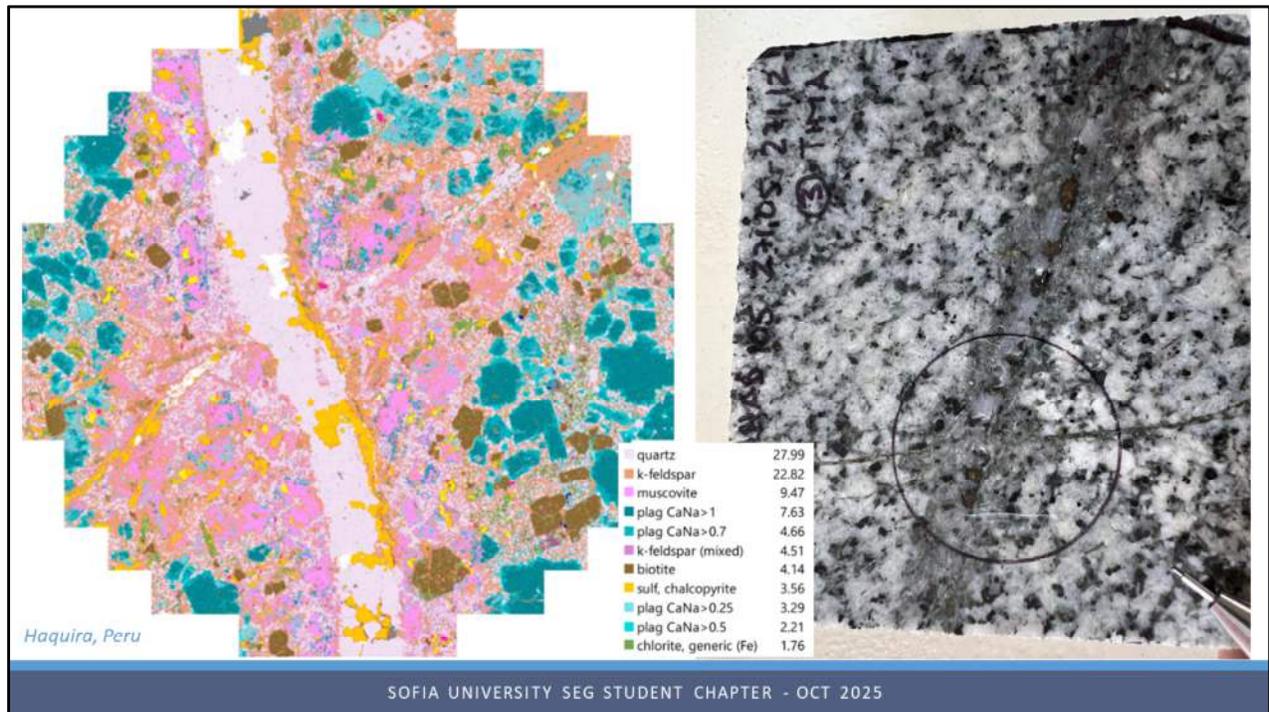
Some, like this one, also have K feldspar.

Biotite, K-feldspar. That makes them some species of potassic alteration

Note again here the sulfides disseminated IN the halo; and the lack of much real vein.

Where are the vein walls? Can't see them because the halo is replacive of the host rock

And again, here we see a cross-cutting relationship. Here a D-vein (bottom left, with clean muscovitic halo and pyrite centerline) cuts the early halo.

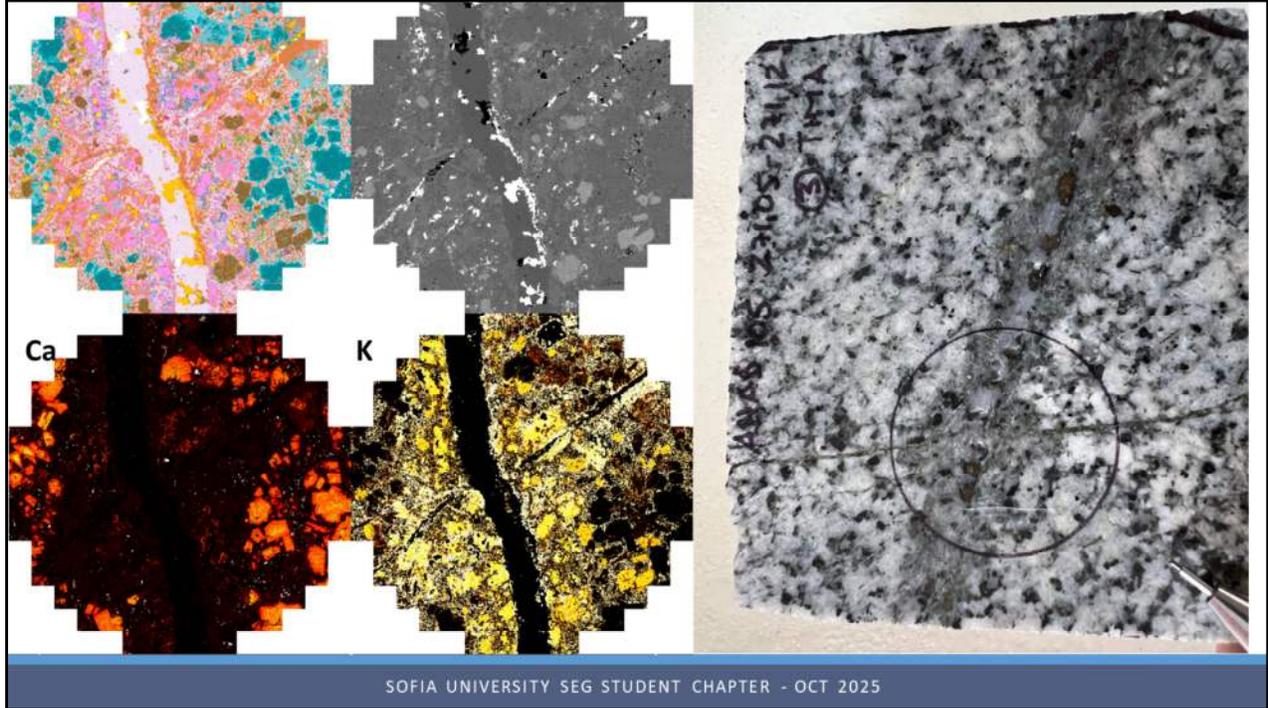


One more example, this time from Haqira, in Peru.

Again, we see a halo with muscovite, and distinct, obvious preservation of magmatic biotite.

There's also K-feldspar that isn't visible in hand specimen, and a bit of chlorite that is enough to give the halo a greenish colour.

Also, in this example we see the halo re-opened by a quartz vein that has Cu sulfides. Important to note that most deposits have both A-veins **and** early halos. The distinction I'm making is to ask which vein type is the **main host of Cu sulfides**.



To emphasise what's happening here, chemically

The halo is absolutely devoid of Ca, but strongly enriched in K → so it broadly follows the idea of early potassic alteration associated with grade.

It's important to consider what is missing, as compared with typical A-vein type porphyry ore.

Bornite? Absent. Sulfides are pyrite-cpy.

Magnetite? Absent.

So the oxidation state of these haloes is different to that of A veins: availability of reduced S is higher...they're not as oxidised.

Early halo-veins are mostly in the wallrocks

Ti



There's also an important point of difference with location wrt causative porphyry intrusions.

Halo veins tend to occur in the wallrocks to the causative intrusion, and the size of these intrusions can be small wrt the deposit.

Example here from Taca Taca

Early halo-veins are mostly in pre-mineral stocks (and causative porphyries are small)



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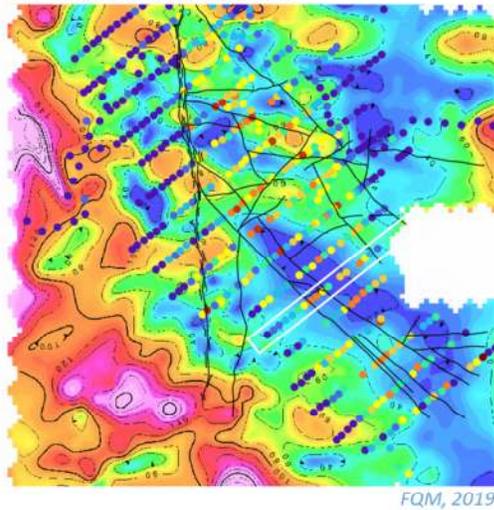
Example here from Haquira.

Note that at Taca Taca the 'wallrock' is hundreds of millions of years older than the hydrothermal system, whereas at Haquira, as at Quebrada Blanca, Chuquicamata and many other examples the host is a premineral stock <5 million years older than ore formation

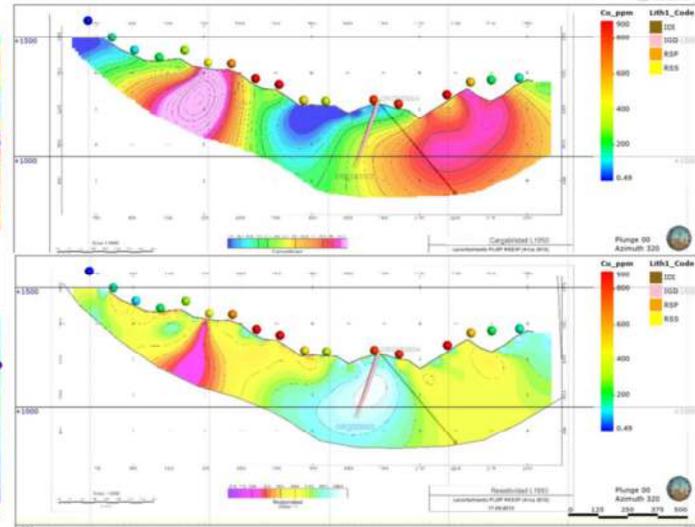
Physical response of early halo-veins



RTP magnetic map; Cu in soils



Pole-dipole Induced Polarisation



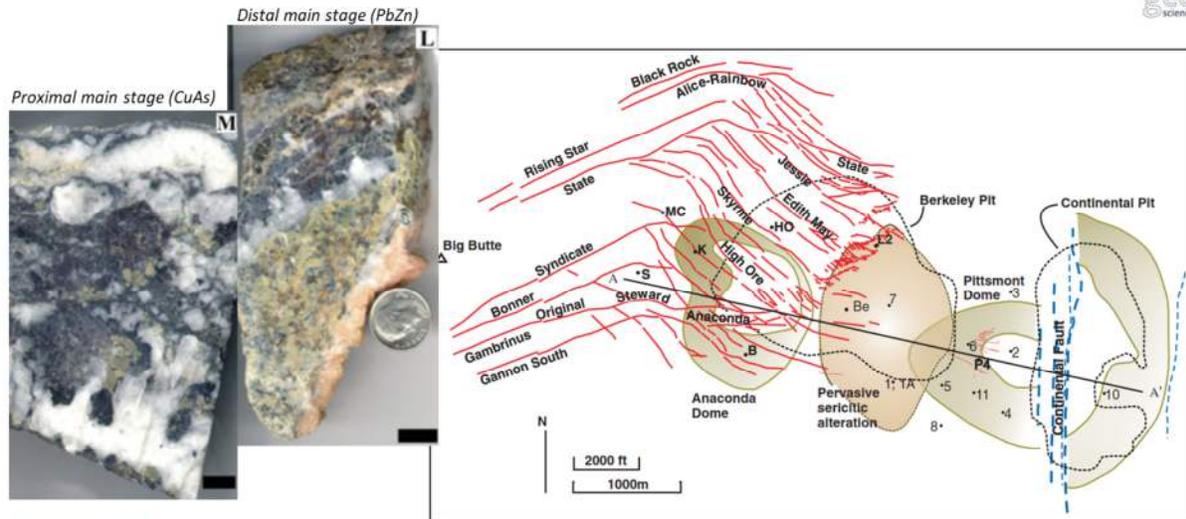
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So what about the physical response of these Early Halo-dominated deposits?

- Since there's no magnetite in the stockwork nor potassic assemblages... they're not a magnetic target. In fact they're often pervasively demagnetising.
- Since the haloes that contain Cu, hold the Cu as disseminated sulfide, then they charge. In the example shown, the Cu anomalies in soil are – in the southern part of the project – aligned on a structural zone that is mainly demagnetised. Along the highlighted line, the IP response shows two combined chargeability-low resistivity anomalies, separated by a non-chargeable resistor. Drilling initially tested the gap between chargers, as if following an A-type model. It failed. The second, shallowly inclined hole partly tested the weaker of the IP anomalies and yielded weak halo-type mineralisation. The stronger IP anomaly was never tested... but that looks like an oversight, because by this point the halo-type mode of mineralisation is understood and now this charger becomes a target in its own right, rather than the inferred phyllic shoulder of a qtz vein stockwork.

Note however that halo-type porphyries also evolve, eventually, to a D-vein stage, and this is still often the strongest chargeability feature in the system. So the ore in halo-type porphyry deposits is often at the inner edge of the main chargeability feature.

Halo-type porphyries lack lithocaps



Rusk et al., 2008

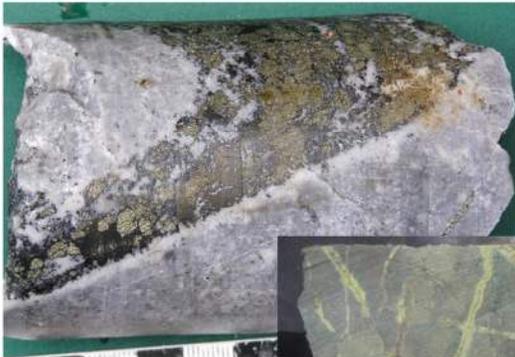
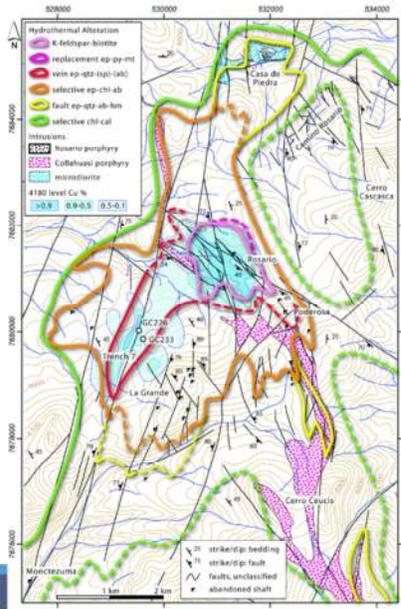
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Another aspect of halo-type systems is their relationship with hypogene upgrading and telescoping.

One aspect is the lack of known examples of halo type porphyries overprinted by classic high sulfidation lithocap environments. That could be a depth/erosion/exhumation likelihood function, but a related observation is the frequency with which halo-type deposits have telescoping of IS lodes zoned from Cu to base metals, and that these can represent a substantial proportion of the contained Cu.

Famously, at Butte, the main stage veins are covellite-energite bearing in the proximal domain and zone out to sphalerite-quartz-carbonate in the distal environs.

Halo-type porphyries lack lithocaps



Ireland, 2010

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At Collahuasi – which is a suspected but not yet demonstrated halo-type system – the camp of semimassive sulfide veins also covers a very large footprint, again is zoned from bornite-energite to sphalerite. The alteration attendant to these lodes is also zoned: narrow haloes of advanced argillic alunite-quartz in proximal environs, but more broadly pyrophyllite, and crystalline kaolinite at high levels I the distal environment. Outboard of the acid lodes is generally a epidote-rich propylitic assemblage, ie the lodes don't occupy a broad acid altered environment, but represent very discrete fluid flow channels in a generally background environment above and outboard of the porphyry,

Halo-type porphyries lack lithocaps



Ireland, 2010

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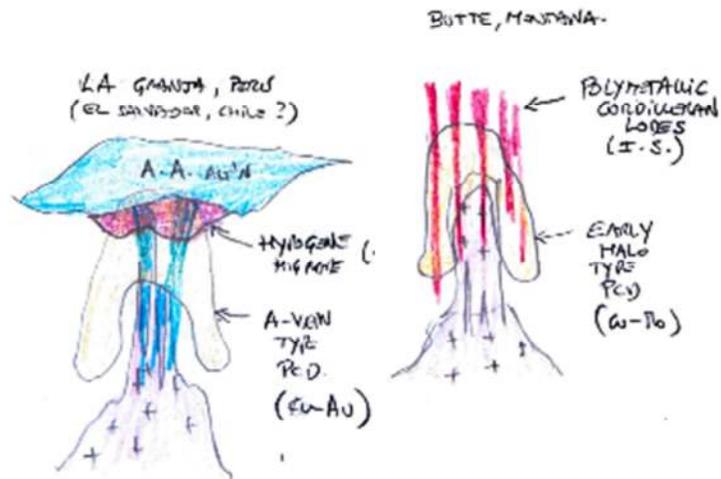
At Collahuasi – which is a suspected but not yet demonstrated halo-type system – the camp of semimassive sulfide veins also covers a very large footprint, again is zoned from bornite-energite to sphalerite. The alteration attendant to these lodes is also zoned: narrow haloes of advanced argillic alunite-quartz in proximal environs, but more broadly pyrophyllite, and crystalline kaolinite at high levels I the distal environment. Outboard of the acid lodes is generally a epidote-rich propylitic assemblage, ie the lodes don't occupy a broad acid altered environment, but represent very discrete fluid flow channels in a generally background environment above and outboard of the porphyry,

Halo-type porphyries lack lithocaps



Model: pre-erosion, porphyry Cu deposits mostly generate an epithermal acid zone closer to surface (a lithocap). Epithermal processes in this zone can include HS Epithermal sulfide mineralisation, and syn-mineral exhumation can cause overprinting of the epithermal ore on the porphyry intrusions and qtz vein stockwork.

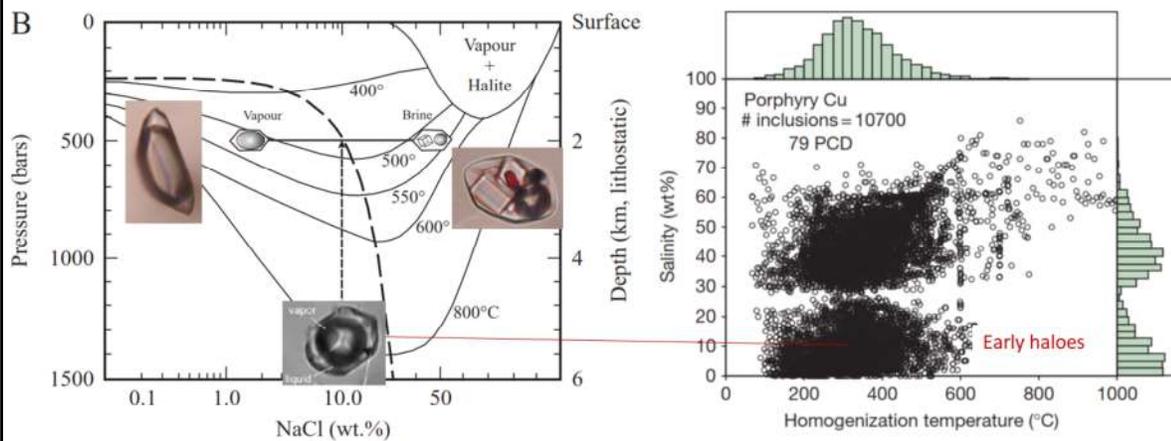
Reality: Many deposits with prominent IS lode-style hypogene upgrading don't show evidence of a broad lithocap. These are mostly EH-type porphyry deposits, pointing to a relationship between stockwork type & overprint type.



Fede Cernuschi, 2025 (unpubl.)

Federico sketched the two end member scenarios like this

Why the haloes?



Hedenquist et al 1998, after Shinohara 1994 and Bodnar et al., 1985

Bodnar et al., 2014

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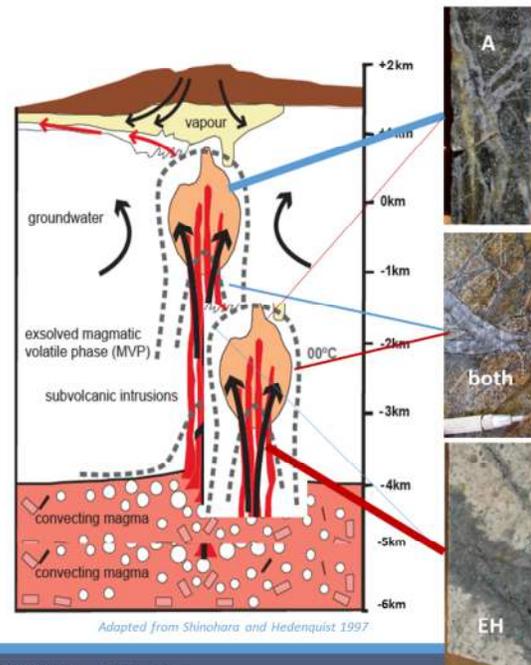
Earlier I used the spontaneous dissociation of magmatic volatiles at low pressure as an explanation for the origin of the brines related to potassic alteration and A veins, and for the low-salinity gas related to phyllic & argillic alteration. Among EH veins, by contrast, the average salinity of fluid inclusions is lower, and these tend to have approximately equal content of liquid and vapour. Quartz in these veins is high-T, CL-bright and contains only a single population of fluid inclusions. This suggests a single fluid exsolved without dissociation. As Proffett (2009) first argued, that condition is met at pressures that exceed the critical point for hydrous liquids at a given salinity; commonly >4 kms for fluids at ~600°C. At this pressure, that fluid is 'supercritical' and has physical properties intermediate between liquid and gas; hence the tendency to penetrate along grain boundaries and alter the walls of fractures, rather than precipitate new vein fill. The tendency for these haloes to occur outside their causative intrusion might be related to the greater density contrast between fluid and magma, cf the high density of a true brine. As all the exsolved components are necessarily in a single fluid, so there is no immediate separation of alkali from acid species, hence stability of a mid-pH assemblage including biotite and muscovite. Likewise, there is no partitioning of S into the vapour phase, so the S fugacity and oxidation state of the fluid remains py-cpy stable throughout, hence the lack of magnetite and bornite.

Subsets of the porphyry model

Porphyries can be split into two families:

- “Sillitonian”, or “**A-vein type**” deposits,
 - Target is potassic & magnetic, and *in* the causative intrusion
 - marginal phyllic alteration is barren but chargeable.
 - Common volcanic host and volcanic textures
 - Clearly related to HS epithermals & lithocaps.
 - dominant in island arcs; mostly Cu-Au;
- “Proffettian” or “**early halo-type**” deposits:
 - Target is non-magnetic, but chargeable
 - Target is mostly in wallrocks around intrusion
 - Marginal phyllic alteration is also mineralised
 - Rare breccias; common batholith or basement hosts
 - Perhaps lack lithocaps but have polymetallic lode potential.
 - dominant in continental arcs; mostly Cu-Mo;

Origin of difference is depth/pressure



Adapted from Shinohara and Hedenquist 1997

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Summarising the pitch so far, we can distinguish two subclasses of mineralised porphyries, for which depth is the primary control on the difference in behaviour. Not mentioned here are some features common to both types: banded quartz-Mo veins, & C-type sulfide only veinlets that both occur between the early (EH, A) and late (D) vein stages. Likewise, both types can have a barren deep central zone of abundant white quartz veining, commonly associated with aplite veinlets.

We might illustrate the difference like this, butchering Shinohara’s diagram, to show the typical association of halo type deposits with intrusive, plutonic host rocks, cf a more common association of A type deposits in supacrustal, sedimentary or volcanic host rocks.

Also important to note that most deposits have some haloes and some A veins, and that these are arranged in a vertical column within the deposit: the deeper parts of a “shallow” system dominated by A veins will normally be deep enough that there was some halo formation, and between these will be a domain with a mixture of both (indicated here by the thickness of the lines). Likewise, deeper systems, albeit dominated by haloes, tend to undergo phase dissociation in their shallower, upper parts, leading to development of some A- or B-like quartz veins.

Subsets of the porphyry model

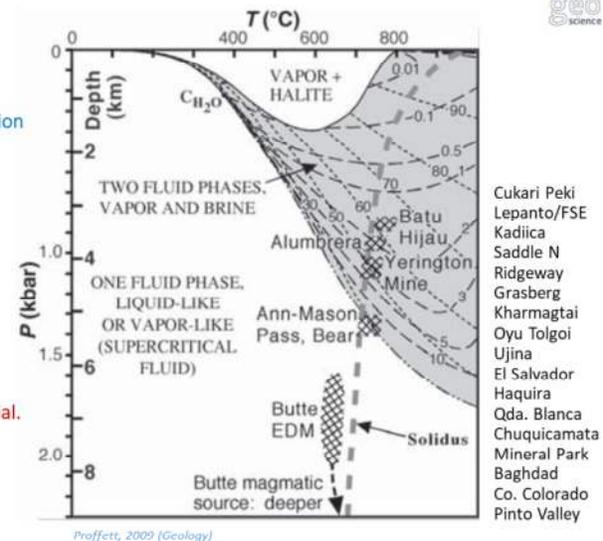


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Origin of difference is depth/pressure



Proffett, 2009 (Geology)

Illustrated using Proffett’s famous diagram

Listed at right are some famous deposits, and those used as examples in this presentation, arranged in approximate order of the depth, implied by the dominance of either the A-type or EH-type modes of Cu occurrence.

Not mentioned here are some features common to both types: banded quartz-Mo veins, & C-type sulfide only veinlets that both occur between the early (EH, A) and late (D) vein stages. Likewise, both types can have a barren deep central zone of abundant white quartz veining, commonly associated with aplite veinlets.

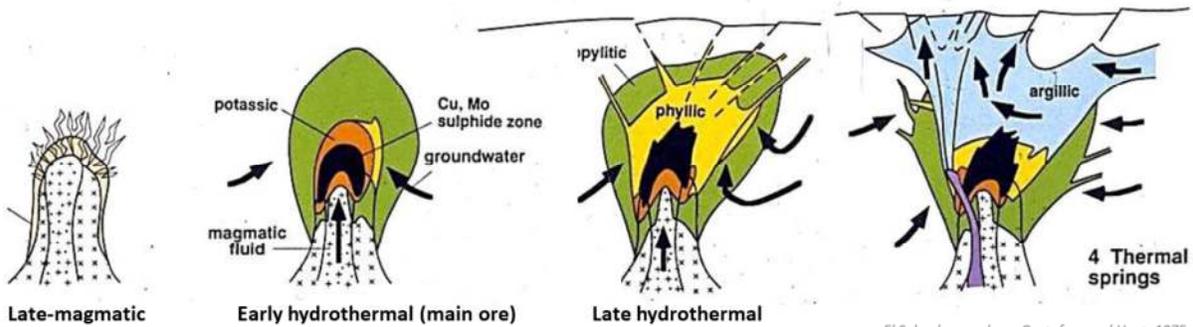
So far so good.

A-vein porphyries, EH porphyries...
they can both make ore.

Some porphyry stockworks are not ore.



Model: implies that processes that lead to origin of porphyry-style veins and alteration (A veins + feldspar alteration, D veins + phyllic alteration etc)... also permit Cu mobility and precipitation



El Salvador porphyry, Gustafson and Hunt, 1975

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Classic models generally portray all the stages of development of zoned porphyry alteration as necessary parts of the anatomy of the system... as if no part can exist without the others.

The authors of these models don't say that, but when I read the model diagram, that's what I imagine.

Why do some porphyries make 'no' ore?

Ti



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Here's a common scenario – some lads ride a donkey up a hill and find a super-looking quartz stockwork like this
Justifiably they feel pretty happy about their discovery
Until...
The assays come back and they learn this rock contains background, or sub-background Cu!

Why do some porphyries make 'no' ore?

Ti



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It happens that this is not rare.

Here's a series of rocks from a project we drilled in Chile.

Left to right is basically centre to periphery.

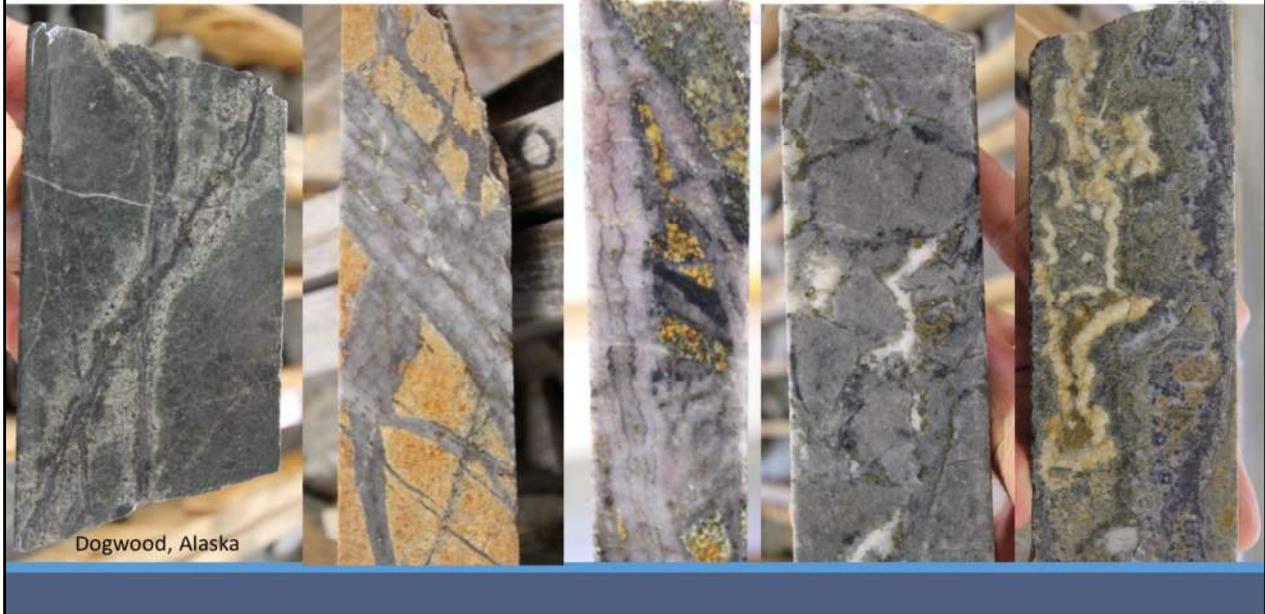
We have an early halo; some A-like qtz veins with sulfides; a tourmaline-altered breccia; some sheeted D veins cutting early A veinlets, and some propylitic alteration in a wallrock andesite.

So to gauge from the textures and the rocks it behaves like a typical A vein porphyry. But there's no significant economic grade in this deposit. The A vein zone is effectively barren: pyrite is the only sulfide mineral. The only place we do see Cu concentrating is in the propylitic zone.

That turns out to be a common phenomenon in failed porphyries (and perhaps the key difference between porphyry & skarn deposits): imagine this magmatic brine, exsolved from the magma, and dissociated from its gas phase – under 'normal' porphyry behaviour it has enough dissolved Cu that during cooling and reaction with the wallrocks it precipitates as CuFe sulfides. But what if the Cu concentration of the brine isn't enough for to achieve saturation under these conditions? In that case Cu would only precipitate in response to a more dramatic chemical change, such as reduction by Fe-rich wallrocks (basalt) or complete neutralisation (limestone; skarn)

Why do some porphyries make no ore?

Ti



One more, this time from Alaska just to prove this isn't a localised phenomenon.
Again left to right, proximal to distal.

Again we see

- A-like quartz veins with sulfides;
- here a transition to banded epithermal-like qtz veins;
- a breccia with hydrothermal cement including quartz and sulfides; and
- lastly a telescoped massive sulfide Zn-Pb rich vein system.

All so well behaved in terms of the expected anatomy of a porphyry, but no Cu
(except for the IS vein)

Why do some porphyries make no ore?

Ti



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And one more – here from Panama.

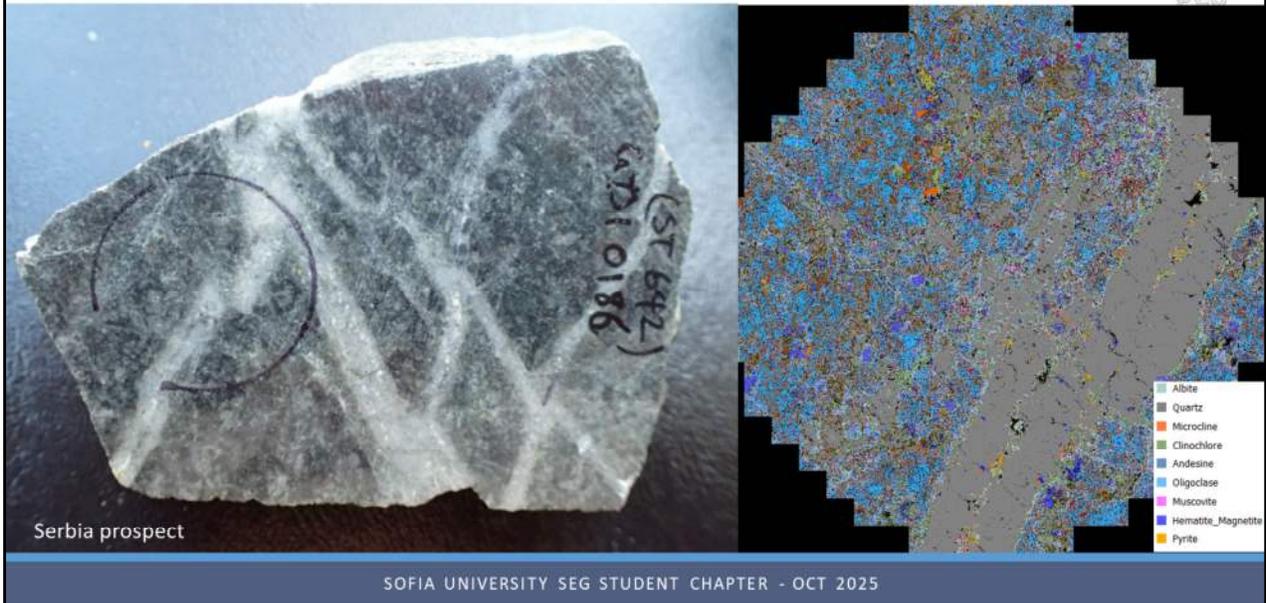
A similar looking sequence with A veins, maricunga-like veins, breccias, and a super imposed base metal rich vein. Again no grade in the A-like veins.

Something interesting here is that if we look at the assays for all the samples with stockwork quartz veins (red points) we see that the modest amount of Cu that is in these rocks – at best 0.1-0.2% Cu - is covariant with Zn. That's not normal in a porphyry stockwork; but it is what you'd expect of the cooler conditions in an epithermal environment.

So again we touch on the idea that these low-grade or barren A-vein stockworks fail to make Cu sulfides because the brine doesn't have enough Cu in it to precipitate at high T.

Why do some porphyries make no ore?

Ti



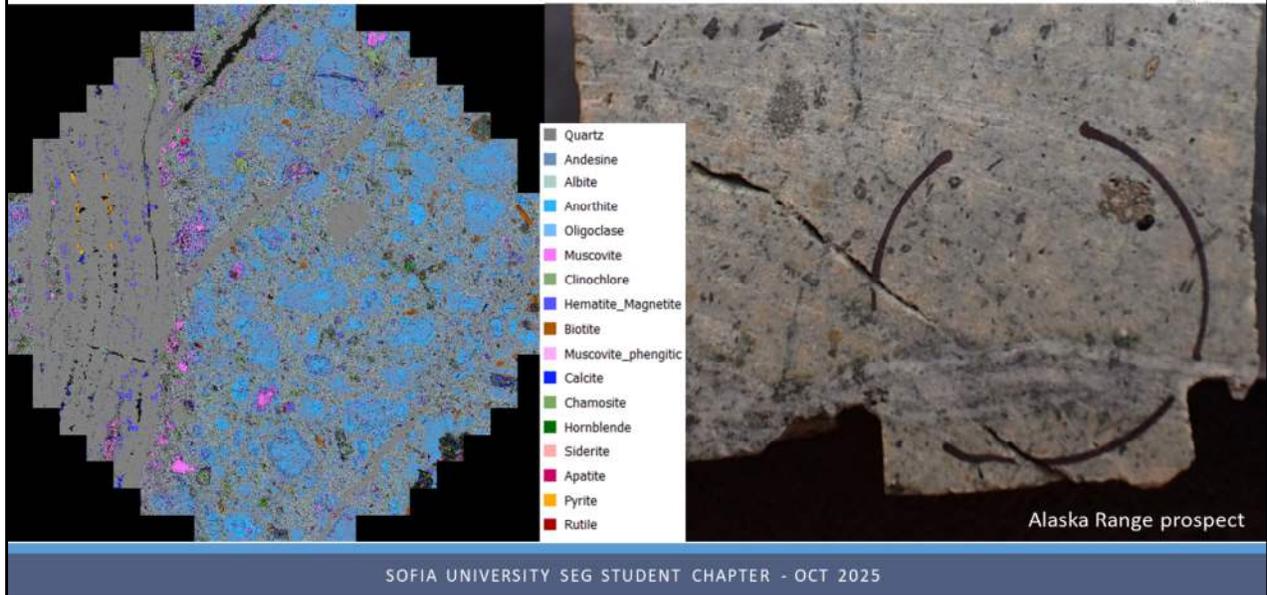
We investigated a lot of rocks with A-like veins to see if there were systematic patterns associated with grade.

Here's one from a failed prospect in Serbia.

Nice looking AB veins, not much sulfide though.

In detail, here represented by a TIMA false colour map, we can see almost no wallrock alteration. Specifically, almost no K-feldspar. There is some conversion of FeMg sites to biotite but little or no bulk K addition. This famous 'shreddy biotite' texture can easily form from reorganisation of K already in the rock. We can't claim this as convincing potassic alteration without evidence of bulk K addition, which is generally marked by the appearance of K feldspar.

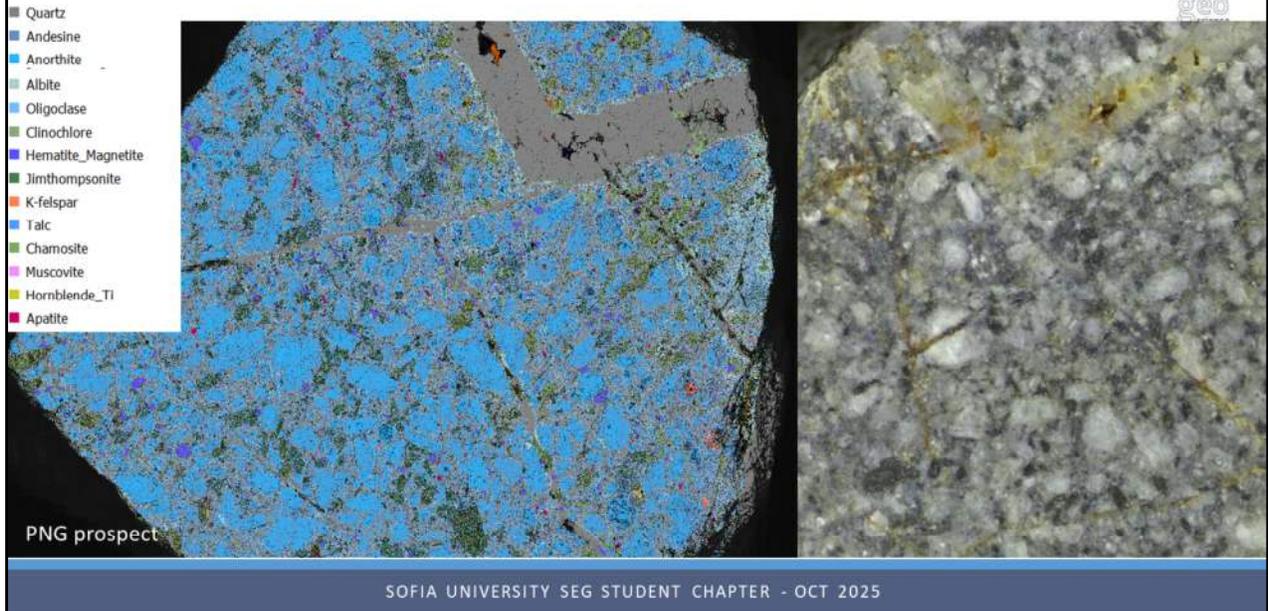
Why do some porphyries make no ore?



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Another, here a different prospect in Alaska.
Neat banded A-like vein with magnetite and pyrite in the seams, but the only alteration in the wallrock is minor muscovite

Why do some porphyries make no ore?

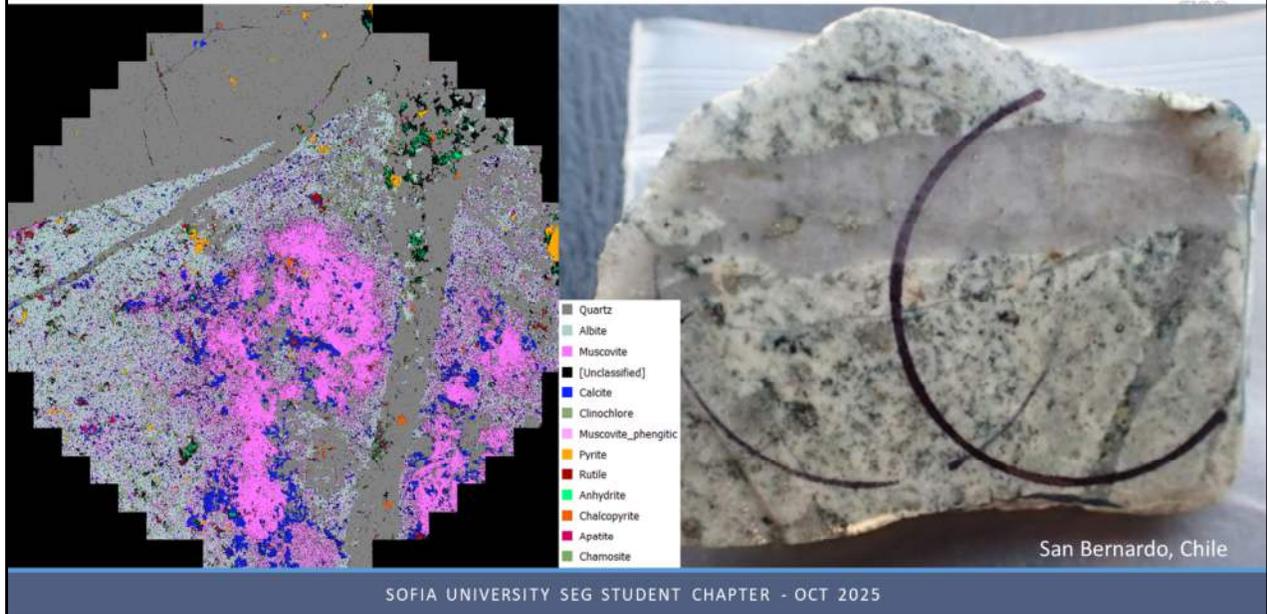


Another, from Papua New Guinea, with only very minor chlorite in the wallrock.

There's a recurring theme here of barren A veins with almost no wallrock alteration.

Why do some porphyries make no ore?

Ti

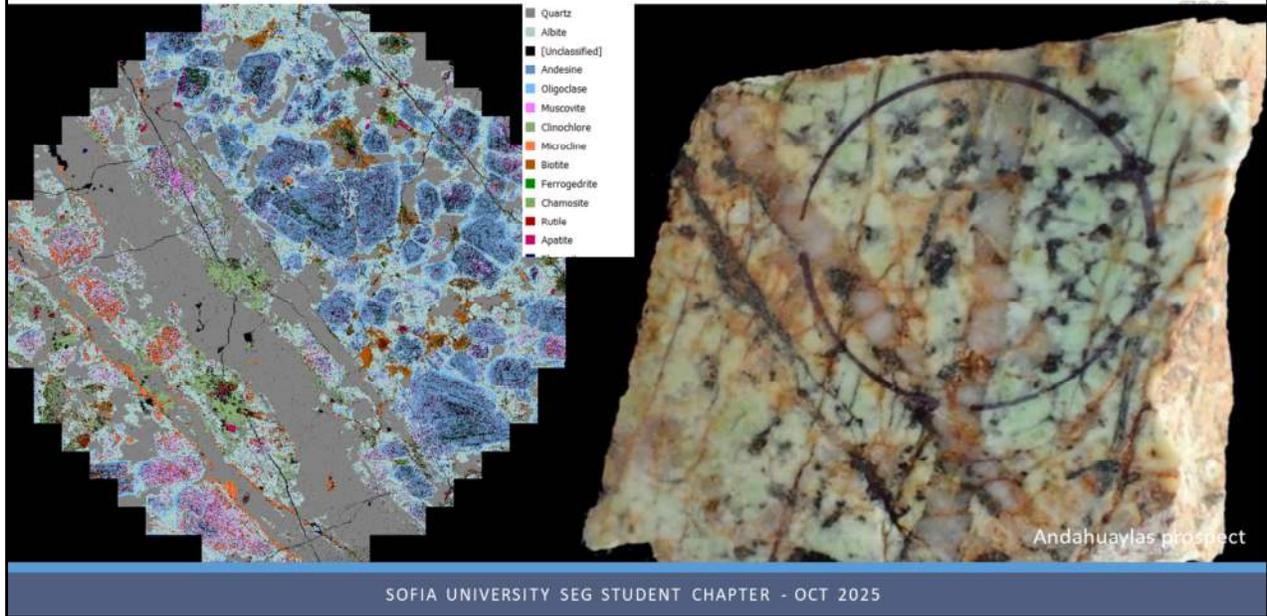


Here's a slightly better one, with some py, cpy and anhydrite in the A vein – overall grade in this deposit is ~0.1 or 0.2% Cu.

Alteration is dominated by albite and muscovite, minor chlorite.

Why do some porphyries make no ore?

Ti



Again, a transitional example, with low grade mineralisation in the veins, from Peru this time

Note the alteration associated with the veins is – again albite-muscovite, but here we see some K feldspar in the mix.

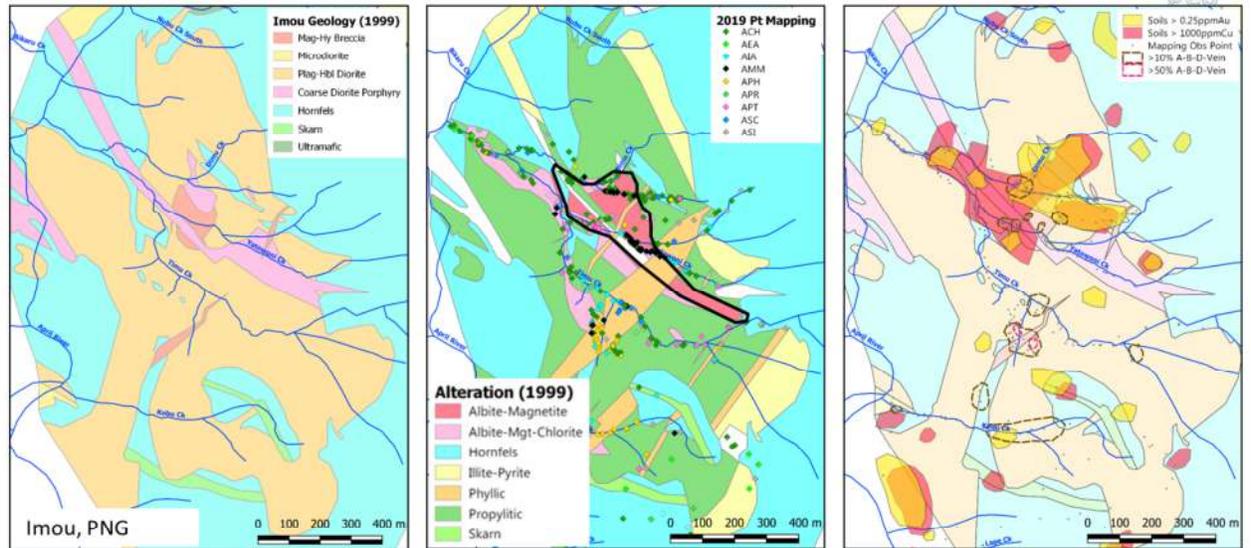
Why do some porphyries make no ore?



Another, here with some impressive copper, but not in the A veins. Wallrock alteration is pervasive albite-muscovite-(chlorite) as we've seen before for low-grade deposits.

We'll have closer look at this deposit because it's informative.

Why do some porphyries make no ore?



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Here are the prospect scale maps of this porphyry, rock units on the left, alteration centre and surface anomalies of Cu & Au at right.

Note that even in the original mapping the alteration was identified as magnetite-albite.

Surface metal anomalies are impressive; >0.25 ppm Au over significant areas, but interestingly these don't neatly correspond to the mapped loci of quartz vein density.

Why do some porphyries make no ore (where we expect it)? Ti



Here are the results of drilling at that project, again left to right is proximal to distal

- Barren, or almost-barren A-like Qtz-magnetite veins
- Barren A-like veins + albite, with magnetite and shreddy 'reorganised' biotite in the wallrocks (but no strong K addition)
- Typical B-type veins in the intrusion
- Then we see a shift to veins that lack quartz:
- Cpy-bn fracture paints, these seem transitional to anhydrite-sulfide veins, and vein breccias. It is this part of the paragenesis that dominates Cu distribution on the deposit (overall grade ~0.26 % Cu)
- and then late barren D veins, as always

So what I hope I've shown is a range of scenarios associated with A-vein development where the alteration and Cu precipitation are not quite what the Sillitonian model predicts. We've seen cases with almost no alteration and no Cu, and cases with albite-sericite in place of potassic, generally related to low grade porphyry orebodies. In all cases, we see Cu precipitation delayed in the paragenesis, and pushed further away from the centre of the zoned alteration: in this case on screen the Cu mainly precipitated during the brittle anhydrite stage, whereas at the extreme Cu doesn't precipitate until it meets Fe-rich or neutralising wallrocks in a propylitic or skarn environment.

Why do some porphyries make no ore?



Model: implies that processes that lead to origin of porphyry-style veins and alteration (A veins + feldspar alteration, D veins + phyllic alteration etc)... also permit Cu mobility and precipitation

Reality: wide range of porphyry-like alteration/vein assemblages that look similar.

- A-vein stockwork is possible with
 - no feldspar alteration (usually barren)
 - albite-muscovite, rather than K-feldspar (usually low grade)

System concentrates water and Si before Na, and Na before K. Cu concentration begins with Na salts but is best among K salts

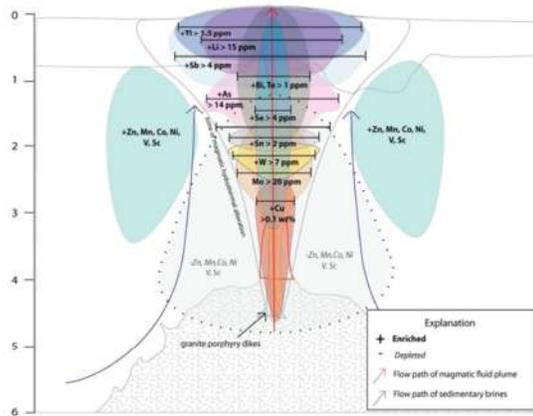
- Cu tends to precipitate late: in breccias (+tourm, anhydrite), skarns or propylitic alteration

If Cu concentration in magmatic water is low; Cu does not precipitate in high-T setting.

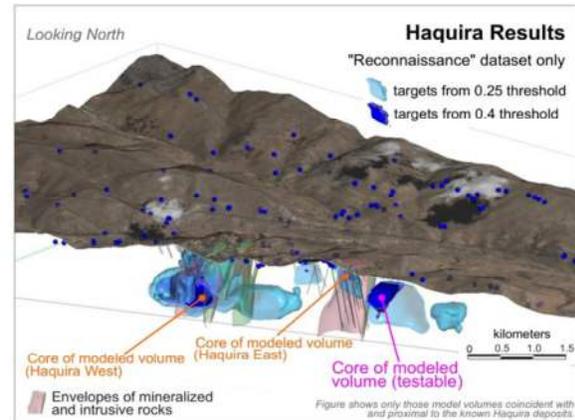
What do chemical anomaly patterns mean?



Model: the presence of zoned peripheral alteration and pathfinder element anomalies (Halley et al, 2015) *implies presence of a mineralised stockwork*



<https://www.fathomgeophysics.com/geochemfootprint.html>



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So let's move to a related subject, especially relevant to exploration geochemistry.

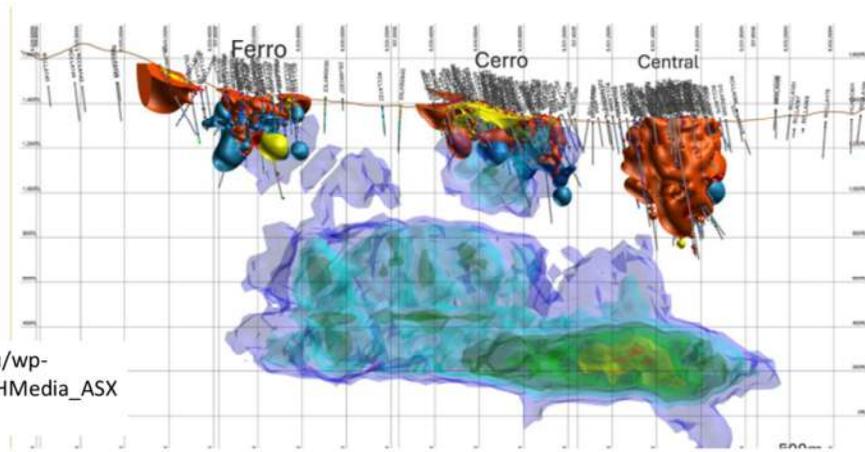
Halley's 2015 model is now very widely used, and if the absolute anomaly thresholds for certain elements are interpreted as evidence of spatial distance from ore, then a whole rock multielement dataset can be converted into a 3D model where each voxel can be assigned a score that is the proportion of distance-to-anomaly tests that it satisfies.

This is a service you can buy.

What do chemical anomaly patterns mean?



Model: the presence of zoned peripheral alteration and pathfinder element anomalies (Halley et al, 2015) *implies presence of a mineralised stockwork*



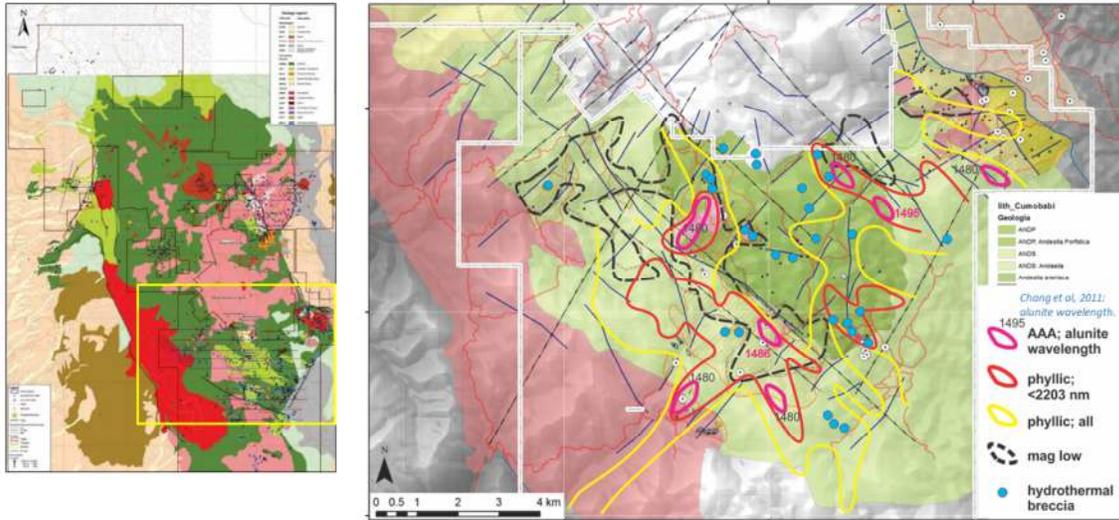
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...and people do.

Here's a recent example from a project in Chile. The modelling yields this lovely attractive target blob that begs to be drilled (nevermind that it's 2.5 km down).

We were involved in the development and testing of this method, and it yields logical results that honour the model predictions.. However I know from experience these anomalies it yields are often not porphyry ore.

What do chemical anomaly patterns mean?



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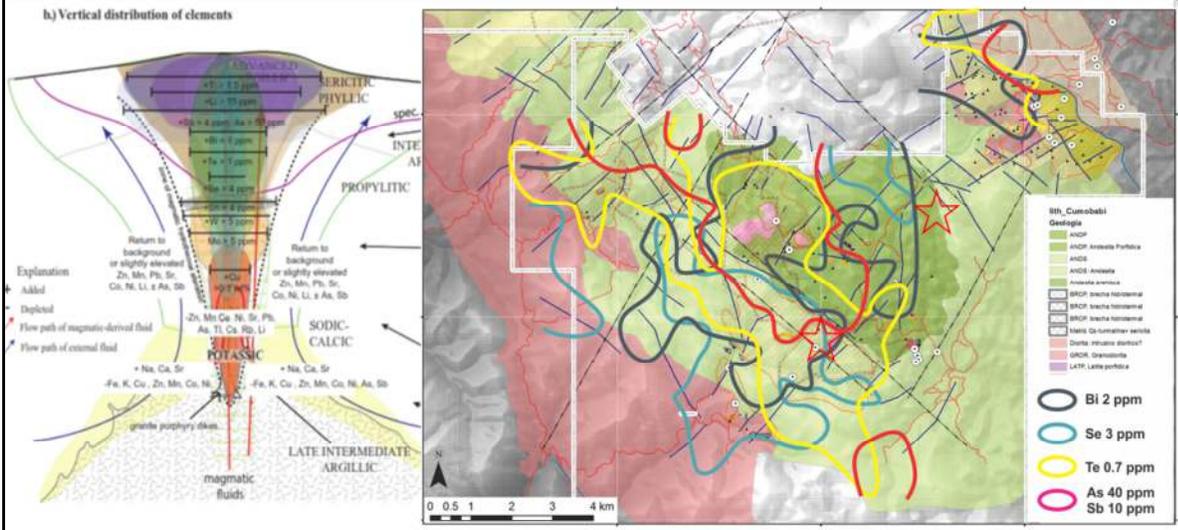
So here's a real world example from the Laramide.

Map at left shows a general erosional setting of fertile plutons and porphyries intruding their own volcanic pile. Generally the strata dip gently NE, so we're looking at a kind of section, with intrusions in the SW, and shallower volcanics to the NE.

In detail, here the mappable surface alteration is represented, warmer colours indicating stronger acid. Advanced argillic minerals are rare, but two alunite occurrences have very long w1480, suggesting high T and possible overlap of the deepest AA on an otherwise mainly phyllic environment.

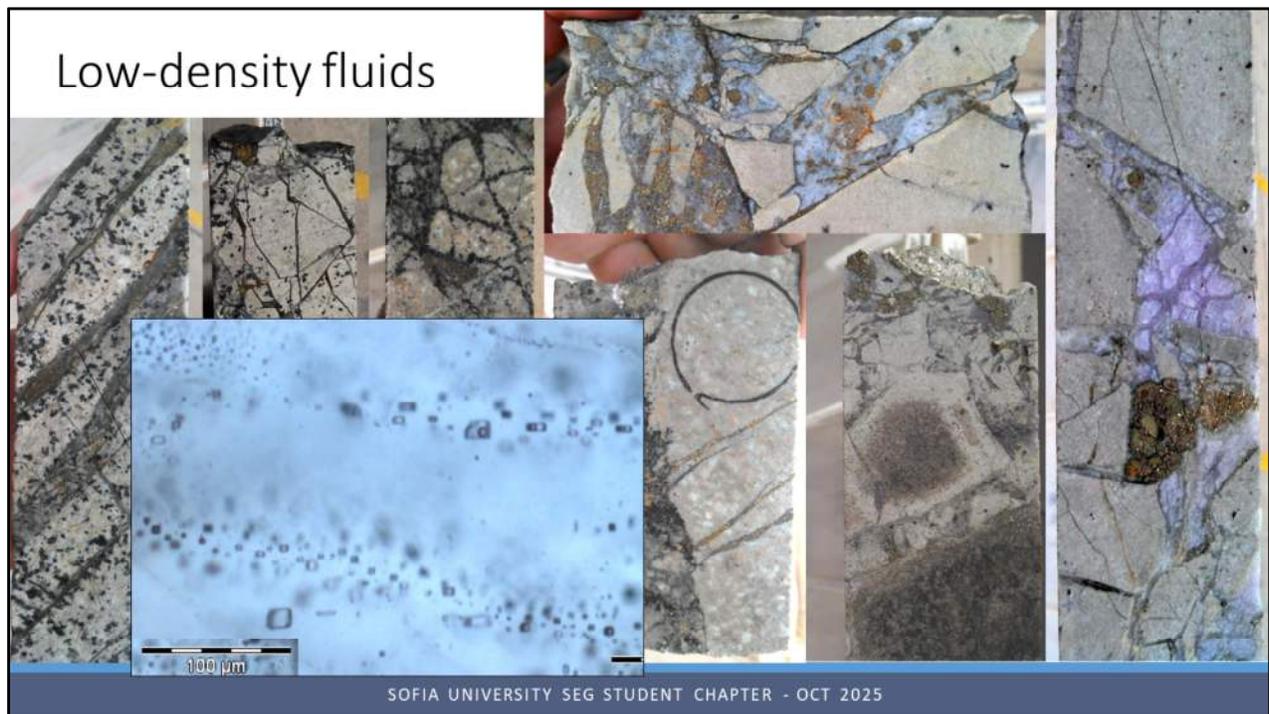
Veining isn't common at this project, but instead the area is punctuated by many tourmaline cemented breccias (blue dots)

What do chemical anomaly patterns mean?



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- If we look at distribution of some key elements from the Halley model:
- As & Sb are broadest and generally match the most acidic alteration and shallowest strata
 - Te & Bi are similar but somewhat more restricted and offset into the deeper volcanic strata, and
 - Se is distinctly offset deeper than As



So what's going on?

There are numerous drill holes into this project, and the best of them look like this: Veins and various breccia facies dominated by tourmaline and anhydrite, with abundant pyrite in the hydrothermal fill.

Notably lacking here are quartz veins, and even true D veins are scarce.

Phyllic alteration tends to be pervasive and preserves primary textures, which is a typical feature of epithermal gas-driven alteration.

We investigated the fluid inclusions in the anhydrite and they're all low-salinity: no brine.

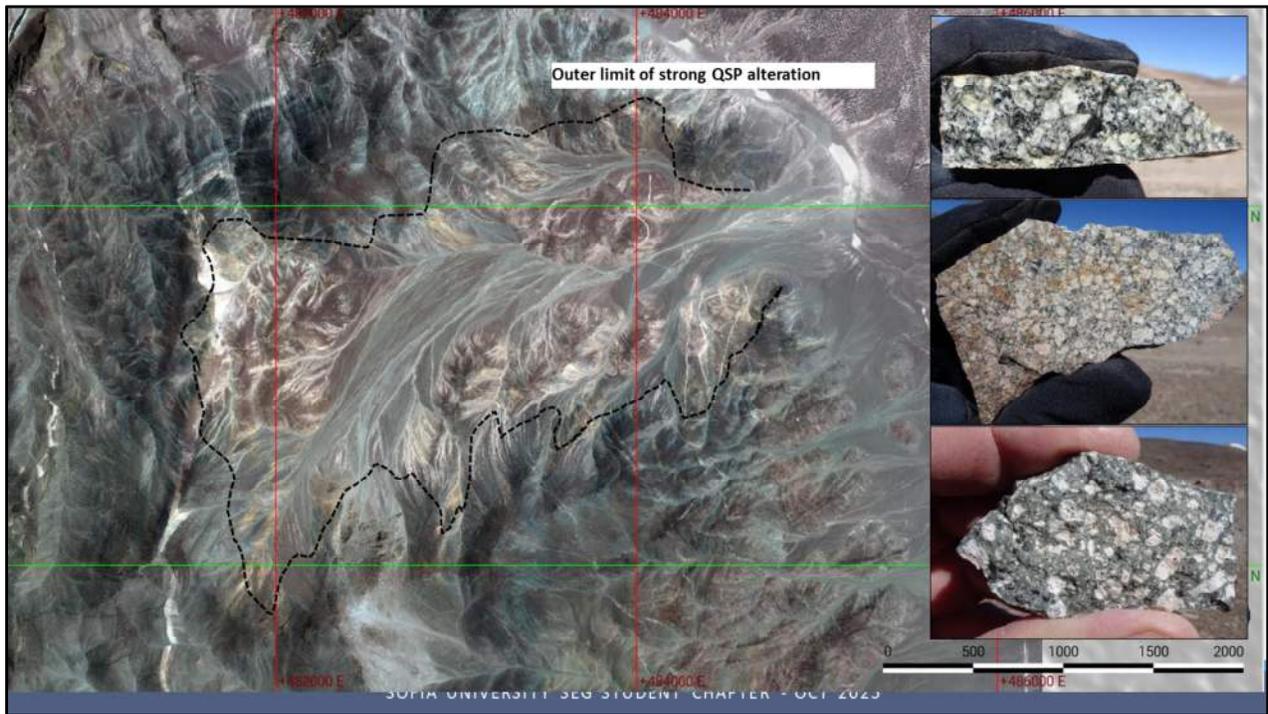
So this leads to a conclusion that the chemical plume of Mo, Se, Te, Bi, As, Sb etc can be generated by a magmatic gas with no brine. That would be the case if exsolution happened really shallow, or if the magma had not yet evolved to the point of concentrating much silica or salt; ie more or less typical fumarolic behaviour of degassing subvolcanic magma chamber.

Somewhere in Argentina

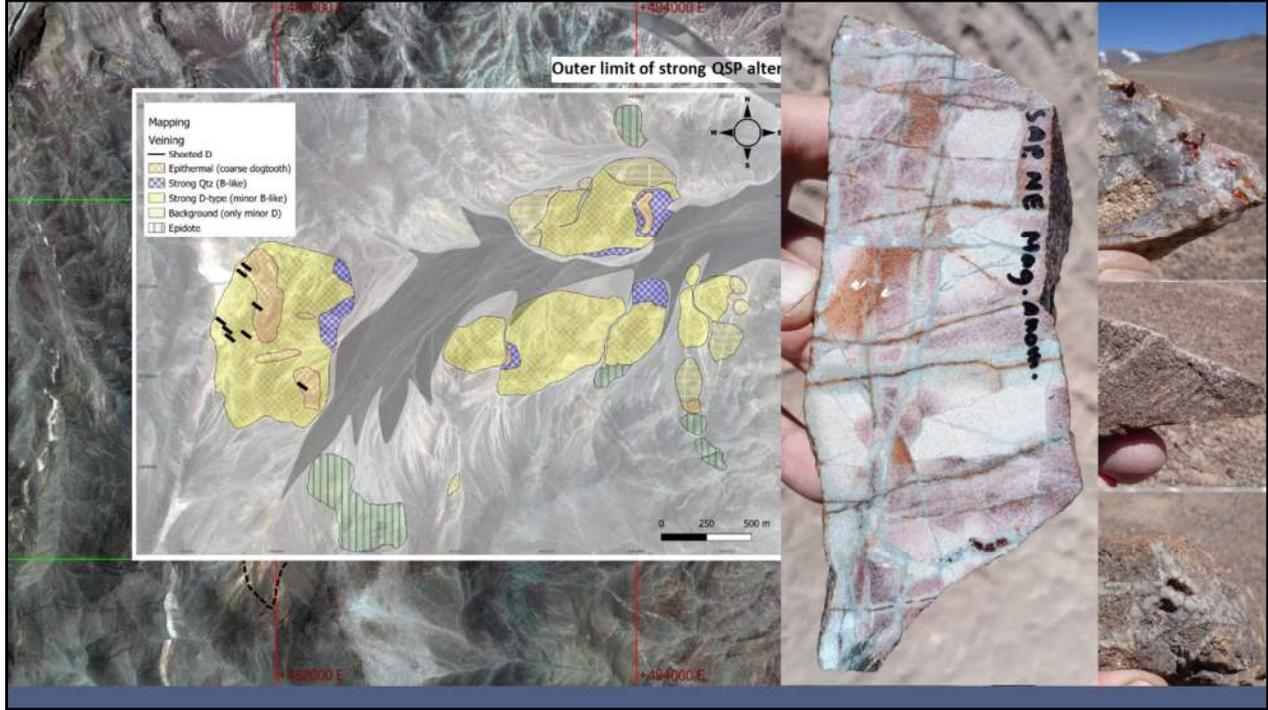


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So now, a quick run through of how this can play out in real life.
Let's go somewhere in Argentina...

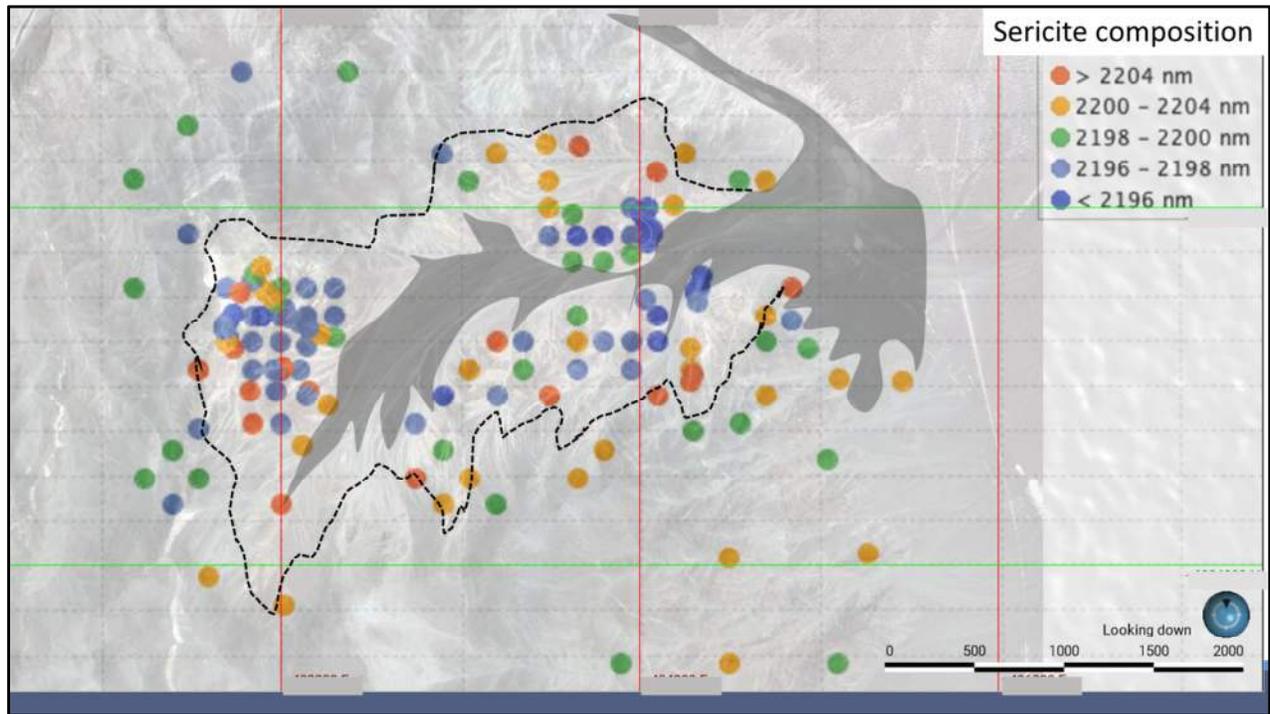


Nice spot; large 4 x 2 km zone of phyllic alteration and obvious surface bleaching
Centre of the valley is covered by gravel, but where there is outcrop we observe mainly sedimentary rocks, with occasional porphyry granodiorite.

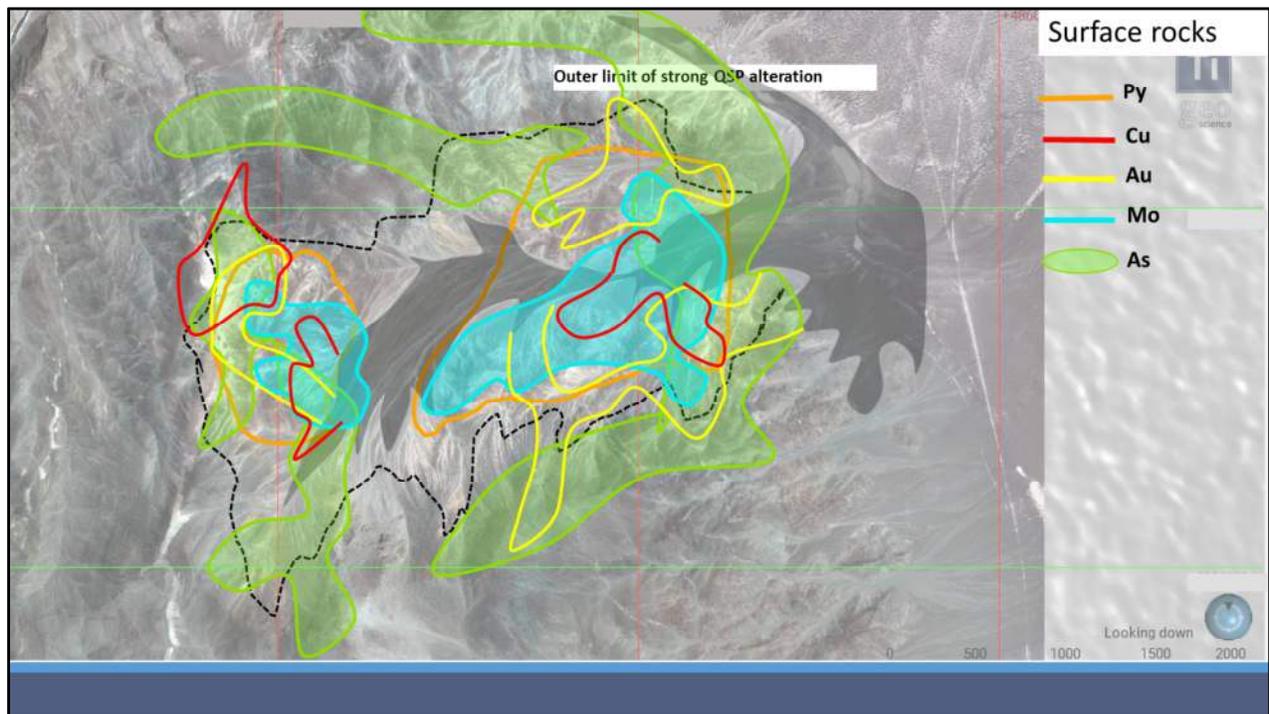


There are many recognisable vein elements:

- AB or B-like quartz veins; generally lacking sulfide (or oxise after sulfide) and sometimes with dogtooth open space fill. Areas with abundant ZVQ are in blue in the map.
- D veins; prominent as sheeted swarms associated with other brittle structures. These are generally present to some extent through the core of the altered, bleached zone (yellow on map)

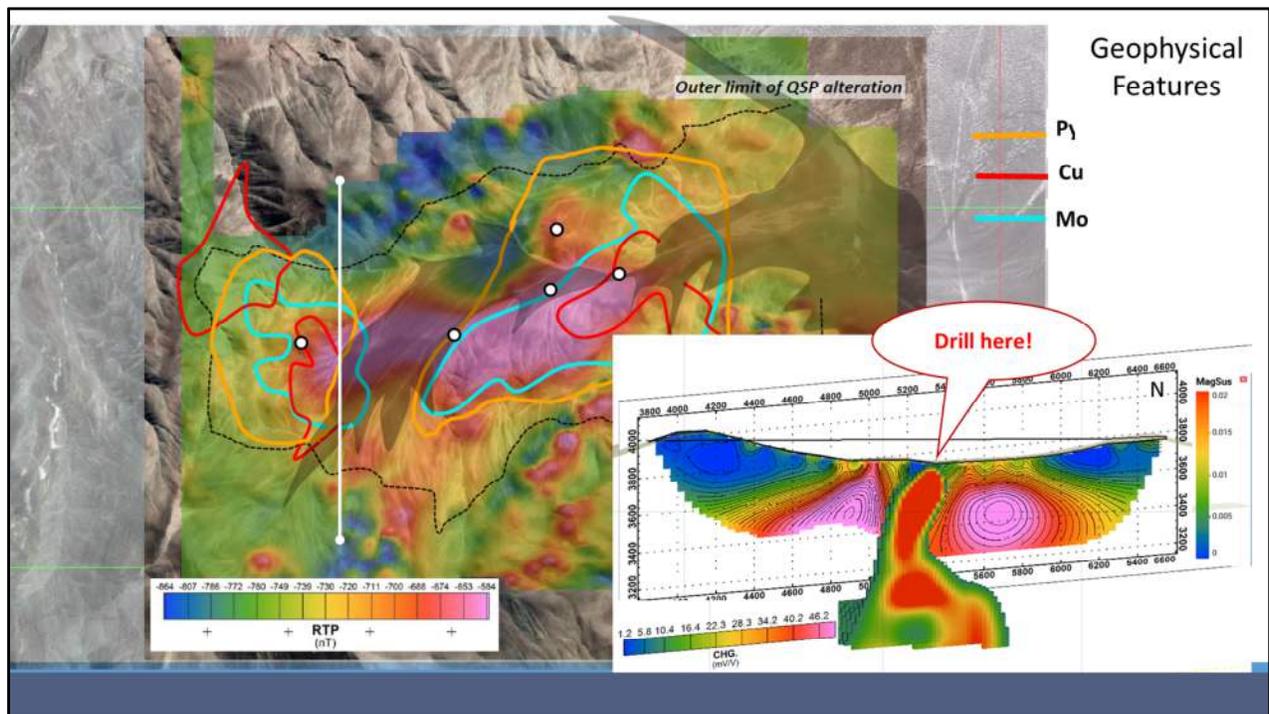


Some detail of the sericitic alteration: SWIR w2200 feature to indicate Al-rich v FeMg-rich sericites.
 This reveals Al-rich (stronger acid) in the same areas with more abundant veins



So this is all lining up quite nicely, and if we look at the more volatile pathfinders, eg As, it is mostly distributed around the outside, as Halley's model predicts...

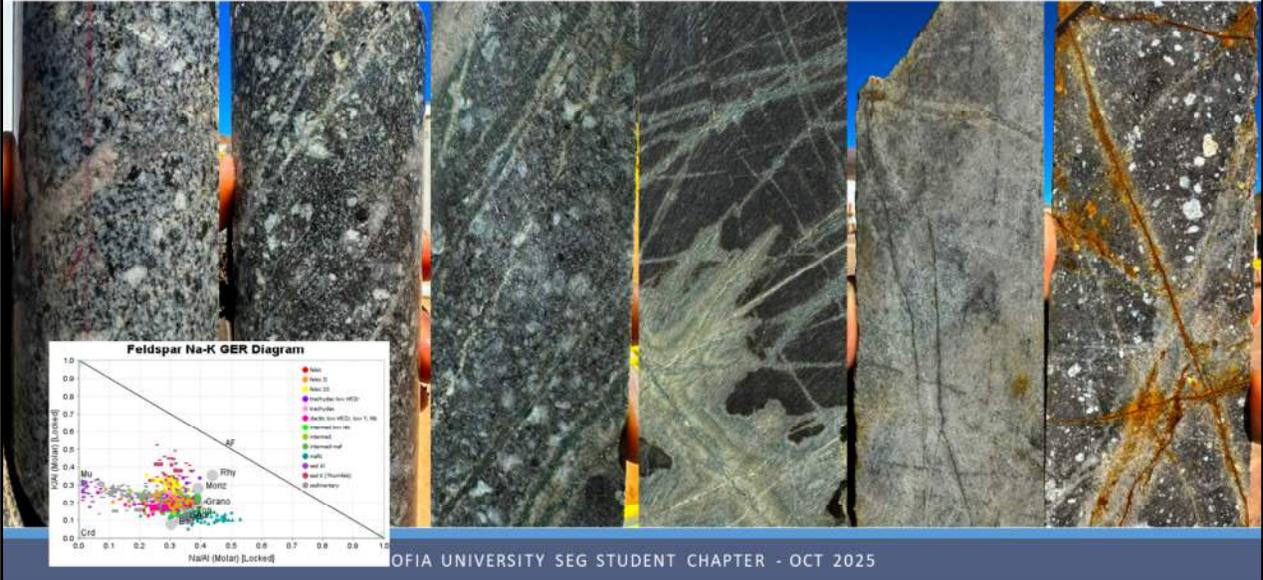
Though the sharper-eyed among you will note most of this anomaly is outside the pyritic, phyllic alteration... so what mineral hosts the As?



Add in the geophysical aspects and this target is looking excellent:

- Magnetic anomaly sits underneath the main chemical and vein density target. Note though the amplitude of the magnetic anomaly is only 200 nT (not the 700-2000 nT of strong magnetite-bearing potassic alteration)
- IP lines across this zone yields strong chargeability corresponding to the D-vein & phyllic alteration as the model predicts.

Somewhere in Argentina (that will not be a mine)



And so we drill...

For these rocks:

- Various porphyritic diorite to granodiorite, as observed in outcrop. Weak redistributive shreddy biotite, very minor fine A-like quartz veins. Some chlorite-veins, possible chl-albite.
- Very distinct hornfels in some sedimentary wallrocks, with many D-like veins, as hornfels is brittle.
- Less well developed hornfels with D-like veins in sandstone
- And some late open-texture porphyry dykes also with D veinlets.

No Cu.

Looking at the alkali-alumina relations in the assays, we can see there's basically no potassium alteration.

Some in the hornfels, and that's it.

The rest of the alteration extends from muscovitic in the D vein zones to weak albite in some of the mafic dykes.

What do chemical anomaly patterns mean?



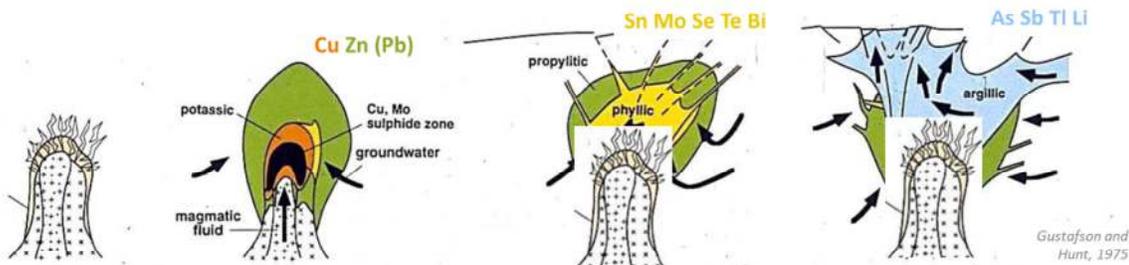
Model: the presence of zoned peripheral alteration and pathfinder element anomalies (Halley et al, 2015) *implies presence of a mineralised stockwork*

Reality: Zoned patterns of pathfinder element distribution from Mo through Tl can be generated by gases or dilute fluids.

These are generally associated with pervasive texture-preserving sericite +/- sulfate-tourmaline gangue.



Zoned pathfinder anomalies serve as vectors to fluid flow paths, but do NOT imply presence of a porphyry stockwork.



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So the reality is that Halley-esque zoned patterns of pathfinder element distribution from Moly through Thallium do NOT demand that there's a porphyry at the centre. It seems that they can form from both simple gas-phase devolatilisation of an undercooked chamber, or porphyry processes with an infertile Na-rich brine lacking Cu & K.

Rather than being unique to a porphyry, they are perhaps a kind of warm-up and/or cool-down phase that can happen without the system evolving to temperatures or fluid compositions required for porphyry formation. Every porphyry has one, but not every pathfinder plume is a porphyry. Like squares and rectangles.

There is lots of hydrothermal background that is useful in vectoring to a *possible* porphyry centre, but is not uniquely indicative of a porphyry Cu deposit.

Porphyry ore deposits have two main classes based on depth of emplacement (A- & EH-). This changes their geological and geophysical appearance.