# Sistemas Hidrotermais e Metalogênese

GSA 0407

Caetano Juliani
(cjuliani@usp.br)
Lena Virgínia Soares Monteiro
(lena.monteiro@usp.br)

Departamento de Geologia Sedimentar e Ambiental
2019

# OBJETIVOS DO CURSO

Propiciar conhecimentos básicos sobre sistemas hidrotermais em ambientes geológicos, bem como seu reconhecimento em terrenos antigos

Estudar a gênese, evolução e tipos de fluidos hidrotermais e os estilos da alteração hidrotermal.

Definir os tipos e zonamentos das fácies de alteração em sistemas hidrotermais e as mineralizações associadas.

Analisar os ambientes geológicos e seus potenciais para mineralizações magmáticas-hidrotermais.

Discutir alguns critérios para exploração mineral em terrenos não metamórficos e metamórficos.

# PROGRAMA

1) Introdução. Conceitos. Fluidos hidrotermais, interação fluido-rocha e alteração hidrotermal.
2) Origem e evolução de sistemas hidrotermais. Classificação e tipos de sistemas hidrotermais. Telescopagem em sistemas hidrotermais.
3) Tipos e estilos de alteração hidrotermal. Metassomatismo sódico e potássico, sericitização, propilitização, alteração argílica, cloritização, carbonatização, silicificação, etc.
4) Alteração hidrotermal e mineralizações em depósitos epitermais, do tipo pórfiro cálcio-alcalinos oxidados e reduzidos e em granitóides alcalinos.
5) Magmatismo associados às mineralizações epitermais, pórfiros e IRGS. A importância dos eventos de *flat-subduction*. Zonamento tectônico, evolução tectono-magmática e estruturas tectônicas. Formação de complexos de caldeiras vulcânicas e sua relação com mineralizações magmática-hidrotermais.
6) *Intrusion Related Gold Systems* (IRGS) e *skarns*
7) Sistemas vulcano-exalativos (VHMS)
8) Alterações hidrotermais em depósitos Sedimentares Exalativos (SEDEX) e Mississippi Valley (MTV).
9) Alterações hidrotermais em depósitos do tipo Carlin e do tipo orogênico de metais preciosos
10) Alterações hidrotermais em depósitos de óxido de ferro-cobre-ouro (IOCG)
11) Critérios gerais para exploração mineral. Índices geoquímicos de alteração hidrotermal. Exemplos de sistemas hidrotermais em depósitos minerais.
12) Produtos metamórficos de rochas alteradas hidrotermalmente em sistemas epitermais vulcano-plutônicos. Exemplos.

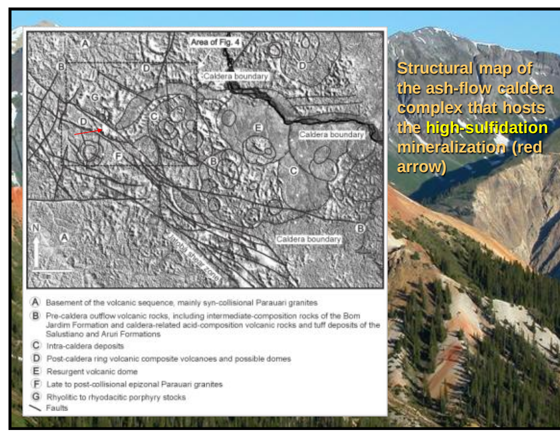
| AULA | DATA | ASSUNTO |
|---|---|---|
| 01 | 05/08 | Introdução. Conceitos. Fluidos hidrotermais, interação fluido-rocha e alteração hidrotermal. |
| 02 | 12/08 | Origem e evolução de sistemas hidrotermais. Classificação e tipos de sistemas hidrotermais. Telescopagem em sistemas hidrotermais. |
| 03 | 19/08 | Tipos e estilos de alteração hidrotermal. Metassomatismo sódico e potássico, alterações sódico–cálcica, propilititica, cloritica, sericitica, argílica e argílica avançada, carbonatização, silicificação, etc. |
| 04 | 26/08 | Magmatismo associados às mineralizações epitermais, pórfiros e IRGS. A importância dos eventos de *flat-subduction*. Zonamento tectônico, evolução tectono-magmática e estruturas tectônicas. Formação de complexos de caldeiras vulcânicas e sua relação com mineralizações magmática-hidrotermais. |
| | 02/09 | **Não haverá aula – Proclamação da Indepedência - Semana de aulas em campo** |
| 05 | 09/09 | Alteração hidrotermal e mineralizações em depósitos epitermais; em depósitos do tipo pórfiro cálcio-alcalinos oxidados e reduzidos e em granitóides alcalinos. |
| 06 | 16/09 | *Intrusion Related Gold Systems* (IRGS) e *skarns*. |
| 07 | 23/09 | Alterações hidrotermais em depósitos de óxido de ferro-cobre-ouro (IOCG). |
| | 30/09 | **PROVA 1** |
| 08 | 07/10 | Sistemas vulcano-exalativos submarinos (depósitos VHMS). |
| | 14/10 | **Não haverá aula – Dia da Padroeira do Brasil - Semana de aulas de campo** |
| 09 | 21/10 | Alterações hidrotermais em depósitos do tipo Carlin e do tipo orogênico de metais preciosos. |
| | 28/10 | **Não haverá aula – Feriado** |
| 10 | 04/11 | Alterações hidrotermais em depósitos Sedimentares Exalativos (SEDEX ou CD) e Mississippi Valley (MTV). |
| 11 | 11/11 | Critérios gerais para exploração mineral. Índices geoquímicos de alteração hidrotermal. Exemplos de sistemas hidrotermais em depósitos minerais. |
| | 18/11 | **Feriado - Dia da consciência negra** |
| 12 | 25/11 | Produtos metamórficos de rochas alteradas hidrotermalmente em sistemas epitermais vulcano-plutônicos. Exemplos. |
| | 02/12 | **APRESENTAÇÃO E DISCUSSÃO DOS SEMINÁRIOS** |

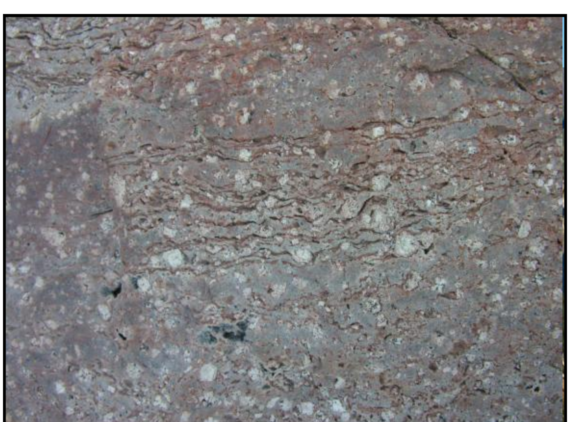

Fumarolas


Sublimação de Enxofre

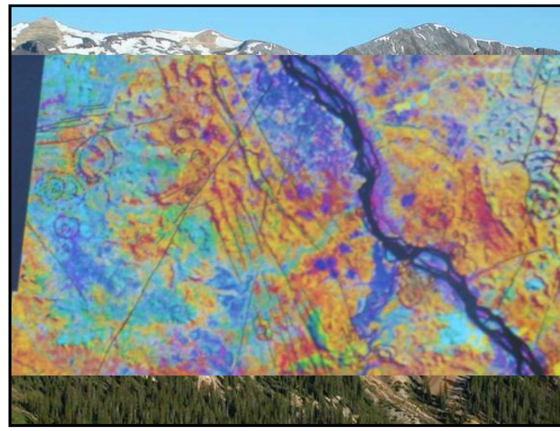

Principal motivação para o curso

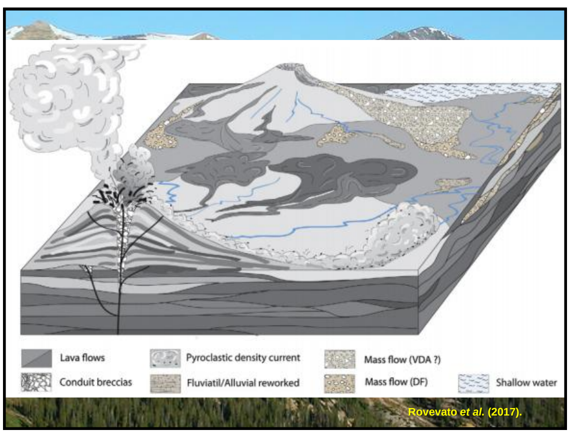

VULCANISMO UATUMÃ, AMAZÔNIA (ca. 2,0 a 1,87 Ga.)

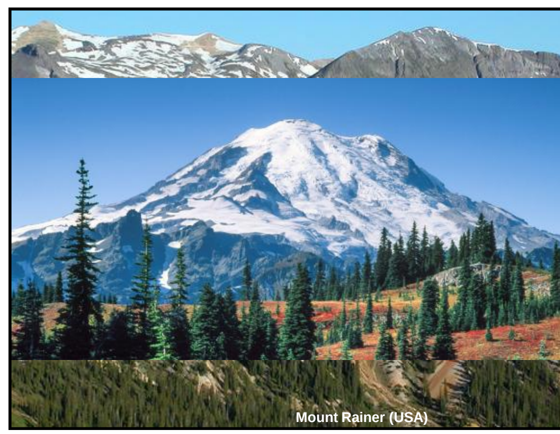

Area of Fig. 4
Caldera boundary
Caldera boundary
Caldera boundary
Jatobá shear zone
A Basement of the volcanic sequence, mainly syn-collisional Parauari granites
B Pre-caldera outflow volcanic rocks, including intermediate-composition rocks of the Bom Jardim Formation and caldera-related acid-composition volcanic rocks and tuff deposits of the Salustiano and Aruri Formations
C Intra-caldera deposits
D Post-caldera ring volcanic composite volcanoes and possible domes
E Resurgent volcanic dome
F Late to post-collisional epizonal Parauari granites
G Rhyolitic to rhyodacitic porphyry stocks
Faults
Structural map of the ash-flow caldera complex that hosts the high-sulfidation mineralization (red arrow)

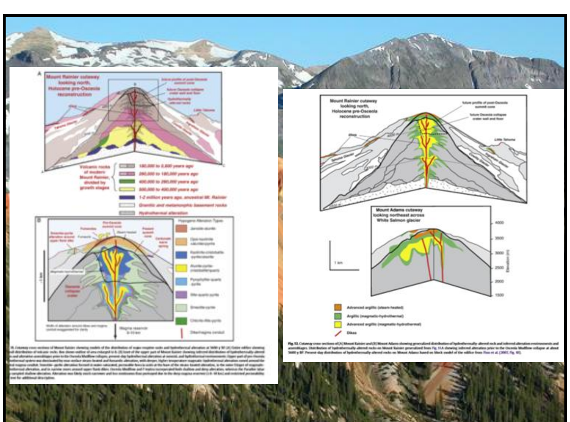


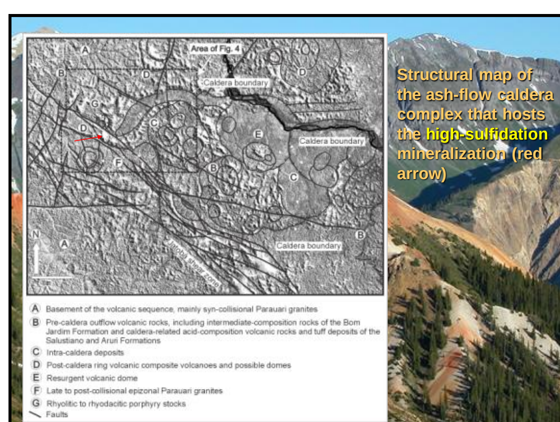

Vulcão Villarrica (Chile)

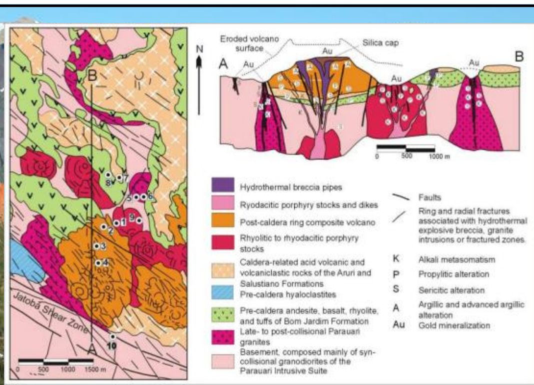



Lava flows
Pyroclastic density current
Mass flow (VDA ?)
Conduit breccias
Fluviatil/Alluvial reworked
Mass flow (DF)
Shallow water
Rovevato et al. (2017).

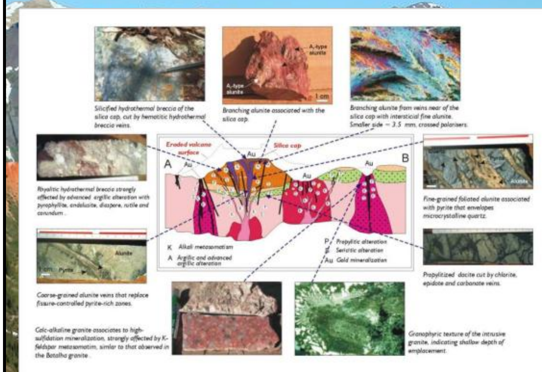

Mount Rainer (USA)



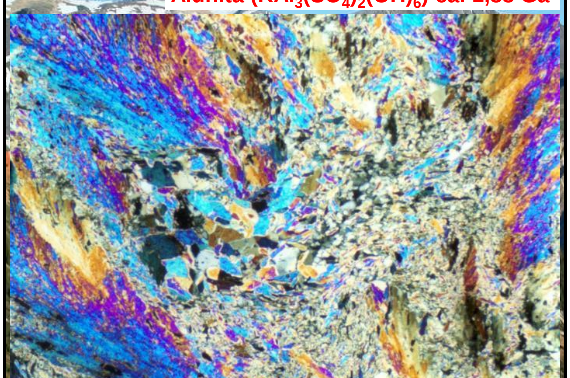

Structural map of the ash-flow caldera complex that hosts the high-sulfidation mineralization (red arrow)
Area of Fig. 4
Caldera boundary
Caldera boundary
Caldera boundary
Jatobá shear zone
A Basement of the volcanic sequence, mainly syn-collisional Parauari granites
B Pre-caldera outflow volcanic rocks, including intermediate-composition rocks of the Bom Jardim Formation and caldera-related acid-composition volcanic rocks and tuff deposits of the Salustiano and Aruri Formations
C Intra-caldera deposits
D Post-caldera ring volcanic composite volcanoes and possible domes
E Resurgent volcanic dome
F Late to post-collisional epizonal Parauari granites
G Rhyolitic to rhyodacitic porphyry stocks
Faults

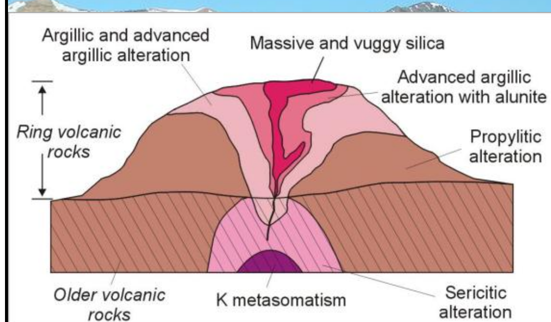



Schematic cross-section of the high-sulfidation mineralization (Juliani *et al.*, 2005)

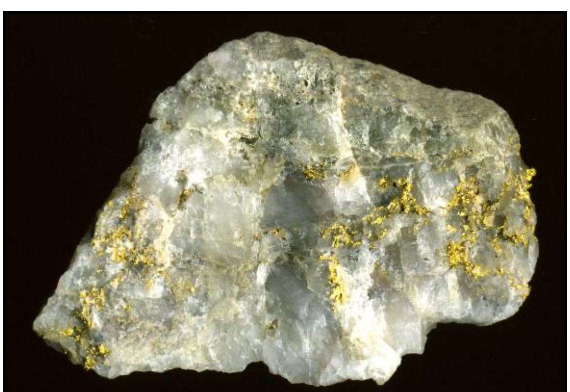



Alunita ($KAl_3(SO_4)_2(OH)_6$) ca. 1,88 Ga





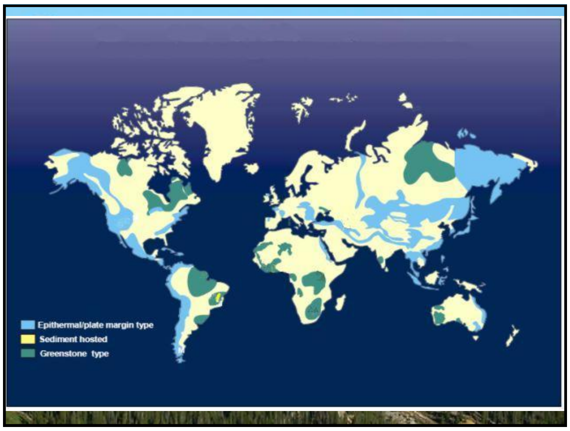

Schematic reconstruction of the hydrothermal alteration zones in the high-sulfidation mineralization (Juliani et al., 2005)



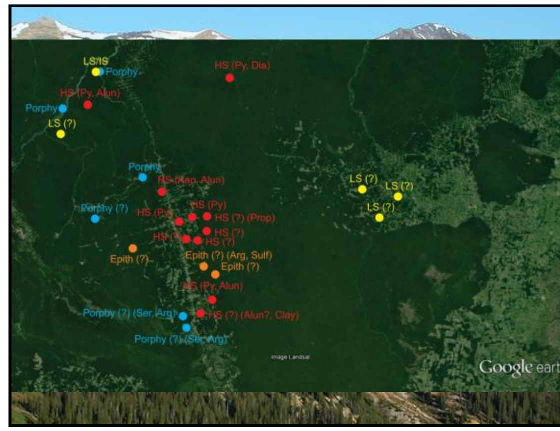
By James St. John - Hydrothermal quartz-gold vein (Mother Lode Gold Ore, California) 1, CC BY 2.0, (https://commons.wikimedia.org/w/index.php?curid=34369741)

Em terrenos antigos, a superposição de eventos orogenéticos, metamorfismo e exumação favorecem a ocorrência de DEPÓSITOS MESOTERMAIS, em detrimento aos típicos depósitos de arcos magmáticos, representados pelos epitermais vulcanogênicos e pelos pórfiros

Apesar dessas premissas serem corretas, a descoberta de mineralizações epitermais *HIGH- e LOW-SULFIDATION* e do tipo PÓRFIRO paleoproterozóicos na Província Aurífera do Tapajós, Iriri e Xingu *demonstram haver potencialidade de mineralizações desses tipos em arcos magmáticos antigos*

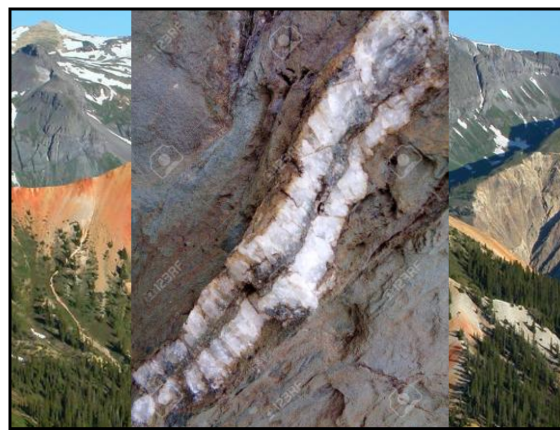


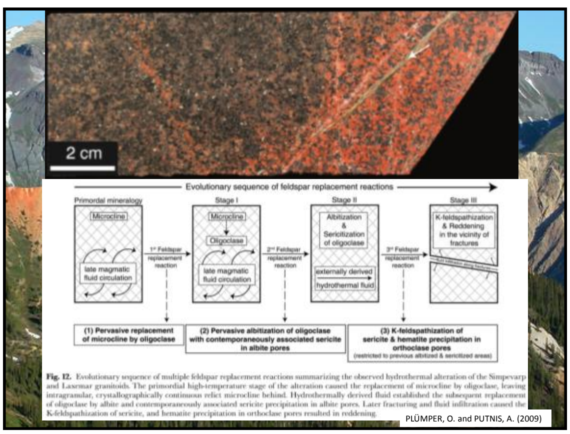
Epithermal/plate margin type
Sediment hosted
Greenstone type

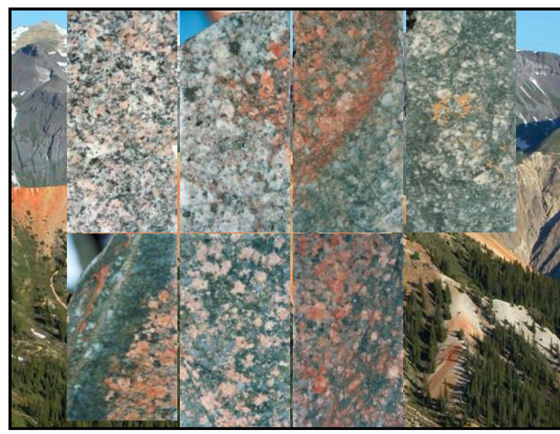



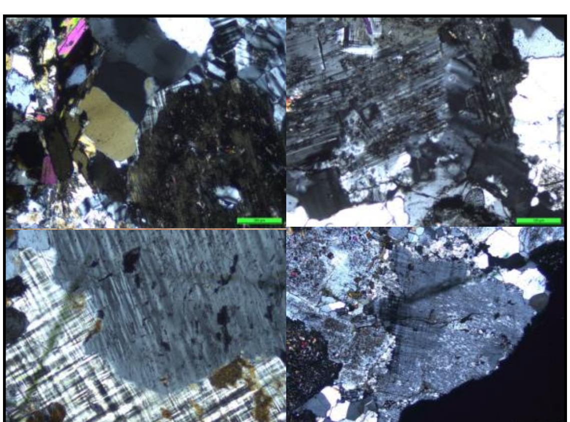
LS/IS
Porphy
HS (Py, Dia)
HS (Py, Alun)
Porphy
LS (?)
Porphy
HS (Kao, Alun)
LS (?)
LS (?)
LS (?)
Porphy (?)
HS (Py)
HS (Py)
HS (?) (Prop)
HS (?)
HS (?)
Epith (?)
Epith (?) (Arg, Sulf)
Epith (?)
HS (Py, Alun)
Porpby (?) (Ser, Arg)
HS (?) (Alun?, Clay)
Porphy (?) (Ser, Arg)
Image Landsat
Google earth

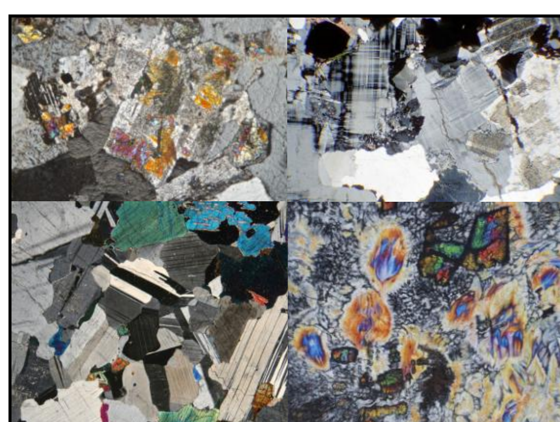

Mas, o que são alterações hidrotermais?

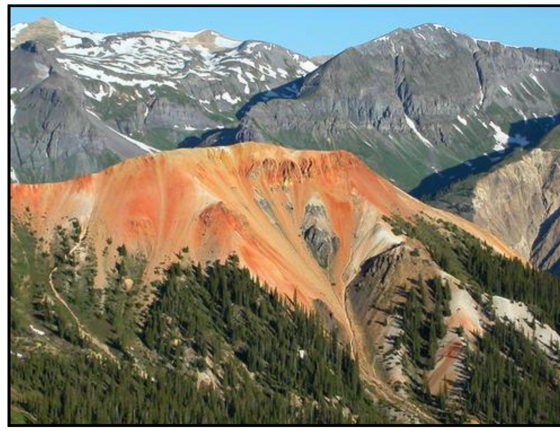



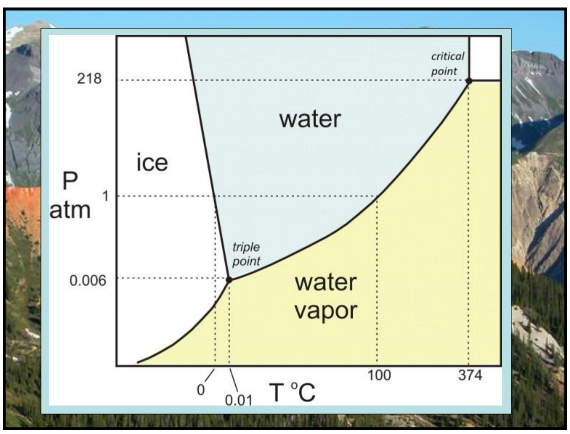

2 cm
Evolutionary sequence of feldspar replacement reactions
Primordial mineralogy
Microcline
late magmatic fluid circulation
1st Feldspar replacement reaction
Stage I
Microcline
Oligoclase
late magmatic fluid circulation
2nd Feldspar replacement reaction
Stage II
Albitization & Sericitization of oligoclase
externally derived hydrothermal fluid
3rd Feldspar replacement reaction
Stage III
K-feldspathization & Reddening in the vicinity of fractures
(1) Pervasive replacement of microcline by oligoclase
(2) Pervasive albitization of oligoclase with contemporaneously associated sericite in albite pores
(3) K-feldspathization of sericite & hematite precipitation in orthoclase pores
(restricted to previous albitized & sericitized areas)
Fig. 12. Evolutionary sequence of multiple feldspar replacement reactions summarizing the observed hydrothermal alteration of the Simpevarp and Laxemar granitoids. The primordial high-temperature stage of the alteration caused the replacement of microcline by oligoclase, leaving intragranular, crystallographically continuous relict microcline behind. Hydrothermally derived fluid established the subsequent replacement of oligoclase by albite and contemporaneously associated sericite precipitation in albite pores. Later fracturing and fluid infiltration caused the K-feldspathization of sericite, and hematite precipitation in orthoclase pores resulted in reddening.
PLÜMPER, O. and PUTNIS, A. (2009)

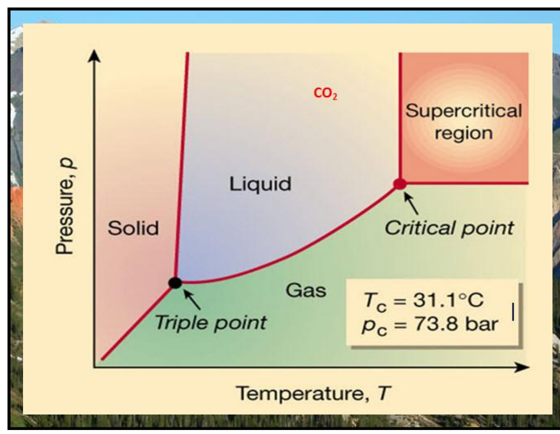


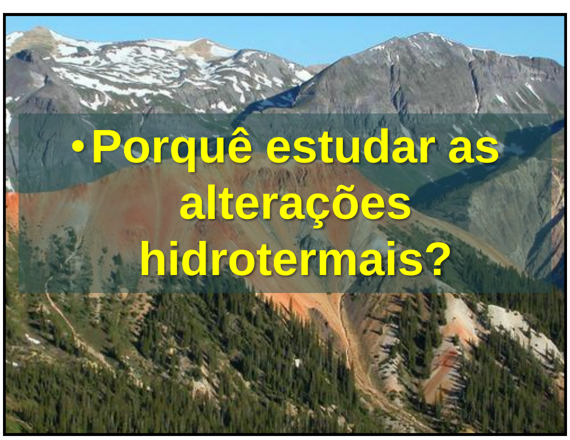




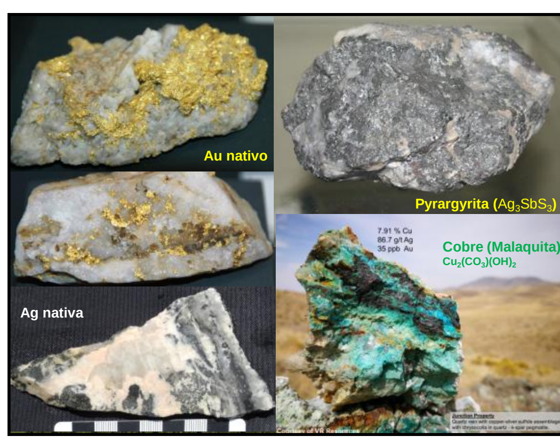




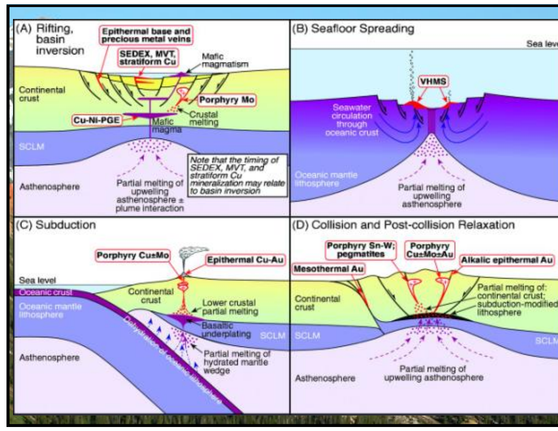



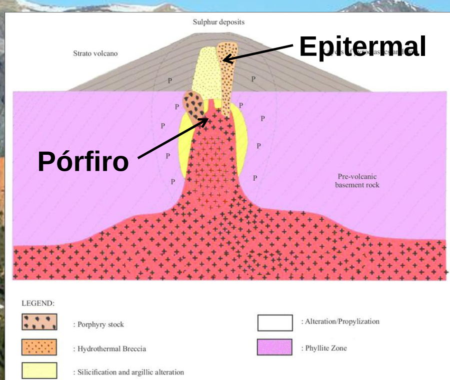
- Porquê estudar as alterações hidrotermais?

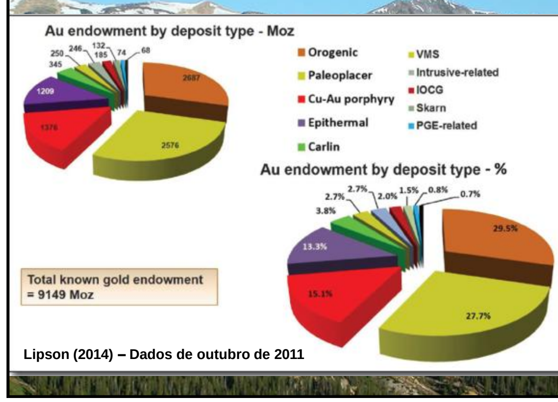


## TIPOS DE DEPÓSITOS MINERAIS RELACIONADOS À ALTERAÇÃO HIDROTERMAL

1) Pórfiros
2) Epitermais
3) Skarn
4) IOCG (*Iron Oxide Copper Gold*)
5) RIRGS (*Reduced Intrusion Related Gold System*)
6) Ouro orogênico
7) MVT (*Mississippi Valley Type*)
8) SEDEX (Sedimentary Hosted)
9) VMS (*Volcanic Massive Sulfide*)
10) Carlin
11) Associados a complexos alcalinos e carbonatitos
12) Etc, etc, etc……..



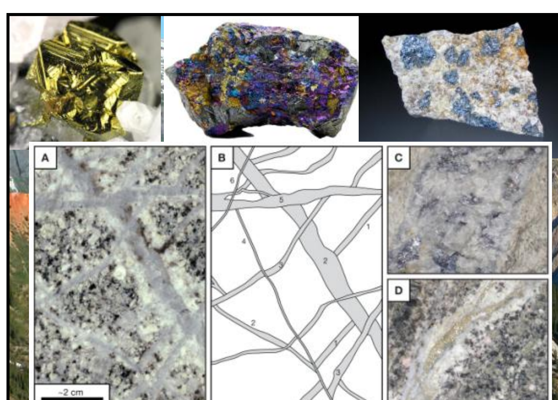




Lipson (2014) – Dados de outubro de 2011

## Mineralizações magmáticas-hidrotermais são fontes importantes de:

**Au, Ag, Hg, Zn, Pb, Cu, Cd, As, Sb, Bi, Se, Te, Ga, Ge, In, Tl, Mo e Sn**


Gruen *et al.* (2010) The Bingham Canyon Porphyry Cu-Mo-Au deposit. II. Vein geometry and ore shell formation by pressure-driven rock extension. Economic Geology,105(1): 69-90

## Porphyries - Bingham Canyon

- Most porphyries are too big and low grade to mine from underground. Usually open pitted.

## Binghan Canyon

330 a 500 t

Here are some of the biggest porphyries in the world you can see that these range in size from 2,000,000,000 tons up to Chuquicamata at a whopping 16,000,000,000

## O estudo da alteração hidrotermal é importante para:

1) Exploração mineral
2) Definição do modelo genético do depósito
3) Localização de corpos "cegos"
4) Localização de extensões de corpos de minérios em minas
5) Identificação de corpos satélites em *brown field*

## Além da exploração mineral:

Migração, geração e formação de *traps* para petróleo (Pré-sal)

Recuperação ambiental (drenagem ácida, etc)

Guzzo *et al.* (2018) Hydrothermal petroleums and solid reservoir bitumens: recognition of an atypical petroleum system in the Brazilian Pre-salt deposits (Santos Basin) November 2018

Conference: XV Latin American Congress on Organic GeochemistryAt: Salvador, Bahia, Brazil


Extensão das Alterações Hidrotermais e Vetorização

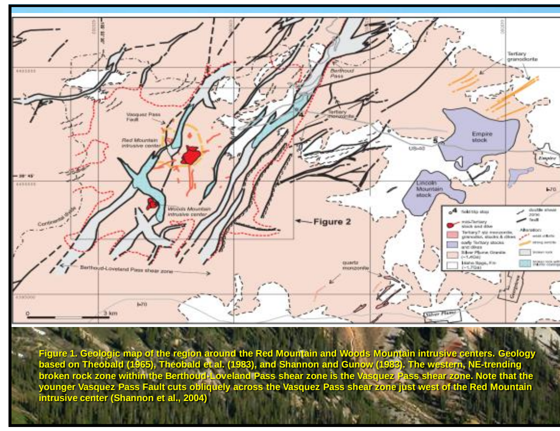


Figure 1. Geologic map of the region around the Red Mountain and Woods Mountain intrusive centers. Geology based on Theobald (1965), Theobald et al. (1983), and Shannon and Gunow (1983). The western, NE-trending broken rock zone within the Berthoud-Loveland Pass shear zone is the Vasquez Pass shear zone. Note that the younger Vasquez Pass Fault cuts obliquely across the Vasquez Pass shear zone just west of the Red Mountain intrusive center (Shannon et al., 2004)
Berthoud-Loveland Pass shear zone
Figure 2
Empire stock
Lincoln Mountain stock
0 3 km

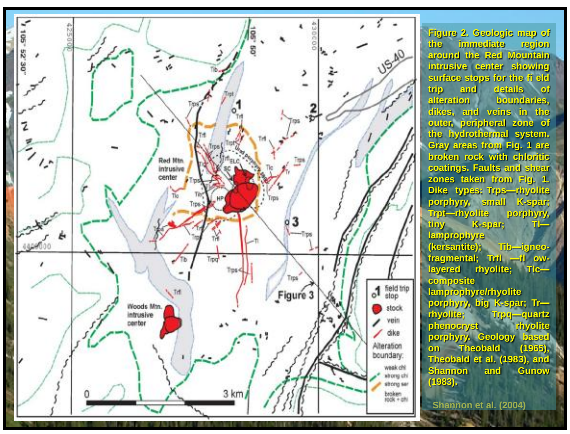
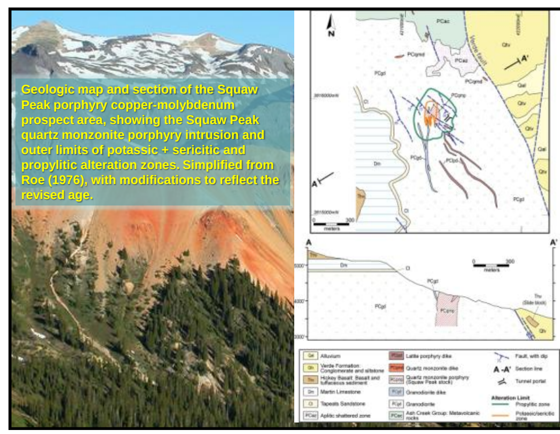
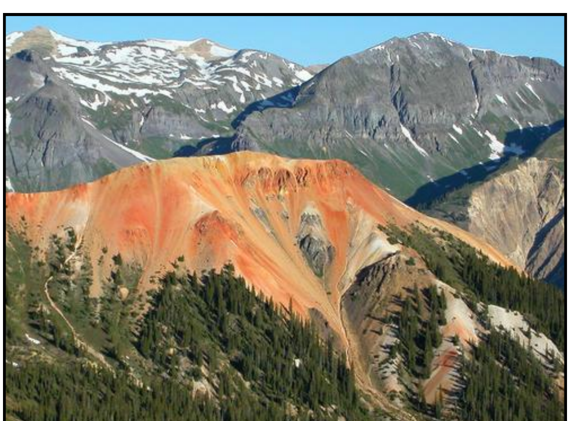
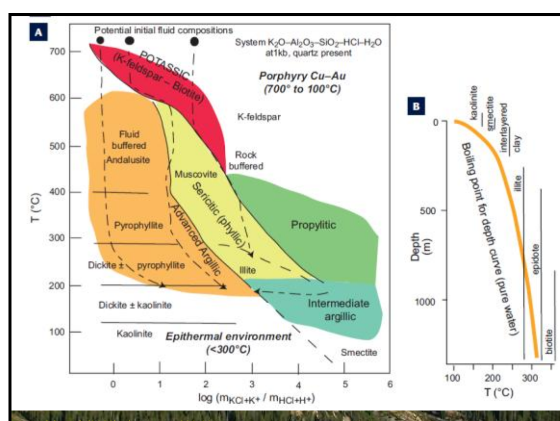
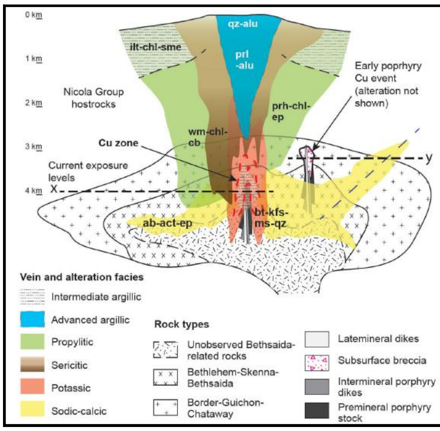


Figure 2. Geologic map of the immediate region around the Red Mountain intrusive center showing surface stops for the fi eld trip and details of alteration boundaries, dikes, and veins in the outer, peripheral zone of the hydrothermal system. Gray areas from Fig. 1 are broken rock with chloritic coatings. Faults and shear zones taken from Fig. 1. Dike types: Trps—rhyolite porphyry, small K-spar; Trpt—rhyolite porphyry, tiny K-spar; Tl—lamprophyre (kersantite); Tib—igneo-fragmental; Trfl —fl ow-layered rhyolite; Tlc—composite lamprophyre/rhyolite porphyry, big K-spar; Tr—rhyolite; Trpq—quartz phenocryst rhyolite porphyry. Geology based on Theobald (1965), Theobald et al. (1983), and Shannon and Gunow (1983).
Shannon et al. (2004)
Red Mtn. intrusive center
Woods Mtn. intrusive center
Figure 3
US-40
0 3 km


Geologic map and section of the Squaw Peak porphyry copper-molybdenum prospect area, showing the Squaw Peak quartz monzonite porphyry intrusion and outer limits of potassic + sericitic and propylitic alteration zones. Simplified from Roe (1976), with modifications to reflect the revised age.




A
Potential initial fluid compositions
System $K_2O$–$Al_2O_3$–$SiO_2$–HCl–$H_2O$ at1kb, quartz present
POTASSIC (K-feldspar – Biotite)
Porphyry Cu–Au (700° to 100°C)
K-feldspar
Fluid buffered
Andalusite
Rock buffered
Muscovite
Sericitic (phyllic)
Advanced Argillic
Propylitic
Pyrophyllite
Dickite ± pyrophyllite
Illite
Dickite ± kaolinite
Intermediate argillic
Kaolinite
Epithermal environment (<300°C)
Smectite
T (°C)
log ($m_{KCl+K^+}$ / $m_{HCl+H^+}$)
B
kaolinite
smectite
interlayered clay
illite
epidote
biotite
Boiling point for depth curve (pure water)
Depth (m)
T (°C)
Tosdal et al. (2009) Elements5: 289-295.




Byrne *et al.* (2017)

### Introduction

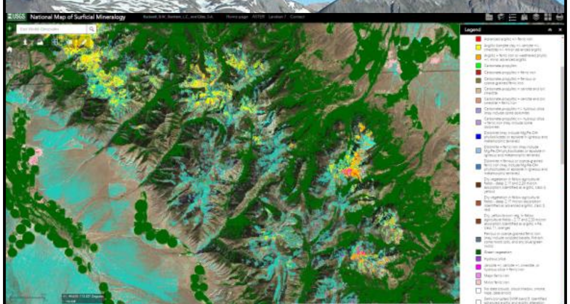
Porphyry Cu deposits are the primary source of Cu globally and, although demand ebbs and flows and recycling is increasing, a pipeline of quality projects and resources is needed to replace decreasing inventories (Seedorff et al., 2005; Sillitoe, 2010; Thompson, 2016). Exploration costs and expenditures have increased approximately threefold during the last 12 years (Wilburn et al., 2015; Wood, 2016), yet discovery rates are down and very few new deposits have been found (Sillitoe, 2013). As a result, exploration is moving into underexplored, high-risk political jurisdictions and beneath cover (systems with no surface expression) in known productive belts, necessitating more effective and efficient exploration methodologies and techniques (Sillitoe, 2013; Schodde, 2014; Wood, 2016).

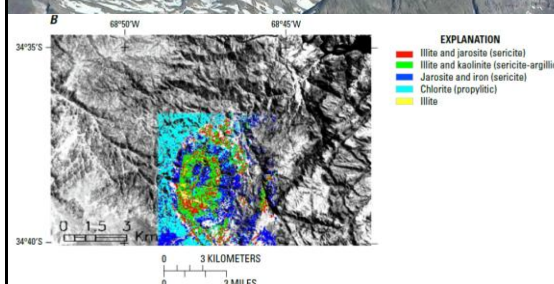
The volume of hydrothermally altered rocks outboard of economically significant concentrations of Cu-Fe–sulphide minerals is termed the porphyry footprint. An understanding of the fluid types that can be present during porphyry Cu formation, how they manifest in the footprint and their spatial distribution with respect to Cu-mineralized portions of the system is critical to developing better exploration tools. This work is part of the Porphyry Copper Footprints Subproject of the Canada Mining Innovation Council (CMIC) and Natural Sciences and Engineering Research Council of Canada (NSERC). Its purpose is to investigate the petrophysical, structural, mineralogical, geochemical and isotopic footprints of the porphyry Cu (±Mo) deposits in the Highland Valley Copper (HVC) district of south-central British Columbia (BC; Figure 1). The Teck Highland

**Large-Scale Sodic-Calcic Alteration Around Porphyry Copper Systems: Examples from the Highland Valley Copper District, Guichon Batholith, South-Central British Columbia**

Byrne *et al.* (2017)

## SENSORIAMENTO REMOTO E GEOTECNOLOGIAS




# EPIGENÉTICOS

# X

# EPITERMAIS

## Mineralizações epigenéticas

1) O depósito forma-se muito depois da rocha hospedeira

2) Usualmente tem que haver uma preparação da rocha (*ground preparation*)

3) Pode se formar desde junto à superfície até muitos quilômetros de profundidade

4) A rocha hospedeira consolidada antes do fraturamento (geralmente rúptil) que proporciona abertura de espaços

5) A mineralização forma-se pela precipitação dos metais e demais componentes de um fluido hidrotermal percolante

6) Mineralizações epigenéticas podem gradar para singenéticas

# Mineralizações epitermais

Forma-se em temperaturas entre 200 e 300 ºC, com variações para < 150 a >400 ºC)

Formam-se em profundidades rasas ou superficiais (pressões baixas), alcançando até ~ 2 km (normalmente formam-se a poucas centenas de metros de profundidade)

➔ Dessa forma, como já foi utilizado, o termo mineralizações epitermais não teriam necessariamente relação com vulcanismo

➔ Entretanto, o grande desenvolvimento da pesquisa mineral em arcos vulcânicos fêz com que o termo passasse a ser utilizado no sentido de Lindgren (1913, 1935, 1985), implicando necessariamente em associação com vulcanismo.

| | | | |
|---|---|---|---|
| Depósitos hidrotermais | Associações de ouro e prata | Série hipoabissal (profunda) | a) filões de ouro-quartzo catatermais (T e P elevadas)<br>b) depósitos disseminados em rochas silicáticas<br>c) depósitos de substituição em rochas carbonatadas<br>d) depósitos ricos de ouro-chumbo-selênio |
| | | Série subvulcânica (pouco profunda) | a) filões propilíticos epitermais ouro-quartzo e filões ouro-prata<br>b) filões epitermais ouro-telúrio<br>c) filões epitermais ouro-selênio<br>d) depósitos de ouro aluníticos<br>e) depósitos de prata epitermais |

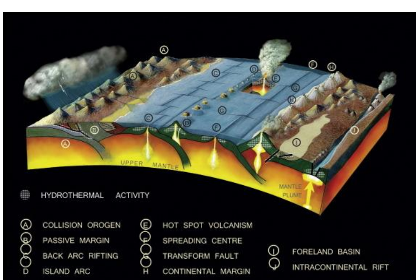
Schneiderhöhn (1941)

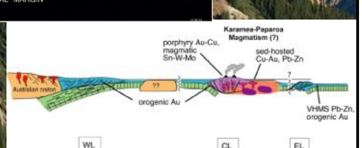
## MINERALIZAÇÕES EPITERMAIS – EVOLUÇÃO DA NOMENCLATURA

| | | | |
|---|---|---|---|
| Goldfield type | | | Ransome (1907) |
| Alunitic kaolinic gold veins | Sericitic zinc-silver veins | Gold-silver-adularia veins<br>Fluoritic tellurium-adularia gold veins | Emmons (1918) |
| Gold-alunite deposits | Gold-quartz veins in andesite | | Lindgren (1933) |
| | Argentite-gold quartz veins<br>Argentite veins<br>Base metal veins | Gold-quartz veins in rhyolite<br>Gold telluride veins<br>Gold selenide veins | |
| Secondary quartzite (Altered host rock) | | | Fedorov (1903); Nakovnik (1933) |
| Acid | Alkaline | | Sillitoe (1977) |
| Epithermal | | | Buchanan (1981) |
| Enargite-gold | | | Ashley (1982) |
| | | Hot-spring type | Giles and Nelson (1982) |
| High sulfur | Low sulfur | | Bonham (1986, 1988) |
| Acid sulfate | Adularia-sericite | | Hayba et al. (1985),<br>Heald et al. (1987) |
| High sulfidation | Low sulfidation | | Hedenquist (1987) |
| Alunite-kaolinite | Adularia-sericite | | Berger and Henley (1989) |
| | Type 1 adularia-sericite | Type 2 adularia-sericite | Albino and Margolis (1991) |
| High sulfidation | High sulfide + base metal, low sulfidation | Low sulfide + base metal, low sulfidation | Sillitoe (1993) |
| Lithocap (Altered host rock) | | | Sillitoe (1995) |
| High sulfidation | Western andesite assemblage, low sulfidation | Bimodal basalt-rhyolite assemblage, low sulfidation | John et al. (1999)<br>John (2001) |
| High sulfidation (HS) | Intermediate sulfidation (IS) | Low sulfidation (LS) | Hedenquist et al. (2000) |

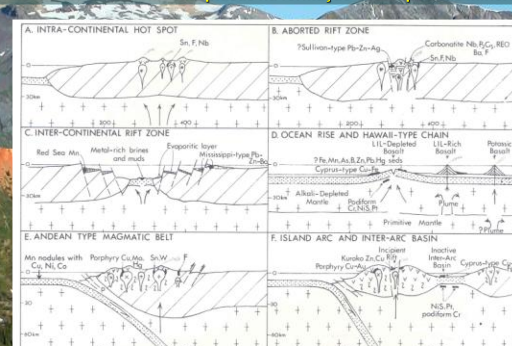
*Hedenquist (2005), based on Sillitoe and Hedenquist (2003) and Einaudi et al. (2003)*

# Ambiente tectônico

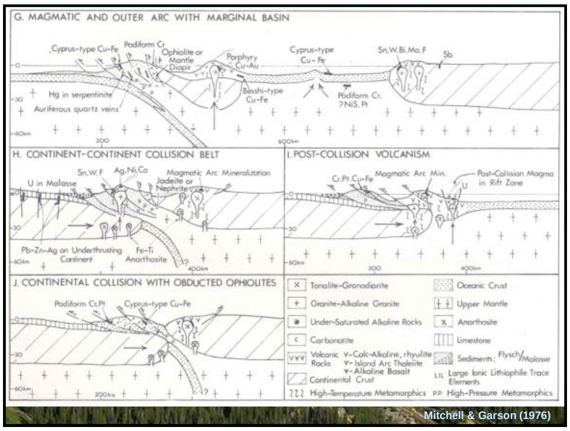



## O controle da tectônica de placas na formação dos depósitos minerais




Mitchell & Garson (1976)



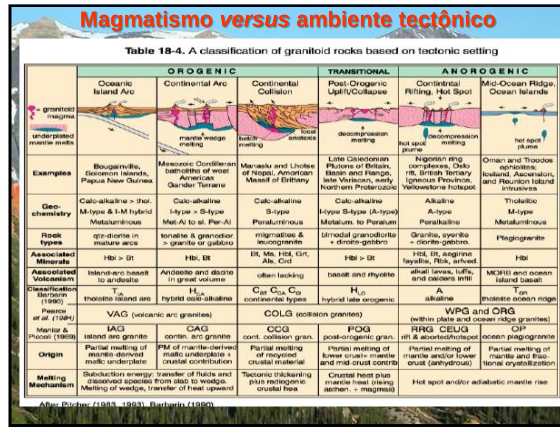
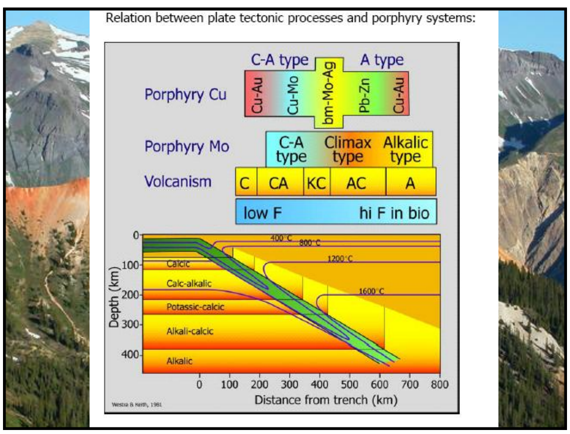
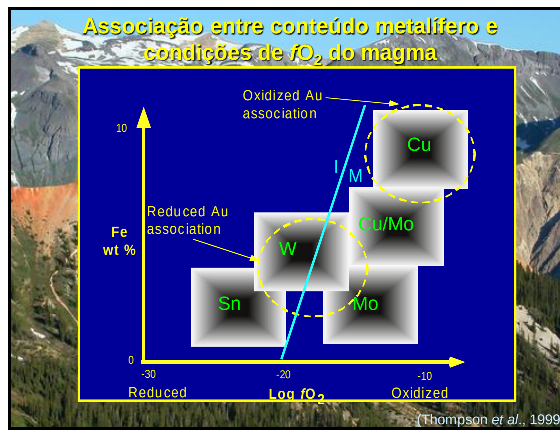



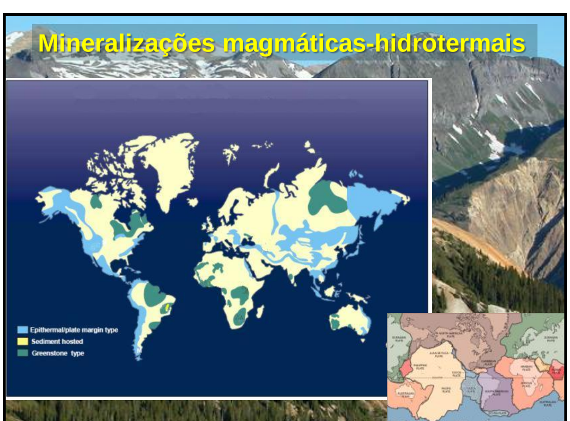

**Table 18-4.** A classification of granitoid rocks based on tectonic setting

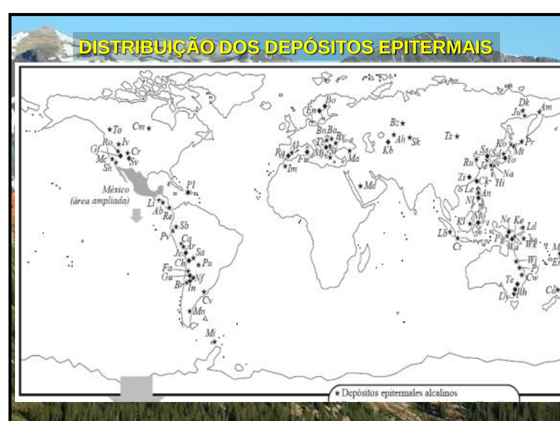
| | OROGENIC | | | TRANSITIONAL | ANOROGENIC | |
|---|---|---|---|---|---|---|
| | Oceanic Island Arc | Continental Arc | Continental Collision | Post-Orogenic Uplift/Collapse | Contintntal Rifting, Hot Spot | Mid-Ocean Ridge, Ocean Islands |
| granitoid magma; underplated mantle melts | | mantle wedge melting | batch melting; local anatexis | decompression melting | hot spot plume; decompression melting | hot spot plume |
| Examples | Bougainville, Solomon Islands, Papua New Guinea | Mesozoic Cordilleran batholiths of west Americas Gander Terrane | Manaslu and Lhotse of Nepal, American Massif of Brittany | Late Caledonian Plutons of Britain, Basin and Range, late Variscan, early Northern Proterozoic | Nigerian ring complexes, Oslo rift, British Tertiary Igneous Province, Yellowstone hotspot | Oman and Troodos ophiolites; Iceland, Ascension, and Reunion Island intrusives |
| Geo-chemistry | Calc-alkaline > thol. M-type & I-M hybrid Metaluminous | Calc-alkaline I-type > S-type Met-Al to sl. Per-Al | Calc-alkaline S-type Peraluminous | Calc-alkaline I-type S-type (A-type) Metalum. to Peralum | Alkaline A-type Peralkaline | Tholeiitic M-type Metaluminous |
| Rock types | qtz-diorite in mature arcs | tonalite & granodior. > granite or gabbro | migmatites & leucogranite | bimodal granodiorite + diroite-gabbro | Granite, syenite + diorite-gabbro. | Plagiogranite |
| Associated Minerals | Hbl > Bt | Hbl, Bt | Bt, Ms, Hbl, Grt, Als, Crd | Hbl > Bt | Hbl, Bt, aegirine fayalite, Rbk, arfved. | Hbl |
| Associated Volcanism | Island-arc basalt to andesite | Andesite and dacite in great volume | often lacking | basalt and rhyolite | alkali lavas, tuffs, and caldera infill | MORB and ocean island basalt |
| Classification Barbarin (1990) | $T_{IA}$ tholeiite island arc | $H_{CA}$ hybrid calc-alkaline | $C_{ST}$ $C_{CA}$ $C_{CI}$ continental types | $H_{LO}$ hybrid late orogenic | A alkaline | $T_{OR}$ tholeiite ocean ridge |
| Pearce et al. (1984) | VAG (volcanic arc granites) | | COLG (collision granites) | | WPG and ORG (within plate and ocean ridge granites) | |
| Maniar & Piccoli (1989) | IAG island arc granite | CAG contin. arc granite | CCG cont. collision gran. | POG post-orogenic gran. | RRG CEUG rift & aborted/hotspot | OP ocean plagiogranite |
| Origin | Partial melting of mantle-derived mafic underplate | PM of mantle-derived mafic underplate + crustal contribution | Partial melting of recycled crustal material | Partial melting of lower crust+ mantle and mid-crust contrib | Partial melting of mantle and/or lower crust (anhydrous) | Partial melting of mantle and frac-tional crystallization |
| Melting Mechanism | Subduction energy: transfer of fluids and dissolved species from slab to wedge. Melting of wedge, transfer of heat upward | | Tectonic thickening plus radiogenic crustal hea | Crustal heat plus mantle heat (rising asthen. + magmas) | Hot spot and/or adiabatic mantle rise | |

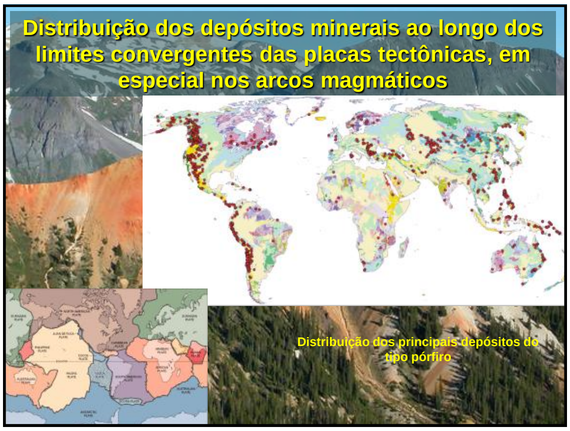
After Pitcher (1983, 1993), Barbarin (1990)

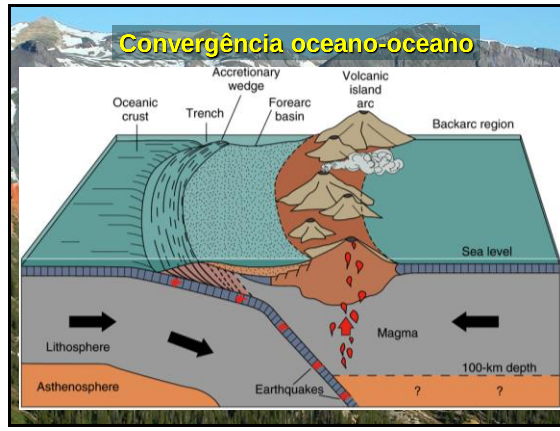


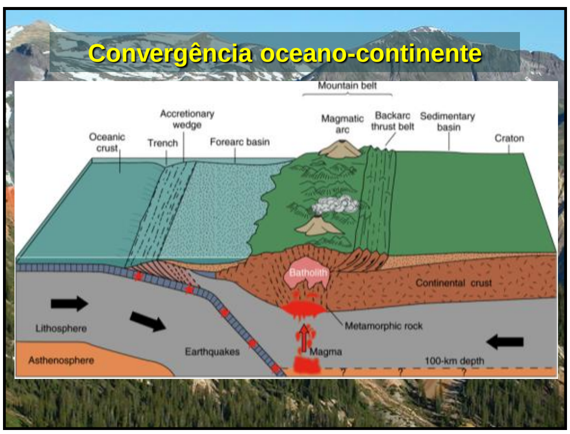



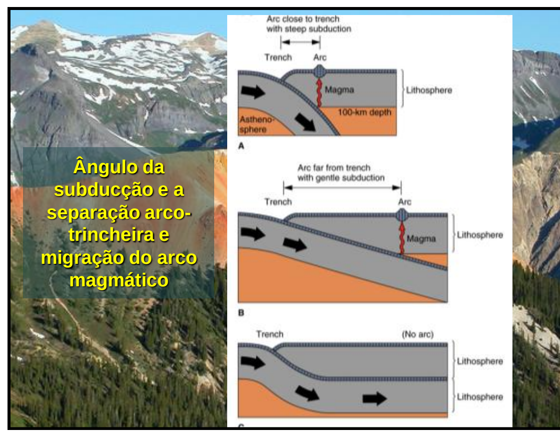



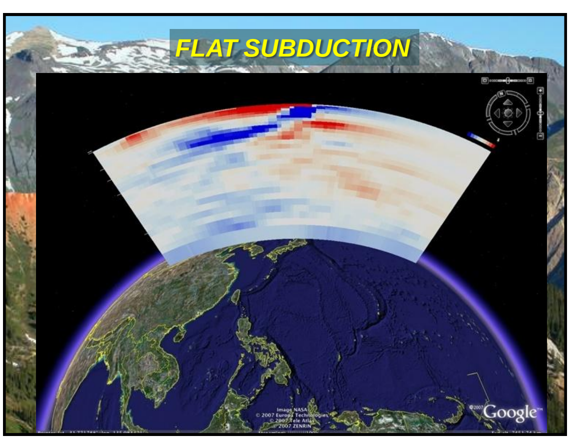



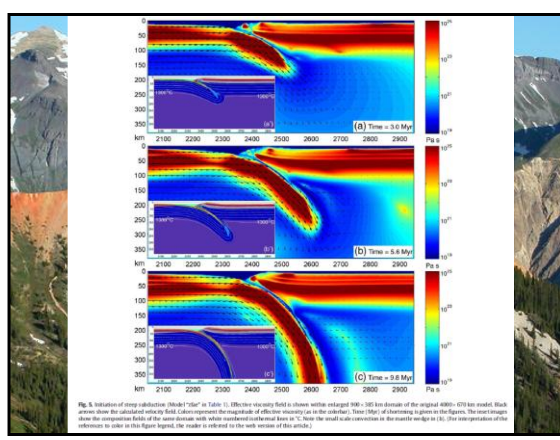

Distribuição dos depósitos minerais ao longo dos limites convergentes das placas tectônicas, em especial nos arcos magmáticos
Distribuição dos principais depósitos do tipo pórfiro

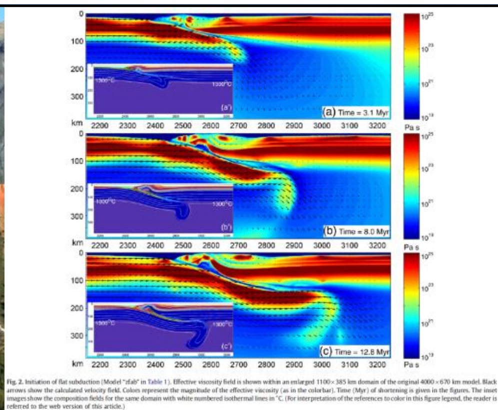

Convergência oceano-oceano
Accretionary wedge
Volcanic island arc
Oceanic crust
Trench
Forearc basin
Backarc region
Sea level
Lithosphere
Magma
100-km depth
Asthenosphere
Earthquakes
?
?


Convergência oceano-continente
Mountain belt
Accretionary wedge
Magmatic arc
Backarc thrust belt
Sedimentary basin
Oceanic crust
Trench
Forearc basin
Craton
Batholith
Continental crust
Lithosphere
Metamorphic rock
Earthquakes
Magma
Asthenosphere
100-km depth


Ângulo da subducção e a separação arco-trincheira e migração do arco magmático
Arc close to trench with steep subduction
Trench
Arc
Magma
Lithosphere
Astheno-sphere
100-km depth
A
Arc far from trench with gentle subduction
Trench
Arc
Magma
Lithosphere
B
Trench
(No arc)
Lithosphere
Lithosphere

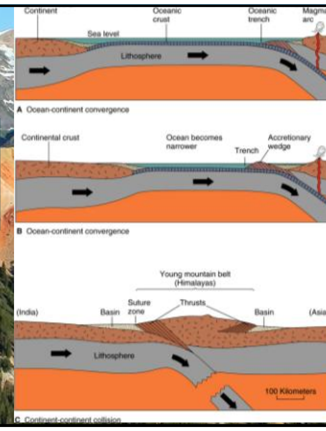

FLAT SUBDUCTION
Google

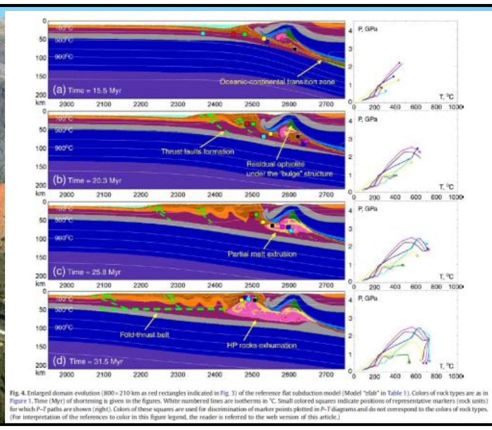

(a) Time = 3.0 Myr
(b) Time = 5.6 Myr
(c) Time = 9.8 Myr
km
2100
2200
2300
2400
2500
2600
2700
2800
2900
Pa s



Li et al. (2010)

## Colisão continente-continente



## O que é importante entender no estudo e na exploração mineral de depósitos magmáticos-hidrotermais?

O contexto tectônico

O tipo do magmatismo, seu zonamento e idade (diferentes arcos vulcânicos)

Identificação de complexos de caldeira vulcânicas e seus contrôles

Estruturas tectônica que controlam a colocação dos magmas e canalizam os fluidos

O estado de oxidação dos magmas

As características do fluidos hidrotermais

Os tipos de alteração hidrotermal, seus estilos, intensidade e distribuição

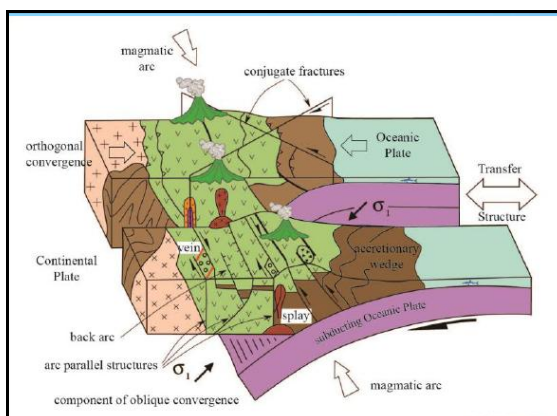
A disponibilidade de metais na fonte ígnea

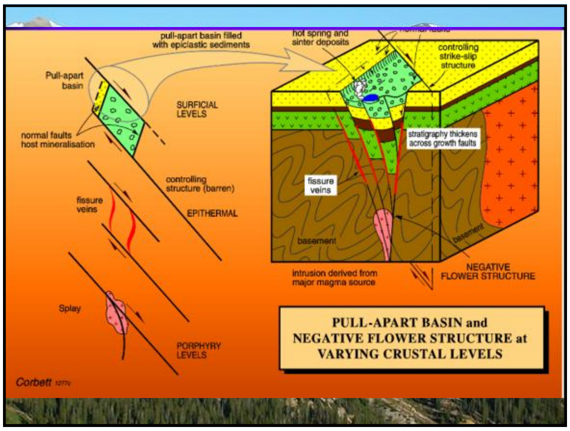
O nível de erosão

A cobertura sedimentar

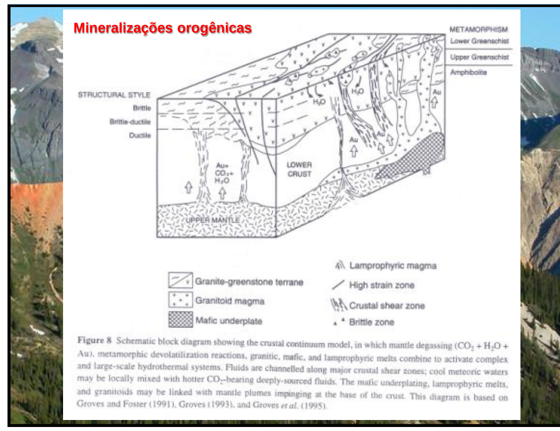
A movimentação vertical de grandes blocos tectônicos

Metamorfismo

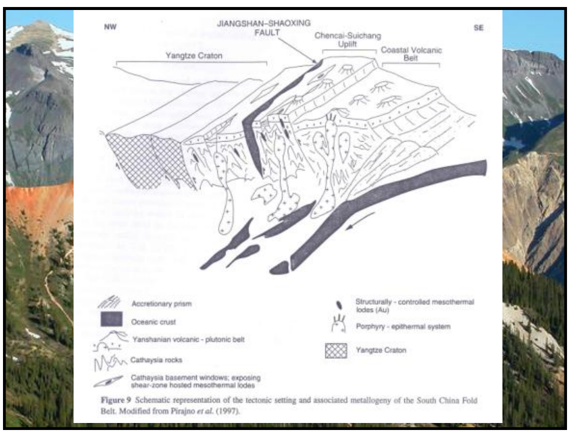




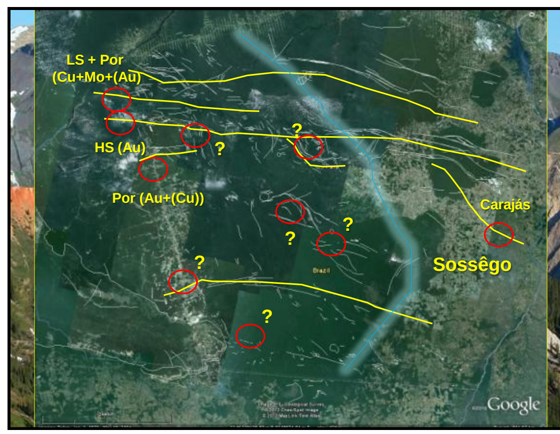
pull-apart basin filled with epiclastic sediments
hot spring and sinter deposits
controlling strike-slip structure
Pull-apart basin
SURFICIAL LEVELS
normal faults host mineralisation
stratigraphy thickens across growth faults
fissure veins
controlling structure (barren)
fissure veins
EPITHERMAL
basement
basement
intrusion derived from major magma source
NEGATIVE FLOWER STRUCTURE
Splay
PORPHYRY LEVELS
PULL-APART BASIN and NEGATIVE FLOWER STRUCTURE at VARYING CRUSTAL LEVELS
Corbett

Mineralizações orogênicas
METAMORPHISM
Lower Greenschist
Upper Greenschist
Amphibolite
STRUCTURAL STYLE
Brittle
Brittle-ductile
Ductile
LOWER CRUST
UPPER MANTLE
Granite-greenstone terrane
Granitoid magma
Mafic underplate
Lamprophyric magma
High strain zone
Crustal shear zone
Brittle zone
Figure 8 Schematic block diagram showing the crustal continuum model, in which mantle degassing ($CO_2 + H_2O$ + Au), metamorphic devolatilization reactions, granitic, mafic, and lamprophyric melts combine to activate complex and large-scale hydrothermal systems. Fluids are channelled along major crustal shear zones; cool meteoric waters may be locally mixed with hotter $CO_2$-bearing deeply-sourced fluids. The mafic underplating, lamprophyric melts, and granitoids may be linked with mantle plumes impinging at the base of the crust. This diagram is based on Groves and Foster (1991), Groves (1993), and Groves et al. (1995).

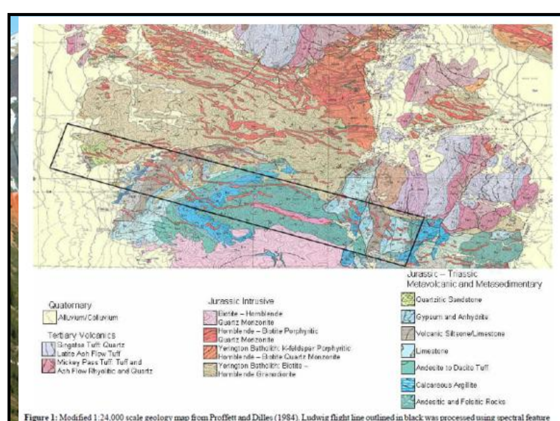



NW
JIANGSHAN–SHAOXING FAULT
SE
Chencai-Suichang Uplift
Coastal Volcanic Belt
Yangtze Craton
Accretionary prism
Oceanic crust
Yanshanian volcanic - plutonic belt
Cathaysia rocks
Cathaysia basement windows; exposing shear-zone hosted mesothermal lodes
Structurally - controlled mesothermal lodes (Au)
Porphyry - epithermal system
Yangtze Craton
Figure 9 Schematic representation of the tectonic setting and associated metallogeny of the South China Fold Belt. Modified from Pirajno et al. (1997).

LS + Por (Cu+Mo+(Au)
HS (Au)
Por (Au+(Cu))
Carajás
Sossêgo
Google


Caldeiras vulcânicas
inner crater
outer crater

Quaternary
Alluvium/Colluvium
Tertiary Volcanics
Singatse Tuff: Quartz Latite Ash Flow Tuff
Mickey Pass Tuff: Tuff and Ash Flow Rhyolitic and Quartz
Jurassic Intrusive
Biotite – Hornblende Quartz Monzonite
Hornblende – Biotite Porphyritic Quartz Monzonite
Yerington Batholith: K-feldspar Porphyritic Hornblende – Biotite Quartz Monzonite
Yerington Batholith: Biotite – Hornblende Granodiorite
Jurassic – Triassic Metavolcanic and Metasedimentary
Quartzitic Sandstone
Gypsum and Anhydrite
Volcanic Siltstone/Limestone
Limestone
Andesite to Dacite Tuff
Calcareous Argillite
Andesitic and Felsitic Rocks
Figure 1: Modified 1:24,000 scale geology map from Proffett and Dilles (1984). Ludwig flight line outlined in black was processed using spectral feature fitting.

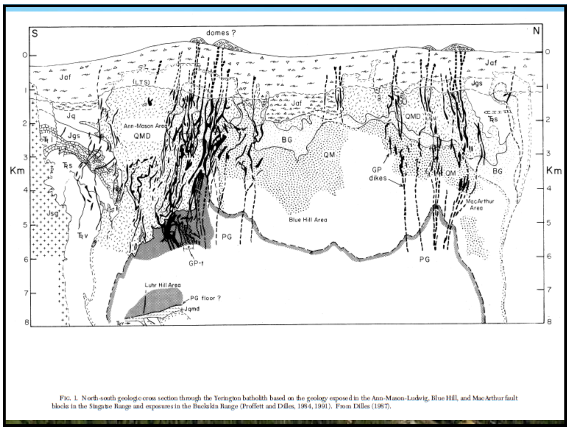
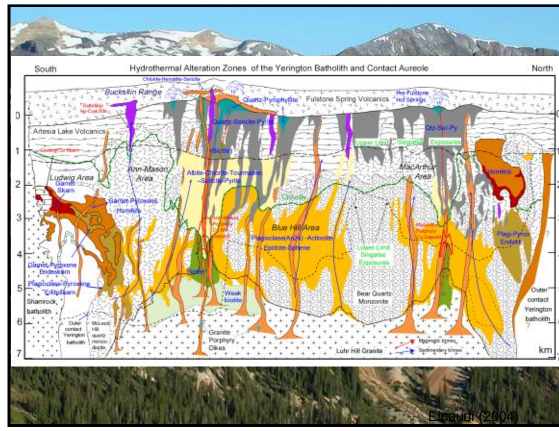
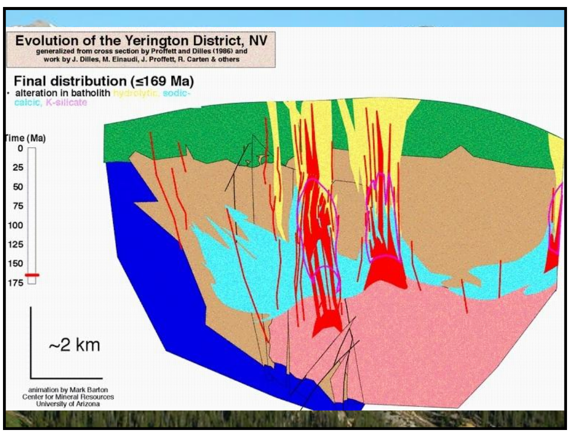



FIG. 1. North-south geologic cross section through the Yerington batholith based on the geology exposed in the Ann-Mason-Ludwig, Blue Hill, and MacArthur fault blocks in the Singatse Range and exposures in the Buckskin Range (Proffett and Dilles, 1984, 1991). From Dilles (1987).





## Fluido hidrotermal

**FLUIDO** = $H_2O$ + SAIS + VOLÁTEIS ($CO_2$, $CH_4$, $N_2$, $H_2S$, etc.)
= Solução aquosa

Soluções diluídas (0,2 – 0,5% solutos) a altamente concentradas (25% solutos) ➔ predominância de $Na^+$ e $Cl^-$.

**Salinidade**:
- Muito baixa = 0,2 - 0,5%
- Baixa = 5 - 10%
- Moderada = 10 - 20%
- Muito alta (hipersalino) > 50%

Temperatura variada: 50 °C a > 600 °C

pH variado (ácido, neutro a levemente alcalino)

Voláteis ($CO_2$, $CH_4$, $N_2$, $H_2S$, etc.) ➔ controlam o estado redox dos fluidos

Metais ➔ complexos iônicos (e.g. $Au(HS)^{-2}$ ; $AuCl^{-2}$ )
Fluidos transportam os metais

## AMBIENTES DA ALTERAÇÃO HIDROTERMAL

1) Diagênese

2) Pós-magmatismo

3) Metamorfismo

4) Metassomatismo

5) Hidrotermalismo sem fontes ígneas

# TIPOS DE SISTEMAS HIDROTERMAIS

a) Magmáticos relacionados a atividade plutônica rasa ou profunda.
Geram depósitos do tipo Sn-W *greisens*.

b) Magmáticos-meteóricos a predominantemente meteóricos, presentes em ambientes vulcano-plutônicos a subvulcânicos, relacionados à atividade vulcânica.
São responsáveis por mineralizações porfiríticas, *skarns*, depósitos epitermais de metais preciosos e de base, assim como por diversos tipos de depósitos na forma de veios.

c) Atuantes sob o assoalho oceânico.
São resposáveis pela formação de uma ampla gama de depósitos vulcanogênicos de sulfetos maciços (Besshi, Cyprus, tipo *Kuroko*, tipo *Noranda*).

d) Associados a *rifts* presentes em bacias sedimentares, podendo ou não estarem associados à atividade ígnea
Formam depósitos de sulfetos estratiformes exalativos sedimentares de Broken Hill e Mount Isa - Austrália, Gamsberg-Aggeneys - África do Sul, Sullivan - Canadá.

e) Depósitos do tipo *stratabound* de sulfetos encaixados em rochas carbonáticas.
Podem ser considerados como membros finais daqueles do grupo (d).

f) Sistemas hidrotermais relacionados ao metamorfismo, estando geralmente relacionados a eventos metamórficos progressivos
Depósitos de Au encaixados em turbiditos, depósitos arqueanos tipo *lode*

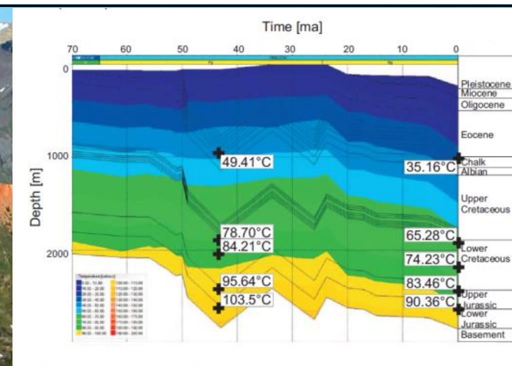
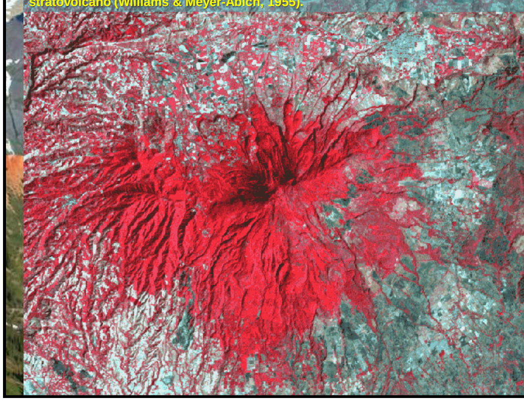
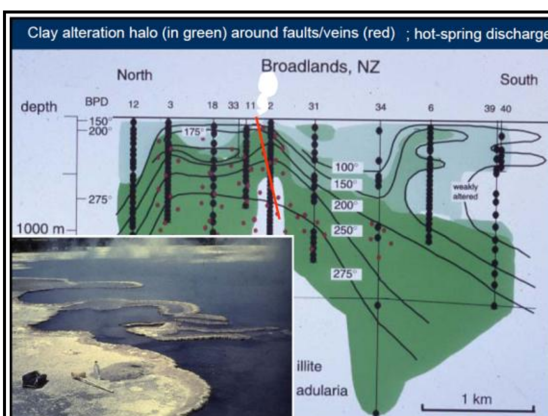


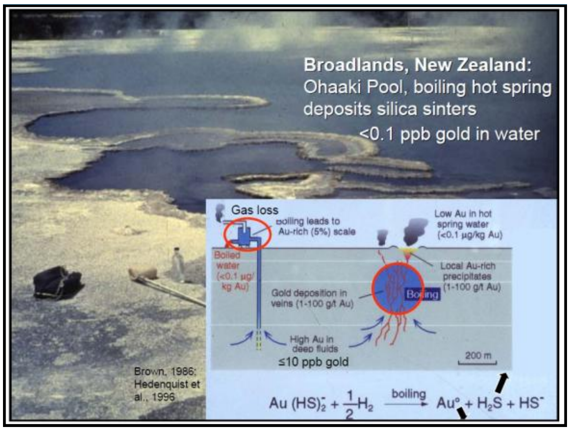

**Fig.5.** Temperature evolution through time in well *26/28-1*. Marked temperatures for Eocene and present-day indicate that maximum temperatures (which closely match AFTA-temperatures as determined by McCulloch, 1993, for the same intervals) were reached during Eocene burial under the influence of the Iceland Plume.

Naeth *et al.* (2005) Journal of Petroleum Geology, 28(2): 147-166

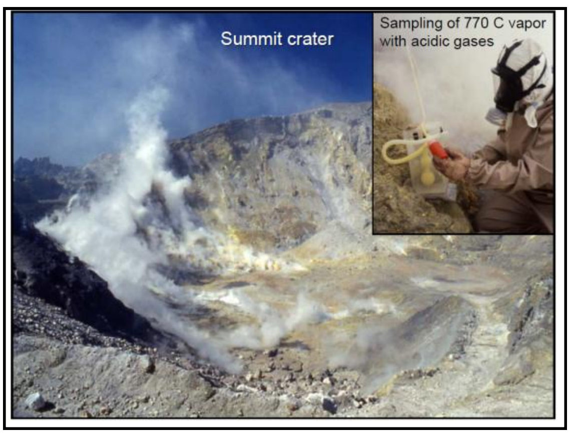

Fumaroles at San Francisco Agua Agria (El Salvador), San Vicente paired stratovolcano (Williams & Meyer-Abich, 1955).

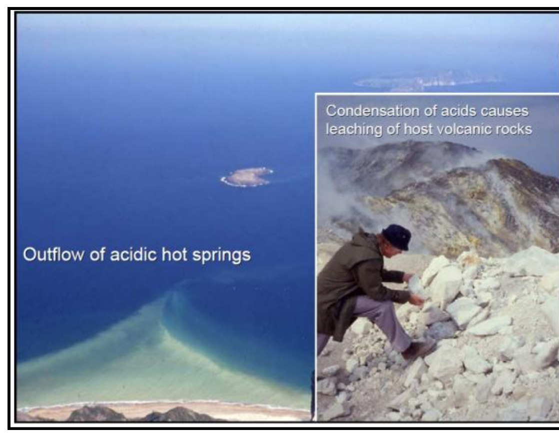


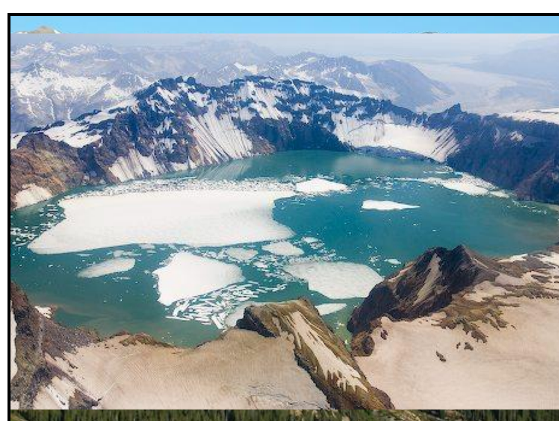

**Broadlands, New Zealand:**
Ohaaki Pool, boiling hot spring deposits silica sinters
<0.1 ppb gold in water
Gas loss
boiling leads to Au-rich (5%) scale
Boiled water (<0.1 µg/kg Au)
Low Au in hot spring water (<0.1 µg/kg Au)
Local Au-rich precipitates (1-100 g/t Au)
Gold deposition in veins (1-100 g/t Au)
Boiling
High Au in deep fluids
≤10 ppb gold
200 m
Brown, 1986; Hedenquist et al., 1996
$Au(HS)_2^- + \frac{1}{2}H_2 \xrightarrow{boiling} Au^\circ + H_2S + HS^-$

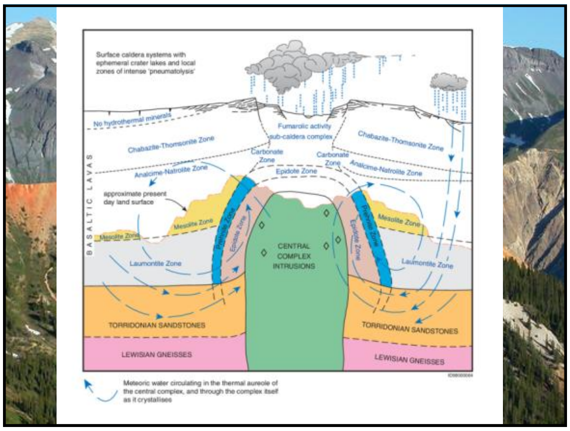

Missing link
Broadlands, New Zealand:
Pilot plant at well head
FeS$_2$, CuFeS$_2$,
+ 5 wt.% gold
Kevin Brown, 1986


Summit crater
Sampling of 770 C vapor with acidic gases

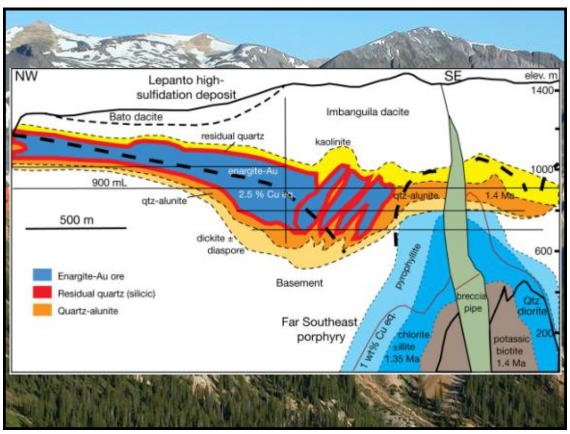

Condensation of acids causes leaching of host volcanic rocks
Outflow of acidic hot springs

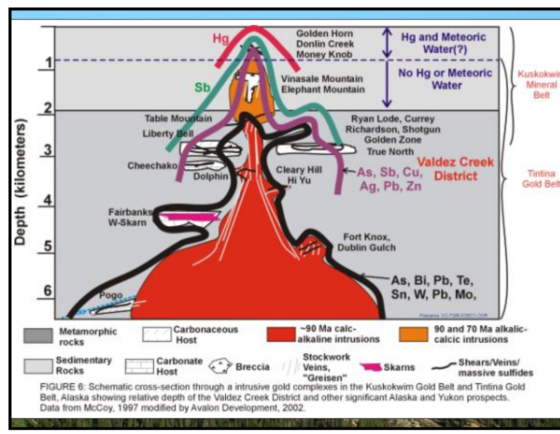

**Kawah Ijen, Java:** volcanic crater with acidic lake
pH 0.0
Application to gold deposits?
Photograph: Pierre Delmelle

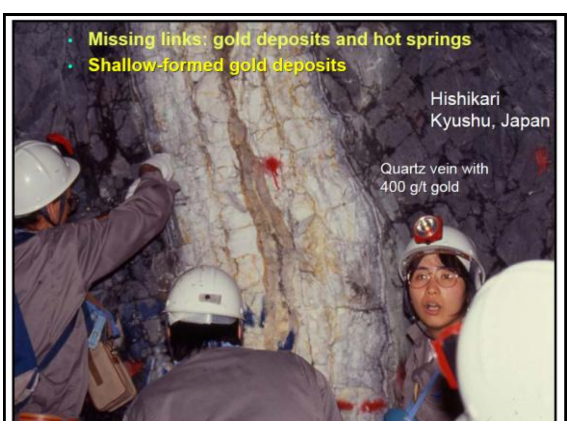



Surface caldera systems with ephemeral crater lakes and local zones of intense 'pneumatolysis'
No hydrothermal minerals
Fumarolic activity sub-caldera complex
Chabazite-Thomsonite Zone
Carbonate Zone
Analcime-Natrolite Zone
Epidote Zone
BASALTIC LAVAS
approximate present day land surface
Mesolite Zone
CENTRAL COMPLEX INTRUSIONS
Laumontite Zone
TORRIDONIAN SANDSTONES
LEWISIAN GNEISSES
Meteoric water circulating in the thermal aureole of the central complex, and through the complex itself as it crystallises

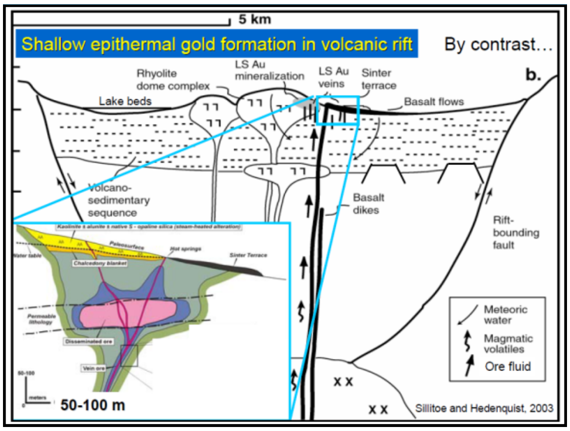

HAND CRAFTED ALES
KONA
BREWING CO.
KONA, HAWAII
Fire Rock
PALE ALE

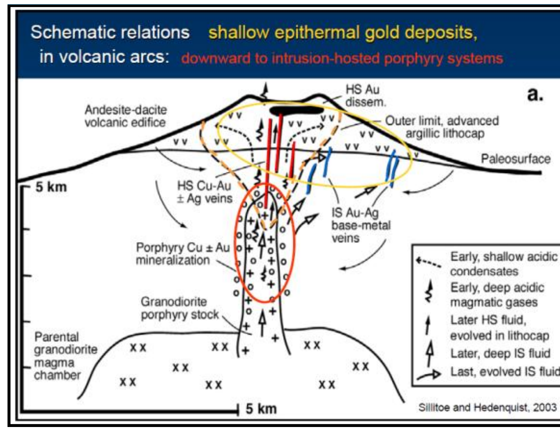

NW
Lepanto high-sulfidation deposit
SE
elev. m
1400
Bato dacite
Imbanguila dacite
residual quartz
kaolinite
enargite-Au
2.5 % Cu eq.
1000
900 mL
qtz-alunite
1.4 Ma
500 m
dickite ± diaspore
600
pyrophyllite
Enargite-Au ore
Residual quartz (silicic)
Quartz-alunite
Basement
breccia pipe
Qtz diorite
Far Southeast porphyry
1 wt% Cu eq.
chlorite illite 1.35 Ma
potassic biotite 1.4 Ma
200

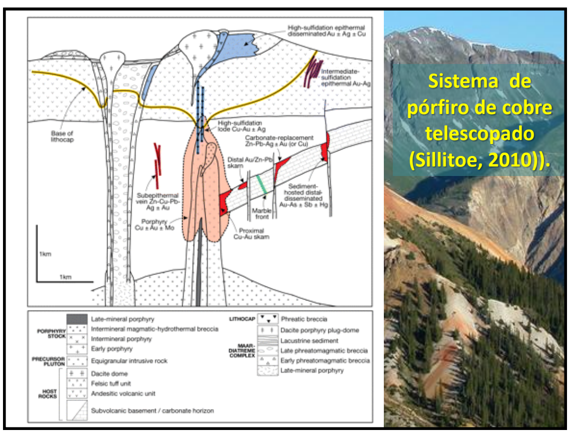

Hg
Golden Horn
Donlin Creek
Money Knob
Hg and Meteoric Water(?)
No Hg or Meteoric Water
Kuskokwim Mineral Belt
Sb
Vinasale Mountain
Elephant Mountain
Depth (kilometers)
1
2
3
4
5
6
Table Mountain
Liberty Bell
Ryan Lode, Currey
Richardson, Shotgun
Golden Zone
True North
Cheechako
Dolphin
Cleary Hill
Hi Yu
Valdez Creek District
As, Sb, Cu, Ag, Pb, Zn
Tintina Gold Belt
Fairbanks W-Skarn
Fort Knox, Dublin Gulch
As, Bi, Pb, Te, Sn, W, Pb, Mo,
Pogo
Metamorphic rocks
Carbonaceous Host
~90 Ma calc-alkaline intrusions
90 and 70 Ma alkalic-calcic intrusions
Sedimentary Rocks
Carbonate Host
Breccia
Stockwork Veins, "Greisen"
Skarns
Shears/Veins/ massive sulfides
FIGURE 6: Schematic cross-section through a intrusive gold complexes in the Kuskokwim Gold Belt and Tintina Gold Belt, Alaska showing relative depth of the Valdez Creek District and other significant Alaska and Yukon prospects. Data from McCoy, 1997 modified by Avalon Development, 2002.

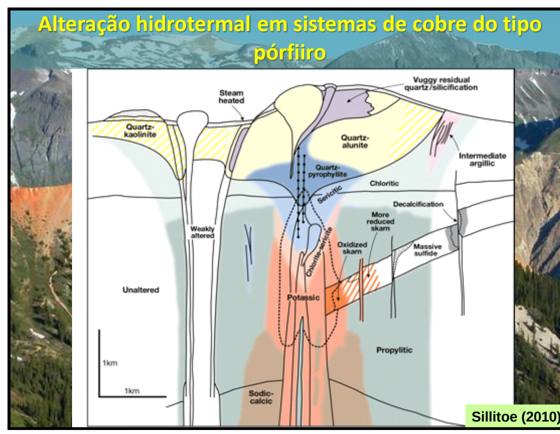

Missing links: gold deposits and hot springs
Shallow-formed gold deposits
Hishikari
Kyushu, Japan
Quartz vein with
400 g/t gold

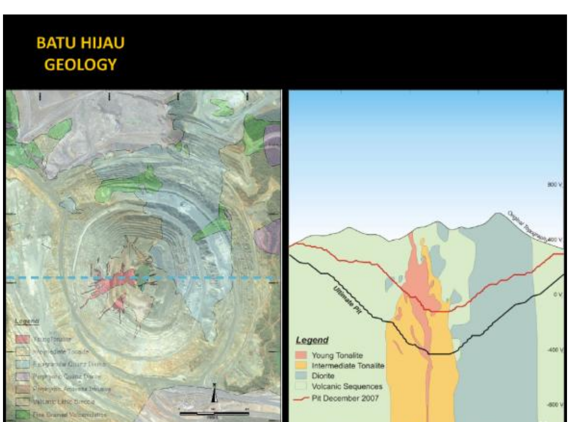

Y. Matsuhisa
R.W. Henley
J. Saunders, Auburn U.
B
Sherlock et al., 1995
Silica sinter
B'
Coast Range ophiolite
Sheeted vein below sinter
Knoxville Formation
W
E

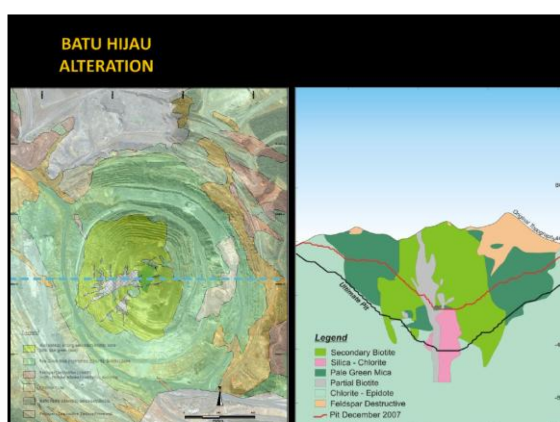

5 km
Shallow epithermal gold formation in volcanic rift
By contrast…
b.
Rhyolite dome complex
LS Au mineralization
LS Au veins
Sinter terrace
Lake beds
Basalt flows
Volcano-sedimentary sequence
Basalt dikes
Rift-bounding fault
Meteoric water
Magmatic volatiles
Ore fluid
50-100 m
Sillitoe and Hedenquist, 2003

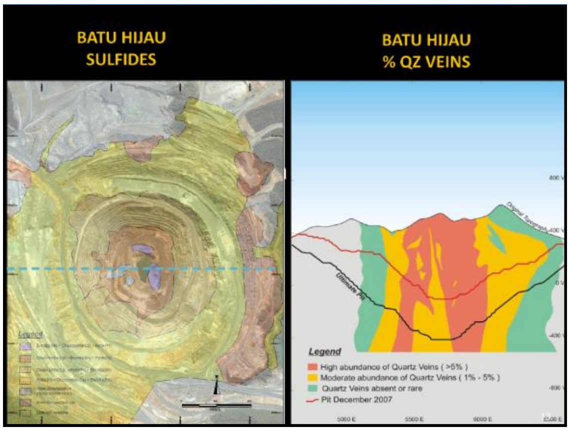

Schematic relations in volcanic arcs:
shallow epithermal gold deposits,
downward to intrusion-hosted porphyry systems
a.
Andesite-dacite volcanic edifice
HS Au dissem.
Outer limit, advanced argillic lithocap
Paleosurface
5 km
HS Cu-Au ± Ag veins
IS Au-Ag base-metal veins
Porphyry Cu ± Au mineralization
Granodiorite porphyry stock
Parental granodiorite magma chamber
Early, shallow acidic condensates
Early, deep acidic magmatic gases
Later HS fluid, evolved in lithocap
Later, deep IS fluid
Last, evolved IS fluid
5 km
Sillitoe and Hedenquist, 2003

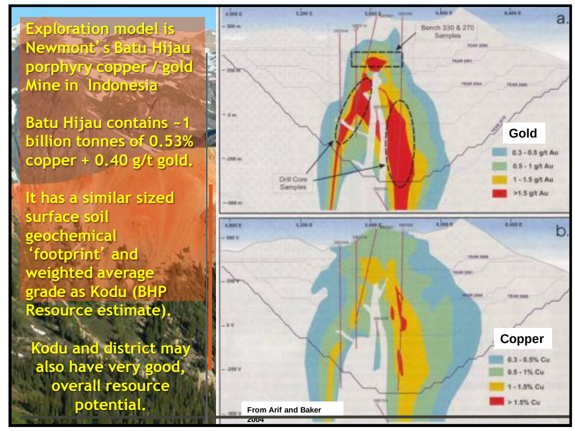

Sistema de pórfiro de cobre telescopado (Sillitoe, 2010)).
High-sulfidation epithermal disseminated Au ± Ag ± Cu
Intermediate-sulfidation epithermal Au-Ag
Base of lithocap
High-sulfidation lode Cu-Au ± Ag
Carbonate-replacement Zn-Pb-Ag ± Au (or Cu)
Distal Au/Zn-Pb skarn
Subepithermal vein Zn-Cu-Pb-Ag ± Au
Porphyry Cu ± Au ± Mo
Marble front
Proximal Cu-Au skarn
Sediment-hosted distal-disseminated Au-As ± Sb ± Hg
1km
1km

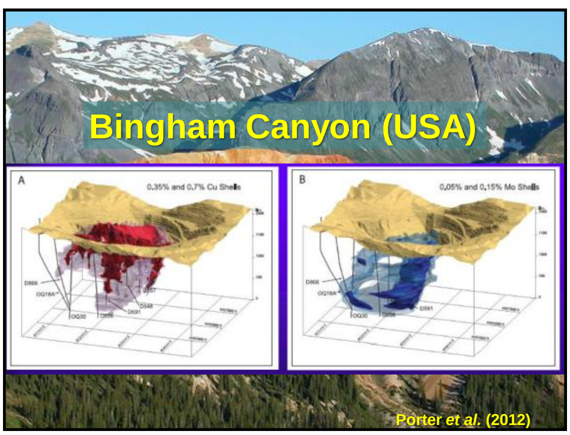

Alteração hidrotermal em sistemas de cobre do tipo pórfiiro
Steam heated
Vuggy residual quartz/silicification
Quartz-kaolinite
Quartz-alunite
Intermediate argillic
Quartz-pyrophyllite
Chloritic
Sericitic
Decalcification
More reduced skarn
Weakly altered
Oxidized skarn
Massive sulfide
Chlorite-sericite
Unaltered
Potassic
Propylitic
Sodic-calcic
1km
1km
Sillitoe (2010)

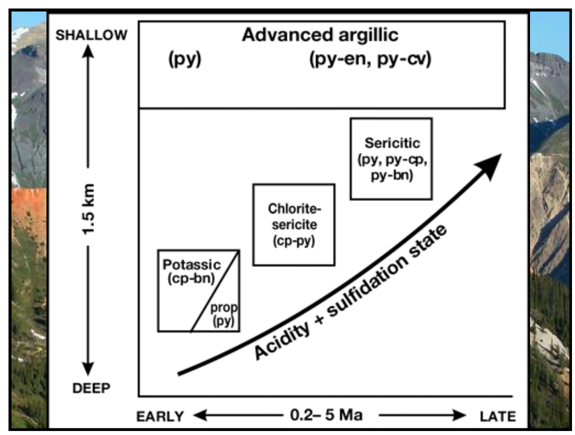

BATU HIJAU GEOLOGY
Legend
Young Tonalite
Intermediate Tonalite
Diorite
Volcanic Sequences
Pit December 2007
Ultimate Pit

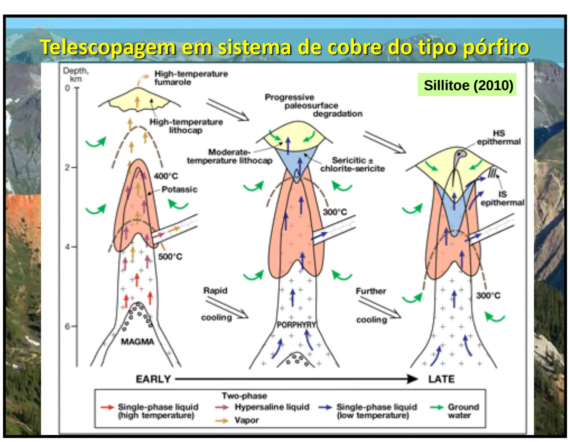

BATU HIJAU ALTERATION
Legend
Secondary Biotite
Silica - Chlorite
Pale Green Mica
Partial Biotite
Chlorite - Epidote
Feldspar Destructive
Pit December 2007
Ultimate Pit


BATU HIJAU
SULFIDES
BATU HIJAU
% QZ VEINS
Legend
High abundance of Quartz Veins ( >5% )
Moderate abundance of Quartz Veins ( 1% - 5% )
Quartz Veins absent or rare
Pit December 2007
Ultimate Pit

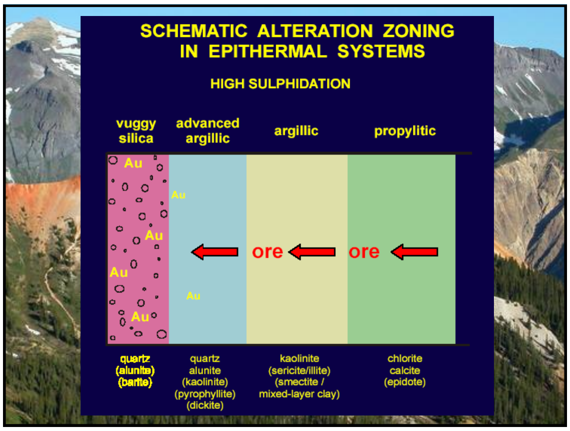

Exploration model is Newmont's Batu Hijau porphyry copper / gold Mine in Indonesia
Batu Hijau contains ~1 billion tonnes of 0.53% copper + 0.40 g/t gold.
It has a similar sized surface soil geochemical 'footprint' and weighted average grade as Kodu (BHP Resource estimate).
Kodu and district may also have very good, overall resource potential.
a.
Gold
0.3 - 0.5 g/t Au
0.5 - 1 g/t Au
1 - 1.5 g/t Au
>1.5 g/t Au
b.
Copper
0.3 - 0.5% Cu
0.5 - 1% Cu
1 - 1.5% Cu
> 1.5% Cu
From Arif and Baker 2004

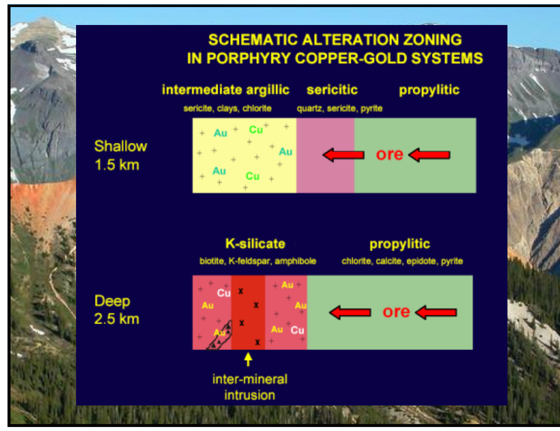

Bingham Canyon (USA)
A
0.35% and 0.7% Cu Shells
B
0.05% and 0.15% Mo Shells
Porter et al. (2012)

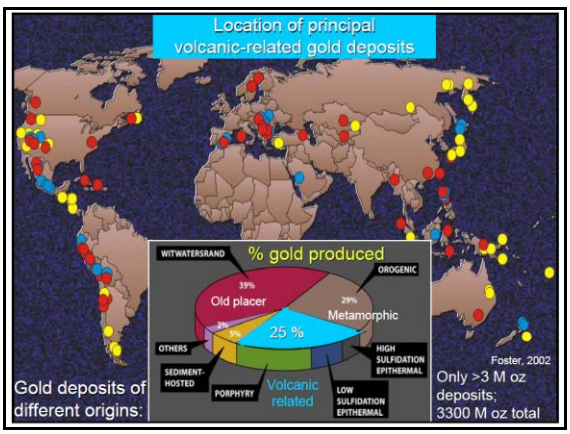

SHALLOW
Advanced argillic
(py)
(py-en, py-cv)
Sericitic
(py, py-cp, py-bn)
Chlorite-sericite
(cp-py)
Potassic
(cp-bn)
prop
(py)
Acidity + sulfidation state
1.5 km
DEEP
EARLY
0.2– 5 Ma
LATE


Telescopagem em sistema de cobre do tipo pórfiro
Sillitoe (2010)
Depth, km
High-temperature fumarole
High-temperature lithocap
Progressive paleosurface degradation
Moderate-temperature lithocap
Sericitic ± chlorite-sericite
HS epithermal
IS epithermal
400°C
Potassic
500°C
300°C
Rapid cooling
Further cooling
MAGMA
PORPHYRY
EARLY
LATE
Single-phase liquid (high temperature)
Two-phase
Hypersaline liquid
Vapor
Single-phase liquid (low temperature)
Ground water


VETORES DE ALTERAÇÃO HIDROTERMAL


SCHEMATIC ALTERATION ZONING
IN EPITHERMAL SYSTEMS
HIGH SULPHIDATION
vuggy silica
advanced argillic
argillic
propylitic
Au
ore
ore
quartz (alunite) (barite)
quartz alunite (kaolinite) (pyrophyllite) (dickite)
kaolinite (sericite/illite) (smectite / mixed-layer clay)
chlorite calcite (epidote)


SCHEMATIC ALTERATION ZONING
IN PORPHYRY COPPER-GOLD SYSTEMS
intermediate argillic
sericite, clays, chlorite
sericitic
quartz, sericite, pyrite
propylitic
Shallow
1.5 km
Au
Cu
ore
K-silicate
biotite, K-feldspar, amphibole
propylitic
chlorite, calcite, epidote, pyrite
Deep
2.5 km
ore
inter-mineral
intrusion


Location of principal
volcanic-related gold deposits
% gold produced
WITWATERSRAND
39%
Old placer
OROGENIC
29%
Metamorphic
25 %
OTHERS
SEDIMENT-HOSTED
PORPHYRY
Volcanic related
LOW SULFIDATION EPITHERMAL
HIGH SULFIDATION EPITHERMAL
Gold deposits of different origins:
Foster, 2002
Only >3 M oz deposits;
3300 M oz total