UNIVERSITÉ DE LORRAINE

geo Ressources

DÉPARTEMENT DES GÉOSCIENCES

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UE904: Processus métallogéniques

Nom du responsable de l'UE et adresse électronique : Antonin RICHARD antonin.richard@univ-lorraine.fr

Semestre : 9

Volume horaire enseigné : 36 heures, Nombre de crédits ECTS : 3

Volume horaire travail personnel de l'étudiant : 36 heures

Langue d'enseignement de l'UE : Français

Enseignements composant	CNU	CM	TD	TP	EI	EqTD
Processus Métallogéniques	35/36	18		18		45

UE904: Processus métallogéniques

Descriptif

- Cycle géochimique de l'uranium et ressources associées : les gisements d'uranium se forment dans des environnements très variés depuis les conditions magmatiques jusqu'aux conditions de surface. En tant qu'élément lithophile, l'uranium est également un excellent marqueur de l'évolution de la croûte continentale depuis l'Archéen. Les processus de formation des principaux gisements d'uranium seront abordés dans une perspective de compréhension du cycle géochimique de l'uranium et de l'évolution séculaire de la croûte continentale.
- Cycle orogénique, magmatisme et ressources associées : le cycle orogénique implique différents types de magmatisme liés notamment au rifting intracontinental, à la subduction et à la collision. Dans une perspective d'évolution séculaire de la géodynamique et de la croissance et différenciation de la croûte continentale au cours des temps géologiques, seront abordés les principaux processus de formation de gisements liés au cycle orogénique : métaux rares (Li, Sn, W, Nb, Ta) et Terre Rares.
- Cycle des fluides géologiques et ressources associés : les fluides géologiques sont des vecteurs essentiels de transfert et concentration de métaux dans le manteau et la croûte. Dans une perspective de compréhension des cycles globaux des éléments volatils, et en lien avec des contextes géodynamiques variés, les principaux processus de transfert et concentration de métaux par des fluides géologiques seront abordés et illustrés à travers plusieurs exemples de gisements (métaux de base, métaux précieux, métaux stratégiques/critiques) : (i) diagénétiques-hydrothermaux, (ii) magmatiques-hydrothermaux et (iii) métamorphiques-hydrothermaux ou encore des gisements associés (iv) aux processus superficiels (alteration supergène telle que la latérisation).

Pré-requis

Métallogénie niveau M1 STPE parcours STR ou équivalent.

Acquis d'apprentissage

Compréhension des relations entre contexte géologique, processus minéralisateurs et types de gisements. Intégration de ces notions dans une perspective de cycles géochimiques et géodynamiques, et d'évolution séculaire de la Terre.

Intervenants:
Antonin Richard
Isabella Pignatelli
Christophe Ballouard
Gaétan Milési
Michel Cathelineau

UE904: Processus métallogéniques

Partie: **Processus hydrothermaux - Intervenant: Antonin Richard**

Objectifs:
Types de fluides dans la croûte
Concentration des métaux dans les systèmes hydrothermaux
Sources, transport, piégeage

Ne pas passer en revue les modèles de formations de tous les types de gisements, mais dégager les grands processus communs

Evaluation:
Exposés
Ecrit à prévoir à la fin de l'UE: questions possibles sur CM – TD – Exposés

Thèmes des exposés:
MVT (groupe de 2)
IOCG (groupe de 2)
Cu stratiforme (groupe de 2)
~~Partitionnement métaux L-V (groupe de 2)~~
Systèmes épithermaux (groupe de 3)
Or orogénique: processus de dépôt (groupe de 2)

Exposés

Dernière séance (date à définir): exposés (évaluation)

Objectifs: Etudier 2/3 articles courts (env. 4-5 p.) par groupe de 2-3 et restituer les idées principales en 20 minutes max, en mettant l'accent sur les processus hydrothermaux de concentration des métaux (fractionnements, mobilisation de sources, transport, dépôt, dynamique des fluides, types de fluides…). Exposez la problématique commune des 2/3 articles, la méthodologie, les résultats et les interprétations. Insistez sur les aspects quantitatifs! N'hésitez pas à rappeler les éléments contextuels essentiels (contexte géologique, type de gisement etc…) en allant chercher si-besoin des informations dans d'autres sources.

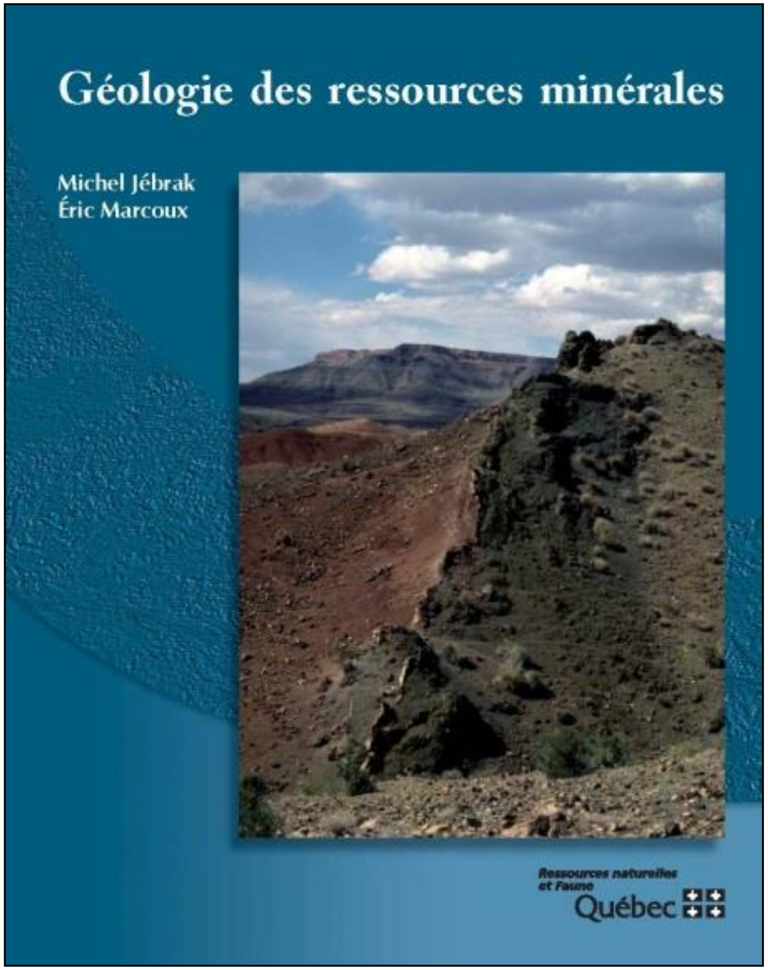
Les 2/3 membres du groupe doivent avoir lu les 2/3 articles et doivent être capables d'en discuter. Idéalement, essayez de trouver un mode de présentation dans lequel il n'y a pas une seule personne qui présente un article.

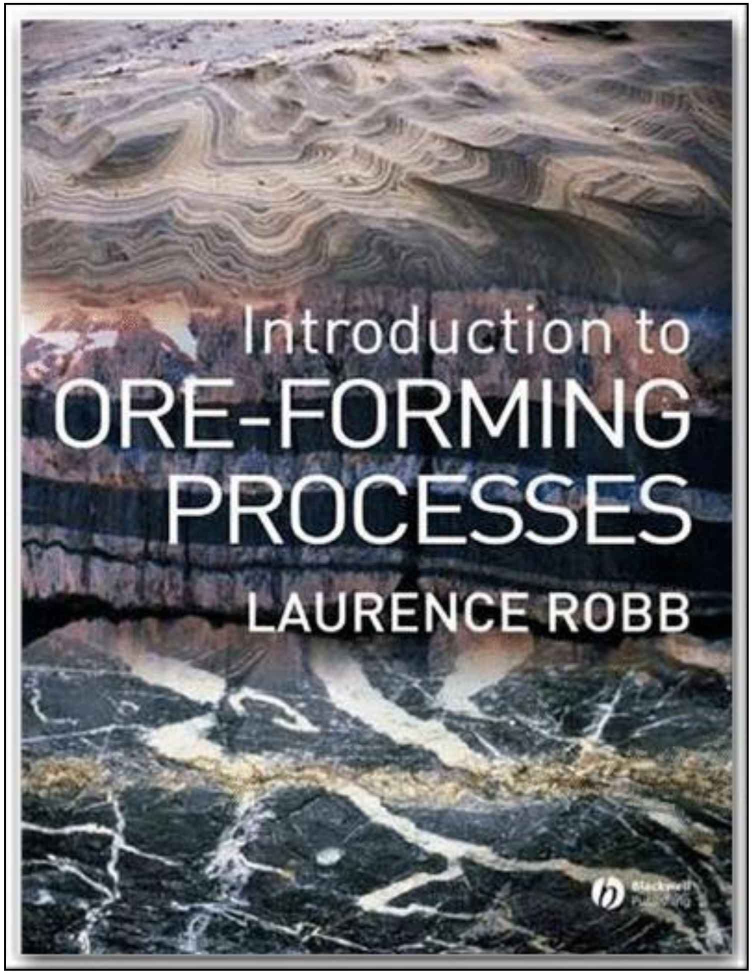
L'exposé doit être compréhensible pour toute la promo! Le support powerpoint sera considéré comme un complément du cours et redistribué à l'ensemble de la promo (donc faites des powerpoints pédagogiques).

20 min max. exposé + 15 min max. de questions/discussion (échange).

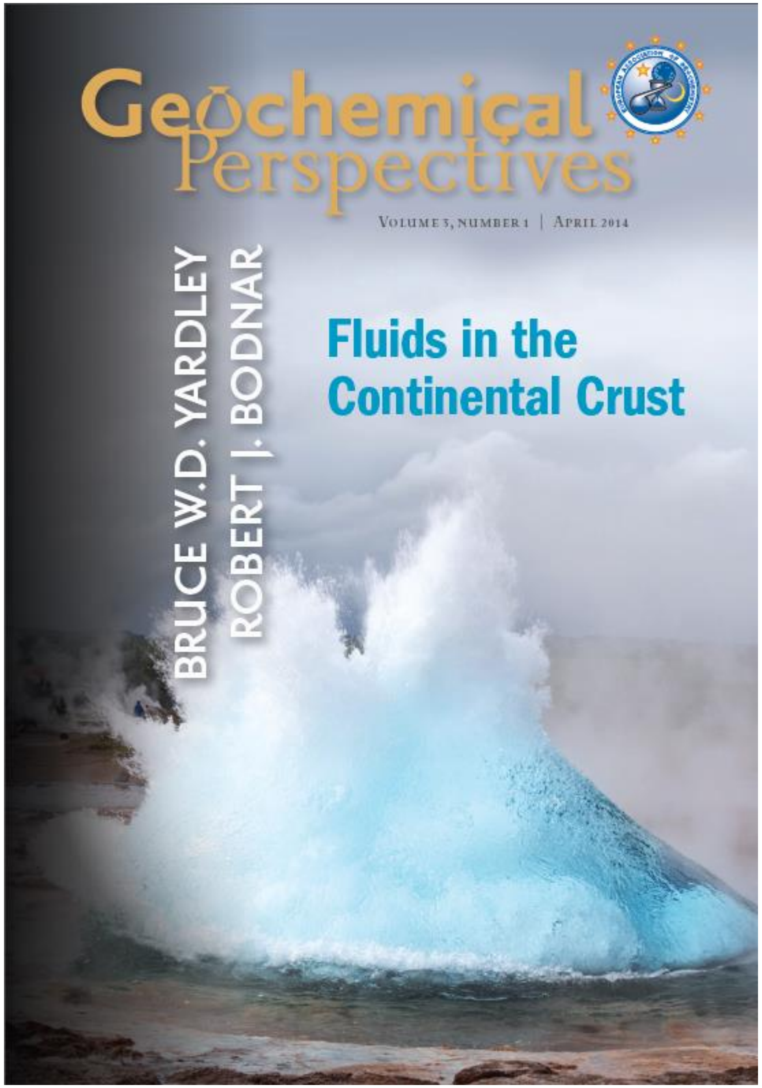
Pas de « doublon » avec projet de recherche, sujet biblio ou UE « Anglais et internationalisation »
Ecrit à prévoir à la fin de l'UE: questions possibles sur parties CM – TD – Exposés (donc soyez pédagogiques et actifs dans la discussion).

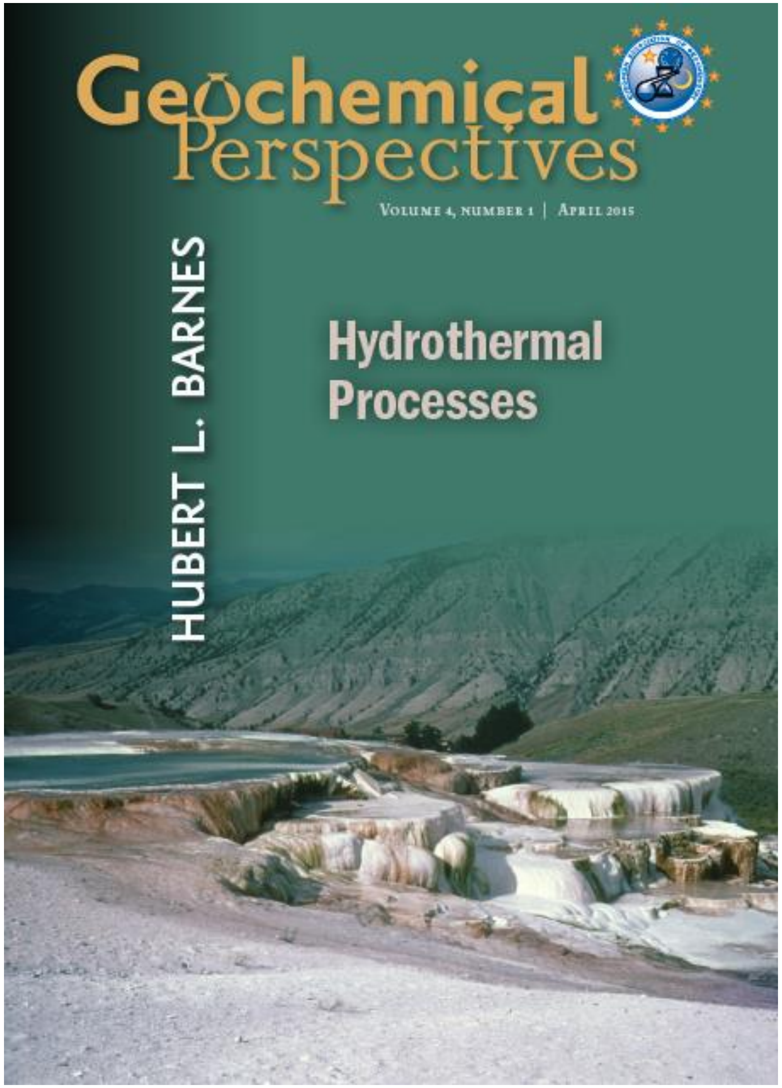
Références conseillées





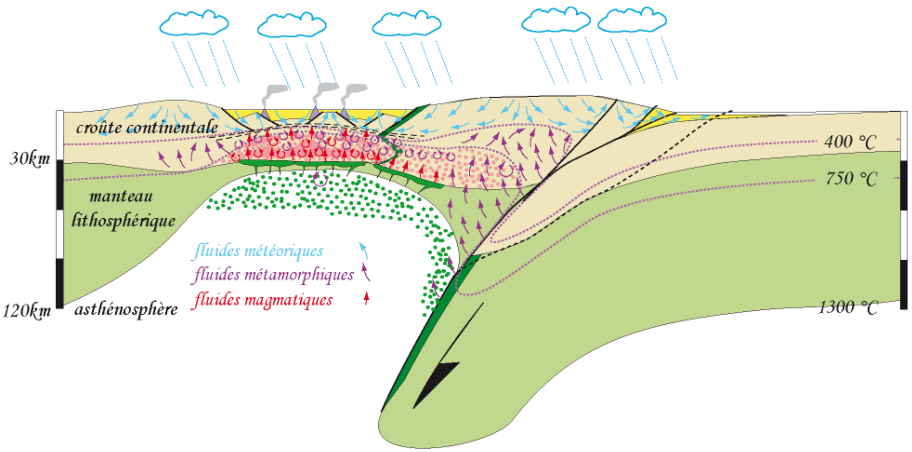
Références conseillées

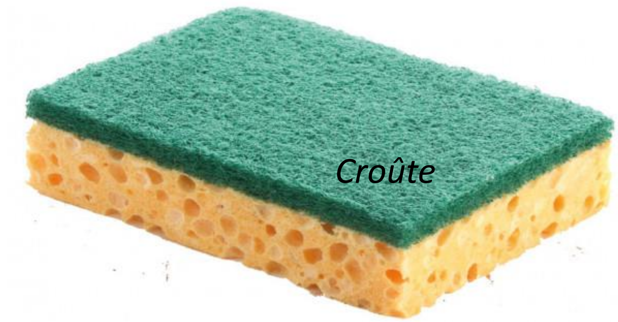




Disponibles en libre accès sur: http://www.geochemicalperspectives.org/

Préambule





Lithosphère

Manteau lithosphérique

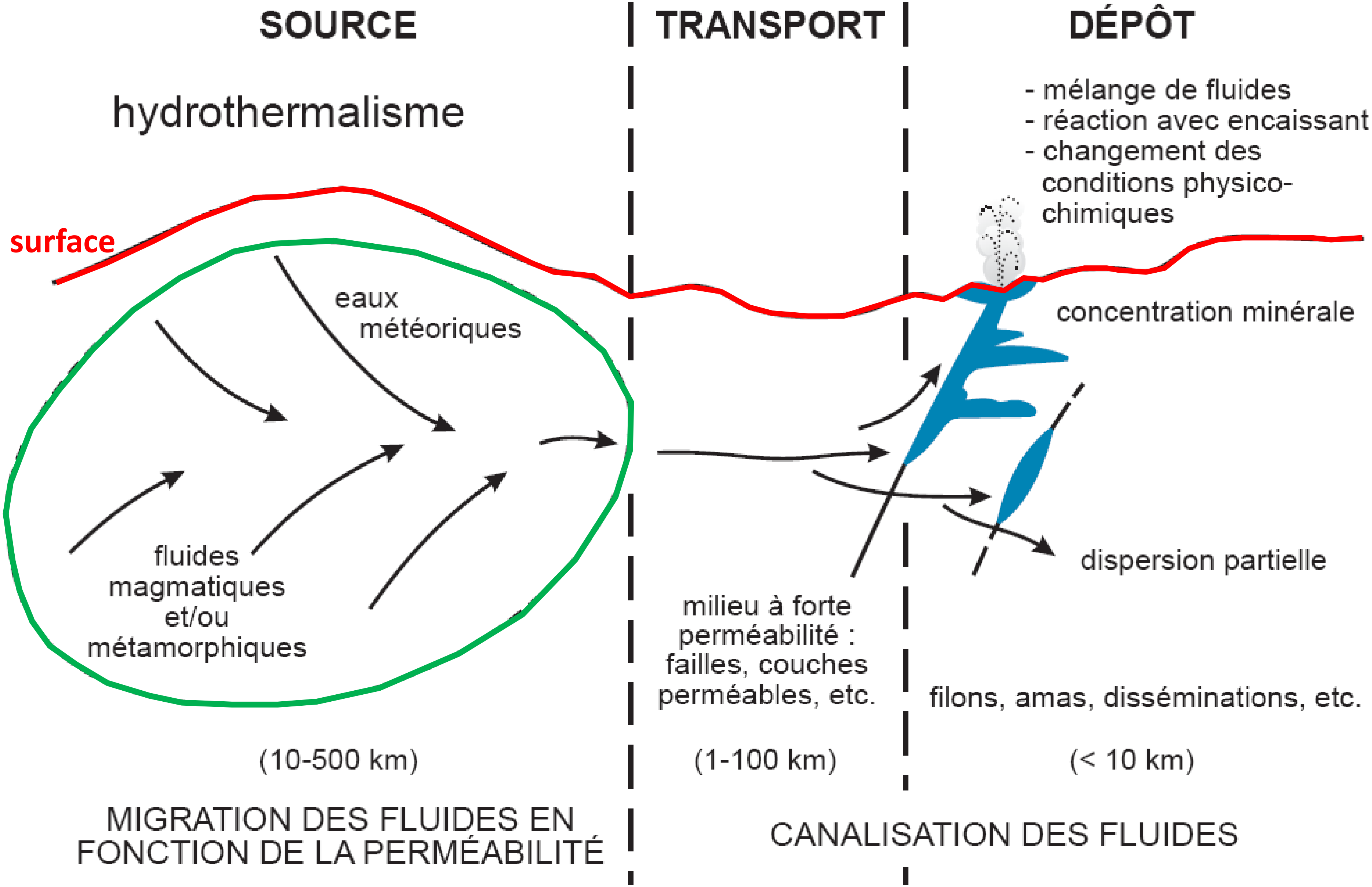
Où? Quand? Comment? Pourquoi?…et alors?

Déformation et mouvements de fluides

Chercheur / étudiant

Déformation + interactions fluides-roches

Préambule



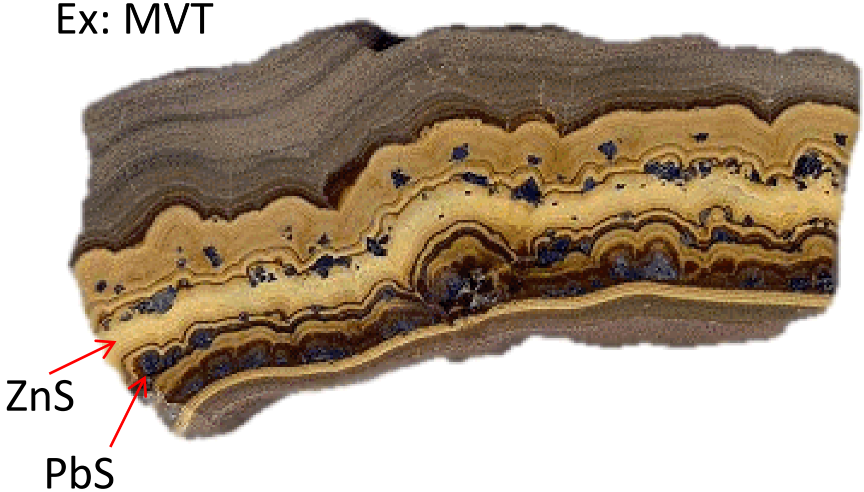
Jébrak et Marcoux (2007)

Préambule

Processus concentrateurs des métaux: systèmes hydrothermaux

Minéralisations (minéraux économiques ou gangue):

Ex: MVT



Témoins des circulations de fluides

Quels types de fluides (Origine, Conditions PTtx)?
Quels drains pour les fluides?
Quels moteurs pour les circulations de fluides?
Quelles sources pour les métaux?
Quels mécanismes pour lessivage des sources et mise en solution des métaux?
Quels sont les volumes de fluides et de roches sources mis en jeu?
Quels mécanismes pour précipitation des minéraux?
Quelle est la durée des processus?
Quelle relation avec contexte tectonique, géodynamique?

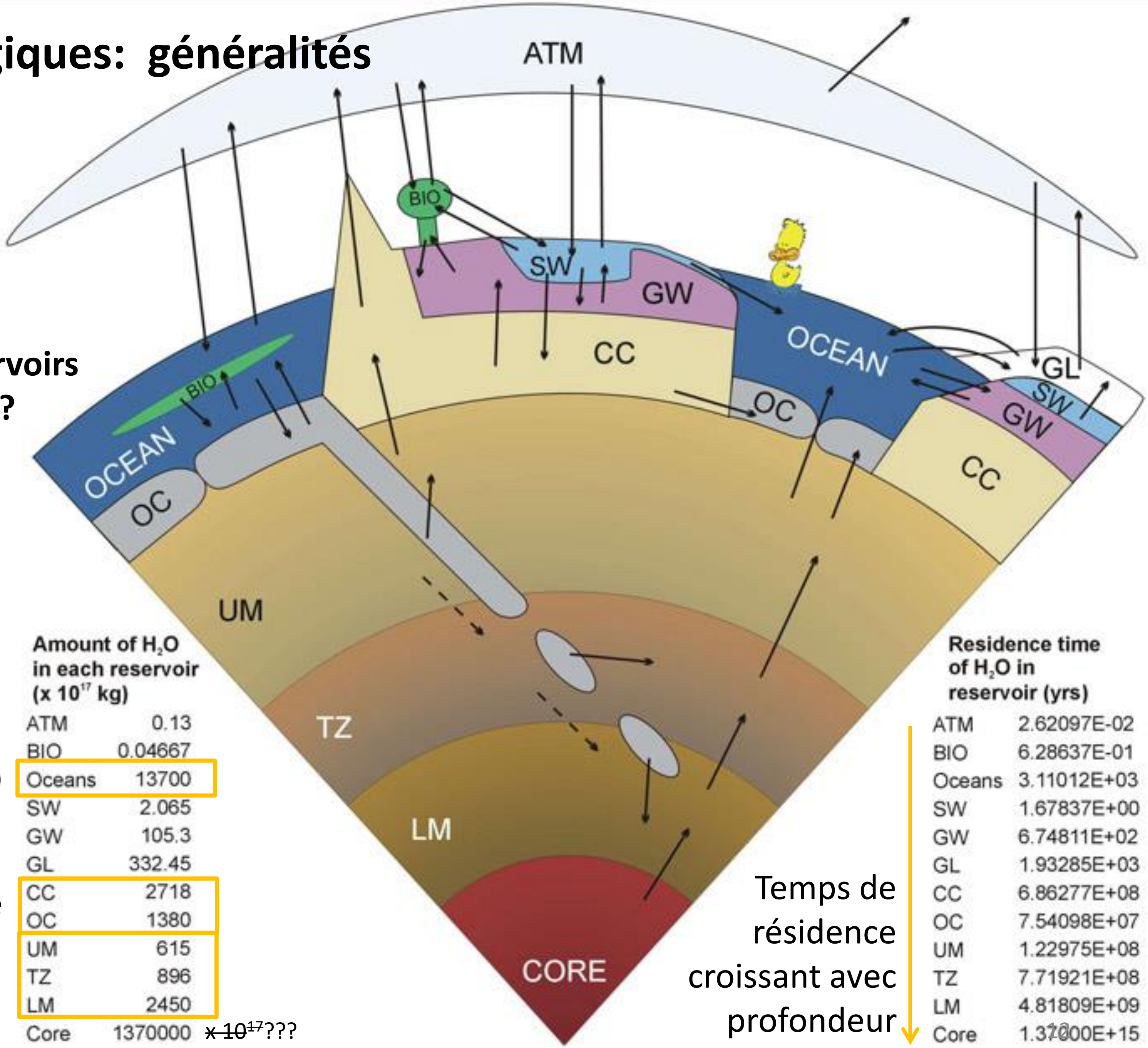
Fluides géologiques: généralités

Fluides géologiques: généralités

Réservoirs d'eau et temps de résidence:

Quels sont les réservoirs les plus importants?

Comment se distribuent les temps de résidences en fonction de la profondeur?



Amount of H_2O in each reservoir (x 10^{17} kg)

	ATM	0.13
	BIO	0.04667
Oceans (1)	Oceans	13700
	SW	2.065
	GW	105.3
	GL	332.45
Croûte	CC	2718
	OC	1380
env. = Manteau	UM	615
	TZ	896
	LM	2450
	Core	1370000 ~~x 10^{17}~~???

Residence time of H_2O in reservoir (yrs)

Temps de résidence croissant avec profondeur

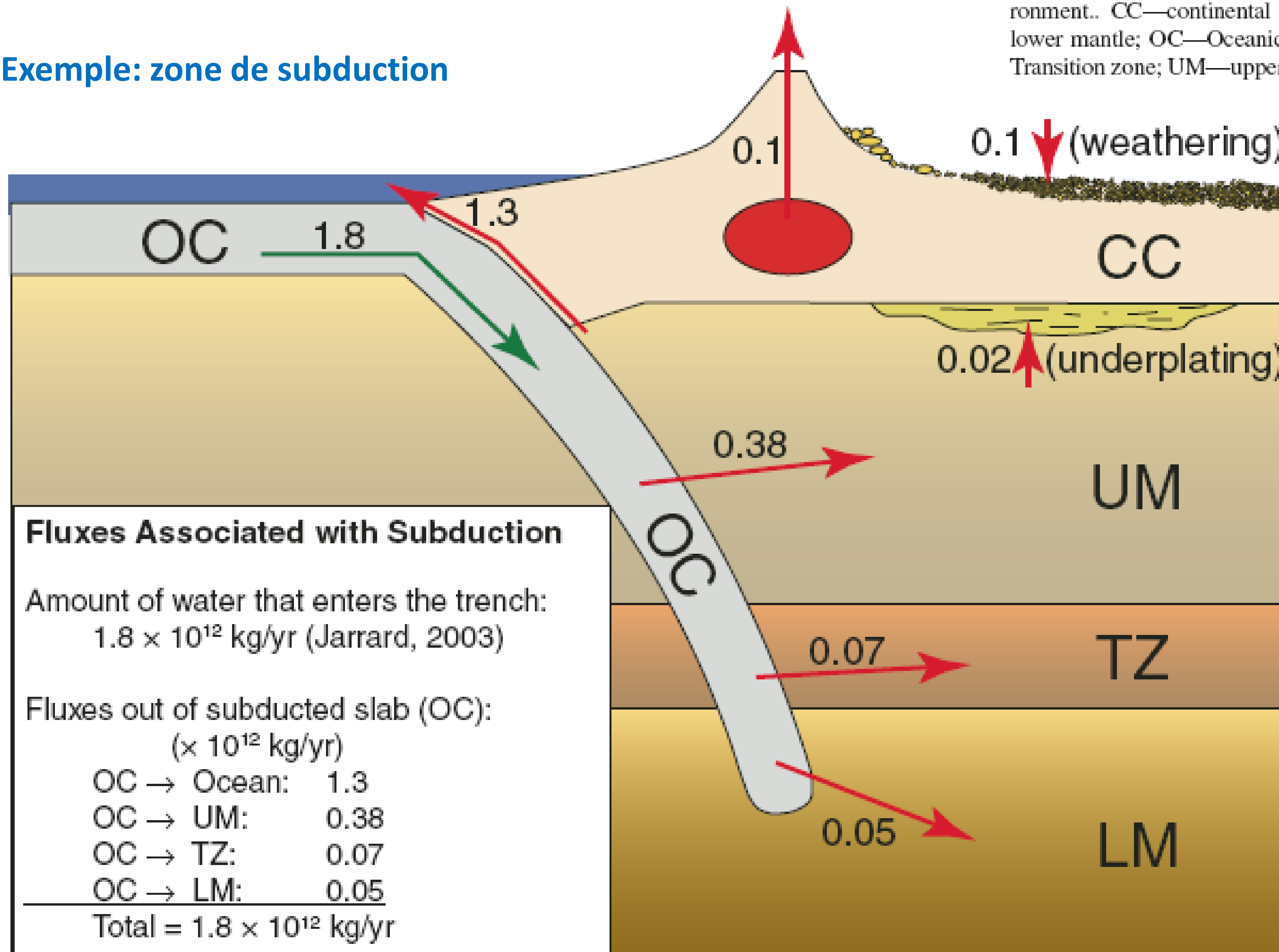
ATM	2.62097E-02
BIO	6.28637E-01
Oceans	3.11012E+03
SW	1.67837E+00
GW	6.74811E+02
GL	1.93285E+03
CC	6.86277E+08
OC	7.54098E+07
UM	1.22975E+08
TZ	7.71921E+08
LM	4.81809E+09
Core	1.37000E+15

Bodnar et al. 2013

Fluides géologiques: généralités

Exemple: zone de subduction

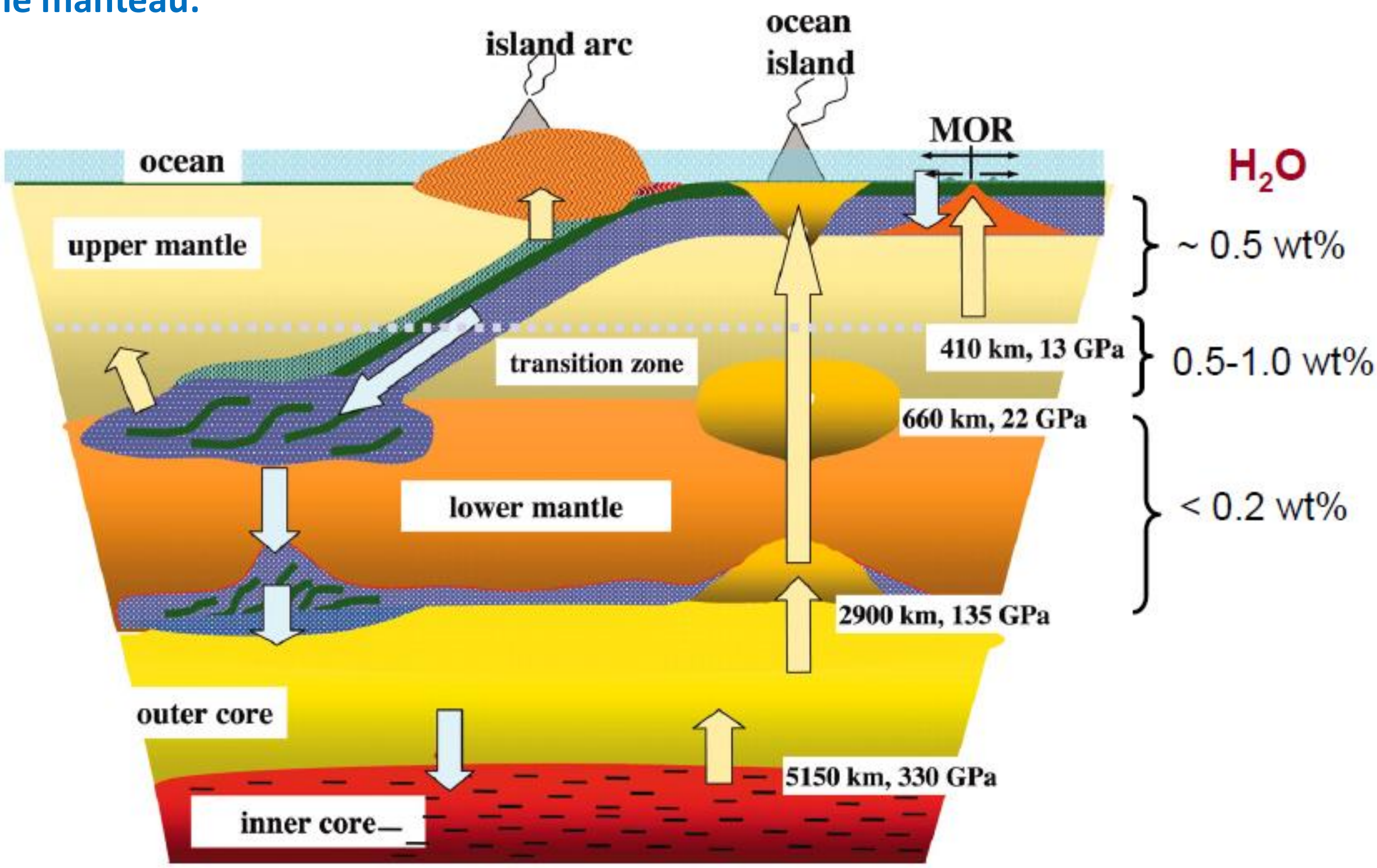
Figure 11. Summary of the fluxes of water between different reservoirs in the geo-hydrologic cycle in the subduction environment.. CC—continental crust; LM—lower mantle; OC—Oceanic crust; TZ—Transition zone; UM—upper mantle.



Bodnar et al. 2013

Fluides géologiques: généralités

Eau dans le manteau:



Ohtani (2005) Elements, 1, 25-30

Fluides géologiques: généralités

Eau dans le manteau (minéraux hydratés):

Table 1. Hydrous phases expected in the Earth's interior

Name	Formula*	Density g/cm^3	Mg/Si	H_2O wt.%
chlorite	$Mg_5Al_2Si_3O_{10}(OH)_8$	2.6-3.4	1.67	13
serpentine	$Mg_3Si_2O_5(OH)_4$	2.55	1.5	14
chondrodite	$Mg_5Si_2O_8(OH)_2$	3.06-3.16	2.5	5.3
hydroxylclinohumite	$Mg_9Si_4O_{16}(OH)_2$	3.14-3.26	2.25	3
10Å phase	$Mg_3Si_4O_{14}H_6$	2.65	0.75	13
phase A	$Mg_7Si_2O_8(OH)_6$	2.96	3.5	12
phase B	$Mg_{12}Si_4O_{19}(OH)_2$	3.38	3	2.4
superhydrous phase B(= phase C)	$Mg_{10}Si_3O_{14}(OH)_4$	3.327	3.3	5.8
phase D(= phase F =phase G)	$Mg_{1.14}Si_{1.73}H_{2.81}O_6$	3.5	0.66	14.5~18
phase E	$Mg_{2.3}Si_{1.25}H_{2.4}O_6$	2.88	1.84	11.4
wadsleyite	Mg_2SiO_4	3.47	2	≤ 3
ringwoodite	Mg_2SiO_4	3.47-3.65	2	1.0-2.2
topaz-OH	$Al_2SiO_4(OH)_2$	3.37	-	10
diaspore	AlOOH	2.38	-	15
phase Π	$Al_3Si_2O_7(OH)_3$	3.23	-	9
phase EGG	$AlSiO_3OH$	3.84	-	7.5
phase δ	AlOOH	3.533	-	15
lawsonite	$CaAl_2Si_2O_{10}H_4$	3.09	-	11.5

* End member formulas

Fluides géologiques: généralités

Eau dans le manteau (minéraux « anhydres »):

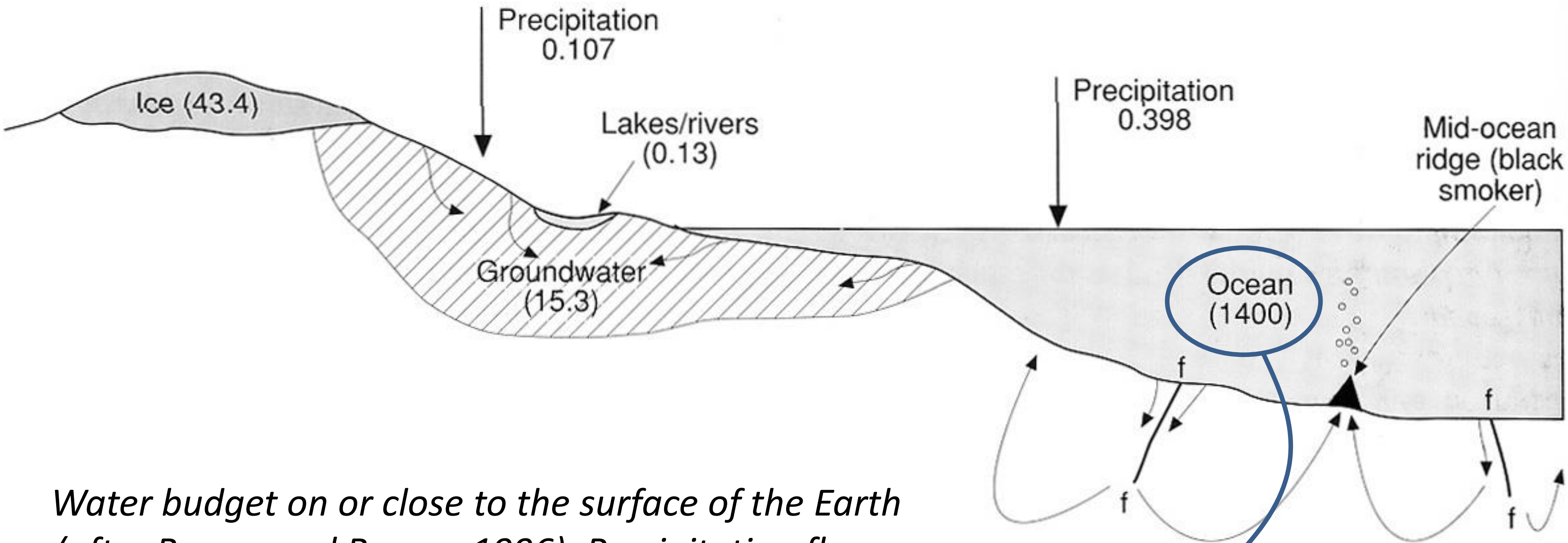
Table 2. Water content in anhydrous mineral phases

Mineral phases	SiO_2	TiO_2	Al_2O_3	$FeO^{\S}$	MgO	Mg#	Pressure GPa	Temperature °C	H_2O ppmwt	1σ	References
$MgSiO_3$ perovskite	60.1				40.36	100	25	1300	104	14	1)
Al-Mg perovskite	59.09		2.03		39.77	100	25	1400	101	19	1)
Al-Mg perovskite	57.86		4.43		39.55	100	25	1200	1101	156	1)
Al-Mg perovskite	55.37		7.16		38.18	100	26	1200	1440	160	1)
Al-Fe-Mg perovskite*	36.73	2.18	14.5	26.23	20.15	57.8	26	1000	110	21	1)
Al-Fe-Mg perovskite*	38.11	1.91	13.16	24.52	21.37	60.8	26	1200	104	26	1)
Al-Fe-Mg perovskite*	38.43		16.77	23.4	20.82	61.3	25	1300	47	12	1)
Al-Fe-Mg perovskite**	52.77		5.5	7.39	34.48	0.18	25	1400	1780	175	1)
Al-Fe-Mg perovskite**	53.11		5.8	6.09	34.94	0.15	25	1600	1460	130	1)
$MgSiO_3$ perovskite	60.1				40.36	100	27	1500	60-70		2)
$MgSiO_3$ perovskite	60.1				40.36	100	24	1600	<1		3)
Al-Fe-Mg perovskite**			2~6	1~4		100	24		<5		3)
Al-Fe-Mg perovskite**							25.5		1000~4000		4)
Magnesiowüstite											
(=Ferropericlase)							25.5		2000		4)
Periclase					100	100	24	1600	2		3)
$CaSiO_3$ perovskite							25.5		3000-4000		4)

*: in MORB; **: in peridotite; 1) Litasov et al. (2003); 2) Meade et al. (1994); 3) Bolfan-Casanova et al. (2000); 4) Murakami et al.(2001)
χ: Iron calculated as ferrous iron

Fluides géologiques: généralités

Eau à la surface:

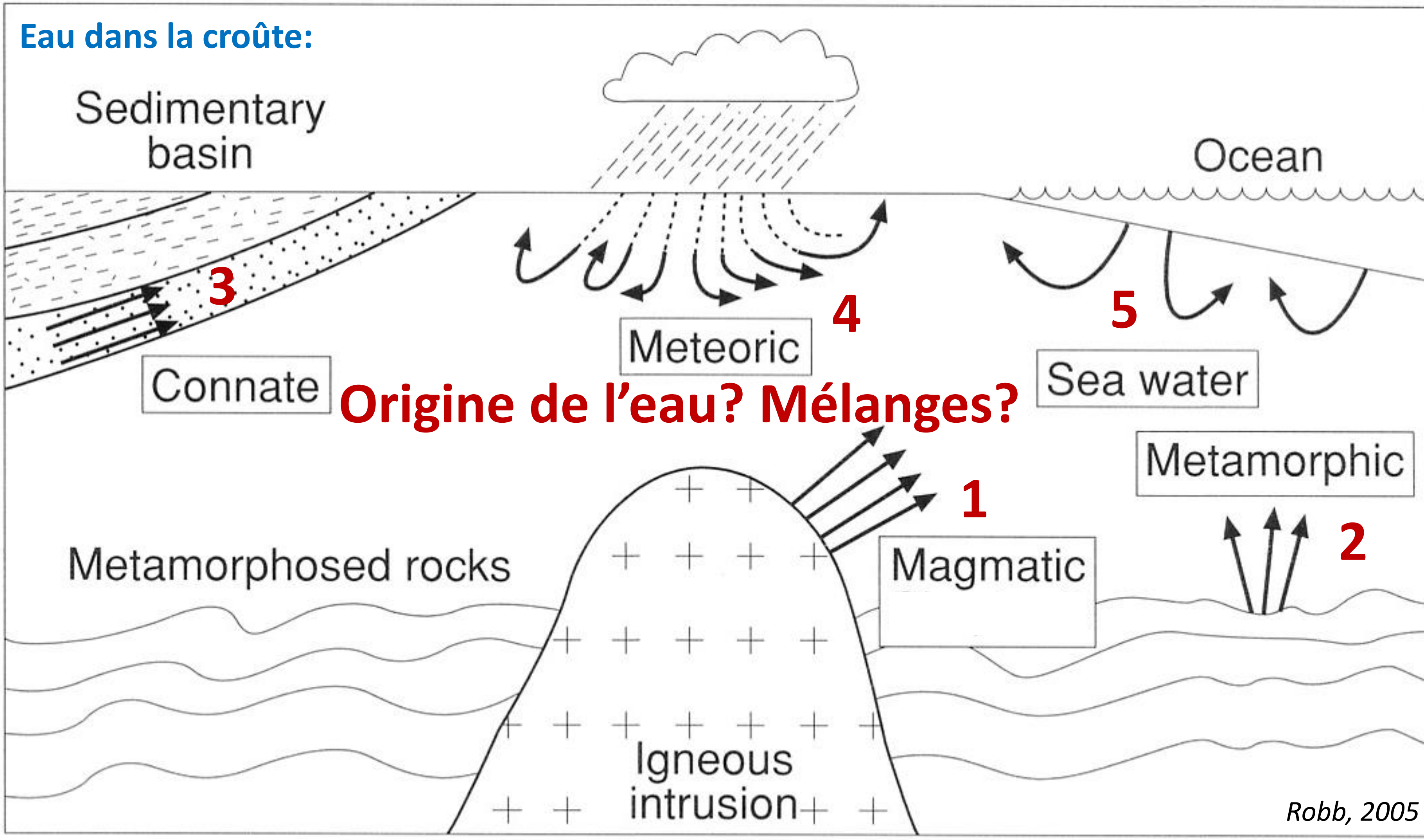


Water budget on or close to the surface of the Earth (after Berner and Berner, 1996). Precipitation fluxes are in 10^6 km^3 yr^{-1} and reservoir volumes in 10^6 km^3.

70% de la surface
98% de l'eau libre

Robb, 2005

Fluides géologiques: généralités



1. Fluides magmatiques 2. Réactions de déshydratation métamorphique
3. Eau connée dans sédiments 4. Fluides météoriques 5. Eau de mer

Fluides géologiques: généralités

Figure 3.2 Champagne Pool, New Zealand. The colourful colloids of S, As and Sb serve to demonstrate that, although much of the geothermal water originated as local rainfall, the high concentrations of many other elements require a magmatic origin.

Yardley and Bodnar, 2014

Fluides géologiques: généralités

Origine de l'eau? Mélanges?

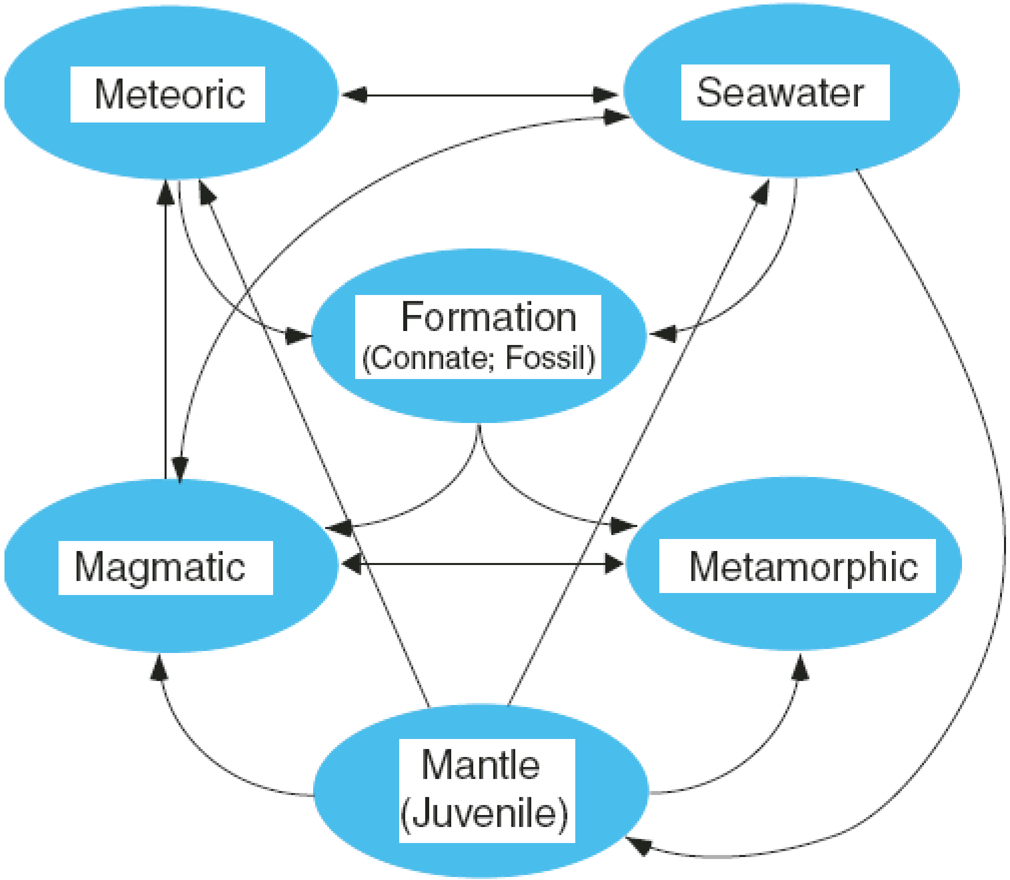


Figure 1. Summary of the different water reservoirs in the Earth (modified from White, 1957). Note that White (1957) defined water buried with sediments as Connate (born with) or Fossil water. Here, we use the nongenetic term "Formation" water to represent water that is transitional between surface reservoirs (Meteoric and Seawater) and waters of deeper origin. Similarly, White's original pre–plate tectonics classification Juvenile water is here referred to as Mantle water.

(Bodnar et al. 2013)

Fluides géologiques: généralités

Origine de l'eau? Mélanges?

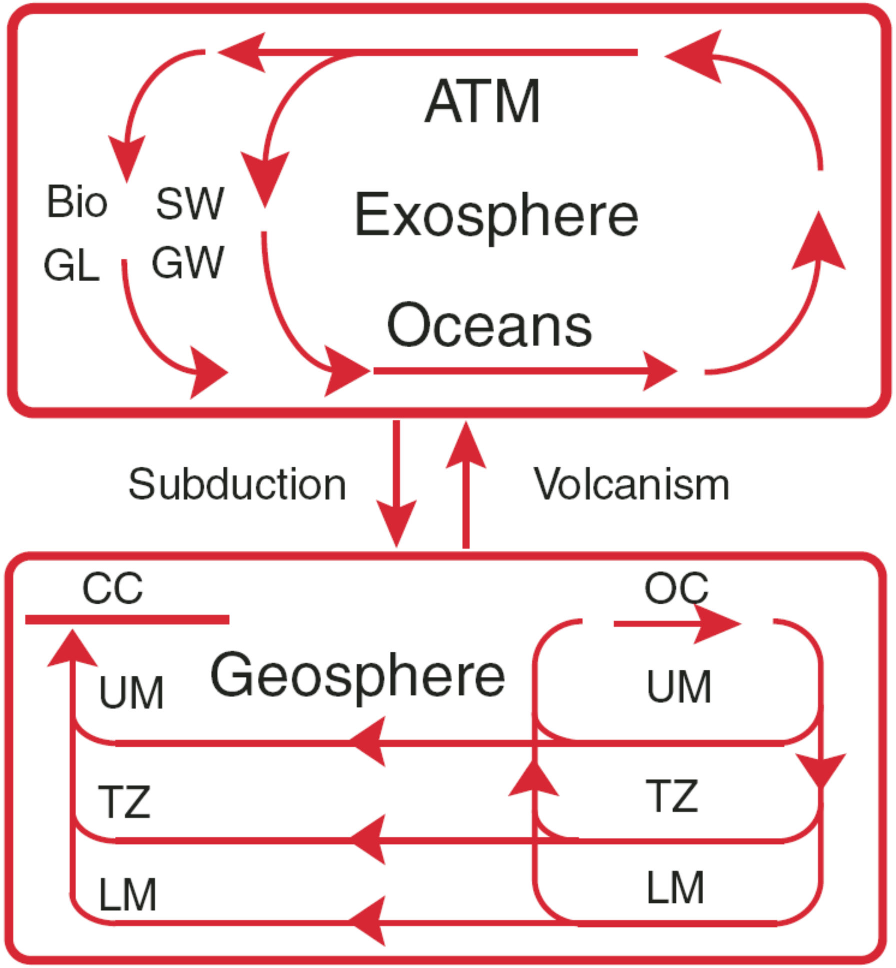


Figure 3. Schematic representation of the various reservoirs for water in the exosphere and the geosphere and the exchange of water between the exosphere and geosphere as a result of subduction and volcanism. Within the exosphere, water is dominantly circulated between the oceans and atmosphere. Precipitation that falls onto the continents is incorporated into the biosphere, surface water, glaciers and polar ice and groundwater, and some returns to the oceans as runoff. Water in the geosphere circulates as a result of mantle convection. Abbreviations: ATM—atmosphere; SW—surface water; GW—groundwater; Bio—biosphere; GL—glaciers and polar ice; CC—continental crust; OC—Oceanic crust; UM—upper mantle; TZ—Transition zone; LM—lower mantle.

(Bodnar et al. 2013)

Fluides géologiques: généralités

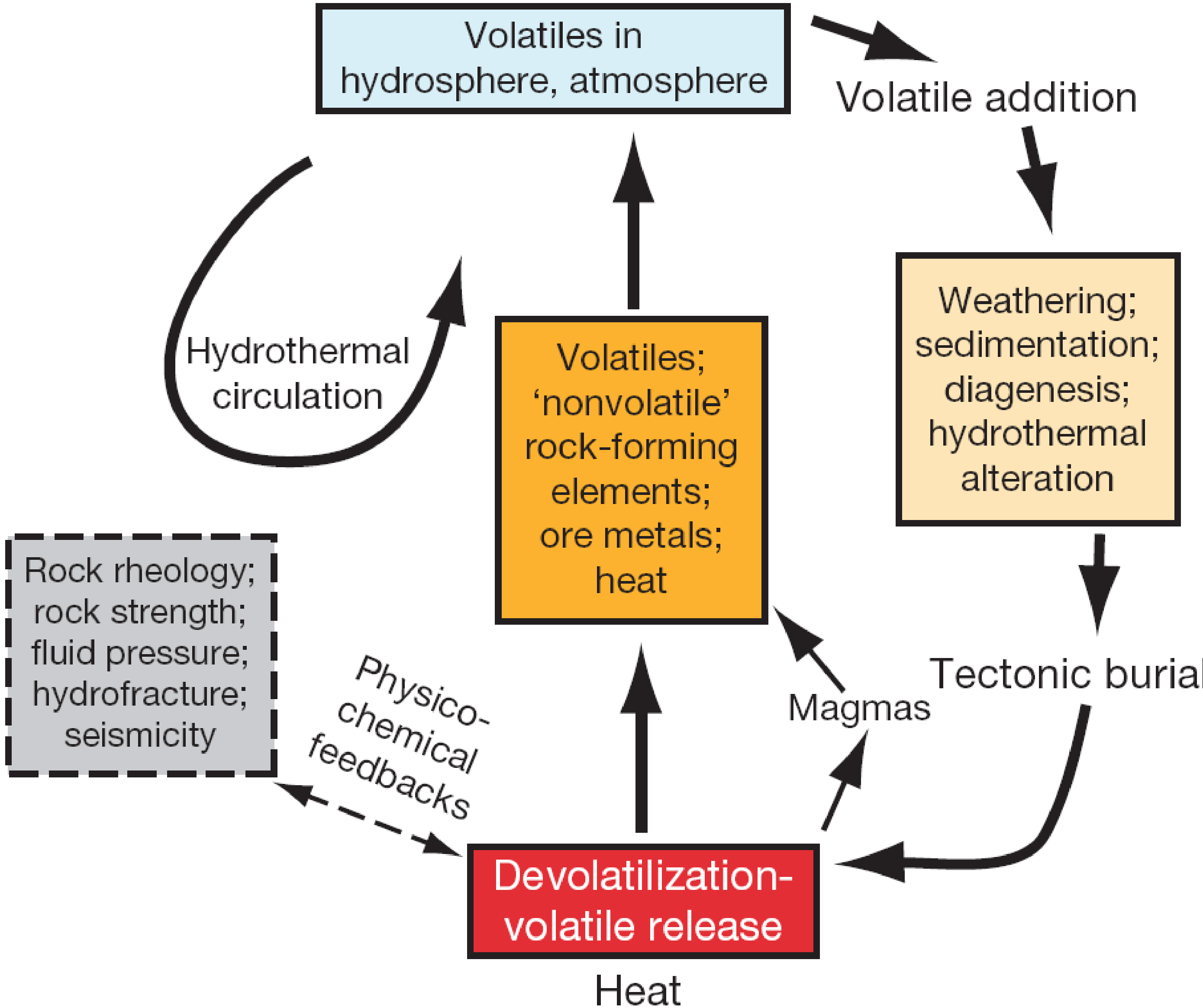
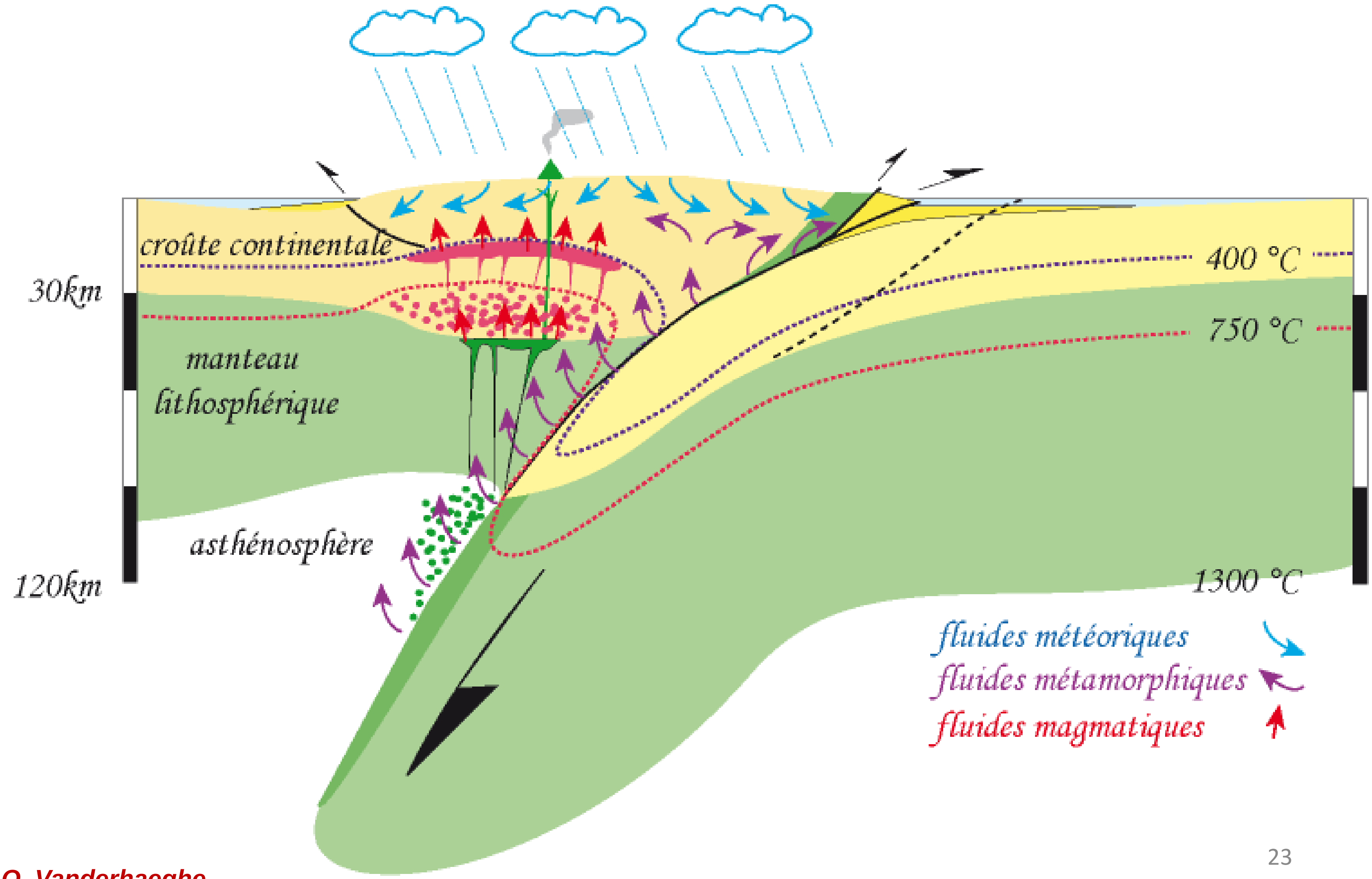


Figure 1 Diagram of crustal fluid cycling.

Ague 2014

Fluides géologiques: généralités

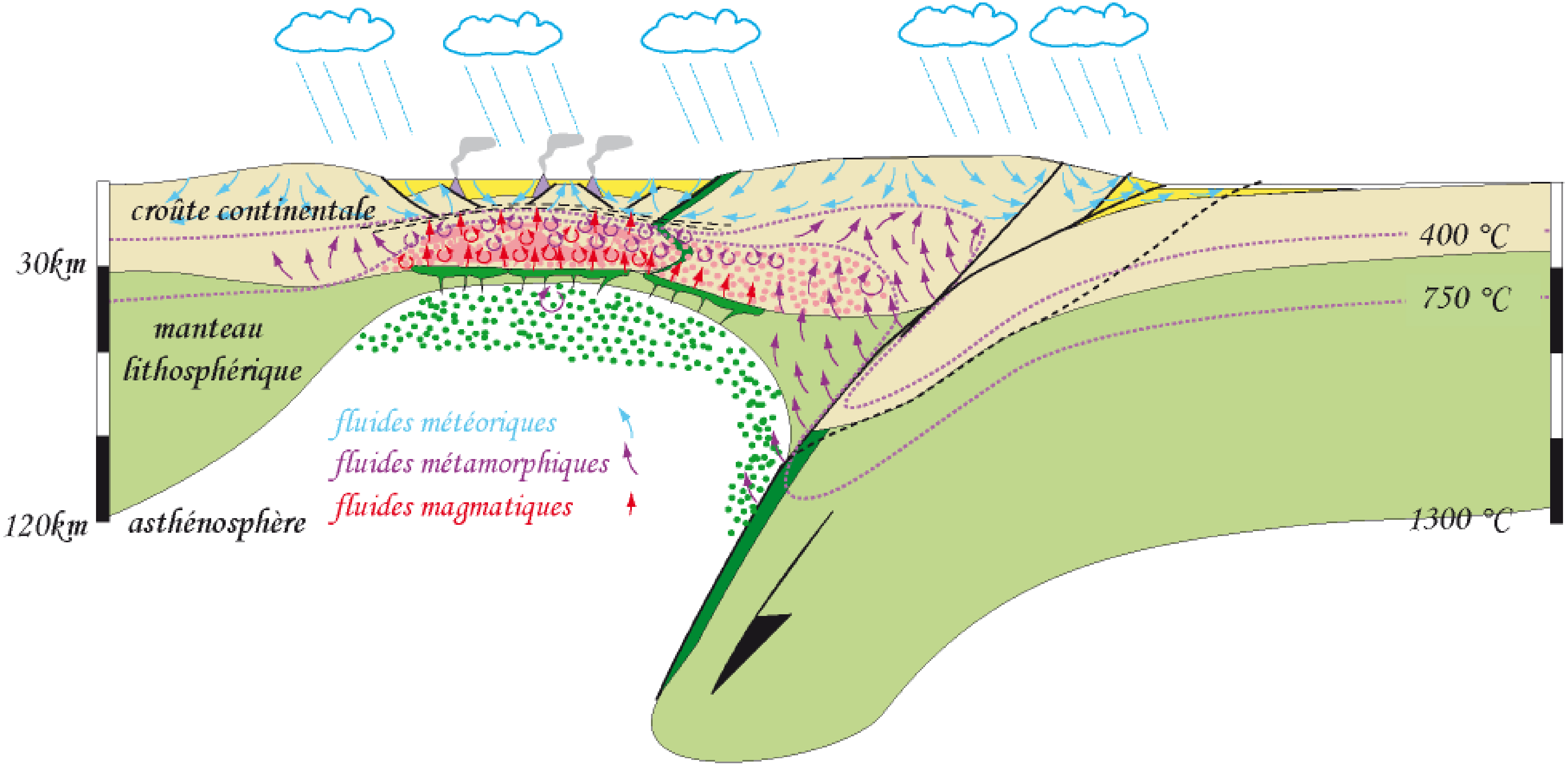
Interaction manteau – croûte – surface:



Source: O. Vanderhaeghe

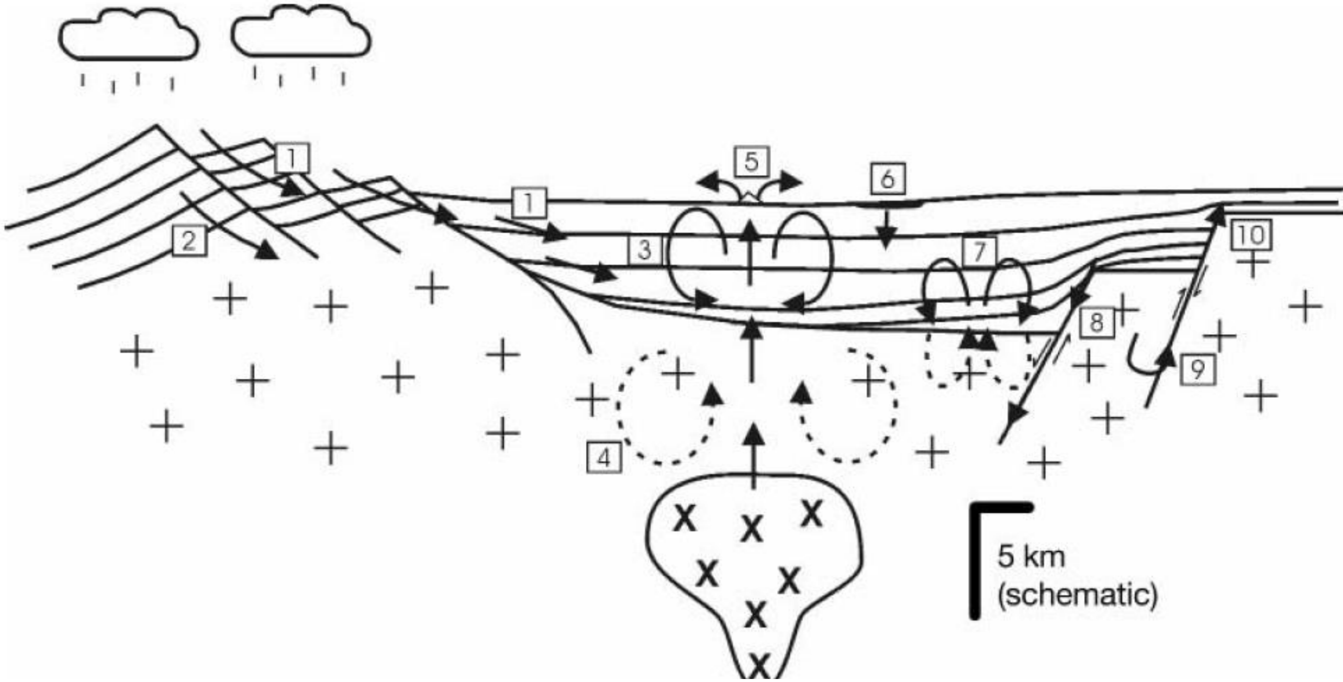
Fluides géologiques: généralités

Interaction manteau – croûte – surface:



Source: O. Vanderhaeghe

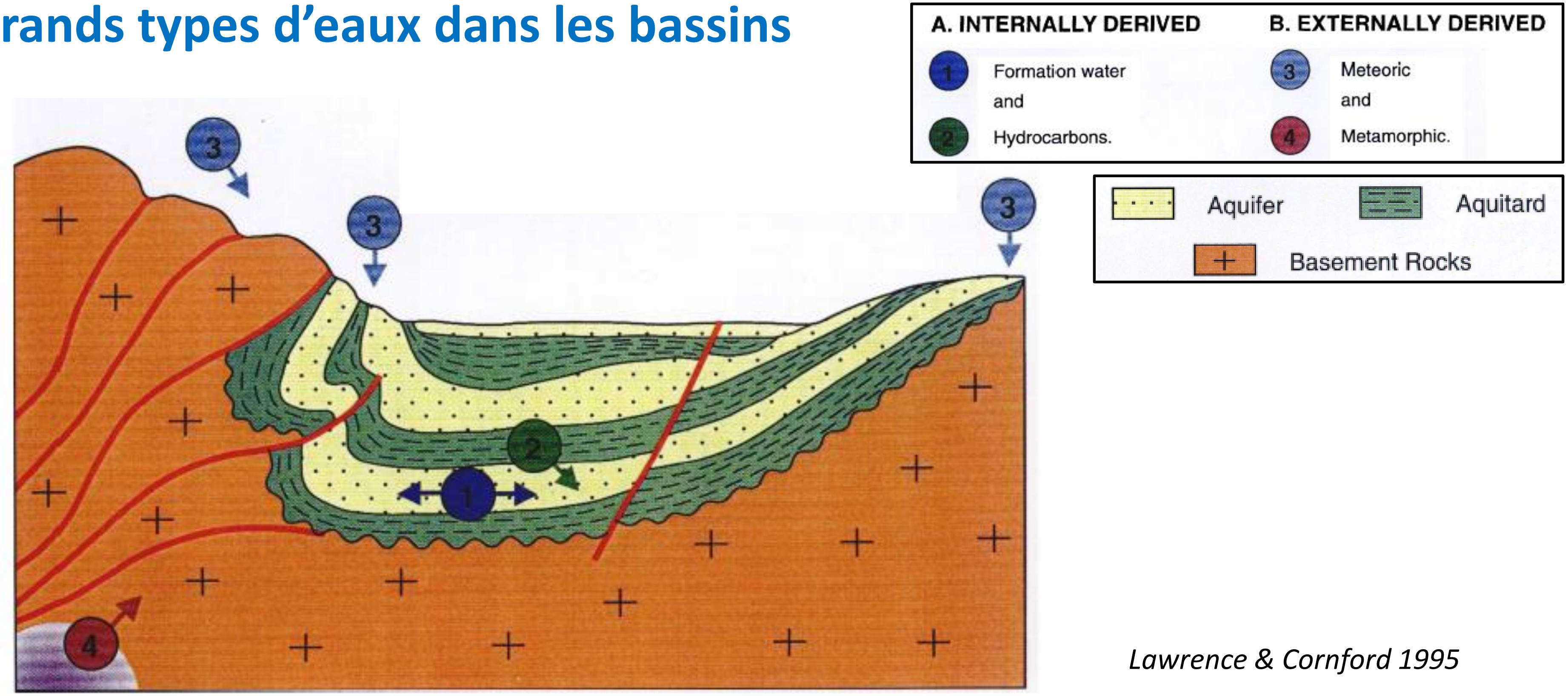
Principaux mécanismes de migration de fluides dans les bassins



Olivier et al. (2006)

FIG. 1. Schematic cartoon summarizing the variety of types of fluid flow proposed for basin-related mineralization. 1 = topography-driven fluid flow in permeable cover sequences, 2 = topography-driven fluid flow into lower permeability basement rocks, 3 = convection in permeable cover sequences, 4 = convection within lower permeability basement rocks, with potential contribution of fluid and heat from crystallizing magmas, 5 = exhalation above convective upflow plumes, 6 = gravity-driven downflow of dense brine, 7 = convection straddling the basement-cover boundary, 8 = deformation driven downflow along active (or reactivated) extensional faults, 9 = convection within and around fault zones in otherwise low-permeability basement rocks, 10 = deformation-driven upflow during inversion of former extensional faults.

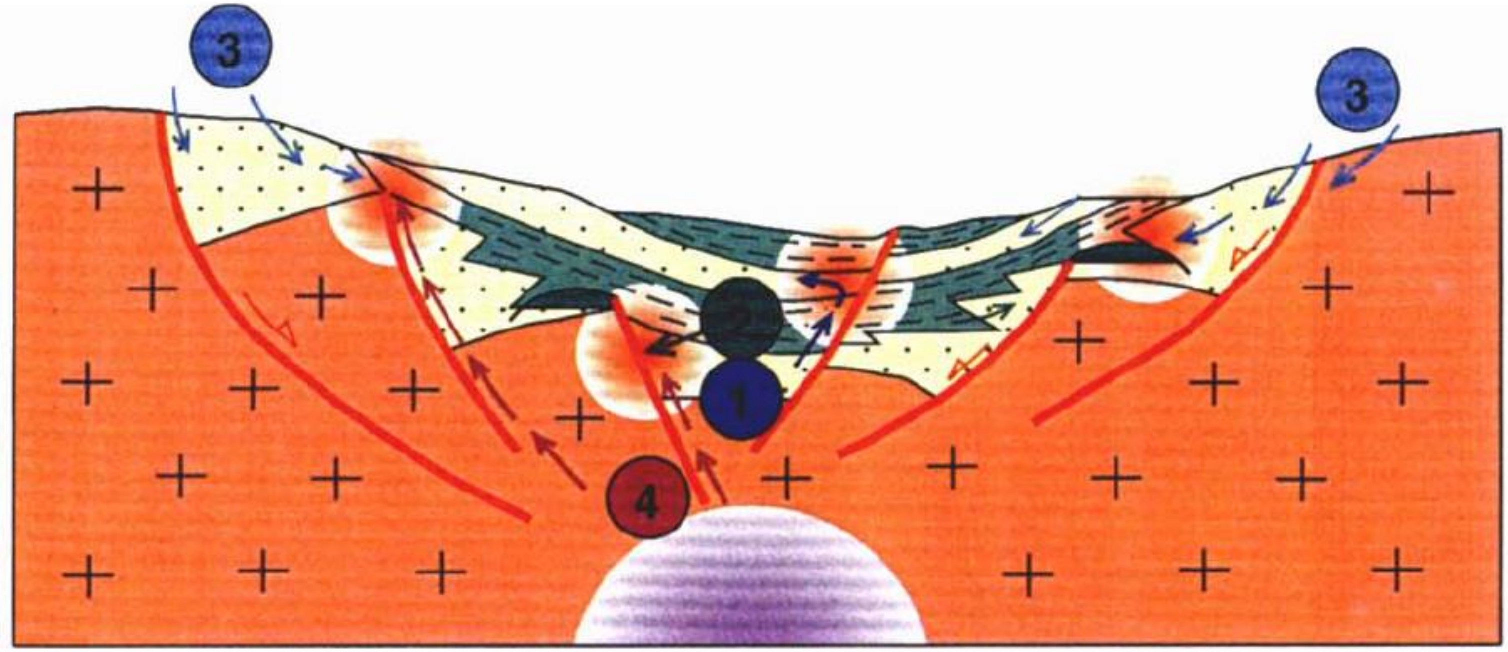
Grands types d'eaux dans les bassins



Lawrence & Cornford 1995

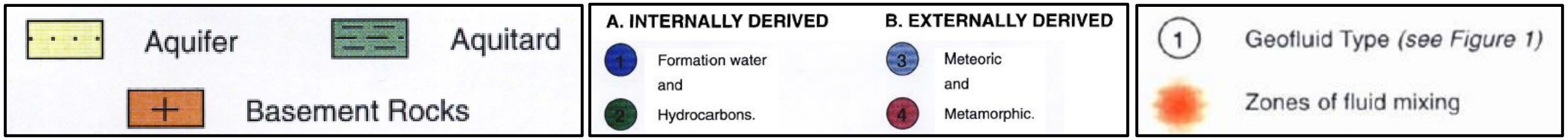
Fig. 1. Fluids internal to basins (A) comprise formation waters (1) initially trapped during sedimentation augmented by water generated during diagenetic and low-grade metamorphic dehydration reactions, together with hydrocarbons (2) generated from organic-rich petroleum source rocks. Externally derived fluids (B) comprise meteoric waters (3) derived from precipitation in areas of topographic elevation, and metamorphic fluids (4) emanating from metamorphic dewatering in zones below and external to the basin. (Note magmatic fluids associated with volcanic activity are included in this category for convenience.)

Migration des fluides en contexte de rift intracontinental

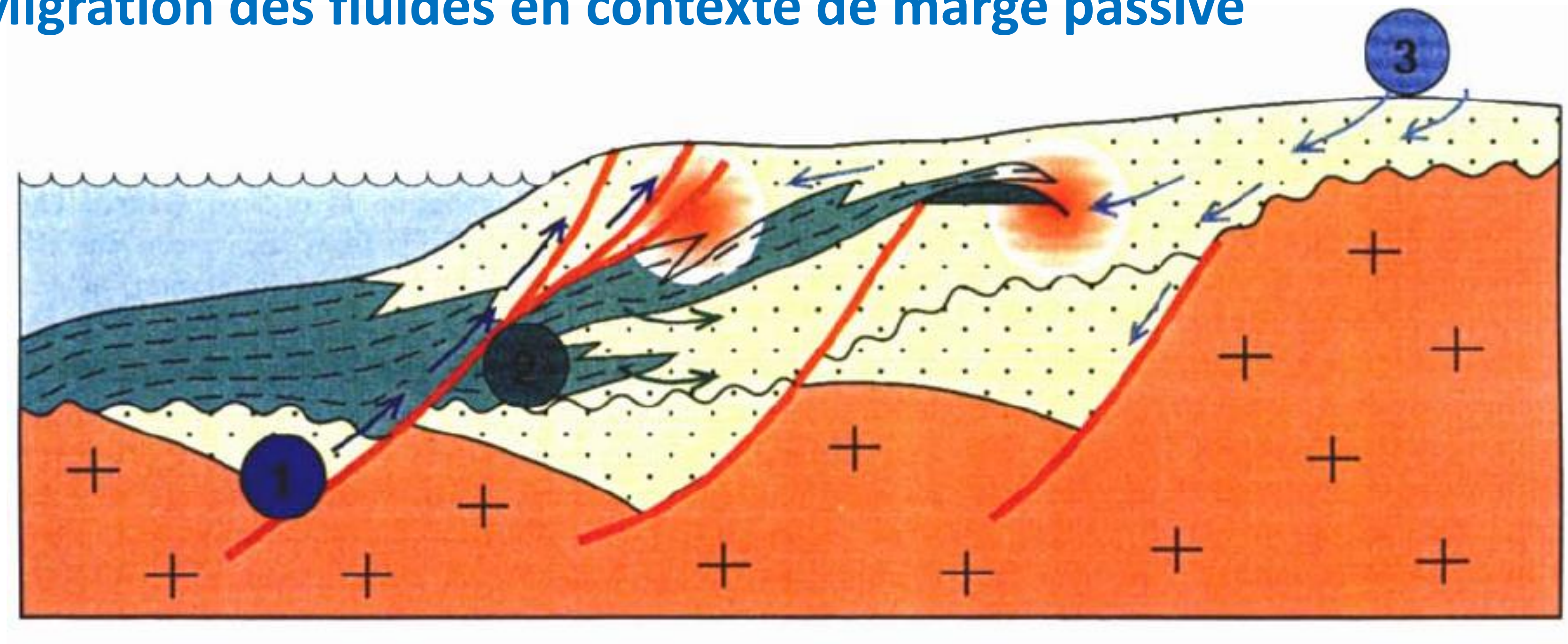


Lawrence & Cornford 1995

Fig. 2. The effectiveness of the various geofluid flow regimes are characteristic of different basin types and settings. Flow regimes and the potential for fluid mixing will evolve with basins as depicted by a plate tectonic (Wilson-cycle) evolutionary path from intracontinental rifting through passive margin and ultimate continental collision with foreland basin development.



Migration des fluides en contexte de marge passive



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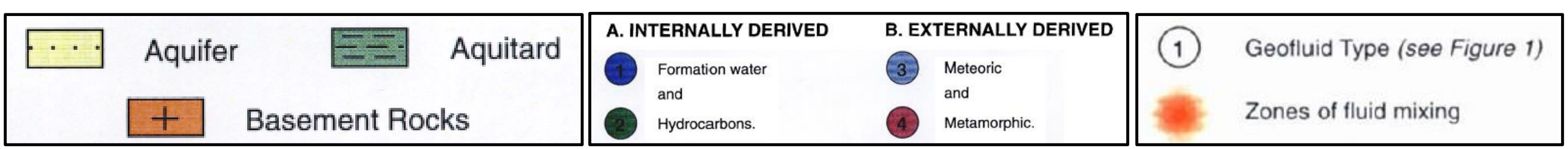
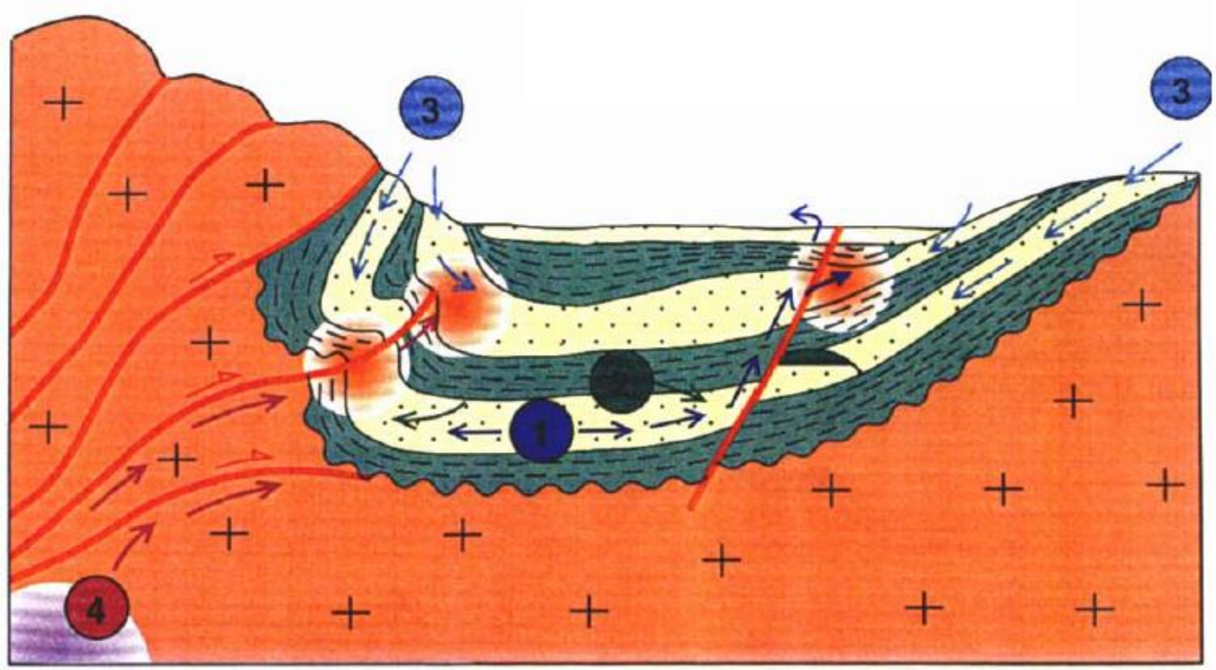
Lawrence & Cornford 1995



Migration des fluides en contexte de bassin d'avant-pays



Lawrence & Cornford 1995

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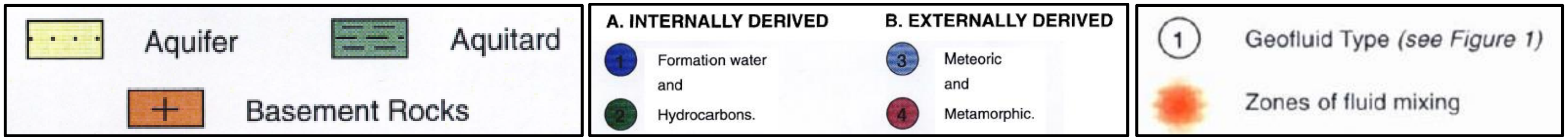


Fluides géologiques: généralités

Origine de l'eau? Mélanges?

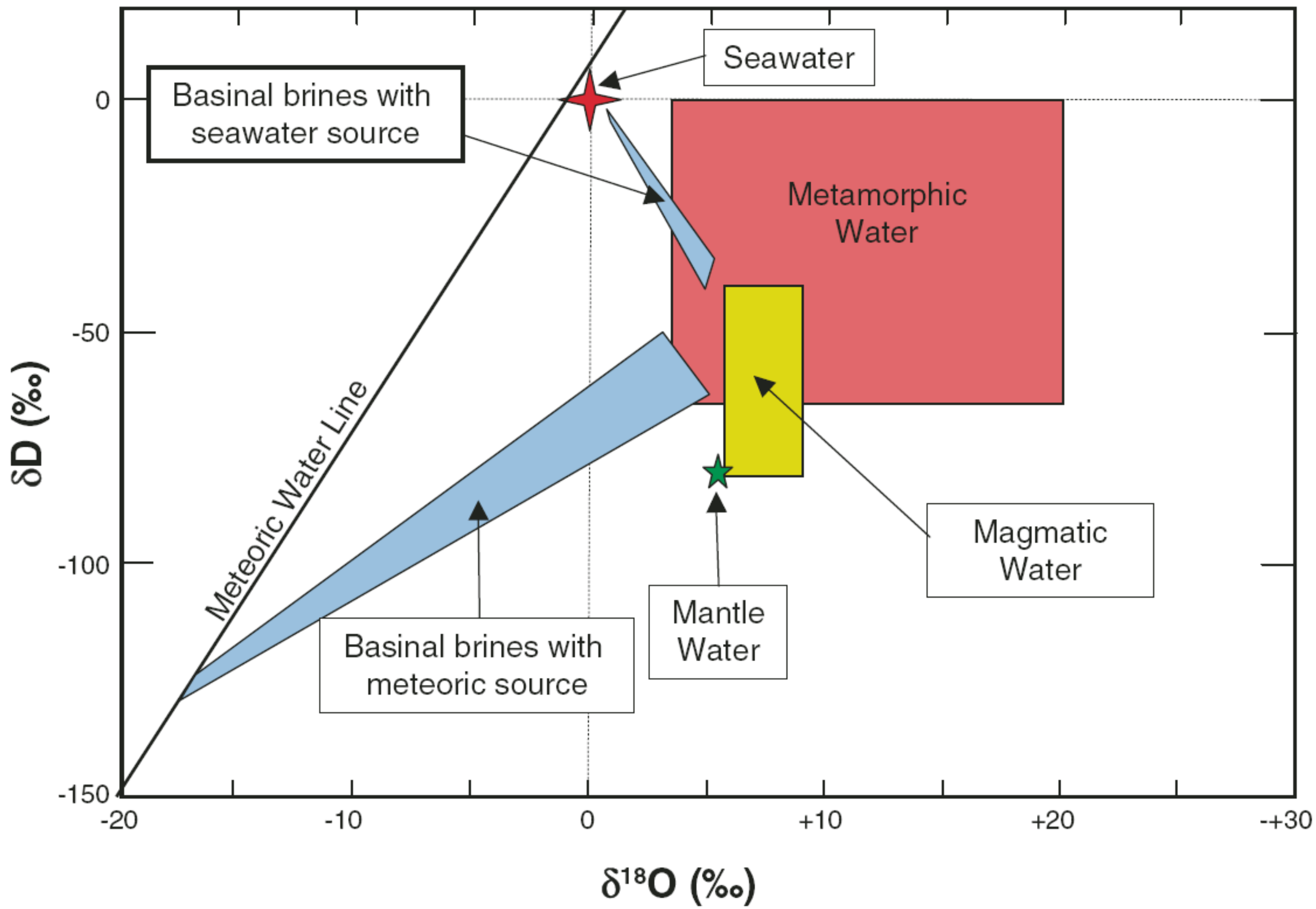


Figure 2. Characterization of the different water reservoirs in and on the Earth based on the oxygen and hydrogen isotopic compositions (modified from Sheppard, 1986).

(Bodnar et al. 2013)

Fluides géologiques: généralités

Définition – Eau/fluide/solution hydrothermal(e): ???

Hydrothermal, e, aux adj. [de hydro-, et du gr. *thermos*, chaleur] - Qui se rapporte aux circulations d'eaux chaudes liées à la fin d'une éruption volcanique, ou à celle de la cristallisation d'un magma, et aux sources qui peuvent, éventuellement en résulter. Les solutions hydrothermales (= hydrothermalytes), à 100-400°C et sous pression, contiennent divers corps avec Fe, Ti, Cu, Pb, Zn, Sn, Hg, U, ... Ces corps issus du magma ou prélevés dans les roches encaissantes peuvent ensuite précipiter et se concentrer en filons. n. m. **hydrothermalisme**.

Sens strict: Eau chaude d'origine magmatique ou mise en circulation autour d'une source de chaleur d'origine magmatique

hydrothermal [GEOL] Of or pertaining to heated water, to its action, or to the products of such action. { ˌhī·drə'thər·məl }

Sens large: Eau chaude pas nécessairement liée à une intrusion magmatique

Au sens très large on dit qu'un fluide géologique est « hydrothermal » lorsqu'il est mis en circulation dans des conditions de T plus élevées que la surface

Fluides géologiques: généralités

Caractéristiques des fluides géologiques / hydrothermaux:

Species (ppm)	Sea water	Black smoker sea water (at 100–300 °C)	Rain water	Meteoric spring water (at 6 °C)	Meteoric geothermal water (at 300 °C)
Na^+	10 000	6000–14 000	1.0	23 ???	187
Cl^-	20 000	15 000–25 000	1.1	3.1	21
SO_4^{2-}	2700	0	1.5	11	103
Mg^{2+}	1300	0	0.2	2.4	0
Ca^{2+}	410	36	0.4	5.1	0.5
K^+	400	26	0.5	1.0	27
Si^{4+}	0.5–10	20	1.2	17	780
Metals (Fe, Cu, Zn, Mn, etc.)	depleted	enriched	depleted	depleted	enriched

Source: after data in Krauskopf and Bird (1995), Scott (1997).

Robb, 2005

Interactions fluides-roches à HT: enrichissement en métaux

Fluides géologiques: généralités

Caractéristiques (très générales) des fluides hydrothermaux:

- ***Solvent:*** water (≥ 90%), at high temperature: mixed fluids H_2O-CO_2, CH_4, N_2, H_2
- ***Major components (0.1-50 wt %):*** Na, Cl, S, C, Si, Ca, K…
- ***Minor/trace components (1 ppt-1000 ppm):*** Al, Fe, Pb, Zn, Cu, REE (Rare Earths), Zr, Au, As, PGE…

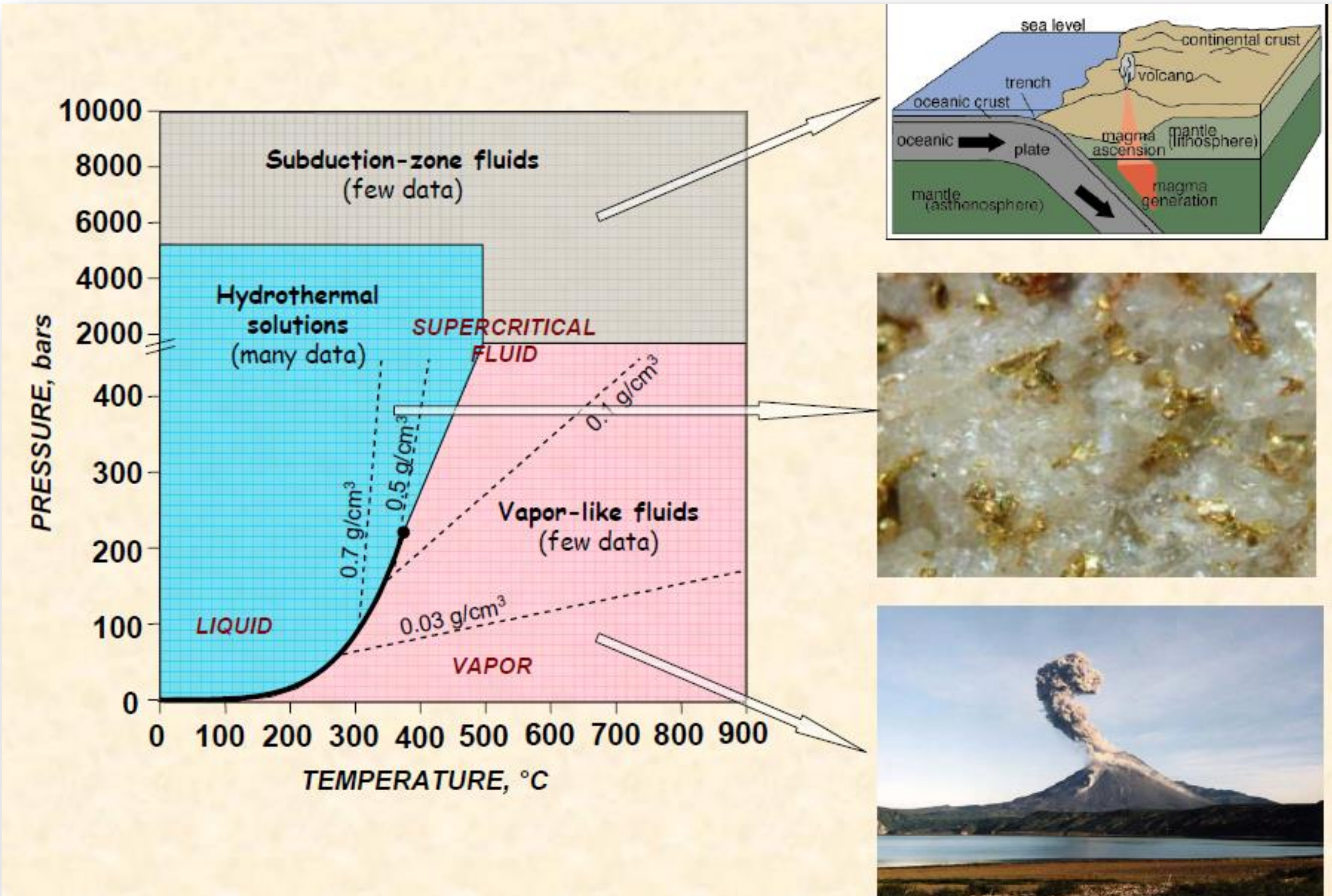
PHYSICAL-CHEMICAL PARAMETERS

- Temperature (0 - ~700°C)
- Pressure (1 - ~30000 bar)
- Oxygene fugacity, f_{O2} (~ 10^{-50} - 0.2 bar)
- Acidity, pH = - $\log_{10} a_{H+}$ (~1 ≤ pH ≤ ~9)
- Sulfur activity, a_{H2S} (0.001-1 mol/kg)
- Chloride activity, a_{Cl^-} (to ~10-20 mol/kg)

Source: G. Porkrovski

Fluides géologiques: généralités

Caractéristiques (très générales) des fluides hydrothermaux:



Source: G. Porkrovski

Fluides géologiques: généralités

Caractéristiques (très générales) des fluides hydrothermaux:

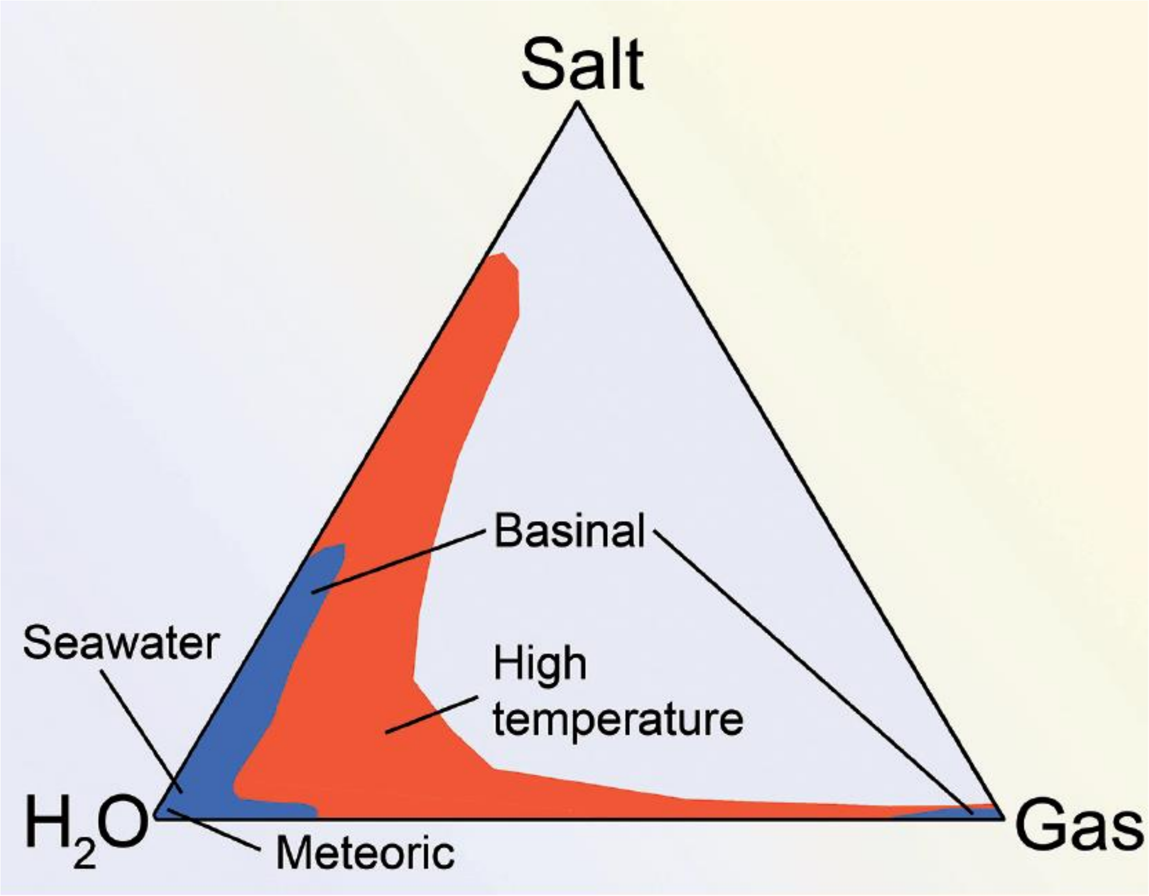
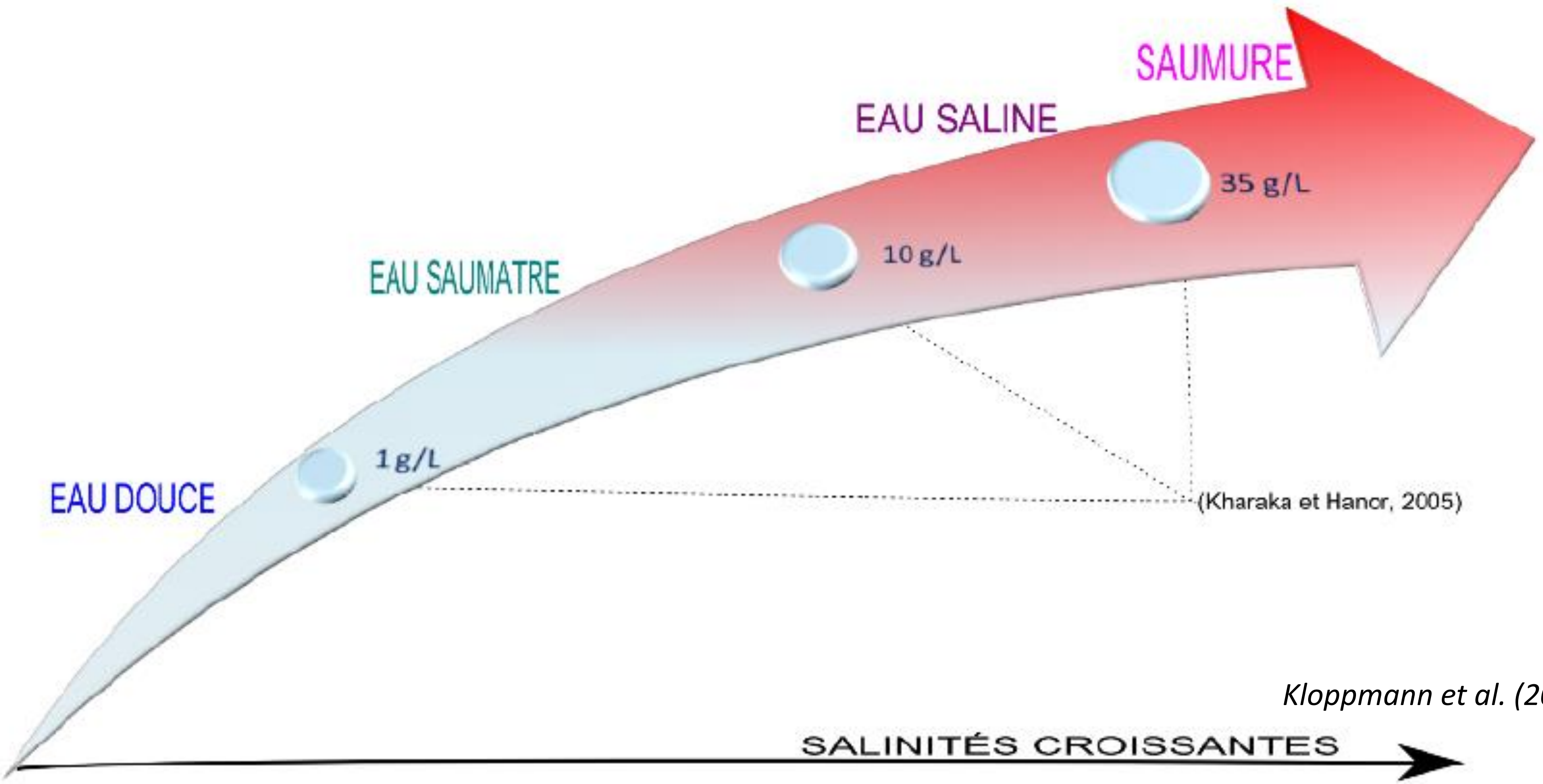


Figure 1.1 Schematic ternary H_2O-"salt"-"gas" diagram showing the possible compositions of fluids in crustal settings at different temperatures (modified from Kesler, 2005). Under crustal conditions, either H_2O-salt or H_2O-CO_2 fluids are possible, with the extent of mutual solubility depending on temperature (and pressure).

Yardley and Bodnar, 2014

Caractéristiques (très générales) des fluides hydrothermaux:



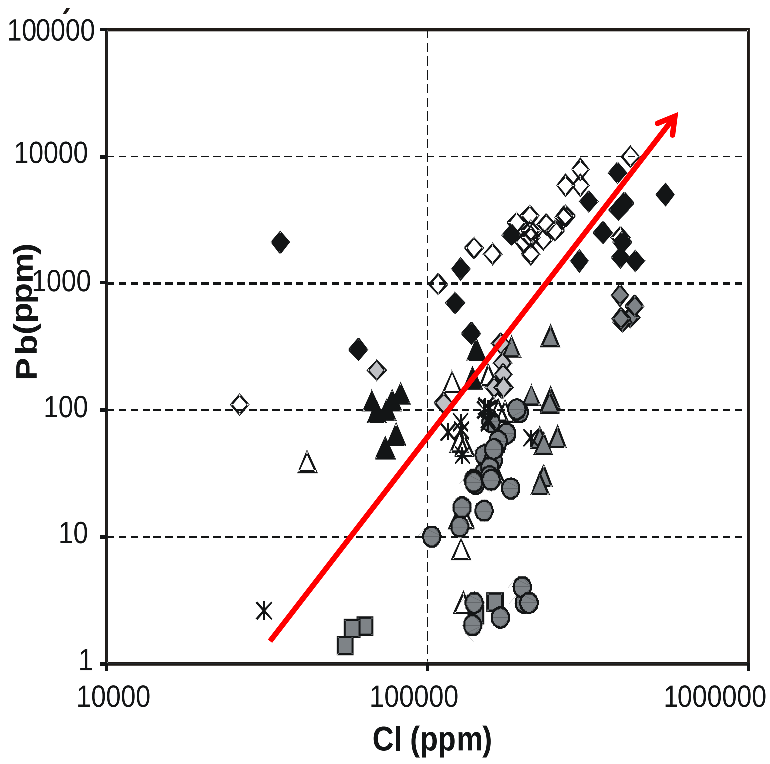
Kloppmann et al. (2011)

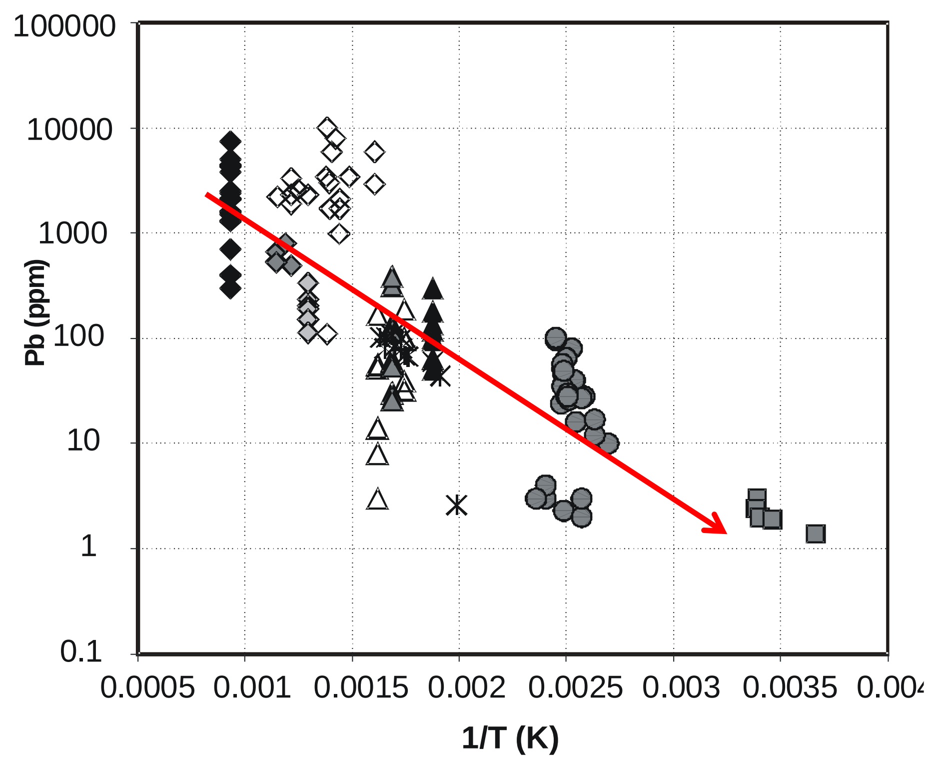
Illustration 53 : Gammes de concentrations et terminologie. (D'après Kharaka et Hanor, 2005).

Fluides géologiques: généralités

Fluides hydrothermaux = fluides minéralisateurs?

Compilation de données dans des environnements magmatique, métamorphiques, géothermique, sédimentaire (Yardley, 2005).





Les fluides salés et chauds sont les plus efficaces pour transporter les métaux (Pb, Fe, Mn, Zn…)
Lessivage des sources et stabilité des complexes chlorurés

Fluides géologiques: généralités

Fluides hydrothermaux = fluides minéralisateurs?

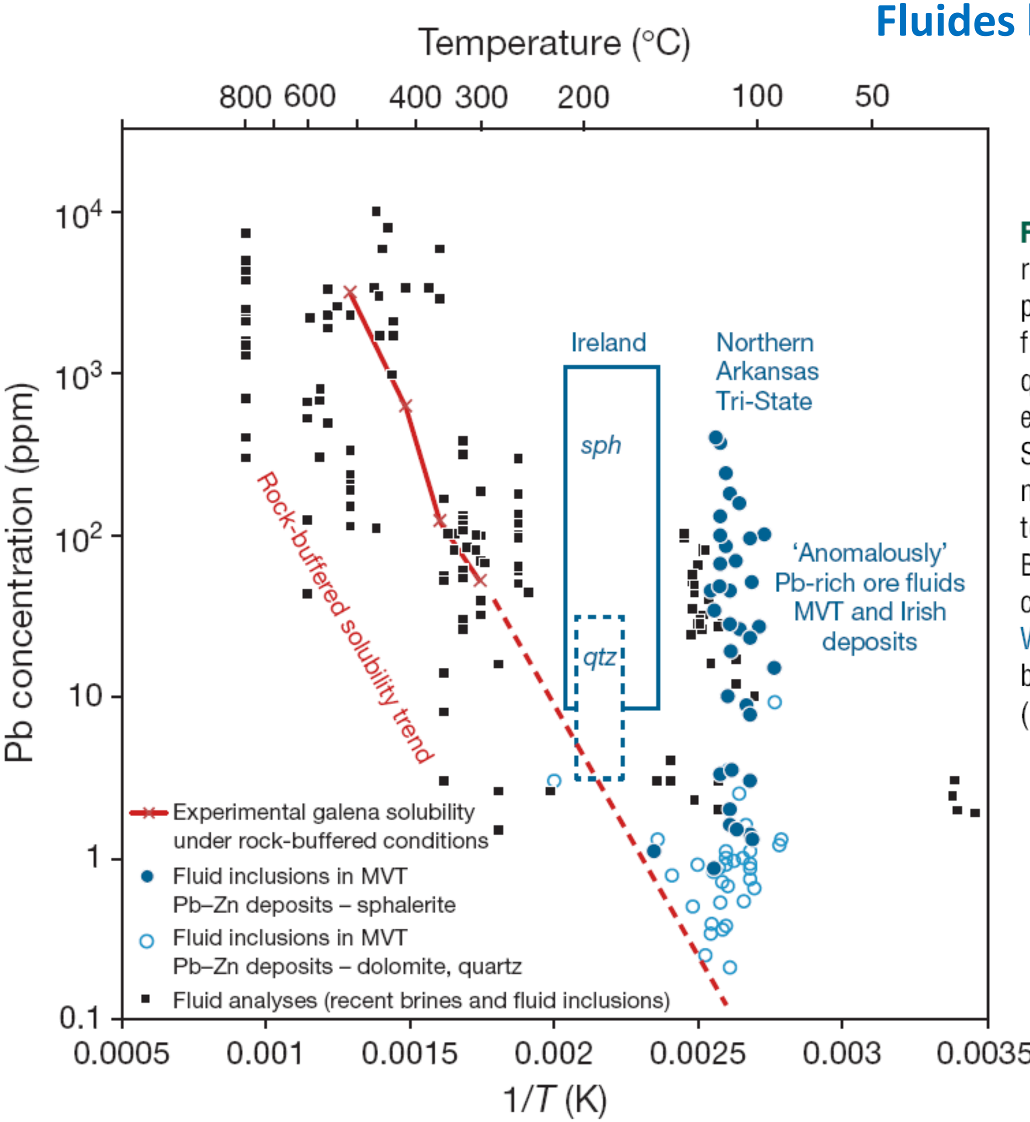
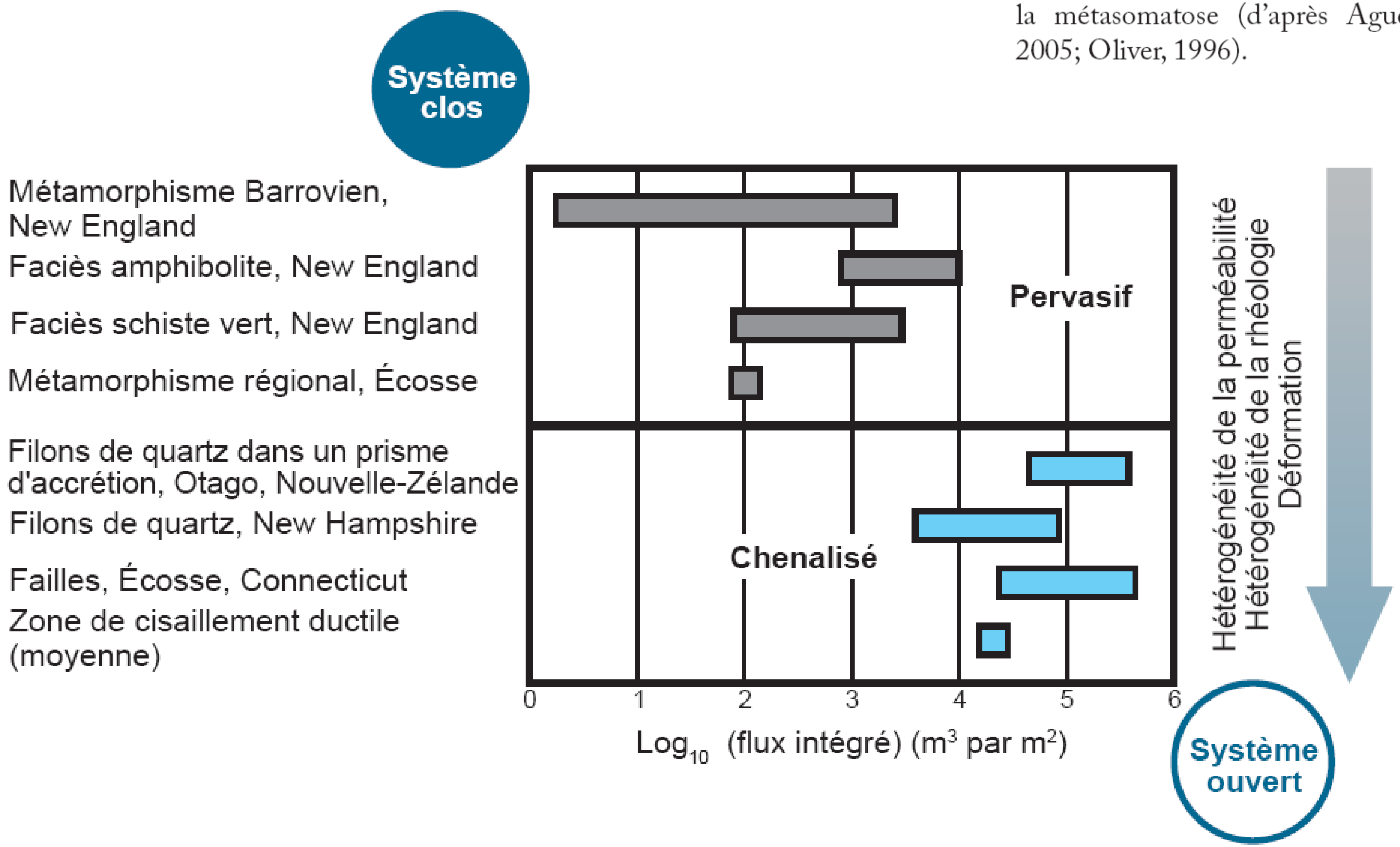


Figure 5 Lead concentration in selected crustal fluids and rock-buffered solubilities of galena (PbS) as a function of temperature, plotted on a 1/*T* scale. Experimental curves from Hemley et al. (1992) for fluids with 1 m total Cl, buffered by excess feldspars + muscovite + quartz + pyrite + pyrrhotite + magnetite + galena (red line; dashed extension by thermodynamic calculation from data cited in **Figure 4**). Small black symbols show analyzed Pb concentrations in natural magmatic–hydrothermal, geothermal, and basin brines with inferred temperatures of crustal rock equilibration, compiled by Yardley (2005). Blue symbols and boxes show fluid-inclusion analyses from carbonate-hosted Pb–Zn ore deposits by Stoffell et al. (2008) and Wilkinson et al. (2009), differentiating ore-stage fluids in sphalerite (solid box, full circles) and intervening stages of gangue mineral precipitation (quartz, carbonates; dashed box and open circles).

(Heinrich and Candella, 2014)

Fluides géologiques: généralités

Figure 2.10 - Flux de fluides dans les métamorphismes régional ou de contact (Barrovien) et lors de la métasomatose (d'après Ague, 2005; Oliver, 1996).



Jébrak et Marcoux, 2007

Fluides géologiques: généralités

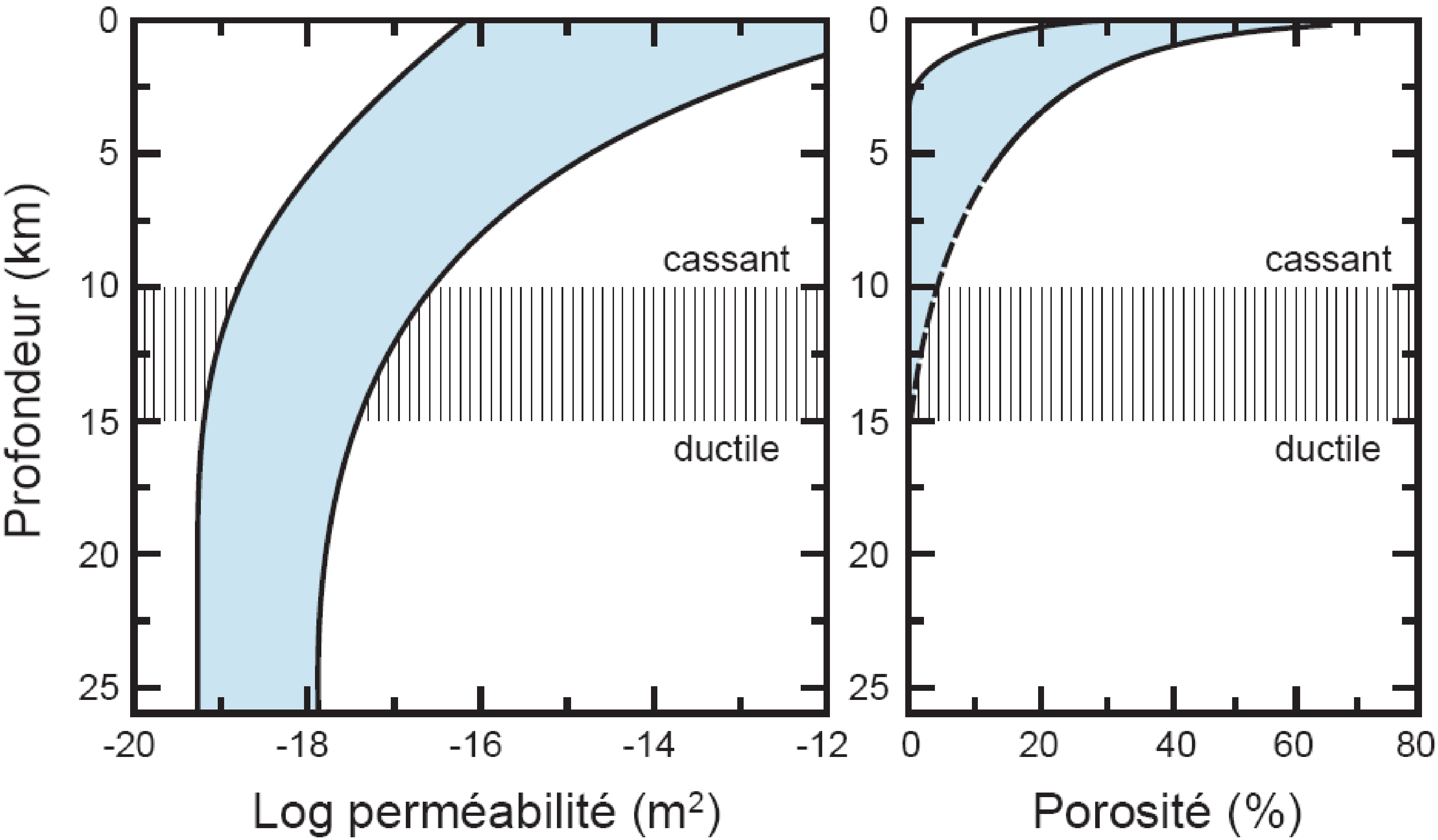


Figure 2.11 - Porosité–perméabilité en domaines ductile et cassant. La porosité connectée se ferme sous la transition ductile-cassant, tandis qu'il reste une perméabilité résiduelle, souvent à caractère pulsatif (d'après Manning et Ingebritsen, 1999; Moore et Saffer, 2001).

Jébrak et Marcoux, 2007

Fluides géologiques: généralités

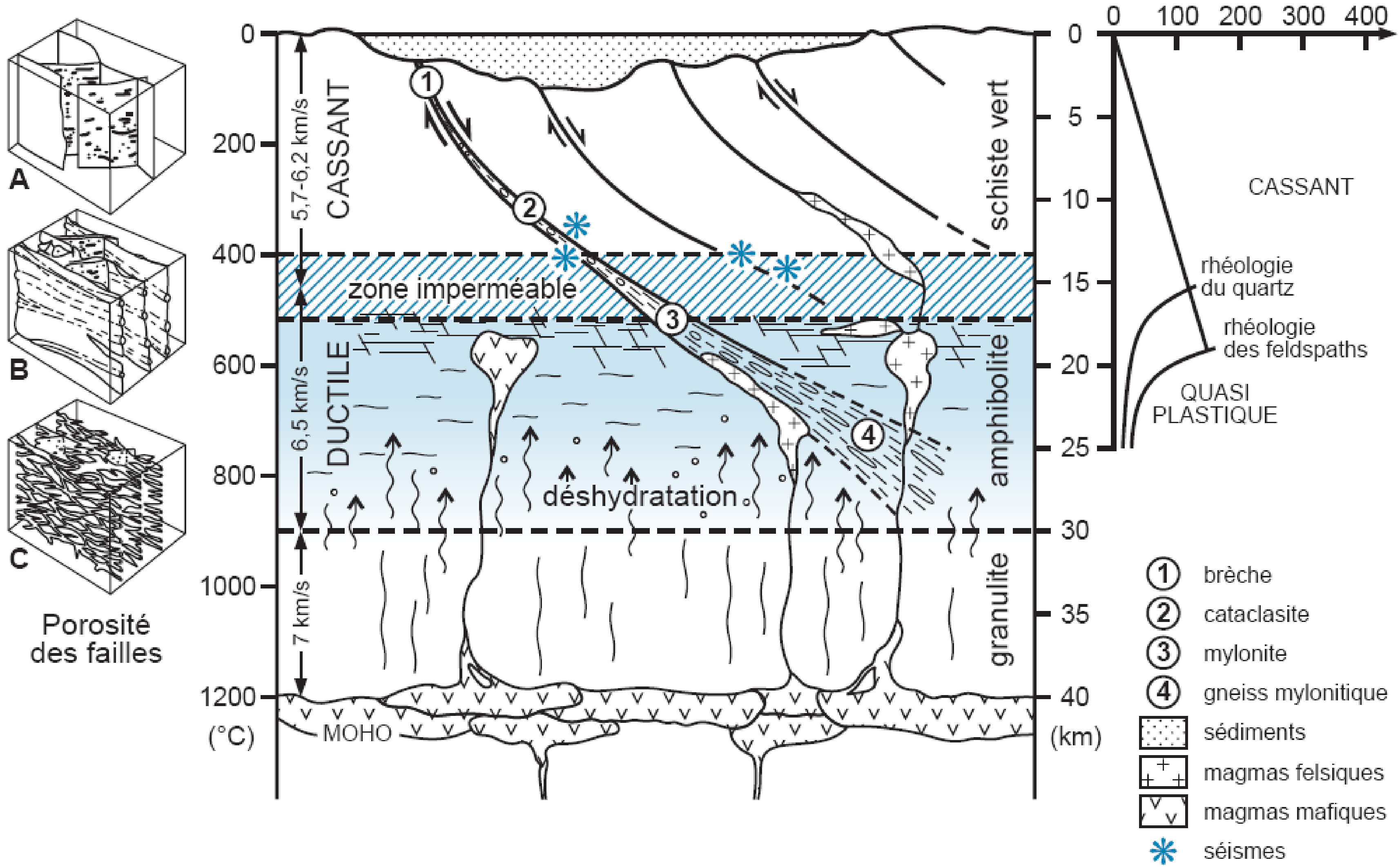


Figure 3.5 - Perméabilité à l'échelle de la croûte (d'après Stanley *et al.*, 1990), style de porosité des failles (d'après Géraud *et al.*, 1995) et conditions de rupture (d'après Scholz, 1990; Sibson, 2001).

Jébrak et Marcoux, 2007

Fluides géologiques: généralités

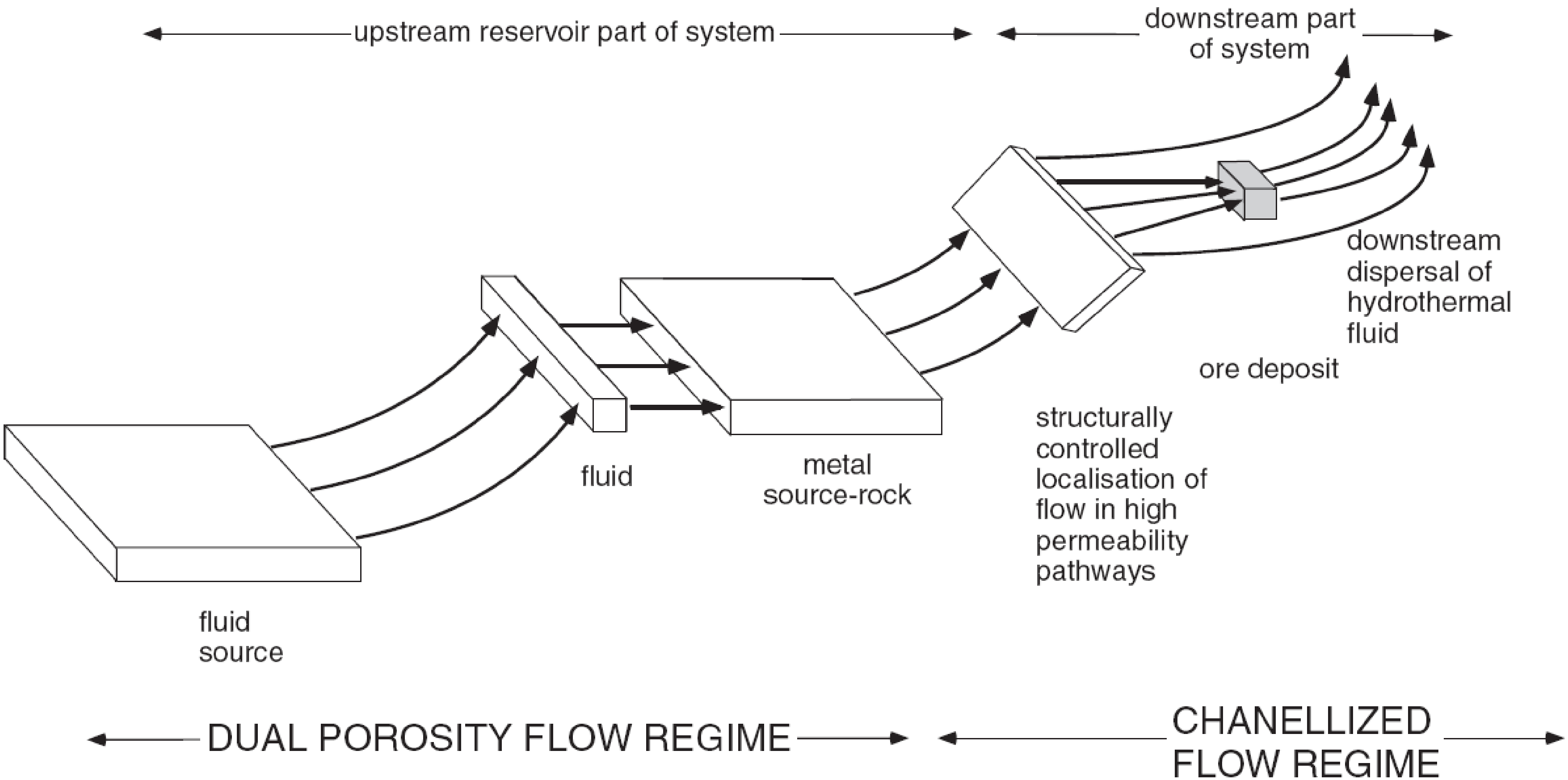


FIG. 1. Schematic overview of the basic structure of a fracture-controlled, hydrothermal ore system involving one fluid reservoir. Fluids and metals are sourced in the upstream parts of the system. Metal scavenging from source rocks in many cases involves pervasive grain-scale flow regimes. Delivery of potentially large fluid volumes to the relatively small volumes of ore deposits involves structurally controlled channelling of fluid into localized pathways such as fracture networks, faults , and shear zones. Spent fluids are dispersed downstream from ore deposits.

(Cox, 2005)

Fluides géologiques: généralités

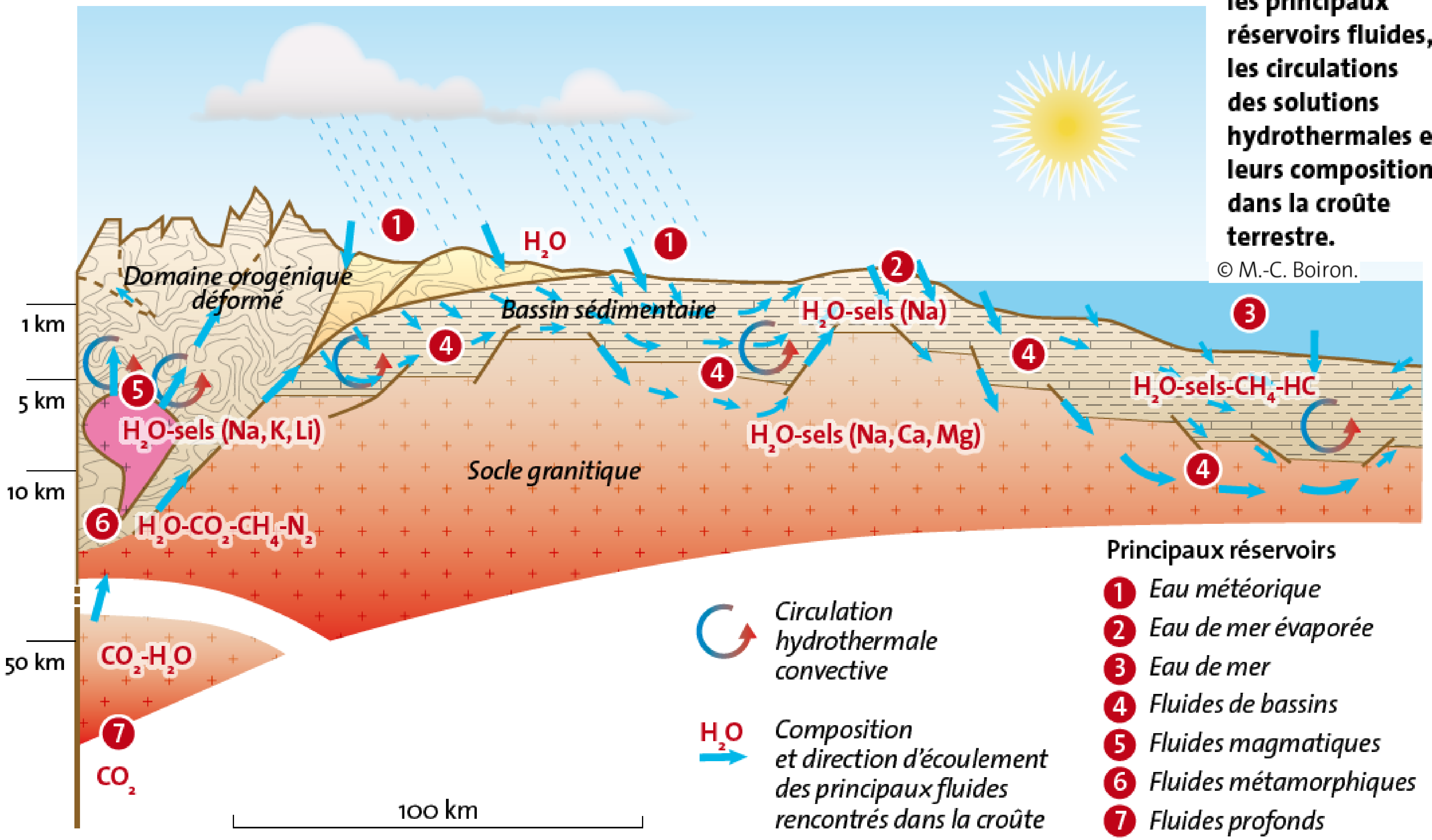
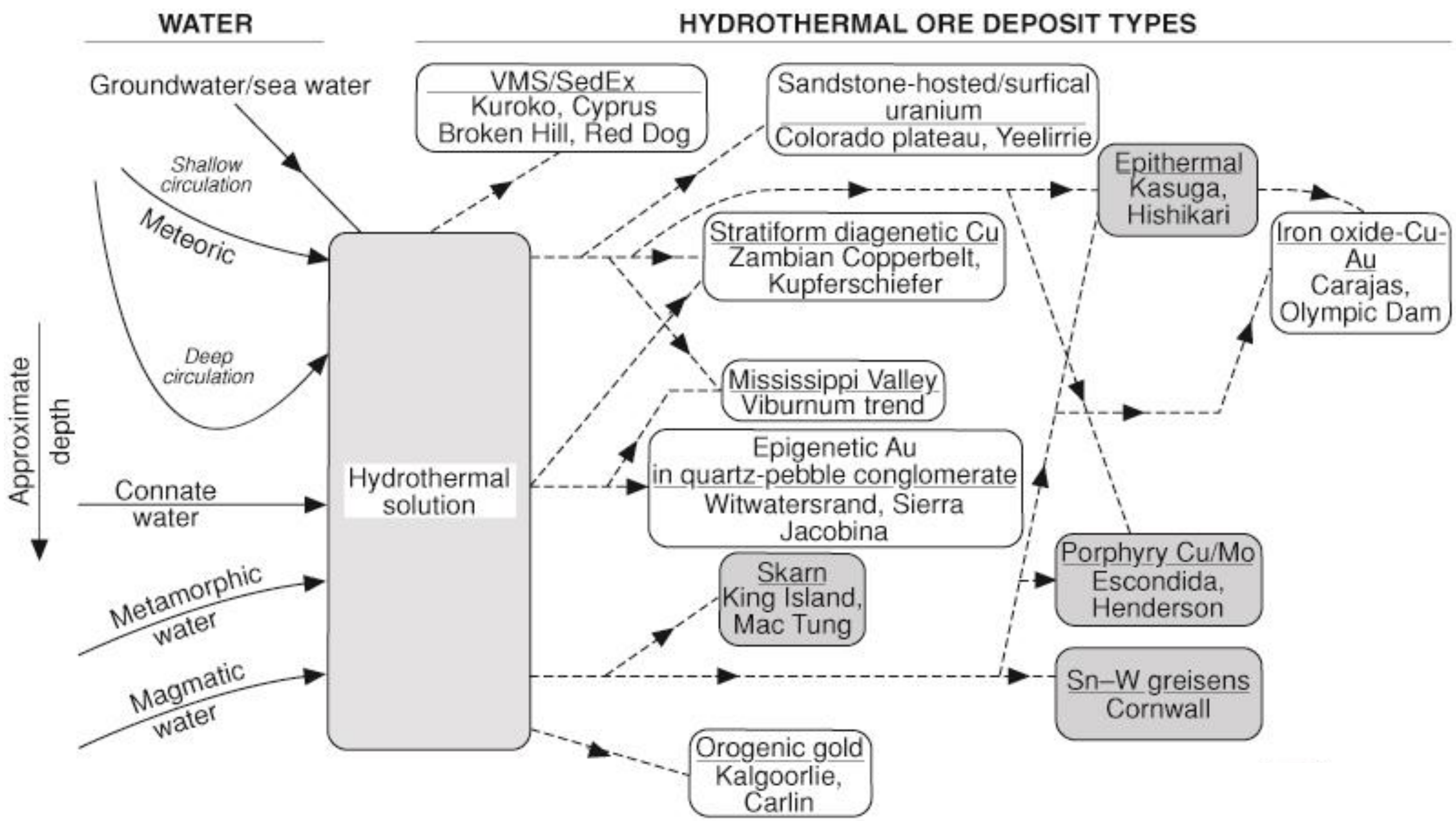


Fig. 1 : Coupe présentant les principaux réservoirs fluides, les circulations des solutions hydrothermales et leurs compositions dans la croûte terrestre.

≠ types de fluides → ≠ potentiels pour gisements hydrothermaux

Fluides géologiques: généralités

Fluide géologique - Fluide hydrothermal - Types de gisements hydrothermaux:



Robb, 2005

hydrothermal deposit [GEOL] A mineral deposit precipitated from a hot, aqueous solution. { ˌhī·drə'thər·məl di'päz·ət }

hydrothermal solution [GEOL] Hot, residual watery fluids derived from magmas during the later stages of their crystallization and commonly containing large amounts of dissolved metals which are deposited as ore veins in fissures along which the solutions often move. { ˌhī·drə'thər·məl sə'lü·shən } ???

Moteurs des circulations de fluides

Moteurs des circulations de fluides

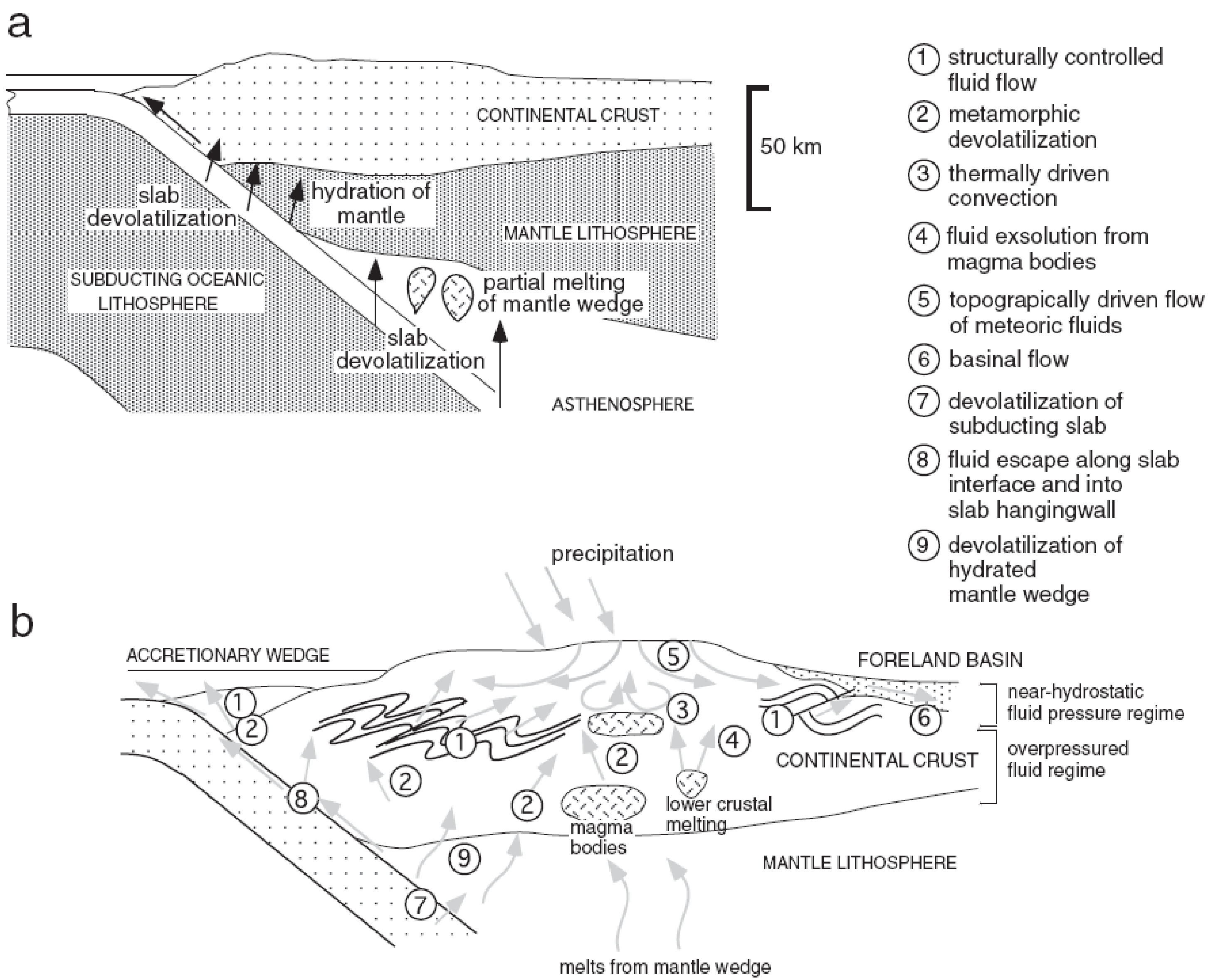
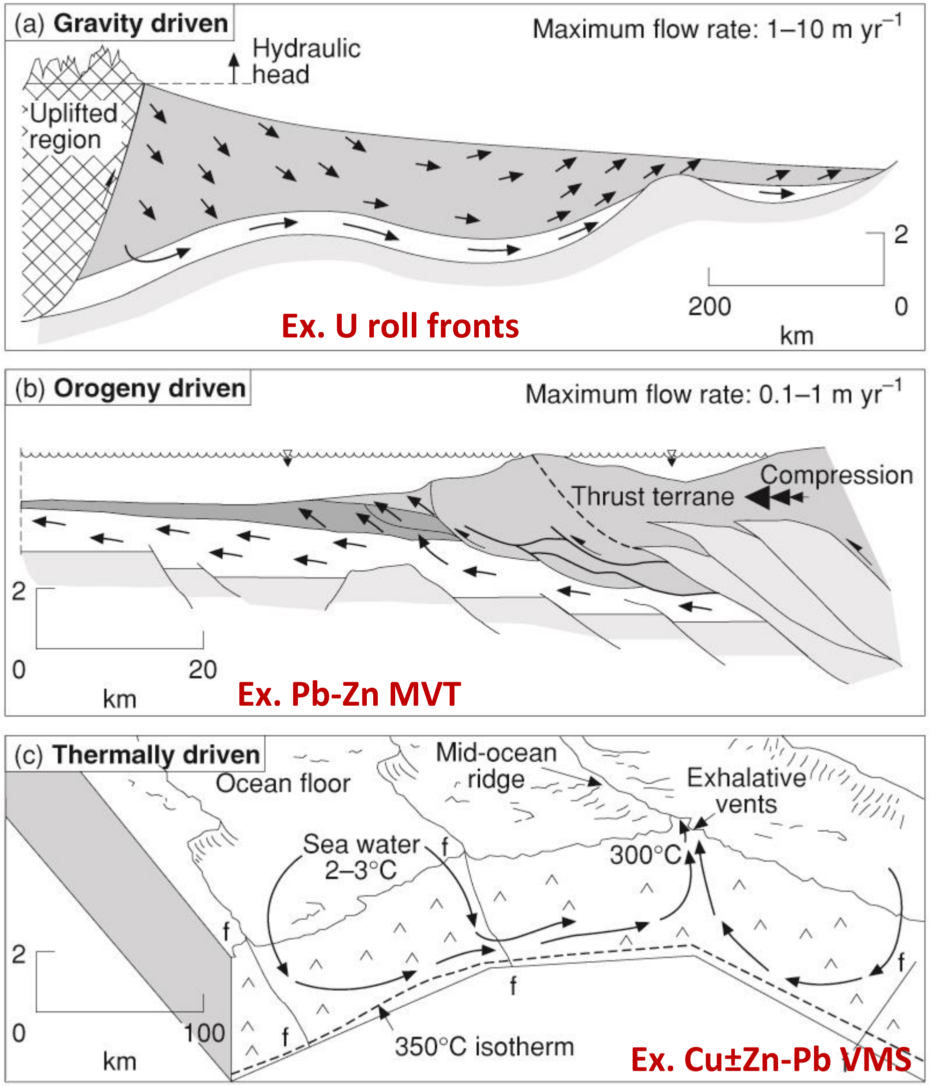
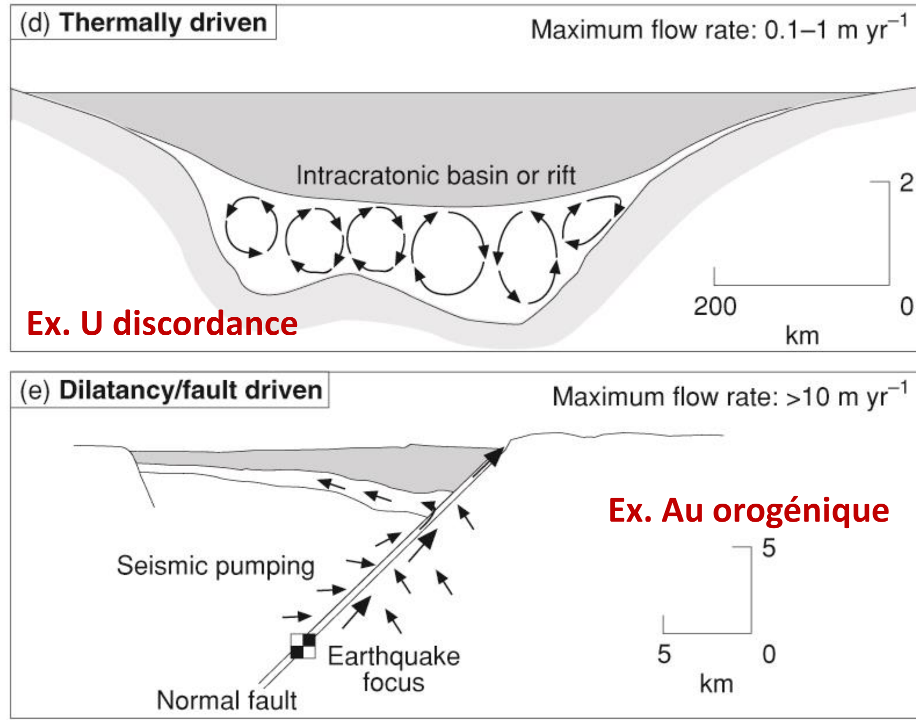


FIG. 3. a. General lithospheric-scale structure at a convergent, oceanic-continental plate boundary . b. Detail of distribution of various fluid sources and pathways.

(Cox, 2005)

Moteurs des circulations de fluides





Various tectonic scenarios illustrating the mechanisms by which major fluid movements in the Earth Crust take place (Robb, 2005)

Différentiels de P et T et salinité

Moteurs des circulations de fluides

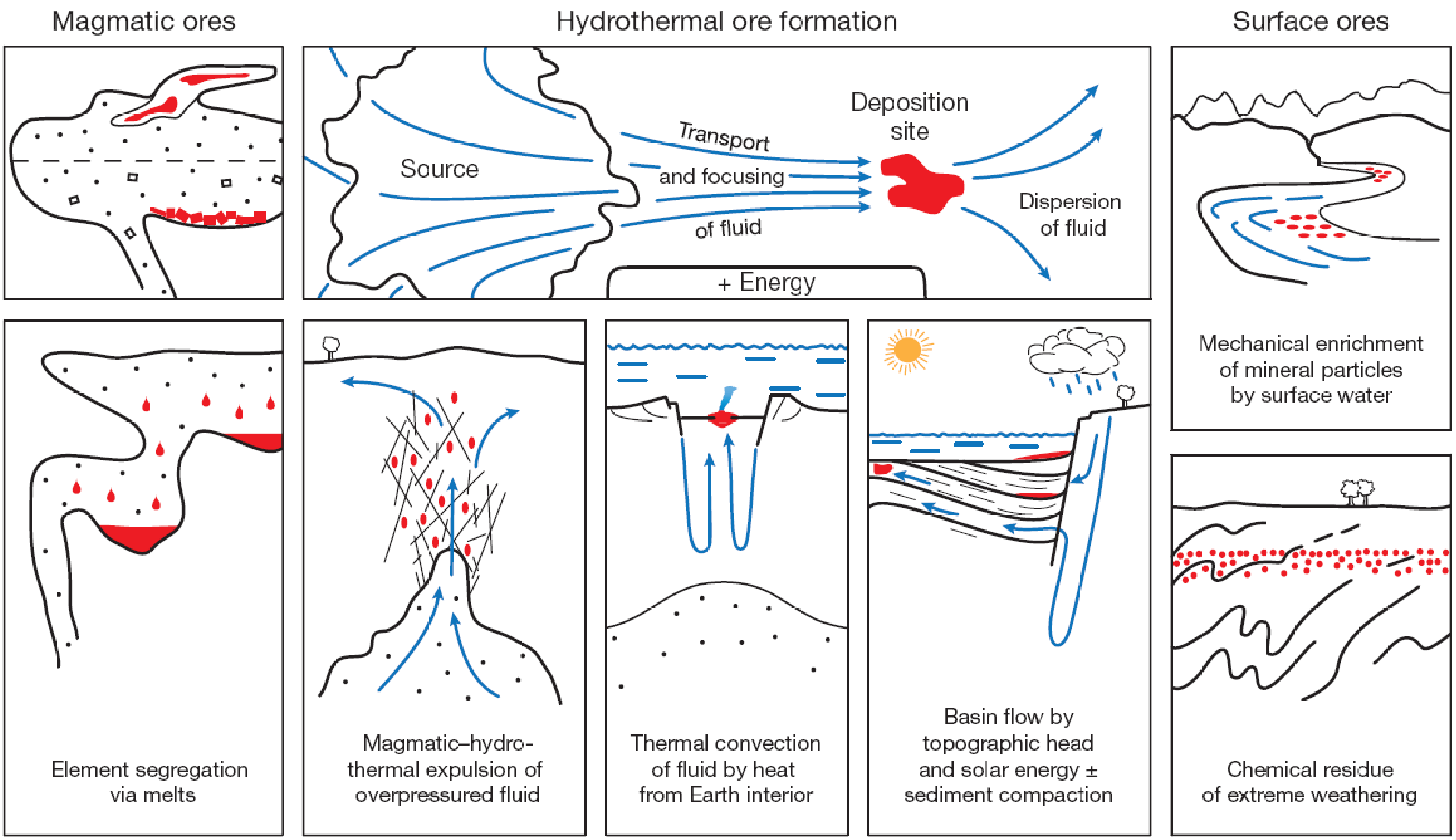


Figure 1 Schematic illustration of three principal processes of selective element enrichment that can produce mineral deposits in the Earth's crust, grouped by the main agent of material transport: magmatic melts, hydrothermal fluids, or surface waters (Kesler, 1994). With permission from S.E. Kesler.

(Heinrich and Candella, 2014)

Témoins des circulations de fluides

Témoins des circulations de fluides

Altération, épigénie, métasomatisme:

altération n. f. - Modification des propriétés physco-chimiques des minéraux, et donc des roches, par les agents atmosphériques, par les eaux souterraines et les eaux thermales (altération hydrothermale). Elle dépend en particulier du climat, de la température des eaux, de la nature des roches et de leur degré de fracturation. Elle a généralement pour effet de rendre les roches moins cohérentes ce qui facilite leur désintégration (V. érosion). Ant. inaltérable. v. **(s') altérer** ; adj. **altéré, e** (qui a subi une altération) ; **altérable** (qui peut s'altérer aisément).

épigénique adj. (parfois épigénétique) - Qui procède de l'épigénie ou qui s'y rapporte. **Couleur épigénique** : coloration apportée par des solutions dans des roches sédimentaires. **Concrétion épigénique** (siliceuse, ferrugineuse,...) formé, tardivement dans des roches sédimentaires par enrichissement secondaire autour d'un point. **Gisement métallifère épigénique** formé secondairement dans une roche, les apports étant liés, p. ex., à des solutions hydrothermales.

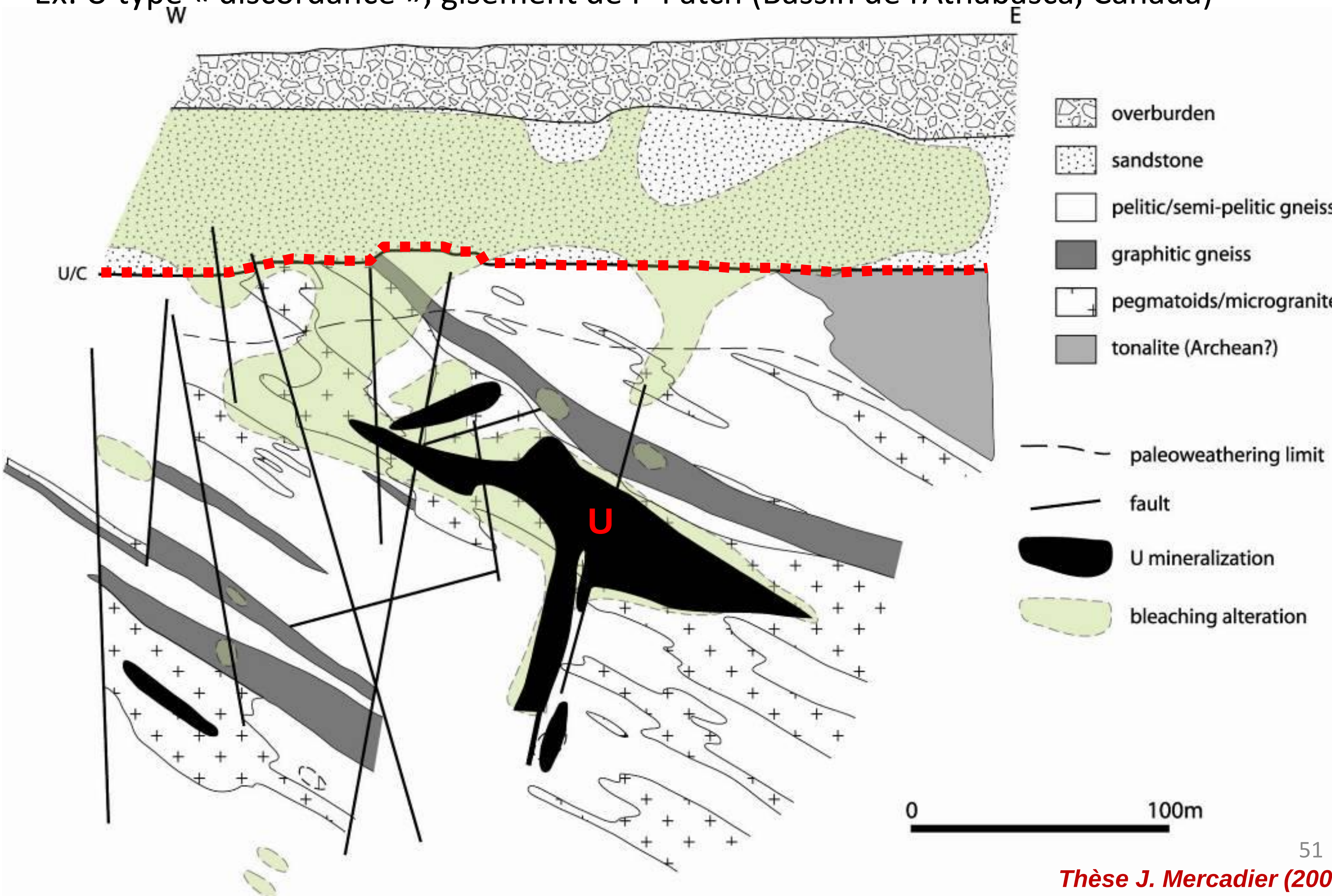
hydrothermal alteration [GEOL] Rock or mineral phase changes that are caused by the interaction of hydrothermal liquids and wall rock.

métasomatisme n. m. [de méta-, et du gr. *sôma*, corps] - Métamorphisme, dit allochimique ou métasomatique, qui s'accompagne d'une modification (**métasomatose**) de la composition chimique globale des roches originelles. V. aussi épigenèse (pour les roches sédimentaires).

Témoins des circulations de fluides

Altération, épigénie, métasomatisme:

Ex: U type « discordance », gisement de P-Patch (Bassin de l'Athabasca, Canada)



Thèse J. Mercadier (2008)

Témoins des circulations de fluides

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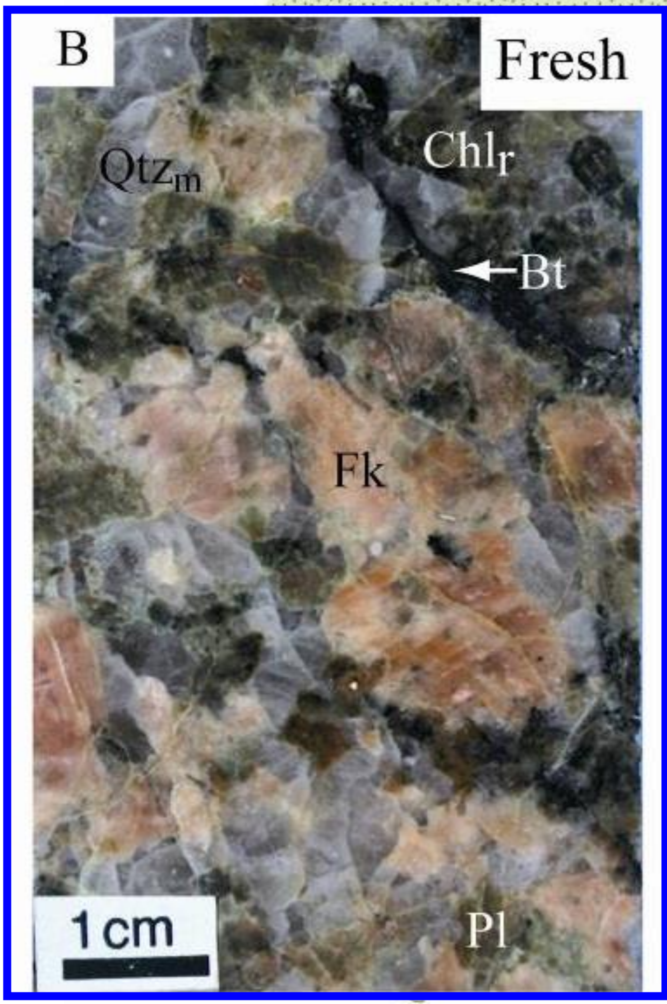

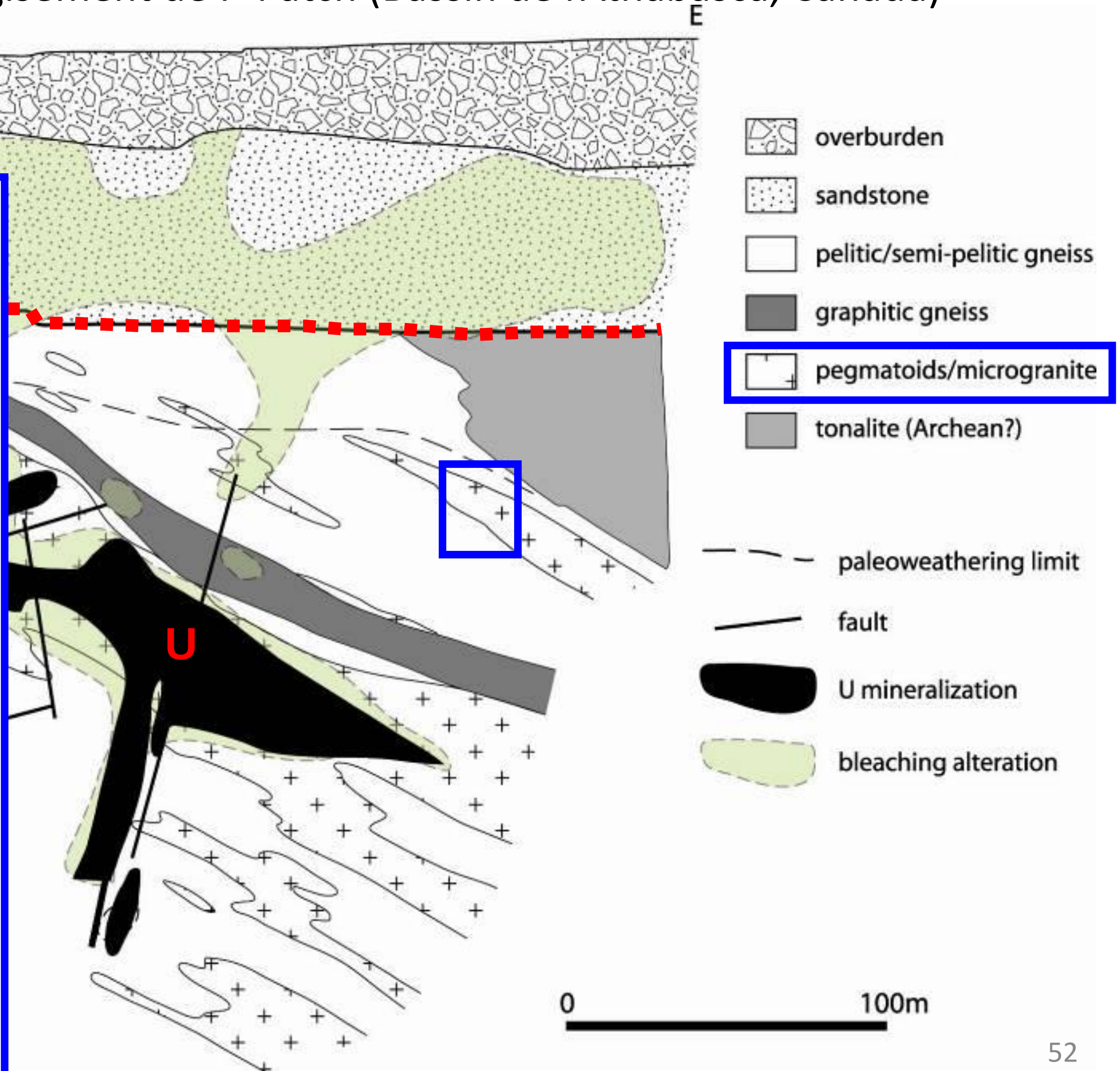

Thèse J. Mercadier (2008)

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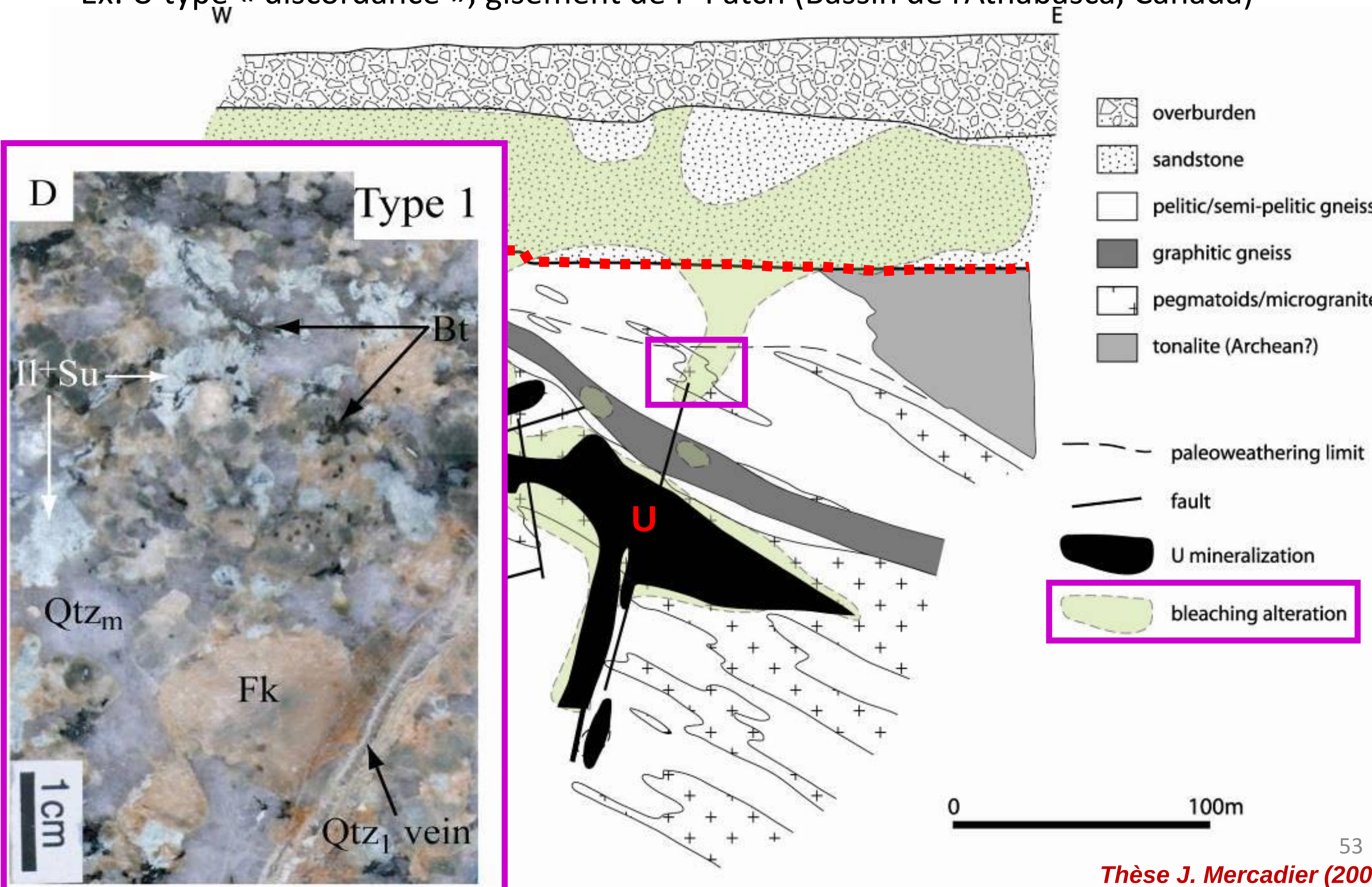

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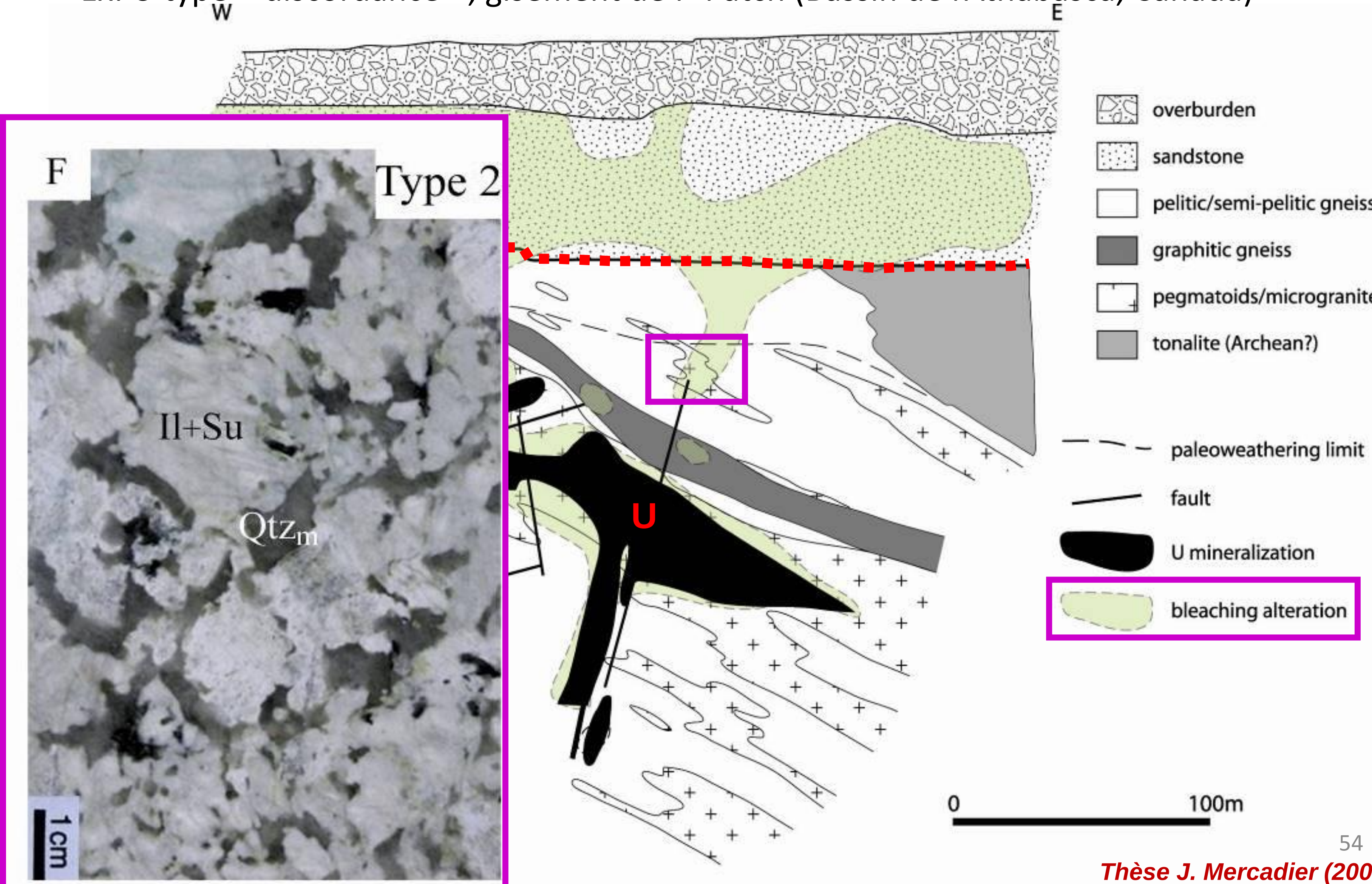

Thèse J. Mercadier (2008)

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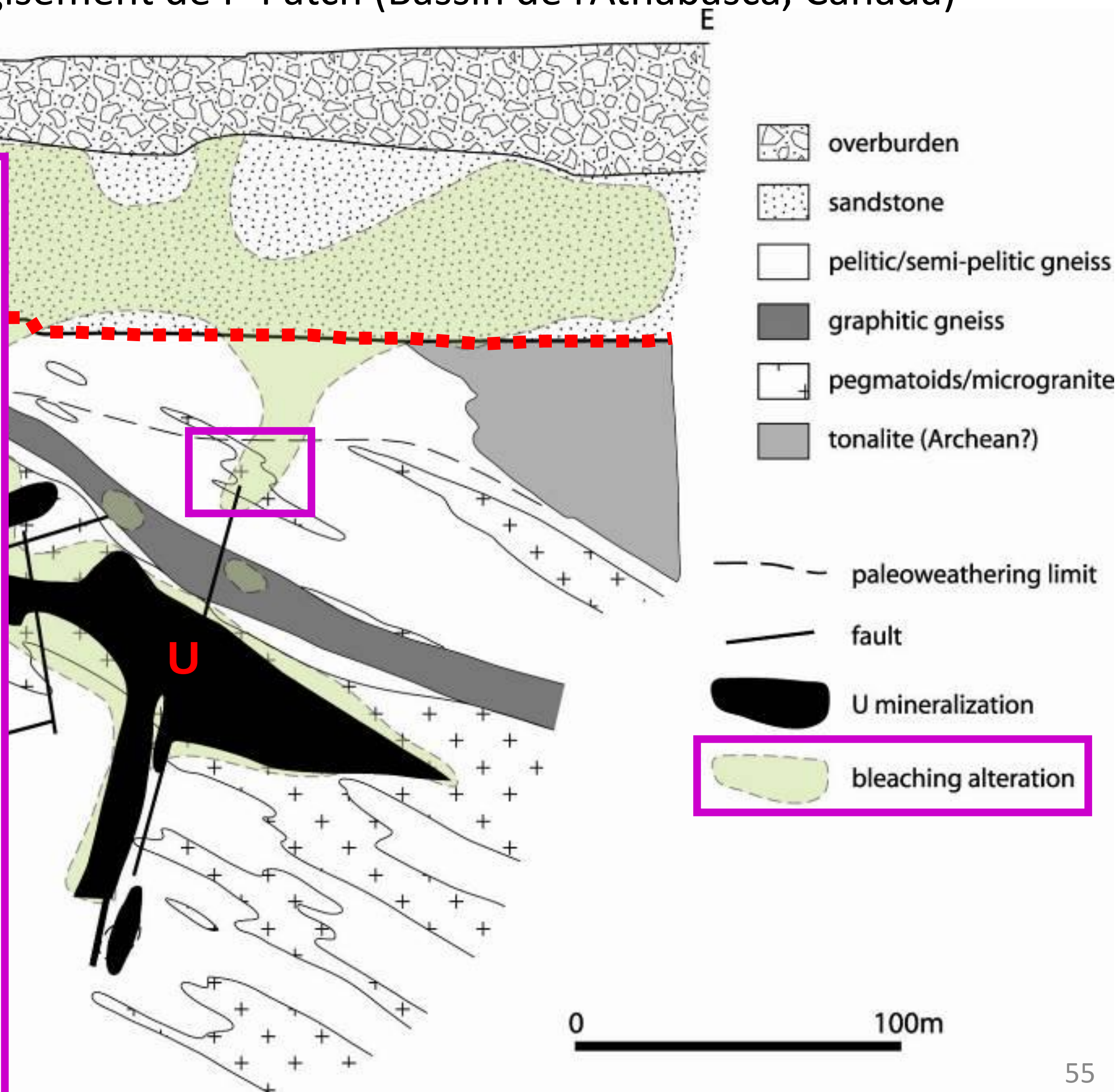

Thèse J. Mercadier (2008)

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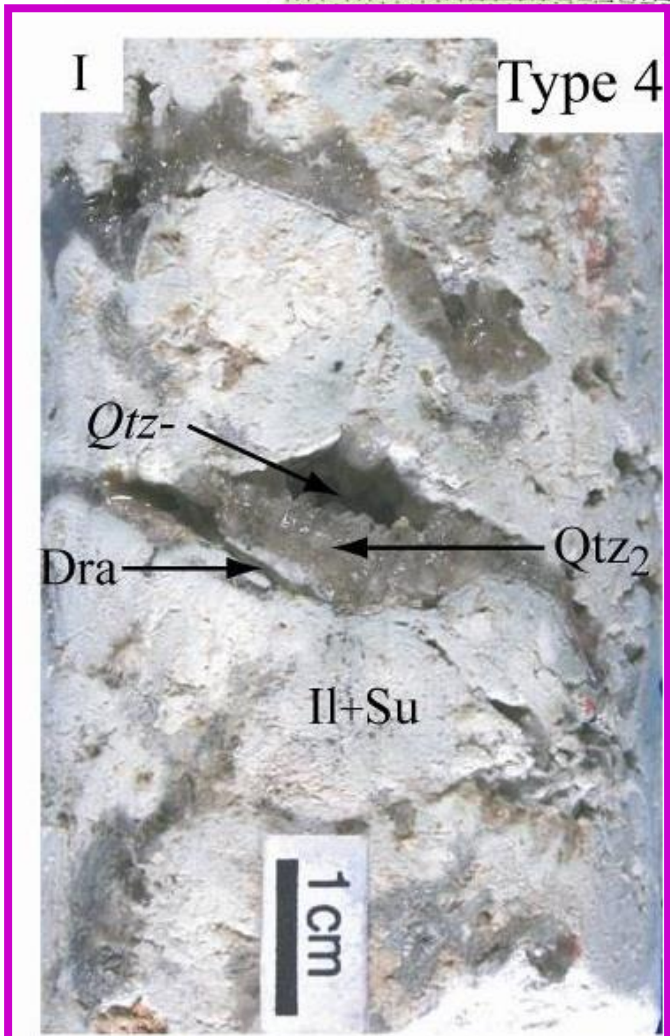

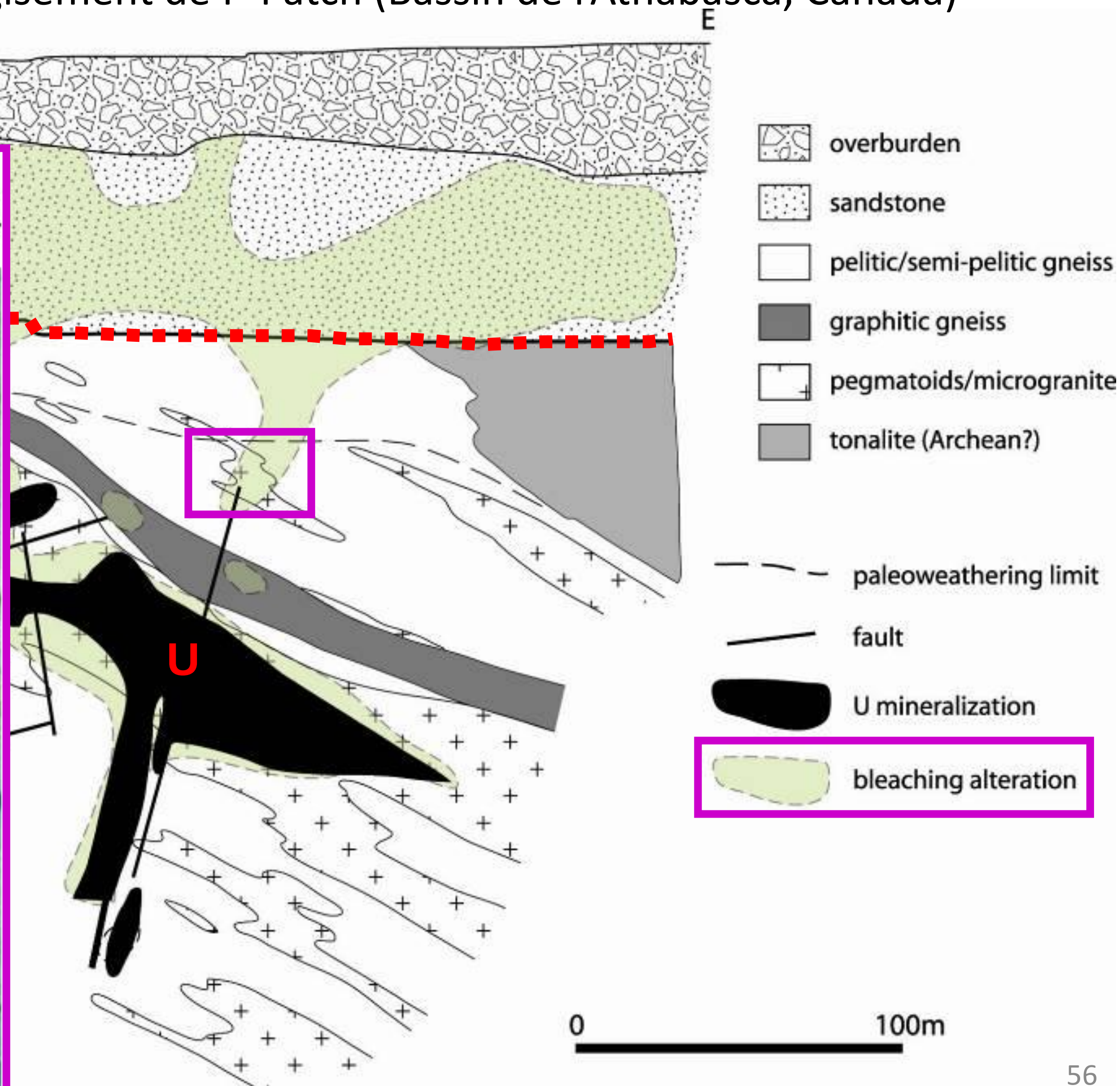

Thèse J. Mercadier (2008)

Témoins des circulations de fluides

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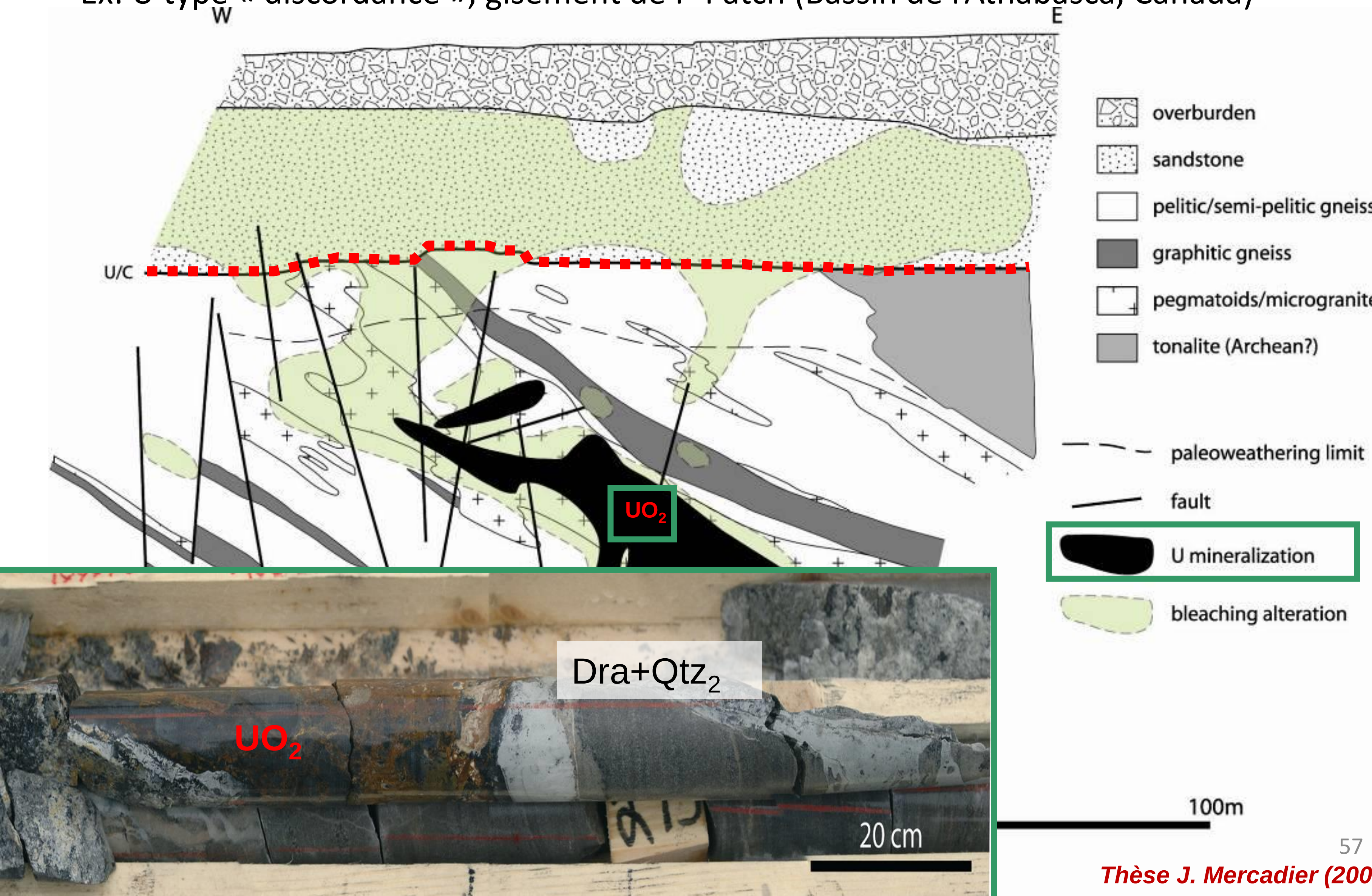


Thèse J. Mercadier (2008)

Témoins des circulations de fluides

Veines, filons, stockworks:

veine n. f. [du lat. *veina*, vaisseau sanguin] **-1.** Mince lame de substance utile : veine de charbon, veine ardoisière, veine (ou filon) minéralisée. **-2.** Zones étroites et colorées se détachant sur le fond d'une roche (marbre blanc à veines rosées). adj. **veiné, e** (sens 2).

filon n. m. [de l'italien *filone*, augmentatif de *filo*, fil] - Lame de roche, épaisse de quelques centimètres à quelques mètres, recoupant les structures de l'encaissant (différence avec le sill ou filon-couche). Un filon correspond le plus souvent au remplissage d'une fracture (diaclase, faille) et est constitué soit de roches magmatiques, soit de roche dont le matériel « souvent enrichi en substances utiles » provient de roches magmatiques ou de l'encaissant p. ex. filon d'origine métamorphique), et a été déplacé par des fluides aqueux eux-mêmes d'origine magmatique ou métamorphique, voire superficielle, d'où une typologie complexe par combinaison de ces diverses modalités. V. aussi dyke, filon-couche (=sill), éponte, salbande, veine. adj. **filonien, nne**.

stockwerk n. m. [mot allemand] - Minéralisation composée d'un réseau très dense de petits filons.

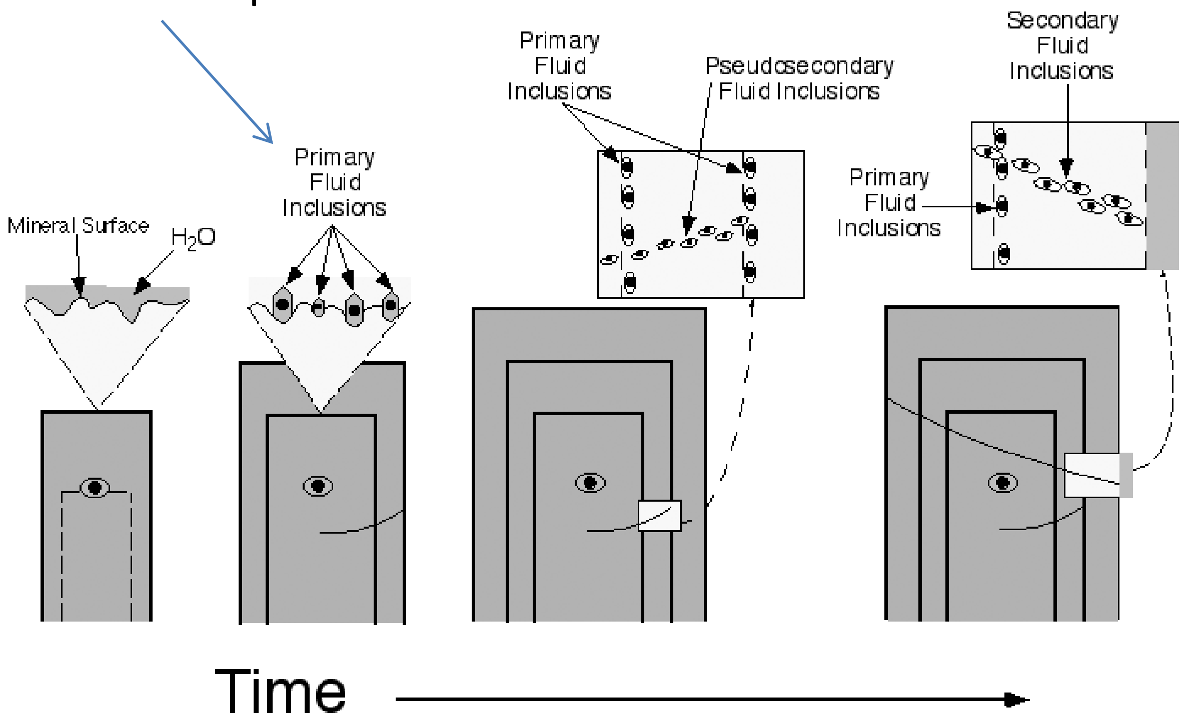
= stockwork

Ex: VMS →

Témoins des circulations de fluides

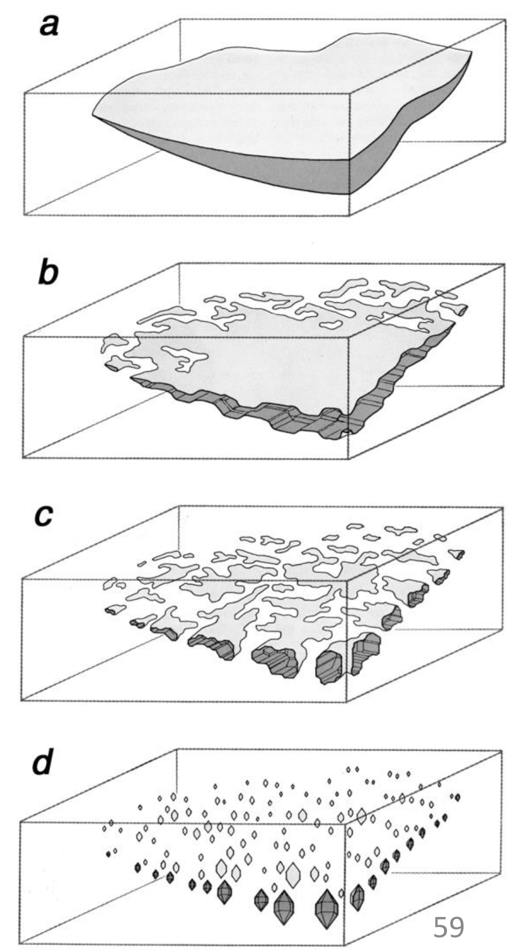
Inclusions fluides: poches de fluides préservées pendant la croissance des minéraux

Inclusions primaires



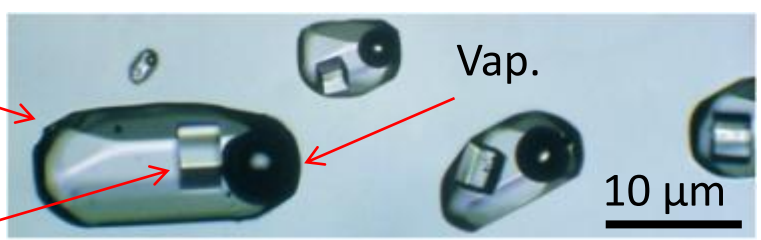
Bodnar, (2003)

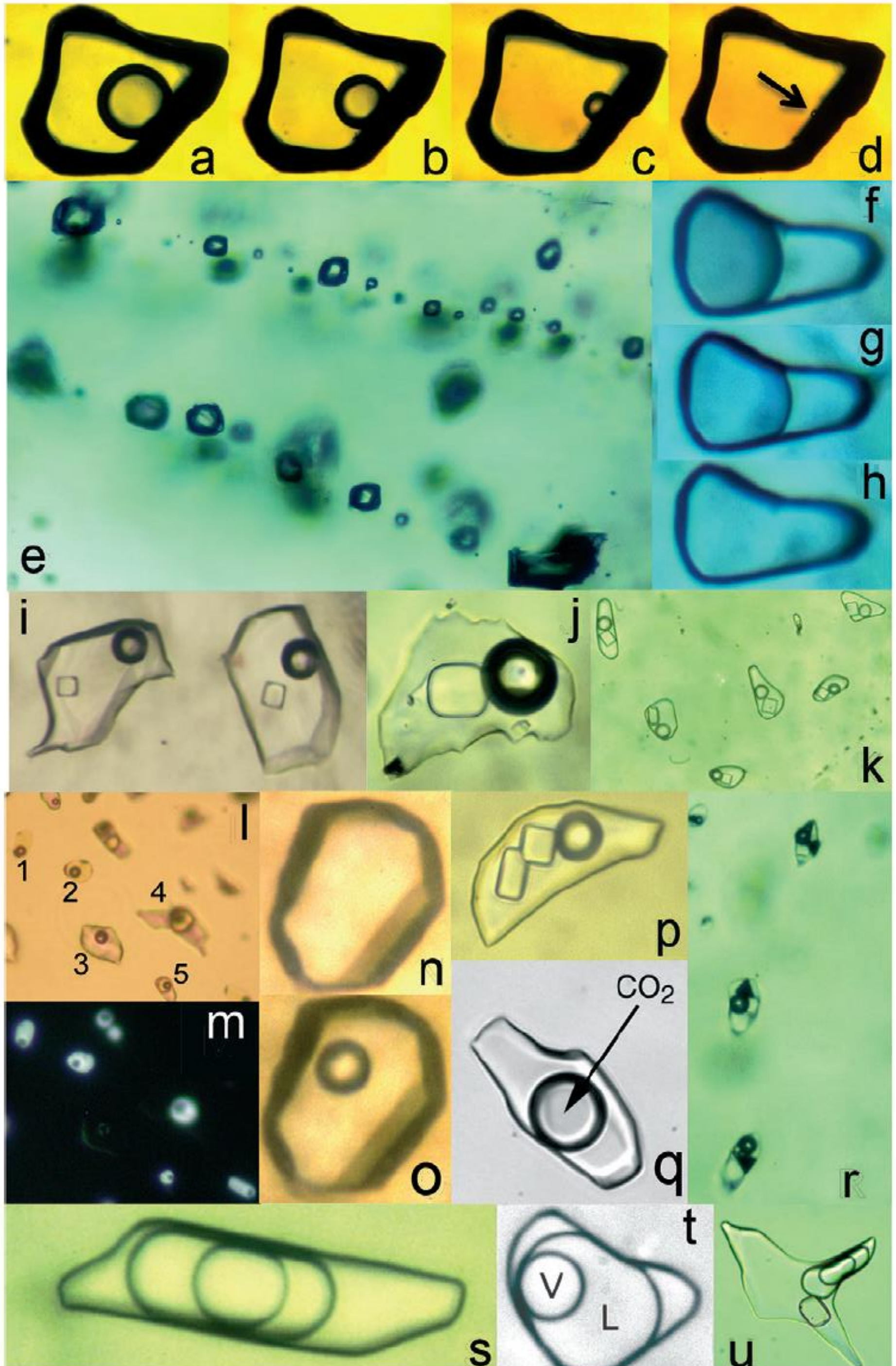
Inclusions pseudosecondaires et secondaires



Liq.

NaCl



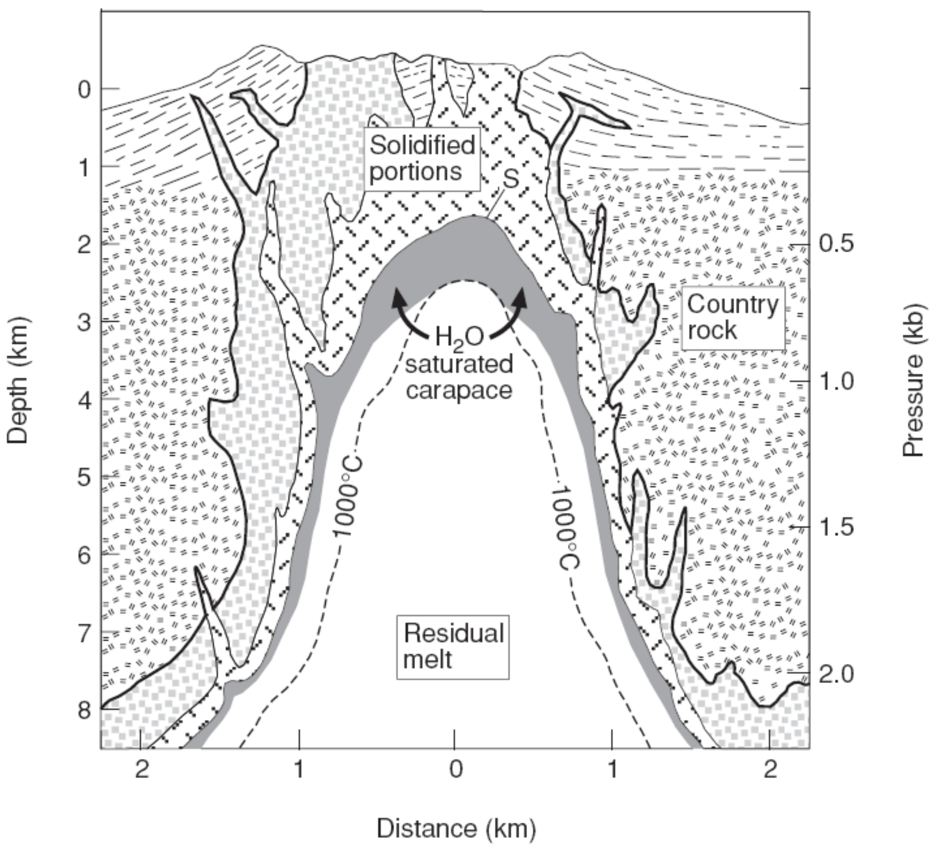


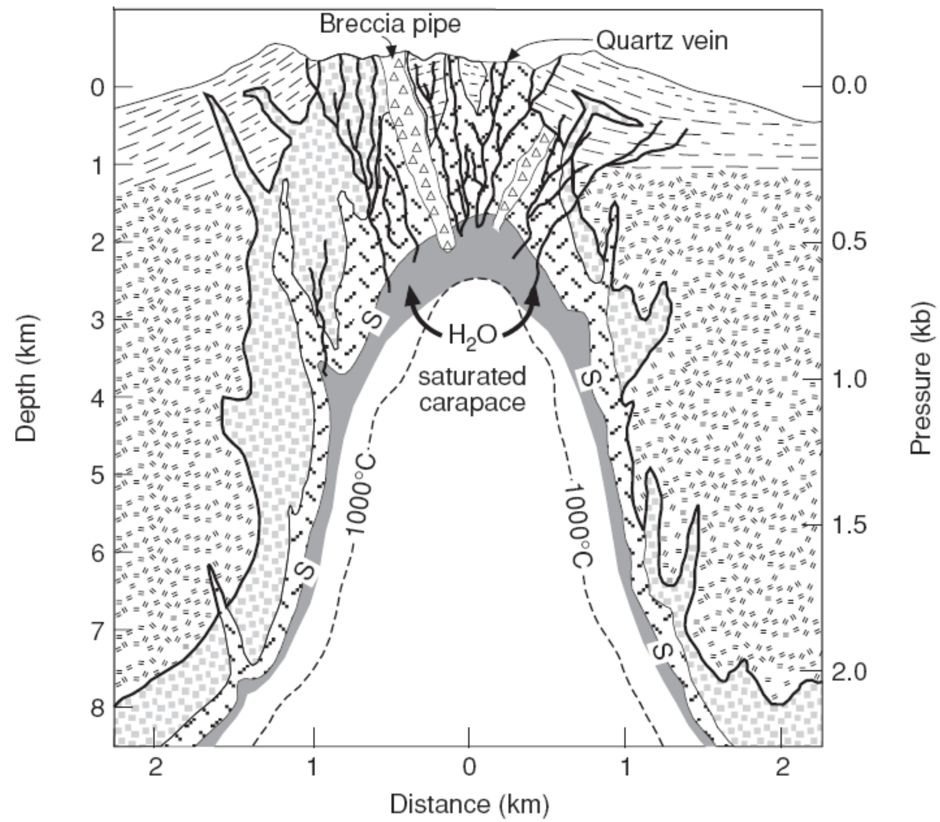
Examples of fluid inclusion types from various crustal environments. **(a-d)** Heating sequence for a large two-phase, liquid-rich fluid inclusion in sphalerite from the Creede, Colorado, epithermal Ag-Pb-Zn-Cu deposit. During heating the vapor bubble becomes smaller and disappears at the homogenisation temperature as the fluid inclusion homogenises to the liquid phase. The arrow in "d" shows the vapor bubble immediately before it disappears. **(e)** Two trails of vapor-rich fluid inclusions in quartz from the Red Mountain, Arizona, porphyry copper deposit. **(f-h)** Vapor-rich fluid inclusion in topaz from the Volnya deposit, Russia. During heating the bubble expands to fill the inclusion at the homogenisation temperature. **(i)** Two halite-bearing fluid inclusions from the Marble Canyon Pegmatite, California. **(j)** Fluid inclusion containing a vapor bubble and several daughter minerals, including a small opaque chalcopyrite crystal. **(k)** Plane of halite-bearing fluid inclusions all containing liquid, vapor, and a halite crystal in uniform volumetric proportions. **(l-m)** Photomicrograph of a group of fluid inclusions in fluorite from the Cave in Rock fluorspar district, Illinois, shown in plane transmitted light (l) and in UV illumination. The entire area of inclusions 1, 2 and 5 (l) is shown to fluoresce under UV light (m), indicating that the inclusions are filled with petroleum. Only the central portion of inclusion 4 fluoresces, indicating that this inclusion contains a droplet of petroleum and an aqueous liquid. Inclusion 3 does not fluoresce, indicating that it contains only brine. **(n-o)** A large inclusion in quartz shown at room temperature (n) and at -90 °C (o). At room temperature the inclusion contains only a single phase, but a vapor bubble nucleates during cooling to -90 °C. This inclusion contains liquid CH_4 at room temperature, and the inclusion has an internal pressure of ~100 MPa. **(p)** Fluid inclusion containing liquid, vapor and both halite and sylvite daughter minerals. **(q)** Two phase fluid inclusion at room temperature containing an aqueous phase and a CO_2-rich vapor bubble. **(r)** Secondary fluid inclusion trail in quartz from the Red Mountain porphyry copper deposit. Each inclusion contains several solid phases, including a large opaque chalcopyrite crystal, indicating that the copper contained in the chalcopyrite was originally dissolved in the trapped fluid, and the chalcopyrite precipitated during cooling to form a daughter mineral. **(s)** Synthetic fluid inclusion containing a CO_2 vapor bubble, liquid CO_2, and liquid H_2O, The composition is 25 mole % CO_2, and this type is characteristic of medium to high grade metamorphic environments. **(t)** Three-phase (CO_2 vapor bubble, liquid CO_2, and liquid H_2O) synthetic fluid inclusion. **(u)** Synthetic fluid inclusion containing a CO_2 vapor bubble, liquid CO_2, an aqueous phase that is saturated in both CO_2 and NaCl, and a halite daughter mineral.

(Yardley and Bodnar, 2014)

Systèmes magmatiques - hydrothermaux

Systèmes magmatiques - hydrothermaux





(g) Section through a high-level granodioritic intrusion undergoing progressive crystallization and showing the **hypothetical position in space of the H_2O-saturated granite solidus** (S), as well as the zone (in gray) where aqueous fluid saturation occurs in the residual magma (after Burnham, 1979). **(dr)** Section through a high-level granodioritic intrusion showing the nature of **hydrofracturing and breccia pipe formation** that could form around the apical portion of a granite body (after Burnham, 1979).

(Robb, 2005)

Systèmes magmatiques - hydrothermaux

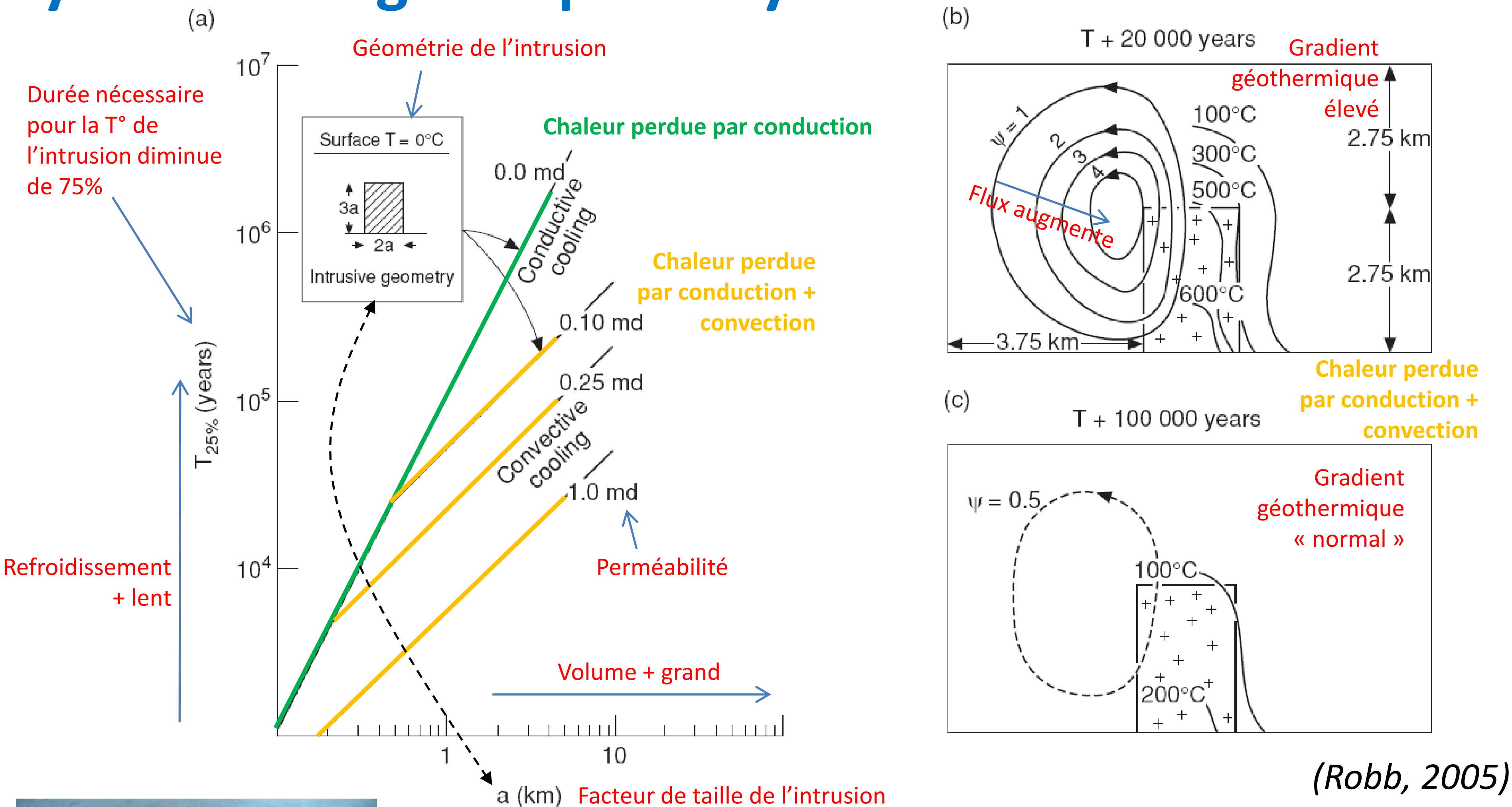
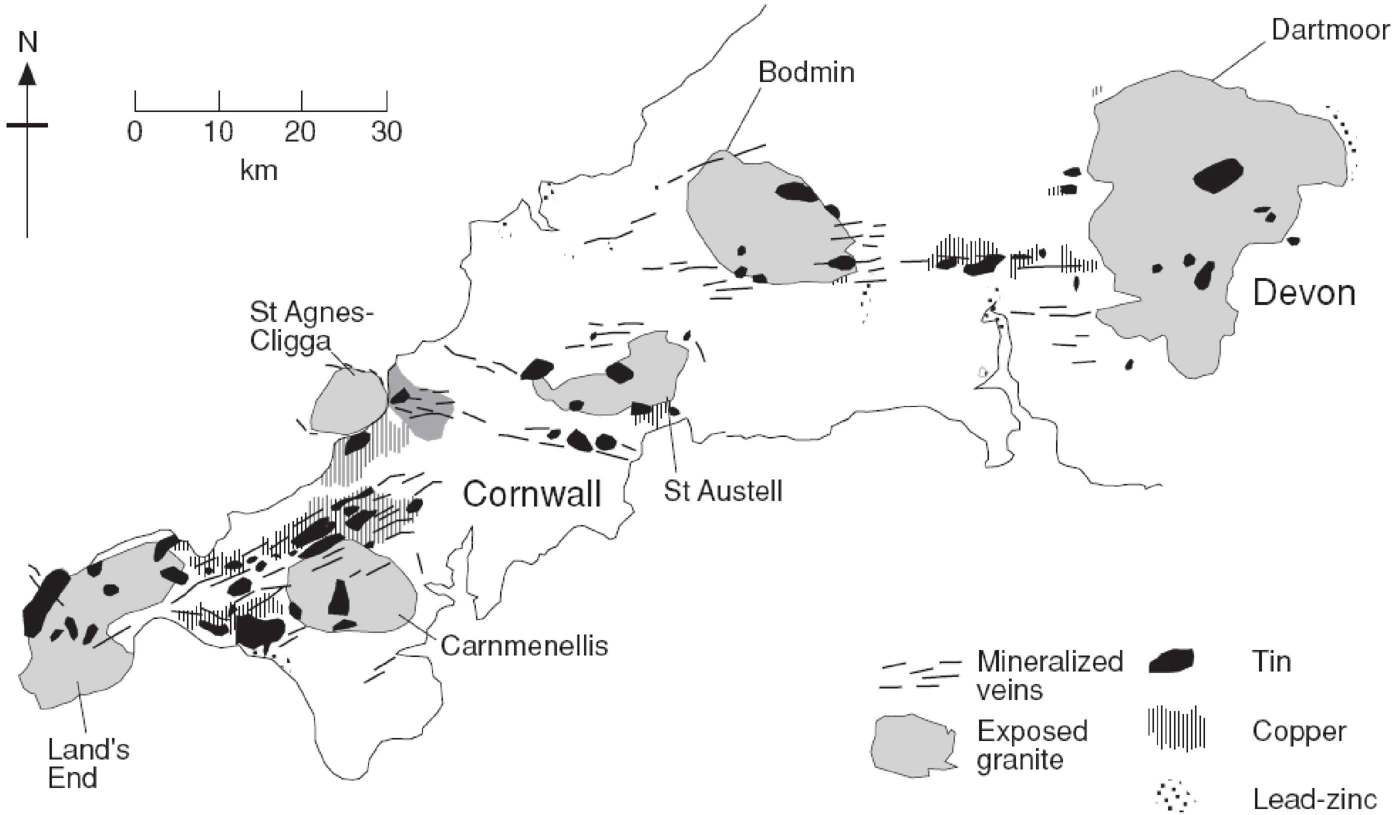


Figure 2.19 Models illustrating the thermal and fluid flow characteristics in and around a cooling igneous intrusive body. (a) Plot of the time taken for the temperature of an intrusion to fall to 25% of its initial temperature ($T_{25\%}$) as a function of the intrusion dimensions (a in km and defined in the inset diagram). Two situations, one where heat is lost by conduction alone (steep slopes) and another where a combination of conduction and convective heat loss occurs (shallow slopes), are shown. Permeabilities (in millidarcy, md) are shown for the two cases (after Cathles, 1981). (b) Thermal model showing fluid flow and temperatures in and around an intrusion some 20 000 years after emplacement. For clarity, streamlines (quantified in terms of the stream function ψ) are shown on the left and isotherms on the right hand side, although the model is symmetric about the intrusion. The intrusion was initially at 750 °C with a permeability of 0.07 md and the country rocks at 0 °C with a permeability of 0.13 md. (c) Similar model for the situation 100 000 years after emplacement. Parts b and c are after Norton and Cathles (1979).

Systèmes magmatiques - hydrothermaux

Une conséquence: zonation de systèmes minéralisés



Distribution of the major exposed plutons in Cornwall and Devon making up part of the Cornubian granite batholith, and the distribution of Sn, Cu, and Pb–Zn mineralization in and around these plutons (after Atkinson and Baker, 1986).

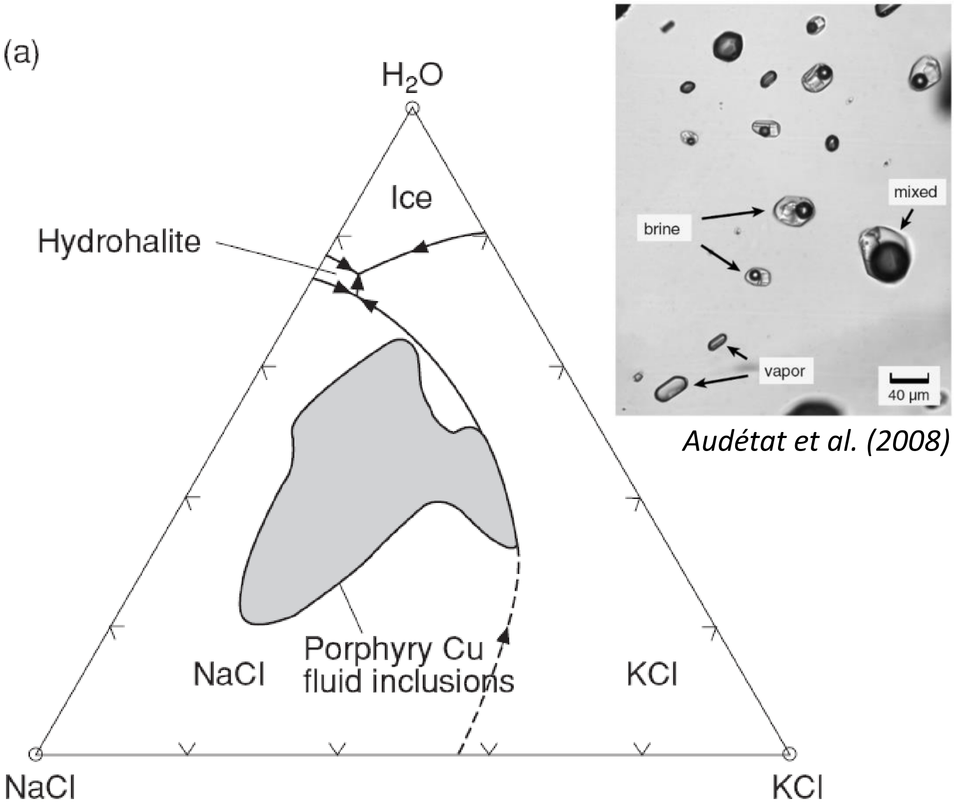
Granites Varisques 280-290 Ma

Peralumineux (S-Type)

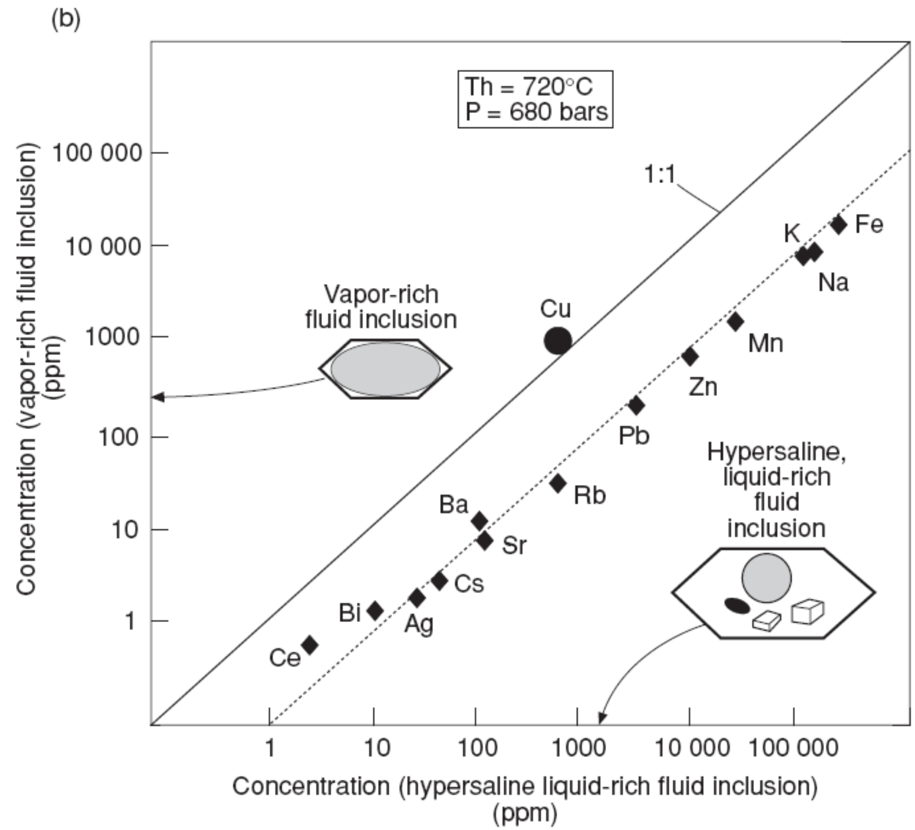
Zonation des minéralisations reflète l'évolution des fluides en terme de température, interaction fluides-fluides et interactions fluides-roches.

(Robb, 2005)

Systèmes magmatiques - hydrothermaux



Audétat et al. (2008)



(a) Plot of the system H_2O–NaCl–KCl showing the compositional range of fluids in fluid inclusions from a variety of different porphyry Cu deposits (after Roedder, 1984). **(b)** Plot of element concentrations (obtained by laserablation ICP-MS analysis) in a vapor-rich fluid inclusion versus element concentrations in a related hypersaline liquid-rich fluid inclusion. Schematic illustrations of the nature of the two fluid inclusions analyzed in order to create the plot are shown next to the respective axes. The data pertain to the Bajo de la Alumbrera porphyry Cu–Au deposit in Argentina. The plot is redrawn after Ulrich *et al.* (2001).

(Robb, 2005)

Systèmes magmatiques - hydrothermaux

Porphyres: voir TD

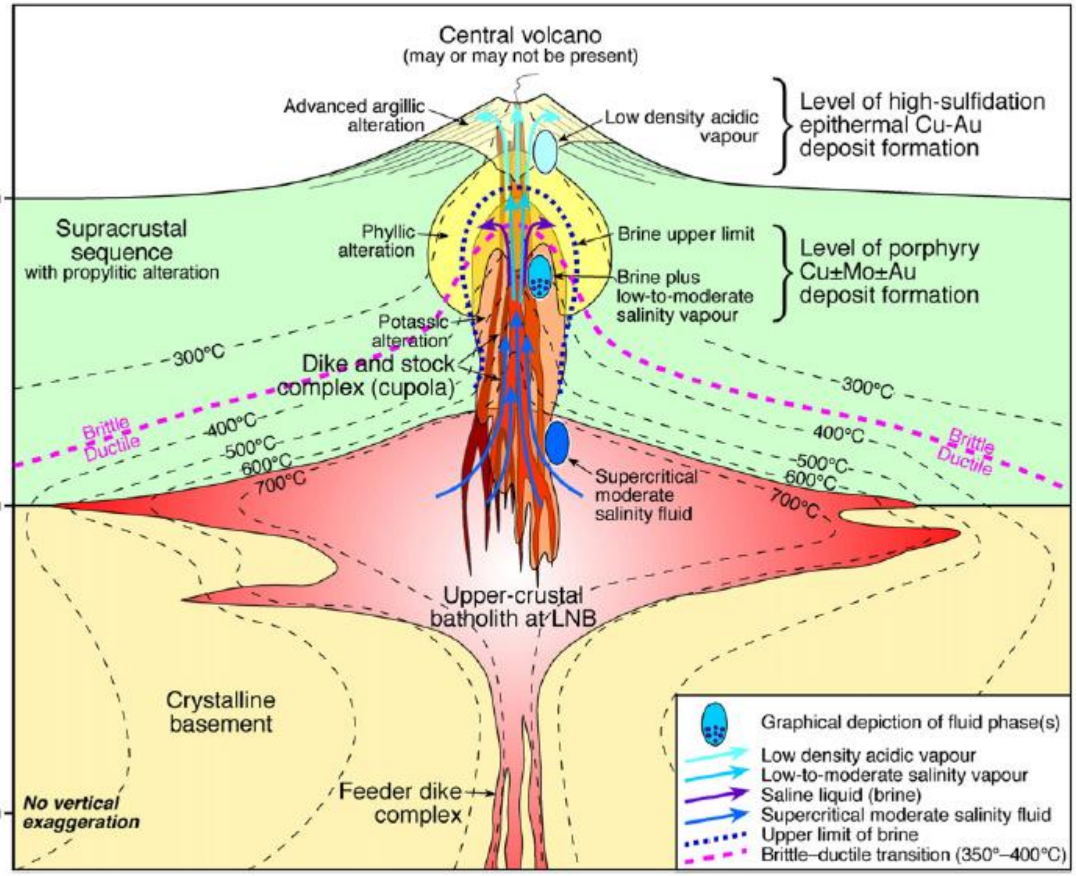


Fig. 7. Schematic cross-section through a typical coupled arc batholith–cupola–volcanic system, with associated porphyry Cu±Au and linked high sulfidation Cu–Au epithermal deposits. Also shown are the thermal structure, fluid flow pathways and characteristics during the main stage of hydrothermal activity, and overlapping hydrothermal alteration zones. Propylitic alteration by circulating heated groundwaters can be assumed to affect all the supracrustal rocks in the field of view, with greatest intensity (epidote, actinolite) close to the intrusions, fading to background distally. Modified from Richards (2005); sources: Sillitoe (1973, 2010), Dilles (1987), Shinohara and Hedenquist (1997), Hedenquist et al. (1998), and Fournier (1999).

(Richards, 2011)

Epithermaux

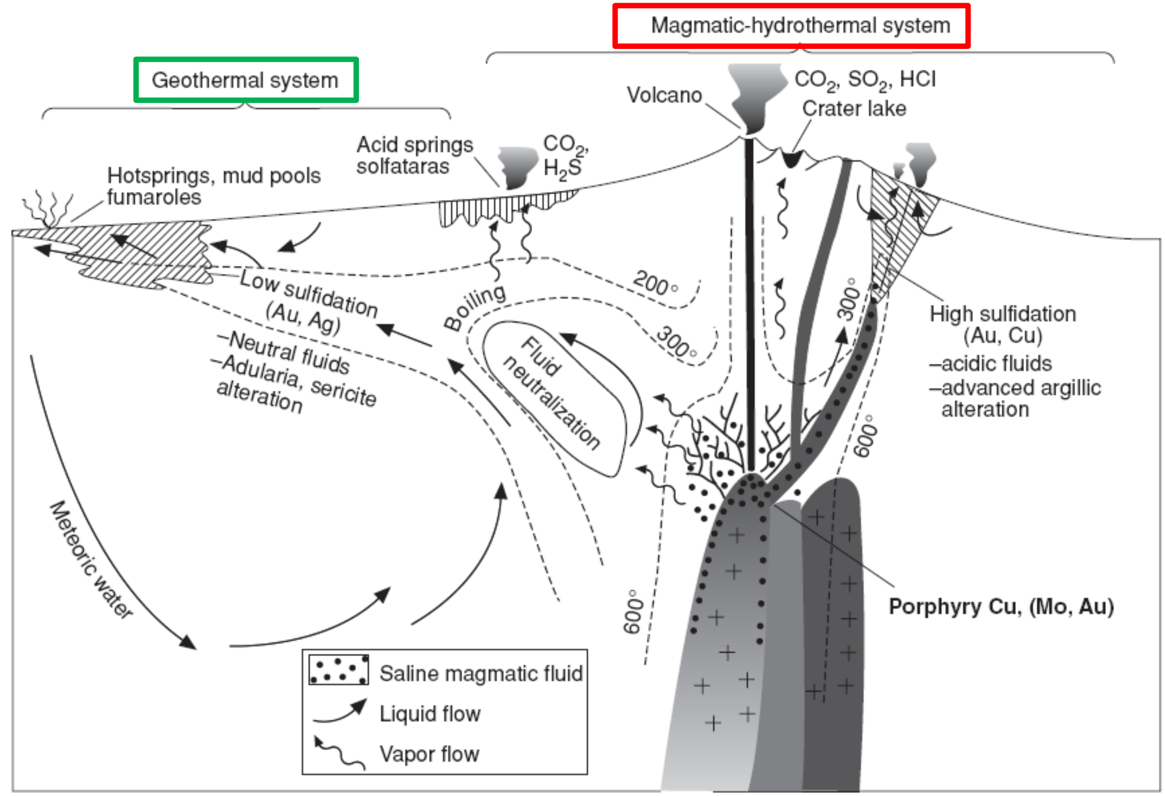
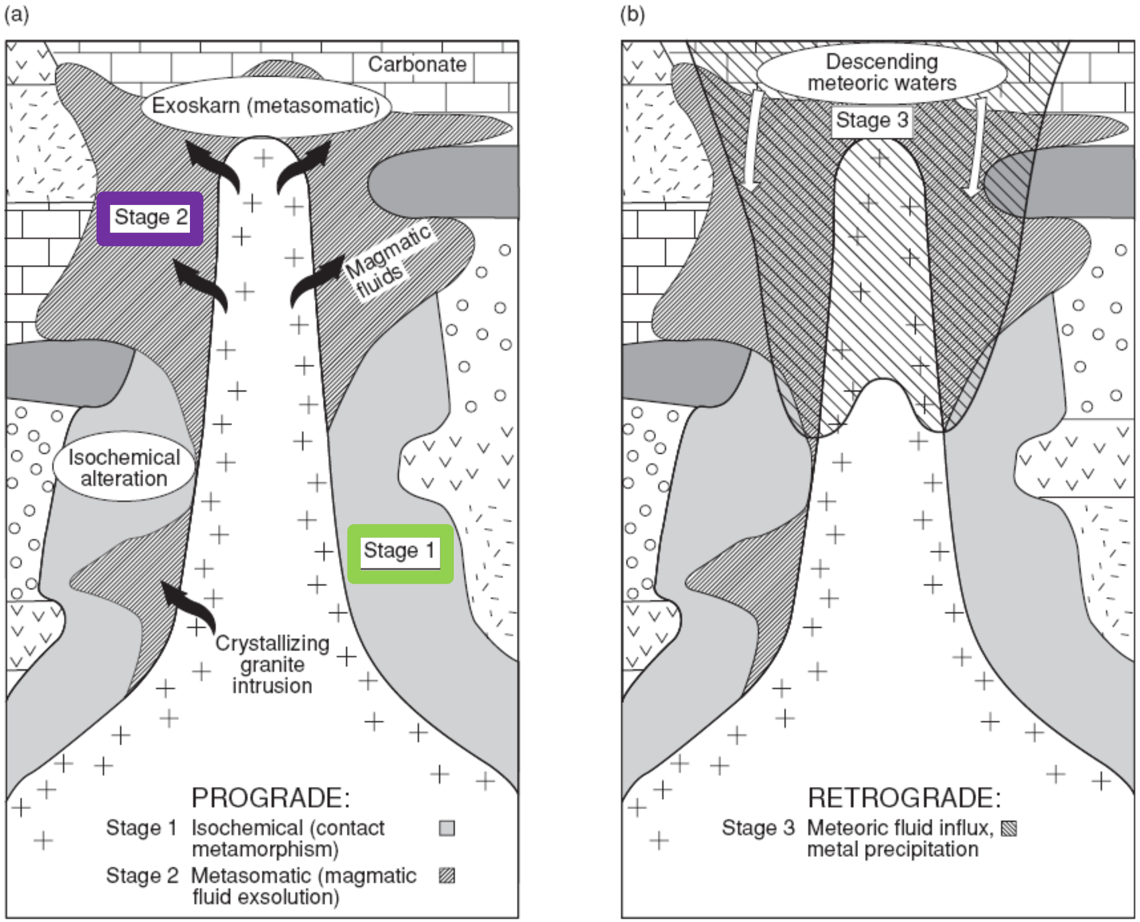


Figure 2.22 The geological setting and characteristics of high-sulfidation and low-sulfidation epithermal deposits. A genetic link between high-sulfidation epithermal Au–Cu and sub-volcanic porphyry type Cu–Au deposits is also suggested (after Hedenquist *et al.*, 2000).

Table 2.2 Characteristics of high- and low-sulfidation epithermal deposits

High-sulfidation Oxidized sulfur species (SO_2, SO_4^{2-}, HSO_4^-) in ore fluid/vapor	**Low-sulfidation** Reduced sulfur species (HS^-, H_2S) in ore fluid/vapor
Also referred to as	
Gold–alunite, acid–sulfate, alunite–kaolinite	Adularia–sericite, hotspring-related
Fluids	
Acidic pH, probably saline initially, dominantly magmatic	Near-neutral pH, low salinity, gas-rich (CO_2, H_2S), dominantly meteoric
Alteration assemblage	
Advanced argillic (zonation: quartz–alunite–kaolinite–illite–montmorillonite–chlorite)	Adularia–sericite (zonation: quartz/chalcedony–calcite–adularia–sericite–chlorite)
Metal associations	
Au–Cu (lesser Ag, Bi, Te)	Au–Ag (lesser As, Sb, Se, Hg)

(Robb, 2005)



Skarns: remplacement métasomatique de roches carbonatées (calcaires ou dolomites) par des assemblages de silicates calciques (grenats, pyroxènes, amphiboles, épidote) pendant le métamorphisme de contact ou régional.

Skarns calciques: associés aux calcaires

Skarns magnésiens: associés aux dolomites

Endo-skarn ou **Exo-skarn** en fonction de la localisation de l'altération et de la minéralisation

Stade 1: métamorphisme de contact (isochimique)

Stade 2: exsolution des fluides magmatiques et métasomatisme (allochimique): précipitation de scheelite ($CaWO_4$).

Stade 3: influx de fluides météoriques et précipitation de pyrite, chalcopyrite, magnétite, bornite, sphalérite, par refroidissement, réaction avec les encaissants, changement redox, neutralisation des fluides par les carbonates, mélange fluides magmatiques/fluides météoriques…

Les métaux précipités sont contrôlés par la nature du magma

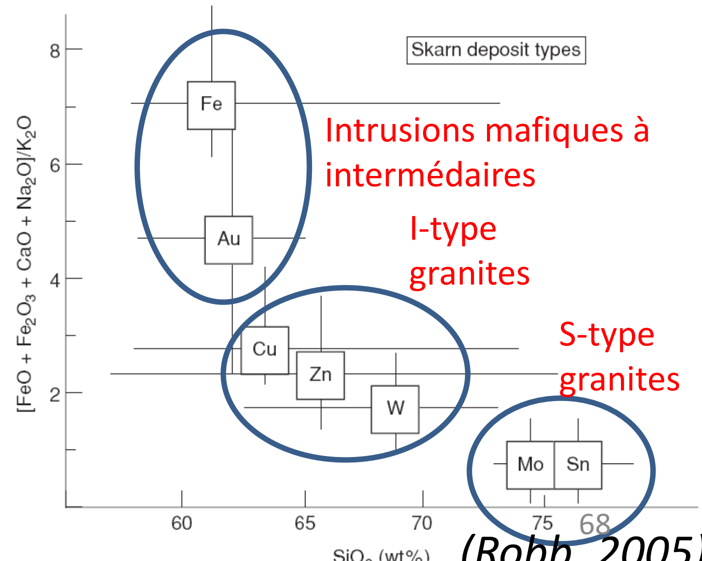
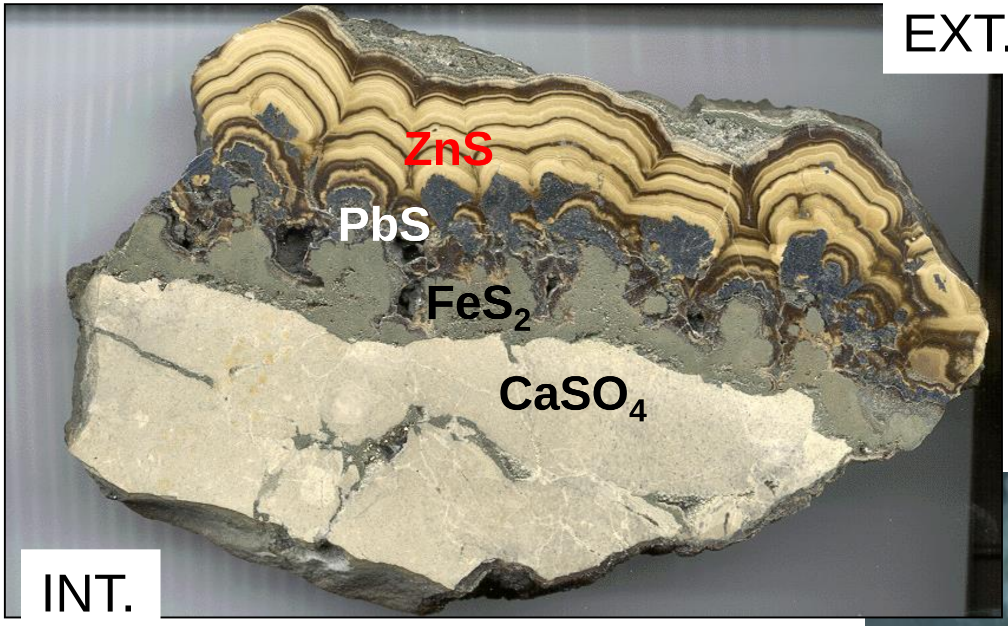


Figure 2.20 Plot of SiO_2 versus $[FeO + Fe_2O_3 + CaO + Na_2O]/K_2O$ showing the relationship between the composition of igneous intrusions and the dominant metal in various skarn deposits (after Meinert, 1992).

(Robb, 2005)

Gisement liés à l’eau de mer

Eau de mer



Paroi de cheminée hydrothermale fossilisée

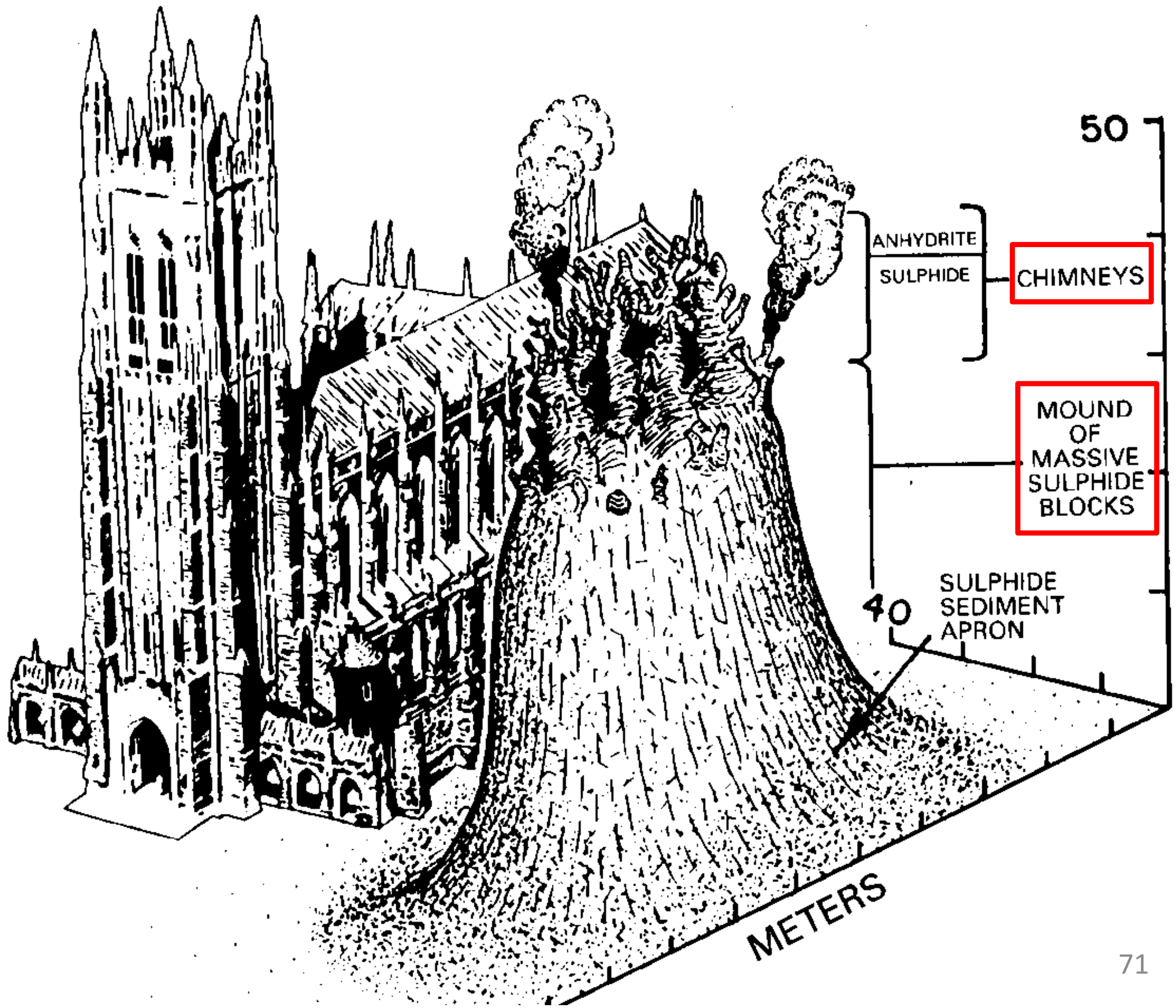
Temperature measurements are taken at a black smoker hydrothermal vent at the East Pacific Rise study site, April 2007. http://media.marine-geo.org/image/temperature-probe-epr-2007.

Eau de mer

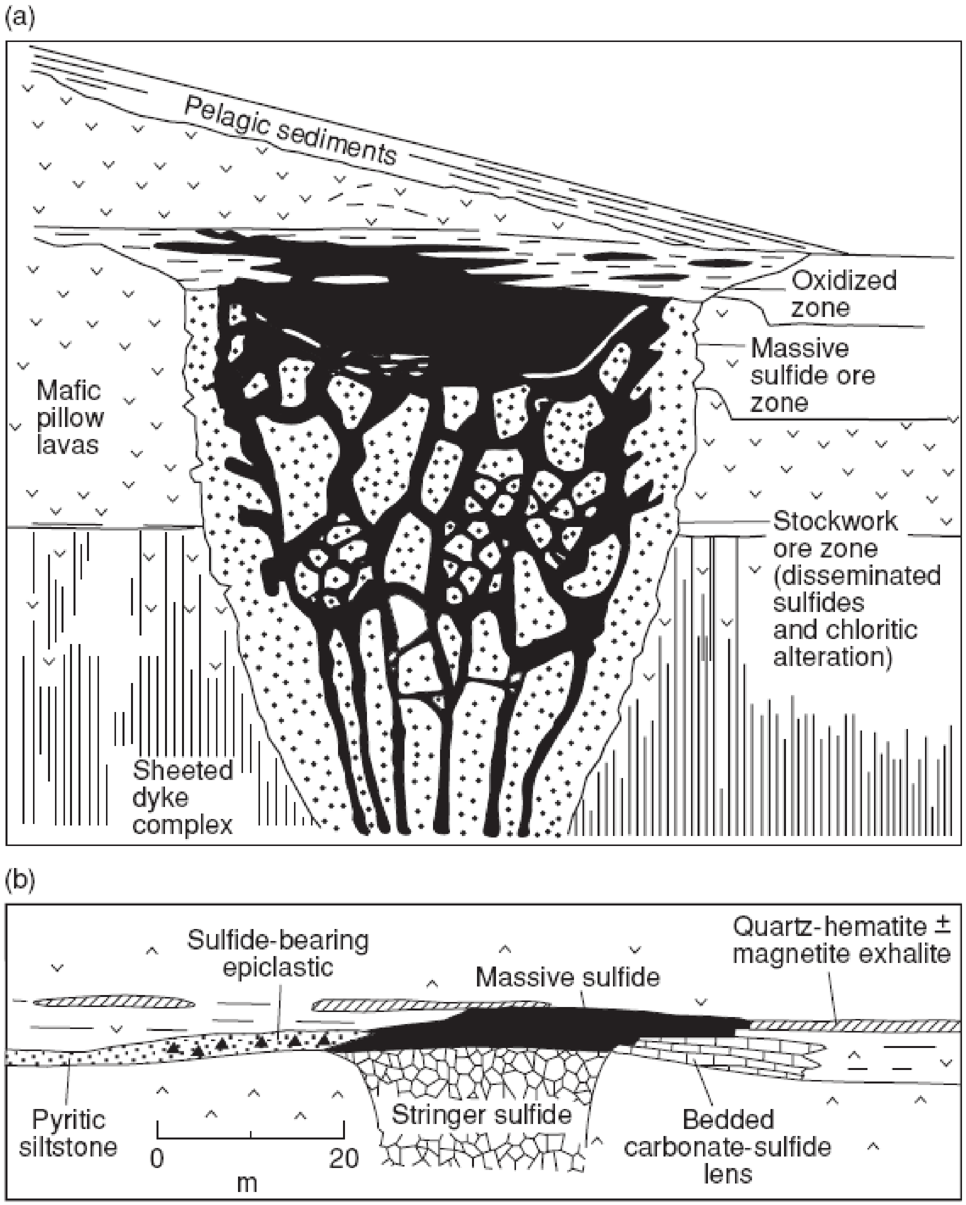
Ex: Snake Pit (Atlantique)

60 % de sulfures

En moyenne : Cu : 1.5%; Zn+Pb>10%; Au = 2 ppm; Ag = 100 ppm



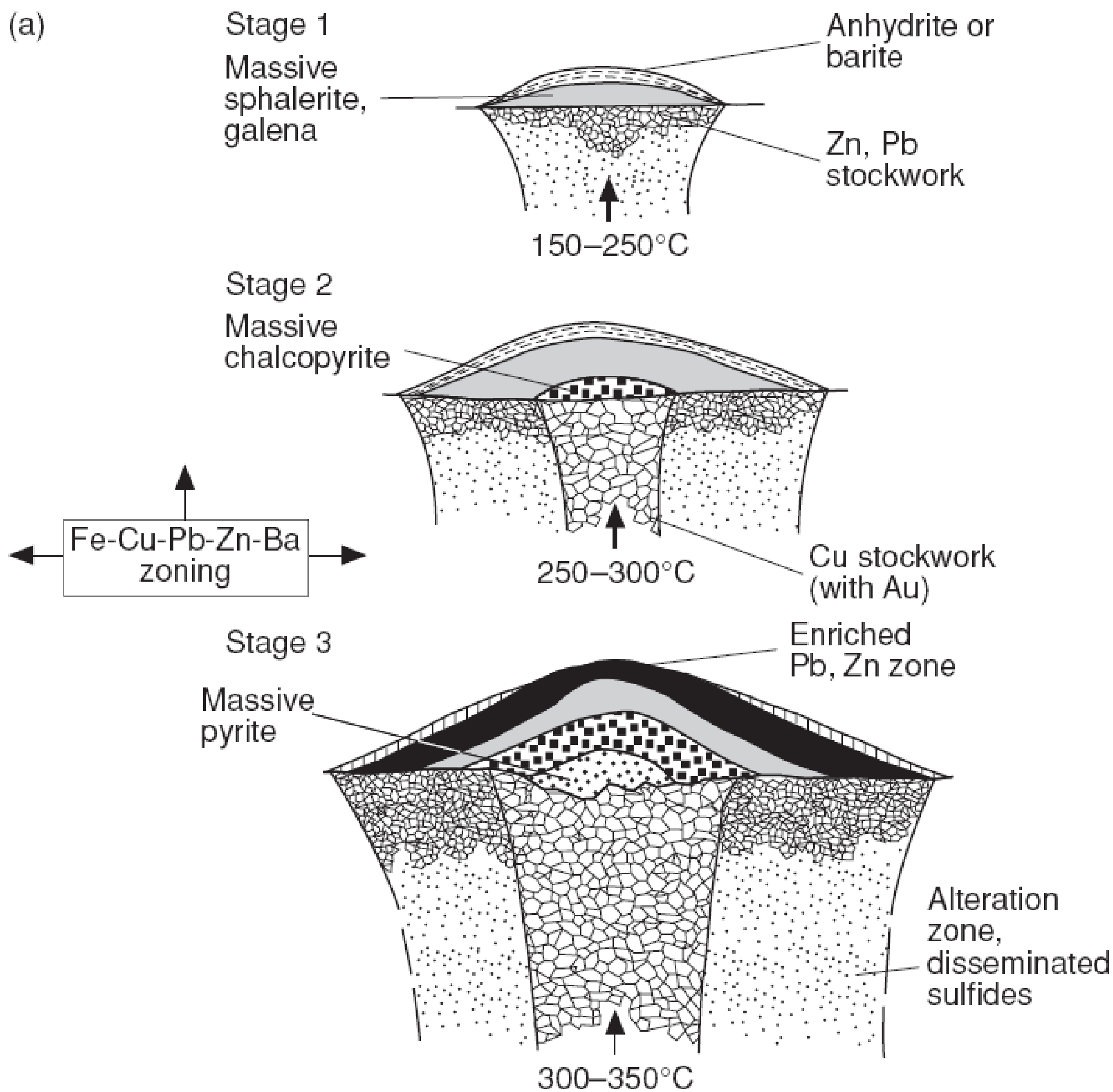
Eau de mer



(a) Section through a typical **ophiolite-hosted, Cyprus-type VMS** deposit. Footwall rocks may consist of a sheeted dyke complex and the associated volcanics are often pillowed and have a tholeiitic composition. After Hutchinson and Searle (1971). **(b)** Section showing the characteristics of **VMS** deposits **other than the ophiolite-hosted type**. Associated volcanics may be intermediate or felsic in composition and a closer lateral link to chemical and epiclastic sediments is often apparent. The lens of massive sulfide ore formed on the ocean floor, underlain by a stockwork zone of disseminated sulfides and intensely altered volcanic rock, is typical of VMS deposits in general (after Large, 1992).

(Robb, 2005)

Eau de mer

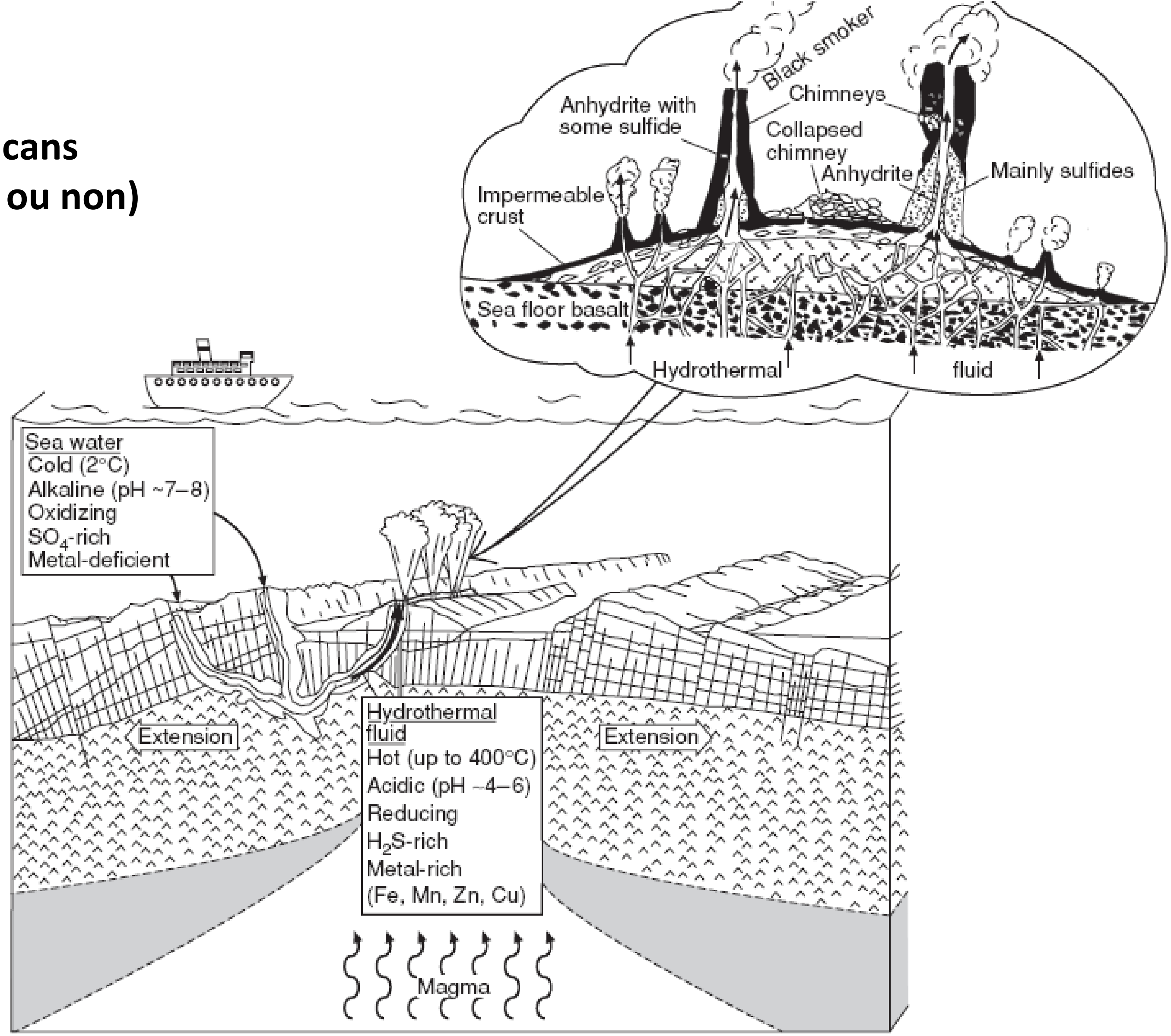


(a) Secular model explaining the evolution of fluids, growth of massive sulfide mounds, zoning, and paragenetic sequence for VMS deposits.

(Robb, 2005)

Eau de mer

En relation directe avec volcans sous-marin actifs (dorsales ou non)



Conceptual diagram illustrating the fluid characteristics and circulation pattern in mid-ocean ridge environments that give rise to the formation of “black smokers” on the sea floor. Inset is a cross section of an exhalative vent site showing the construction of anhydrite–sulfide chimneys on top of a mound of massive sulfide mineralization (after Lydon 1988; Scott, 1997).

(Robb, 2005)

Eau de mer

Continuum VMS – SEDEX (sans lien direct avec du volcanisme)

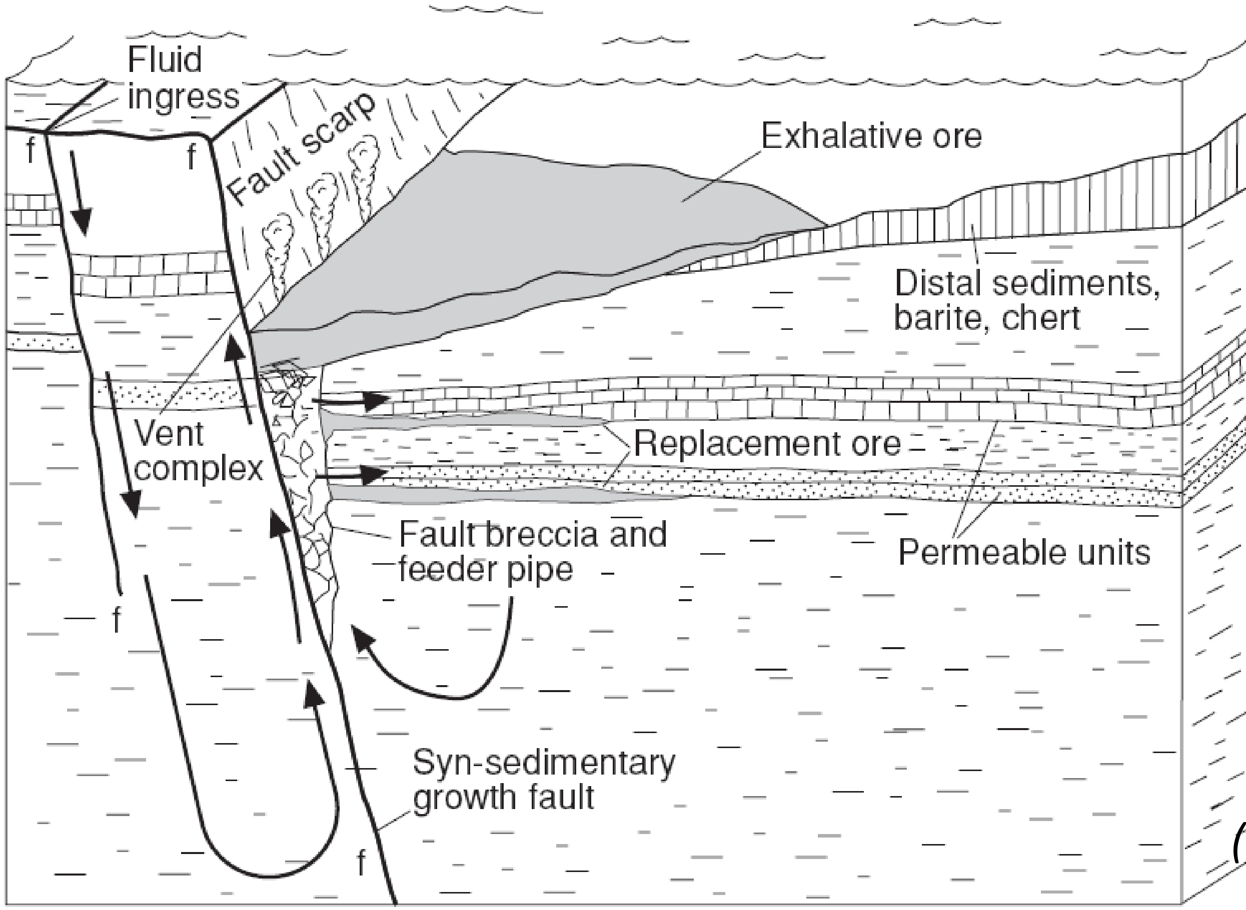


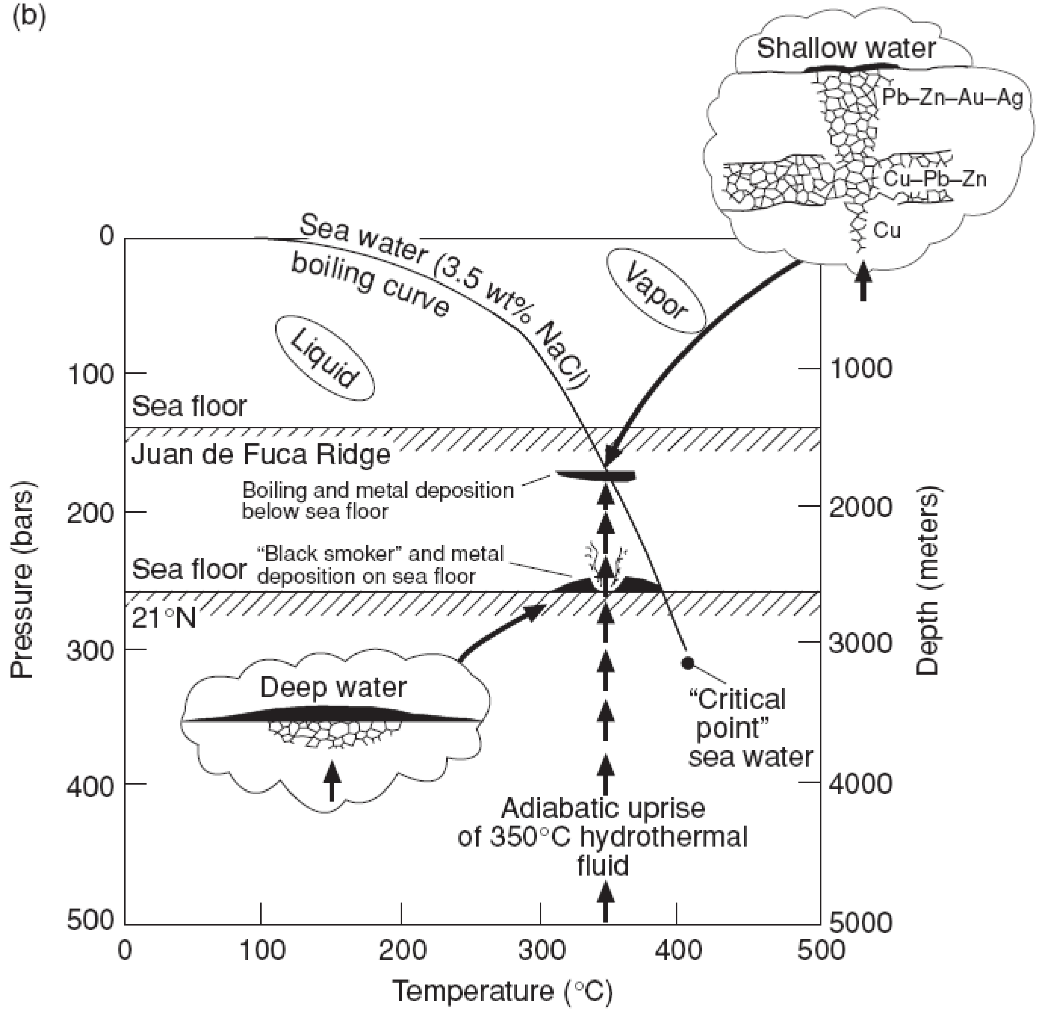
Figure 15.34. Thinly bedded to laminated sphalerite and galena ore typical of the main ore body at McArthur River mine (J Dunster collection).

*(*Ahmad M and Munson, 2013*)*

Diagram illustrating the setting for the formation of SEDEX-type Pb–Zn ores and a scenario which incorporates both exhalative and replacement concepts for the formation of these ores (after compilations by Goodfellow *et al.*, 1993; Misra, 2000).

(Robb, 2005)

Eau de mer

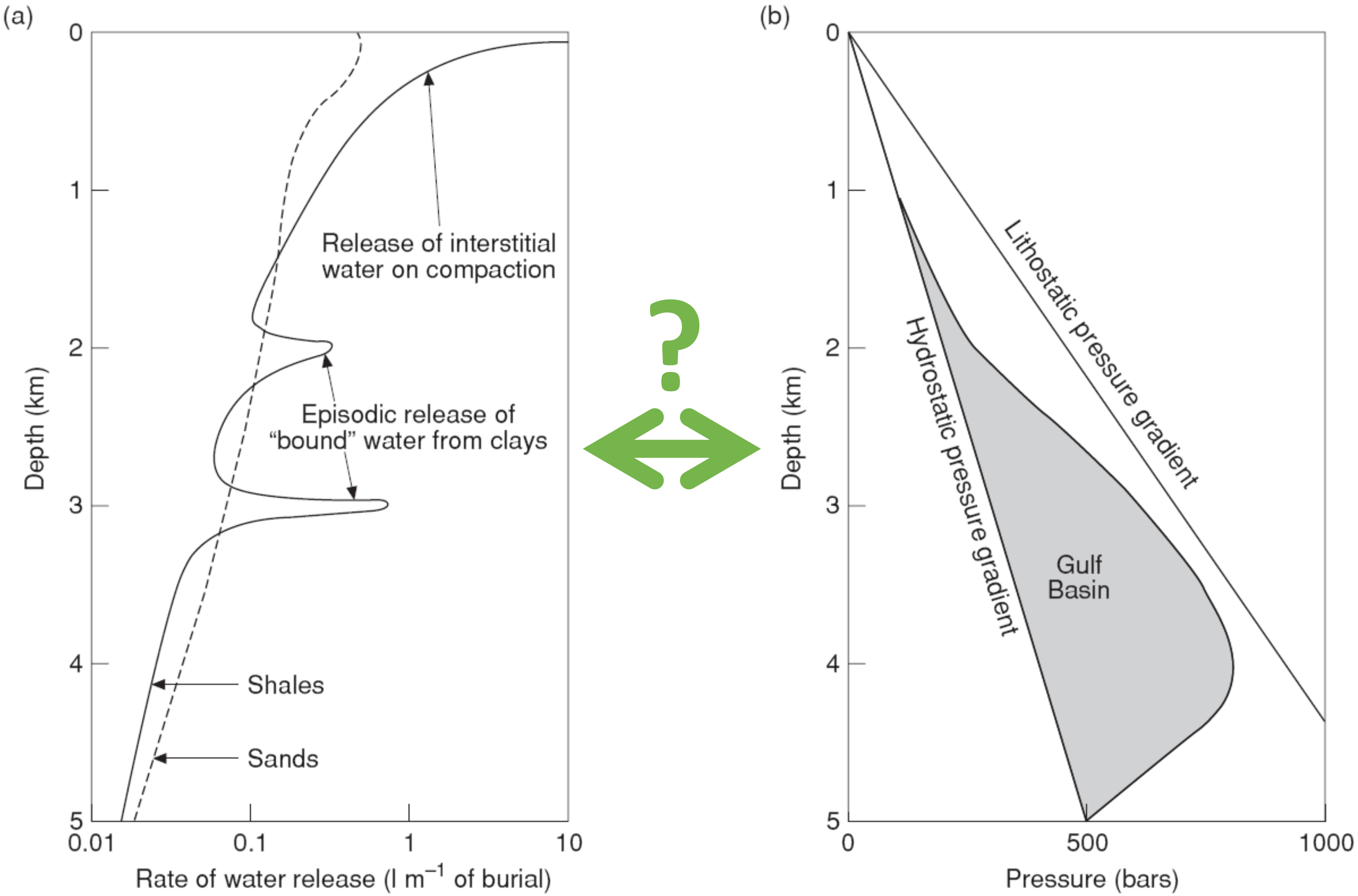


Pressure (or depth) versus temperature plot showing the **sea water (with 3.5 wt% NaCl) boiling curve** relative to deep (21° N East Pacific Rise) and shallow (Juan de Fuca ridge) sea floor. Because of the **strong pressure dependency on boiling**, a 350 °C hydrothermal **fluid rising adiabatically** in the crust would intersect a deep ocean floor as a **liquid** and **would vent as a black smoker** precipitating metals into the sea. The same fluid relative to a shallower ocean would **boil** before intersecting the floor such that only a **vapor phase would reach the surface**. **Metal precipitation** in such a case will likely occur **beneath the ocean floor**. After Delaney and Cosens (1982).

(Robb, 2005)

Gisements liés aux eaux de formations

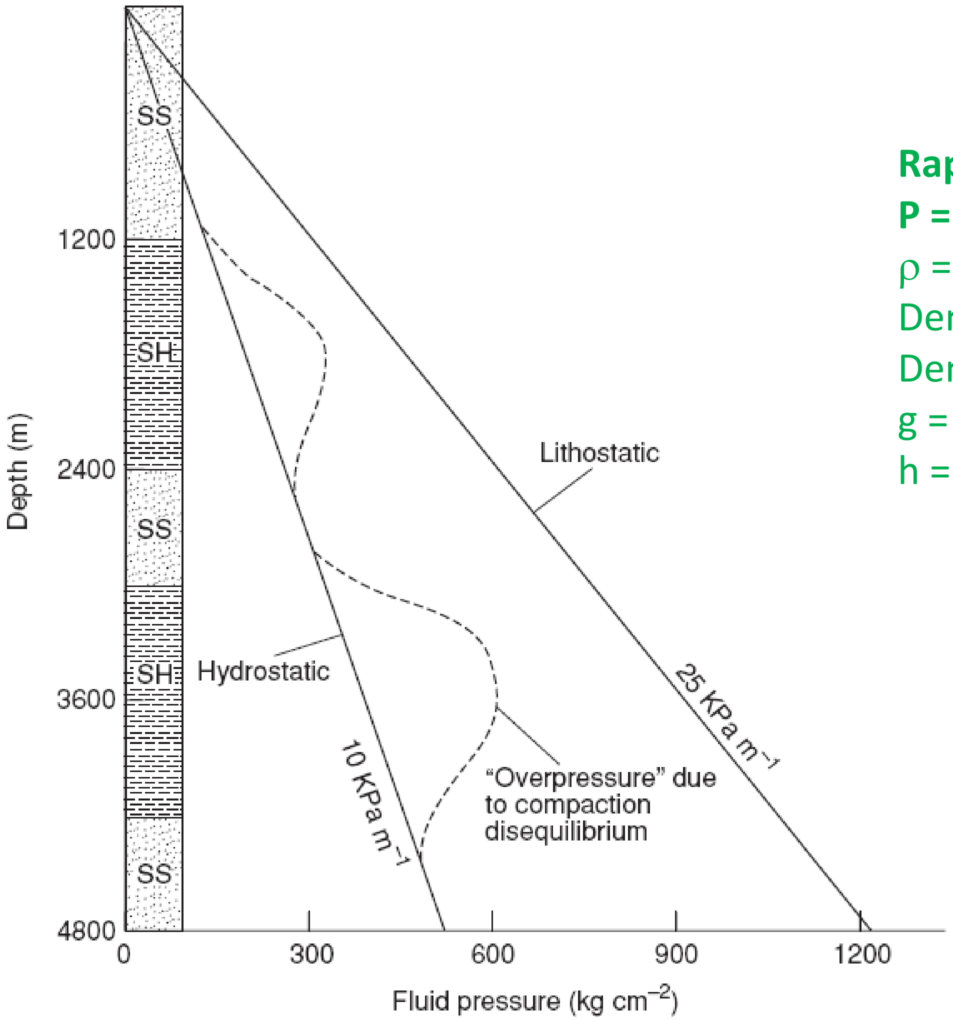
Eaux de formation (eaux connées)



(a) Depth profile illustrating the rate of water release due to initial compaction and **porosity reduction followed by dehydration** of clay minerals such as montmorillonite. **(b)** Depth profiles showing typical fluid pressures in a compacting sediment pile. (Michigan, Alberta, and Gulf basins in the USA, after Hanor, 1979).

(Robb, 2005)

Eaux de formation (eaux connées)



Rappel: calcul de la pression

P = ρgh

ρ = densité de la roche ou de l'eau

Densité moyenne de la roche = env. 2,5 $g.cm^{-3}$

Densité moyenne de l'eau = 1 $g.cm^{-3}$

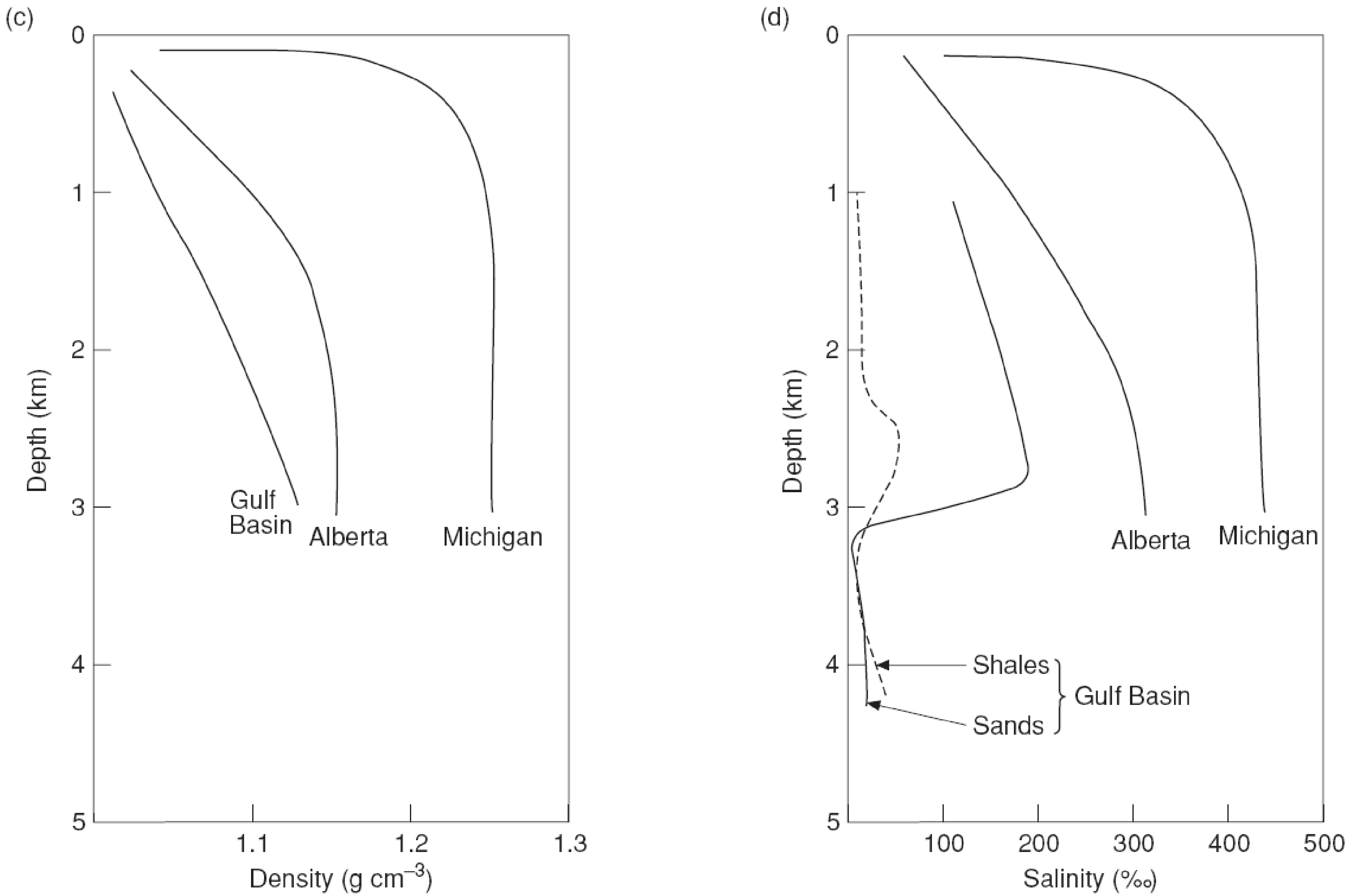
g = 9,81 $m.s^{-2}$

h = hauteur de roche (P litho.) ou d'eau (P. hydro.)

Plot of depth versus fluid pressure to illustrate the difference between hydrostatic and lithostatic presure (i.e. **overpressure**) that can accumulate in low permeabiblity shale horizon (SH) relative to sandstone layers (SS) because of the **inhability of these rocks to efficiently drain off pore waters on compaction** (after Hunt 1979).

(Robb, 2005)

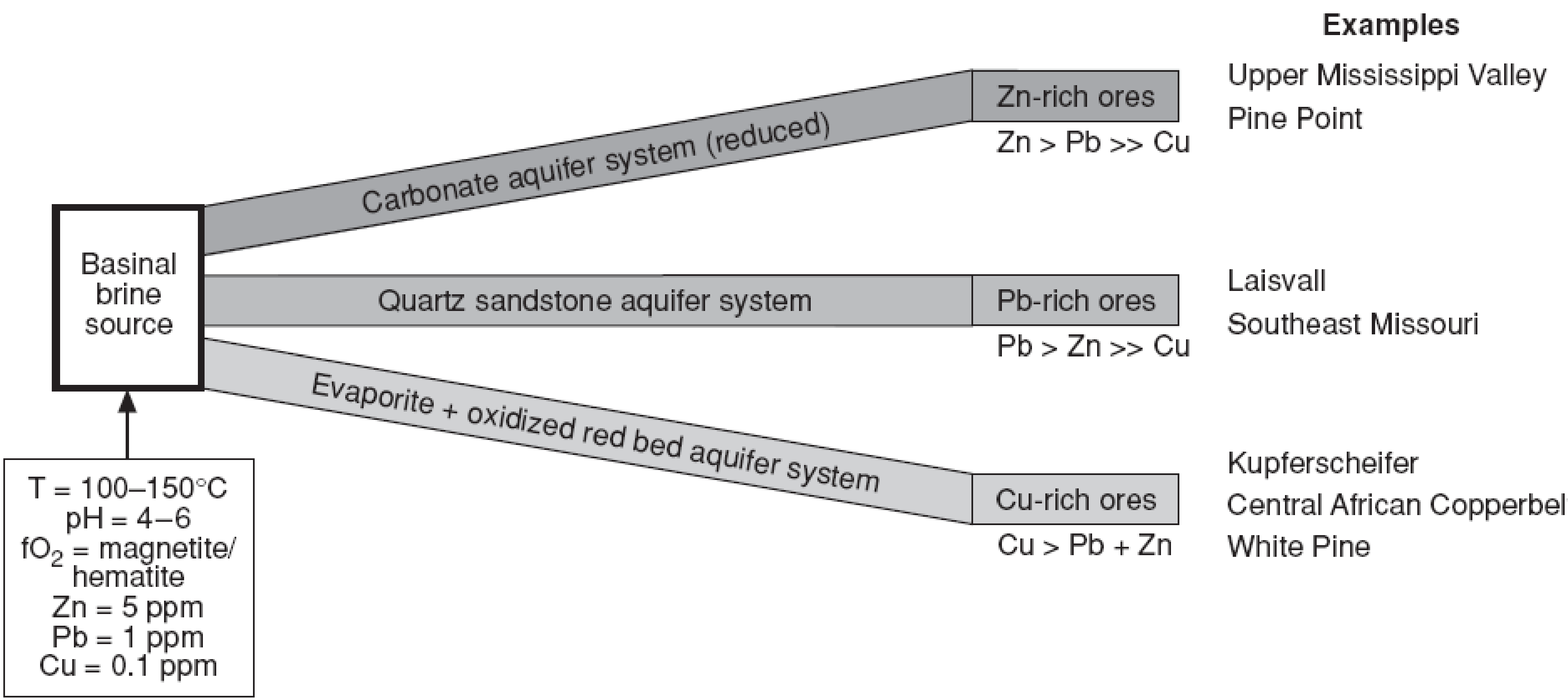
Eaux de formation (eaux connées)



Depth profiles showing typical fluid density **(c)** and salinity **(d)** in a compacting sediment pile (Michigan, Alberta, and Gulf basins in the USA, after Hanor, 1979).

(Robb, 2005)

Eaux de formation

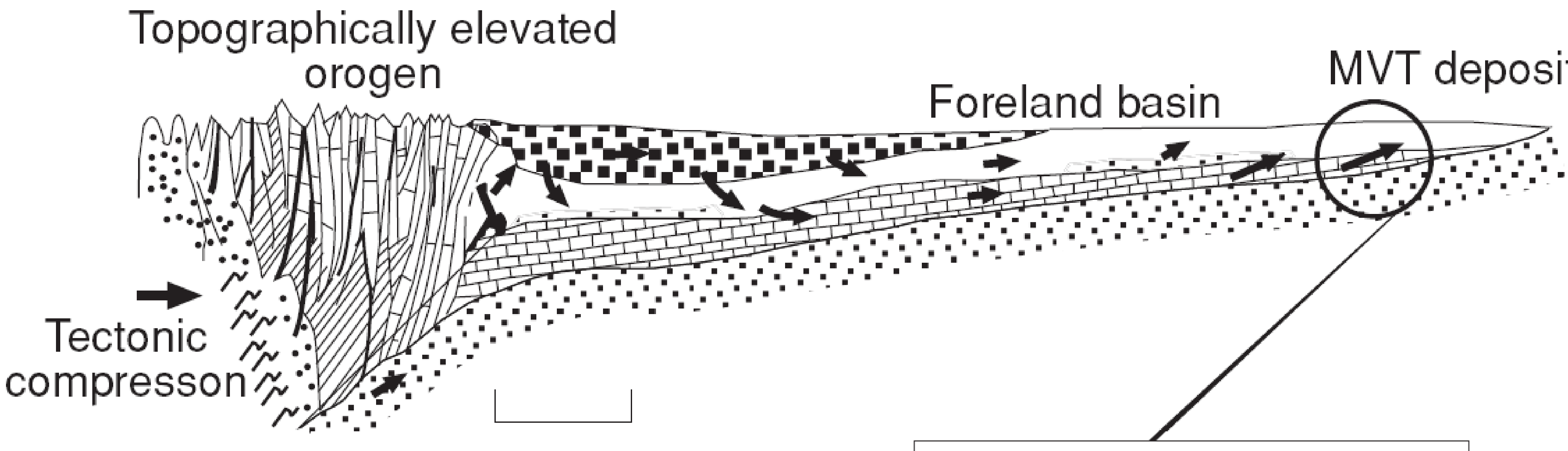


Diagrammatic representation showing the relationship between a single basinal brine and the conditions under which it might form SSC, as well as carbonate- and sandstone-hosted, MVT deposits (after Sverjensky, 1989; Metcalfe *et al.*, 1994).

(Robb, 2005)

Eaux de formation

MVT



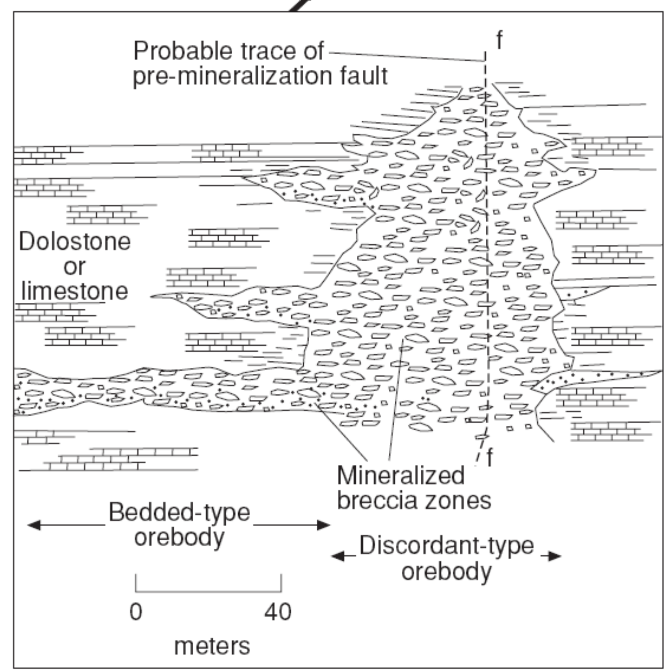
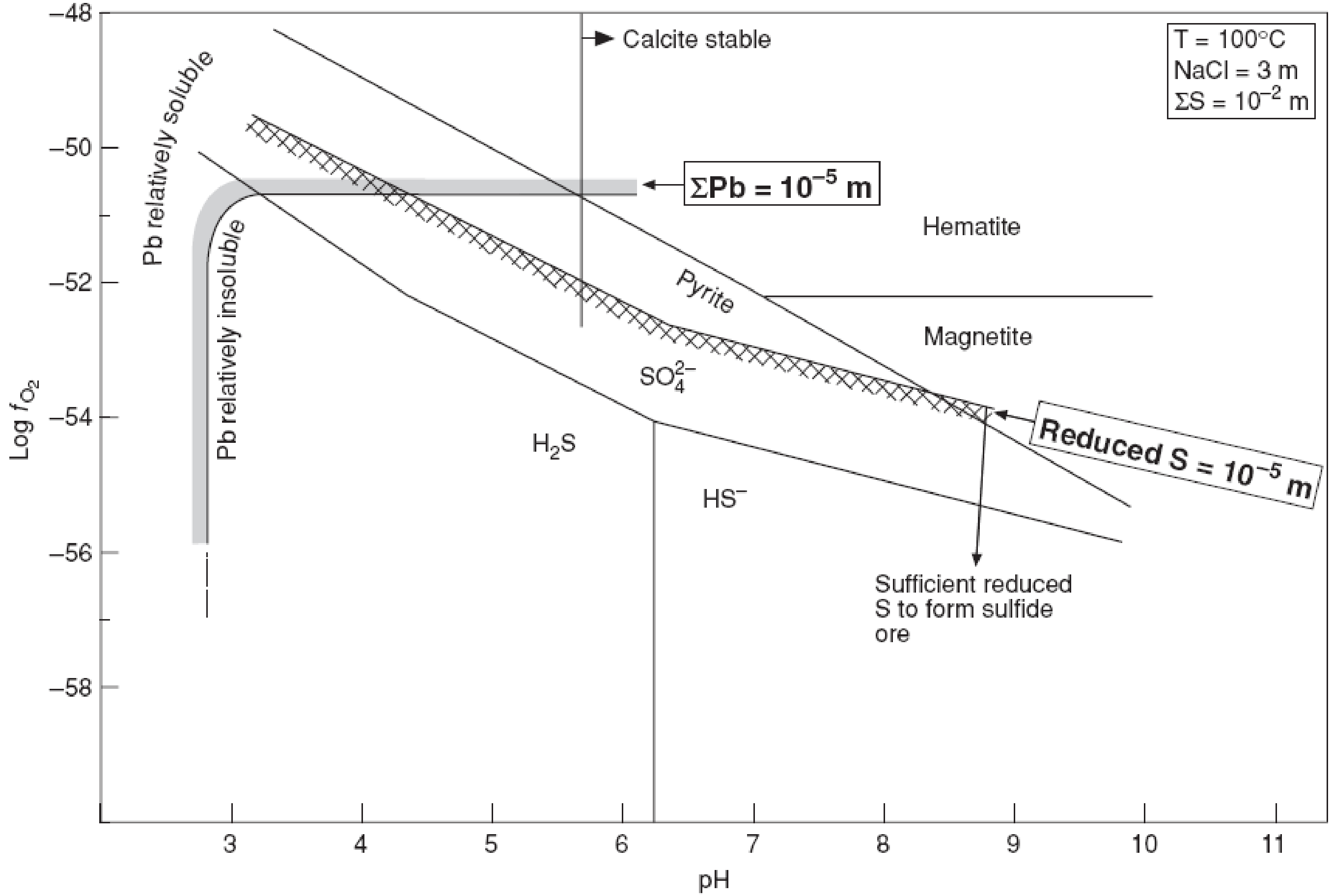


Diagram illustrating the concept of **hydrological continuity between a compressional orogenic belt and a foreland sedimentary** basin through which orogenically and topographically driven fluids flow, and within which MVT Zn–Pb deposits form. Inset shows characteristics of bedded and discordant mineralization at a deposit scale. Mineralization may be bedded and associated with dolostone/limestone sequences, or in discordant carbonate breccia zones (after Garven *et al.*, 1993).

(Robb, 2005)

Eaux de formation

MVT

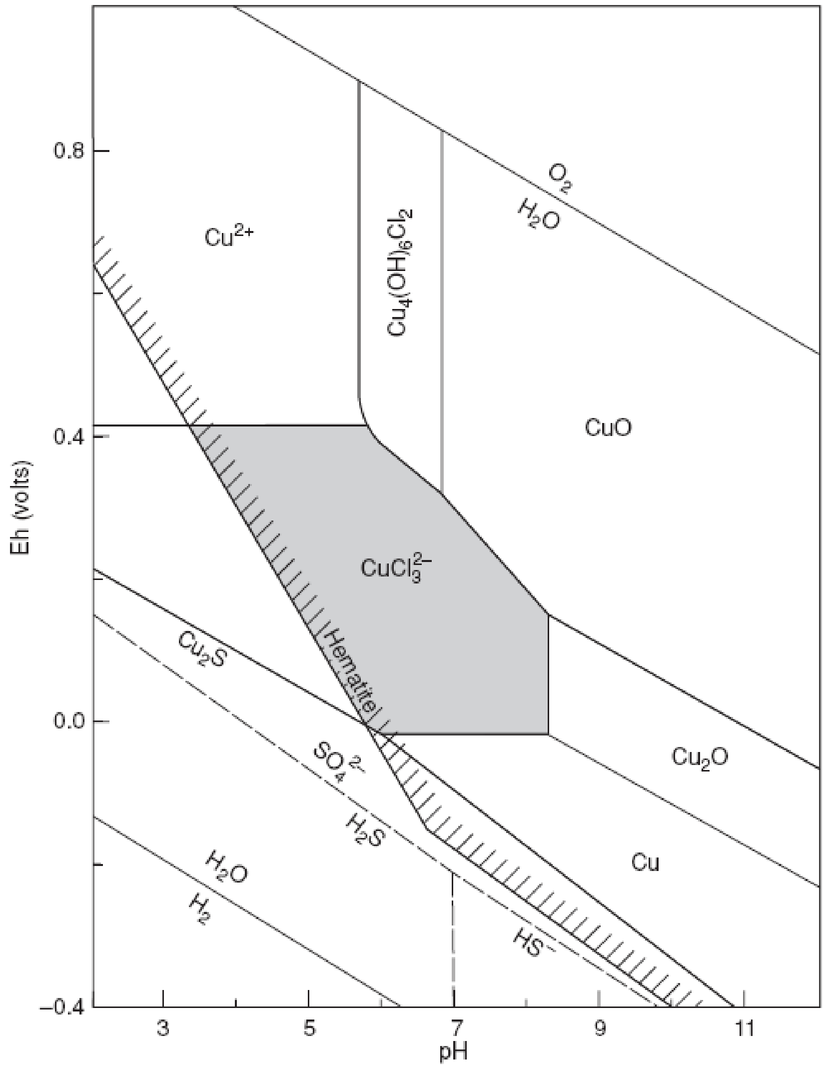


f_{O2}–pH plot showing **key mineral and aqueous species stabilities under the conditions shown**. Solubility contours of $\Sigma Pb = 10^{-5}$ m and reduced sulfur = 10^{-5} m are also shown. Higher solubilities lie to the left of and above the Pb contour, and ~~below~~ (above???) the sulfur contour (after Anderson, 1975).

(Robb, 2005)

Eaux de formation

Cu stratiforme

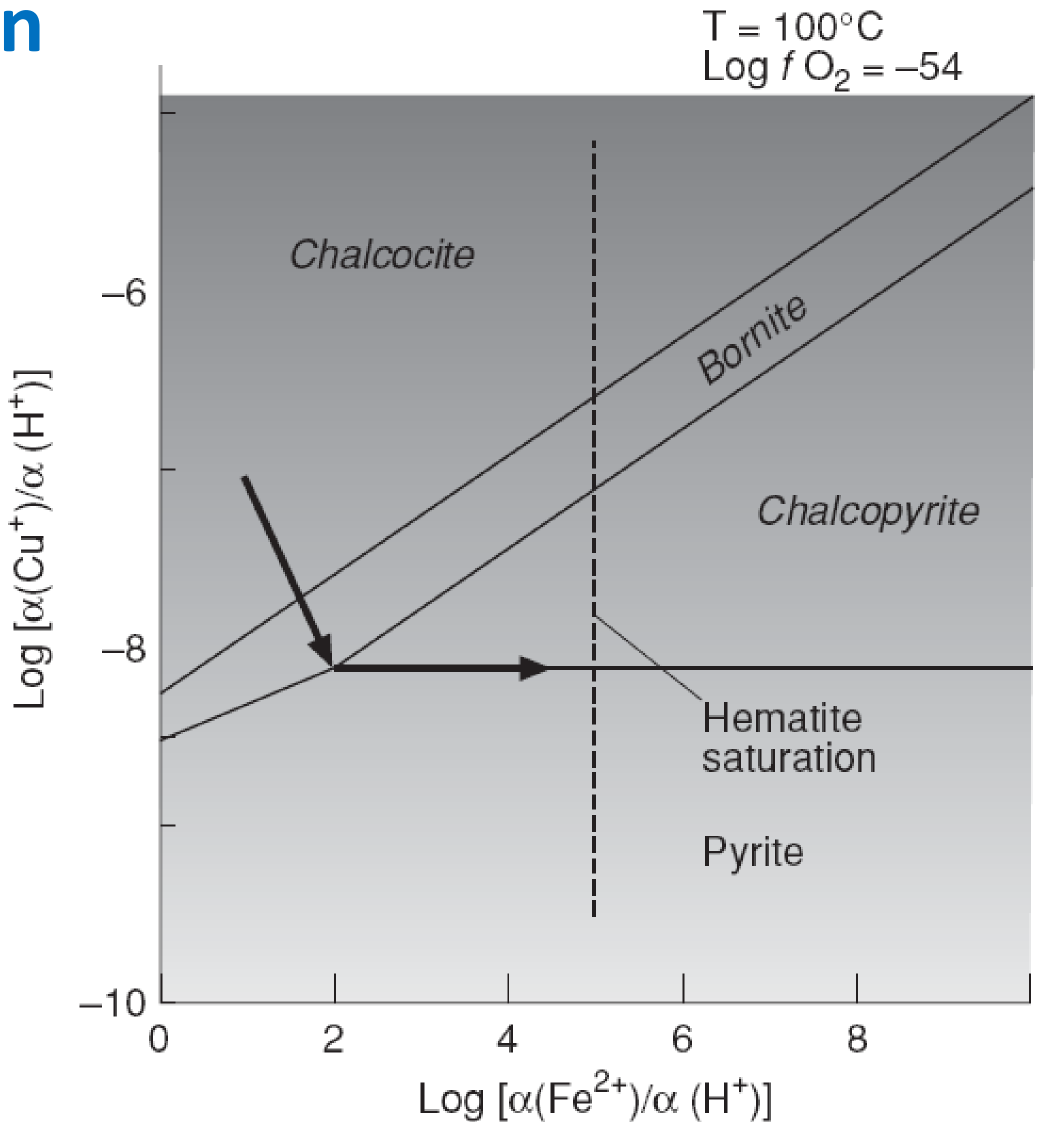


Eh–pH plot for the system Cu–O–H–S–Cl at 25°C (with ΣS = 10−4m and Cl⁻ = 0.5m). Also shown are the stability fields for hematite, various sulfur species, and the **cuprous-chloride complex for conditions compatible with the formation of SSC deposits** (after Rose, 1976).

(Robb, 2005)

Eaux de formation

Cu stratiforme



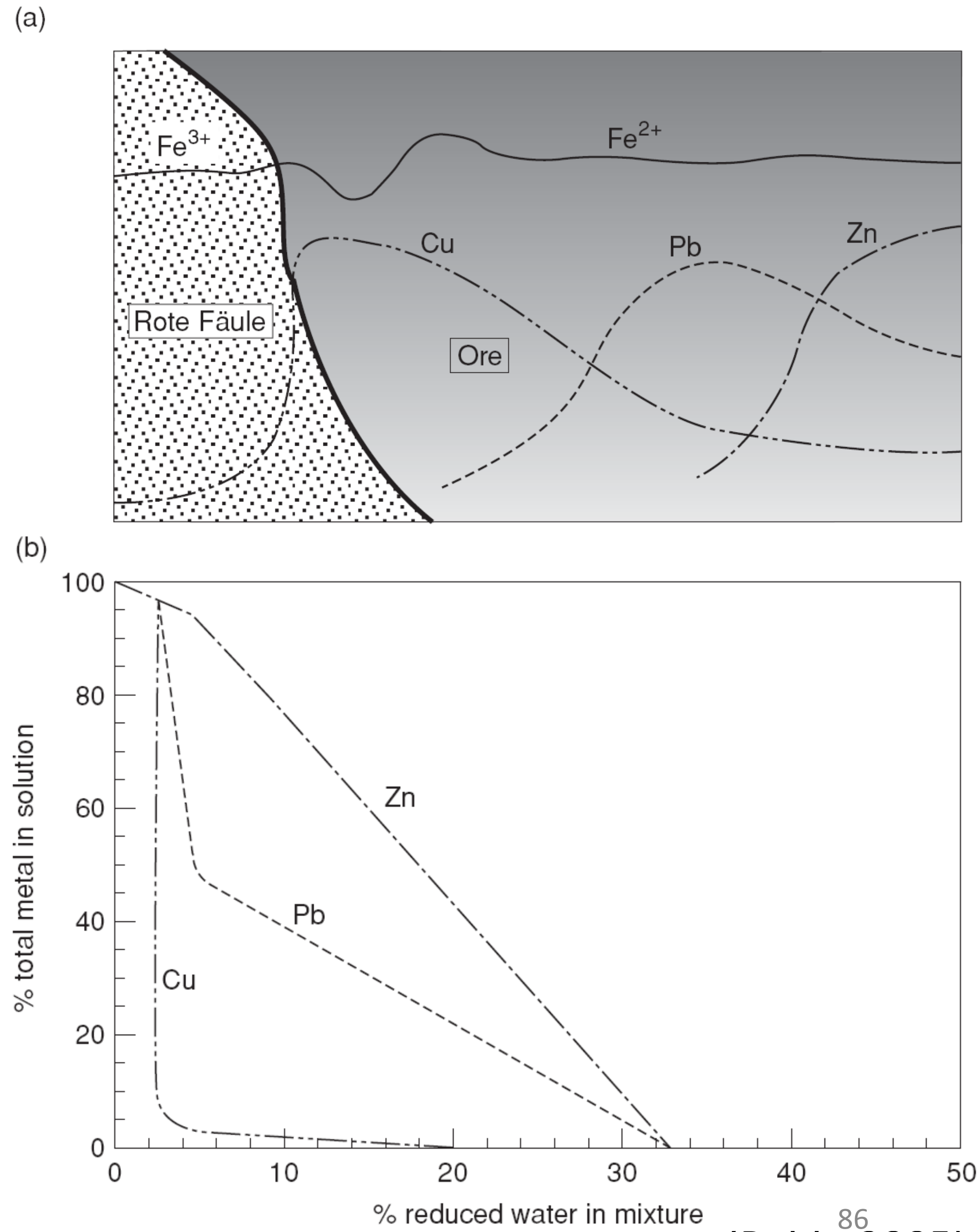
Plot of Cu^+/H^+ versus Fe^+/H^+ activity ratios to **explain the zoning and paragenetic sequence that is often observed in SSC deposits** when a **Cu-bearing fluid reacts with a pyritic shale**. In this situation the original copper content of the fluid is high and then decreases as a function of Cu-sulfide precipitation to form the **paragenetic sequence chalcocite–bornite–chalcopyrite–pyrite** (after Ripley *et al.*, 1985).

(Robb, 2005)

Eaux de formation

Cu stratiforme

Origine des zonations?
Processus Redox
Interactions fluides oxydés / fluides réduits?
Interactions fluides oxydés / roches réduites?

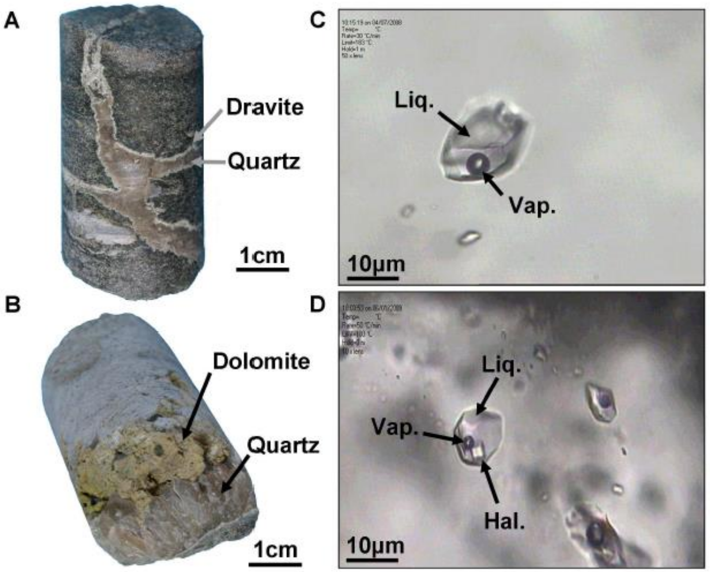


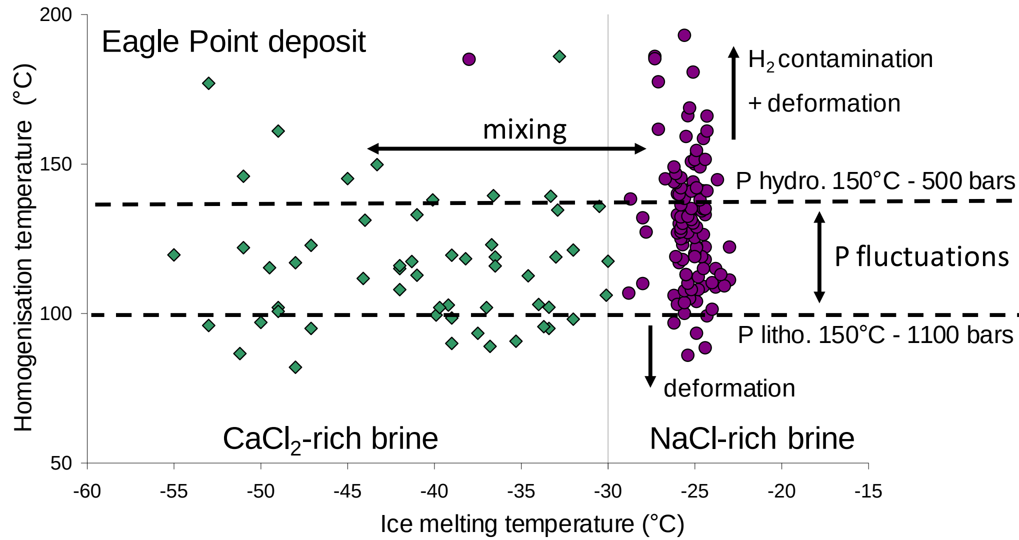
(a) Section showing **metal zonation** in typical Kupferschiefer ores in relation to the transgressive, oxidized "Rote Fäule" zone (after Jowett *et al.*, 1987). **(b)** Model showing the effects of **mixing a typical SSC-type ore fluid with a reduced fluid** on metal precipitation. The sequence of deposition is the same as the zonal pattern observed in the Kupferschiefer (after Metcalfe *et al.*, 1994).

(Robb, 2005)

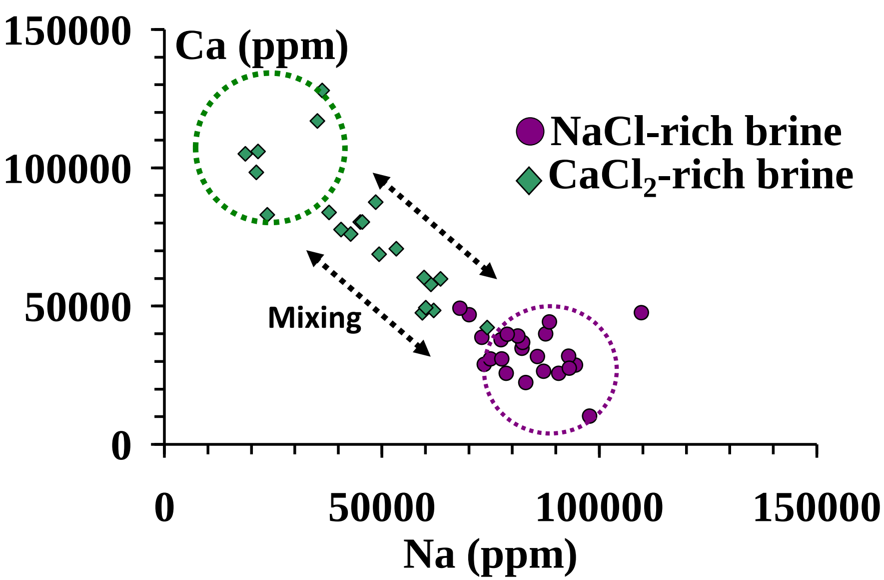
Eaux de formation

U discordance





Richard et al. submitted to Ore Geol. Rev.



Richard et al. (2010) Terra Nova 22, 303–308

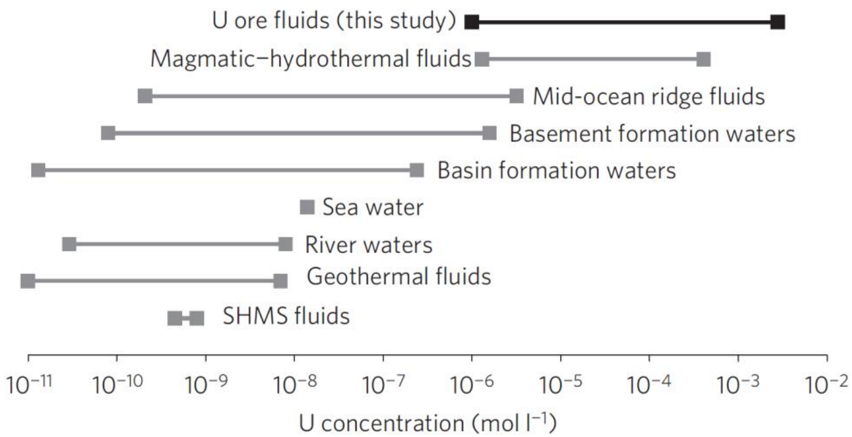
. Na-Ca-Mg-K-Cl brines (~ 6 molal Cl)

. Mixing at 150 ± 30°C and 1000 ± 250 bars

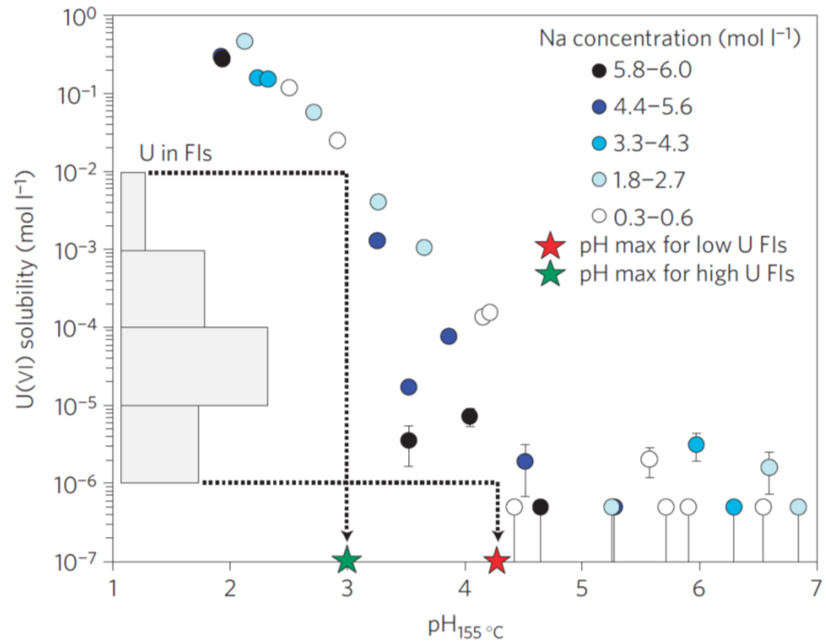
. In all deposits investigated

Eaux de formation

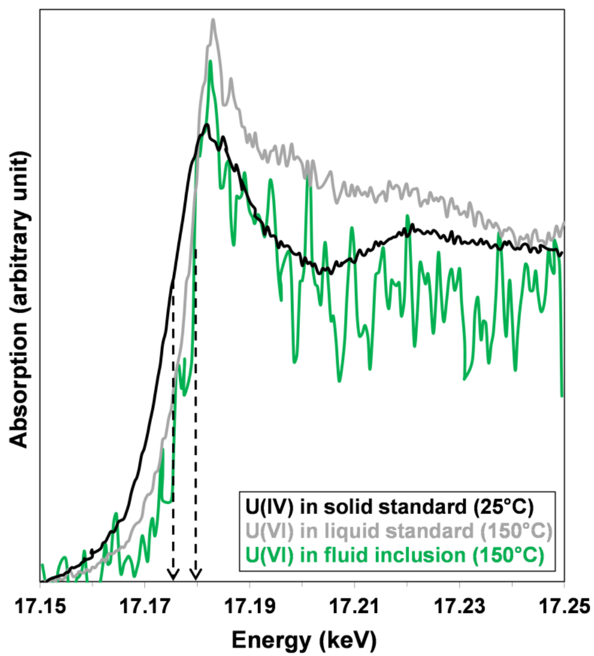
U discordance



Richard et al. (2012) Nat. Geosci. 5, 142–146



Richard et al. (2012) Nat. Geosci. 5, 142–146



Richard et al. (2013) Geofluids 13, 101–111

. U in fluid inclusions: 0.2 - 600 µg.g^{-1} (~10^{-6} - 2×10^{-3} mol.l^{-1})

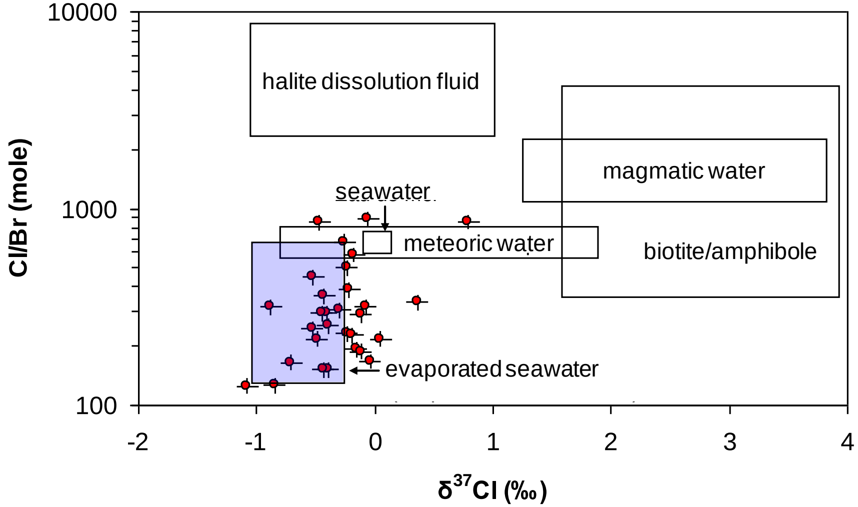
. XANES confirms U(VI) in fluid inclusions

. U(VI) solubility is strongly dependant on pH

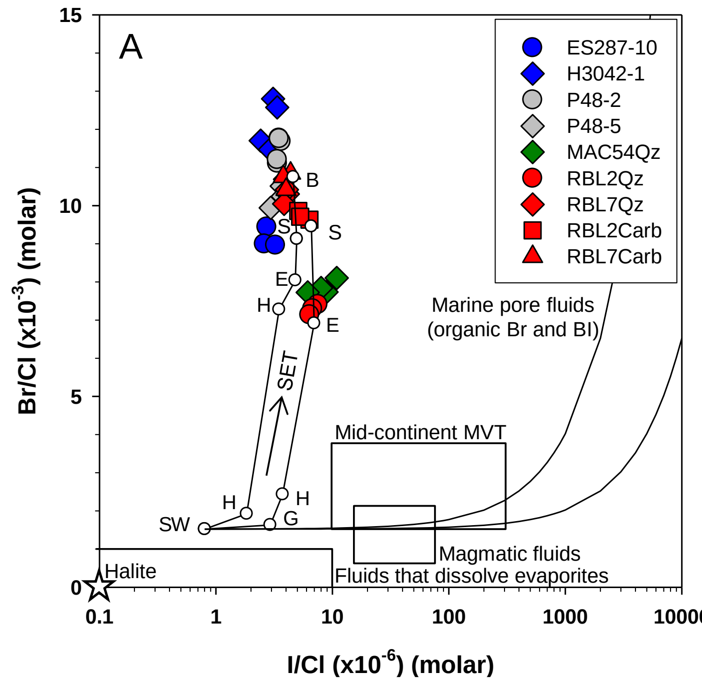
. pH of ore fluids possibly between 3 and 4.5

Eaux de formation

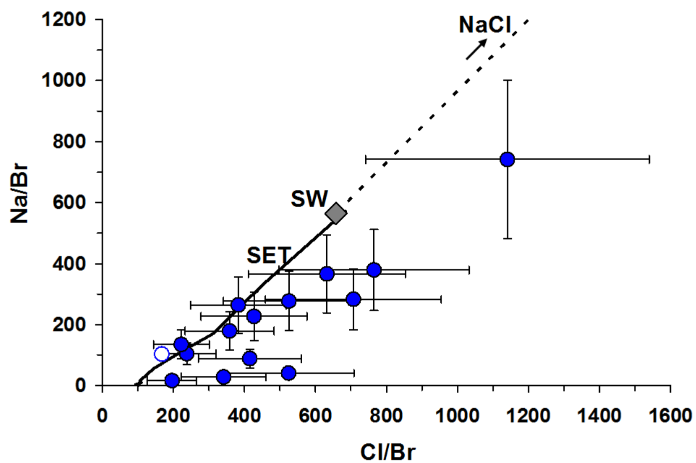
U discordance



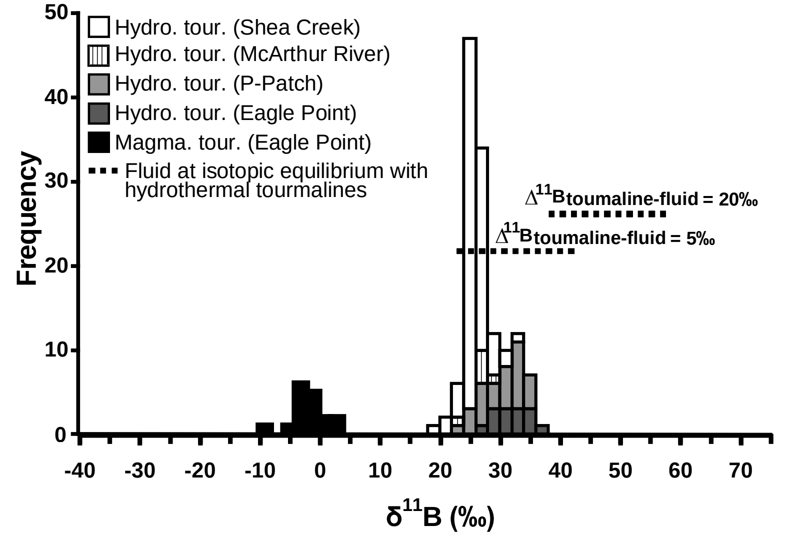
Richard et al. (2011) GCA 75, 2792–2810



Richard et al. submitted to Precambrian Res.



Leisen et al. (2012) Chem. Geol. 330-331,197–206

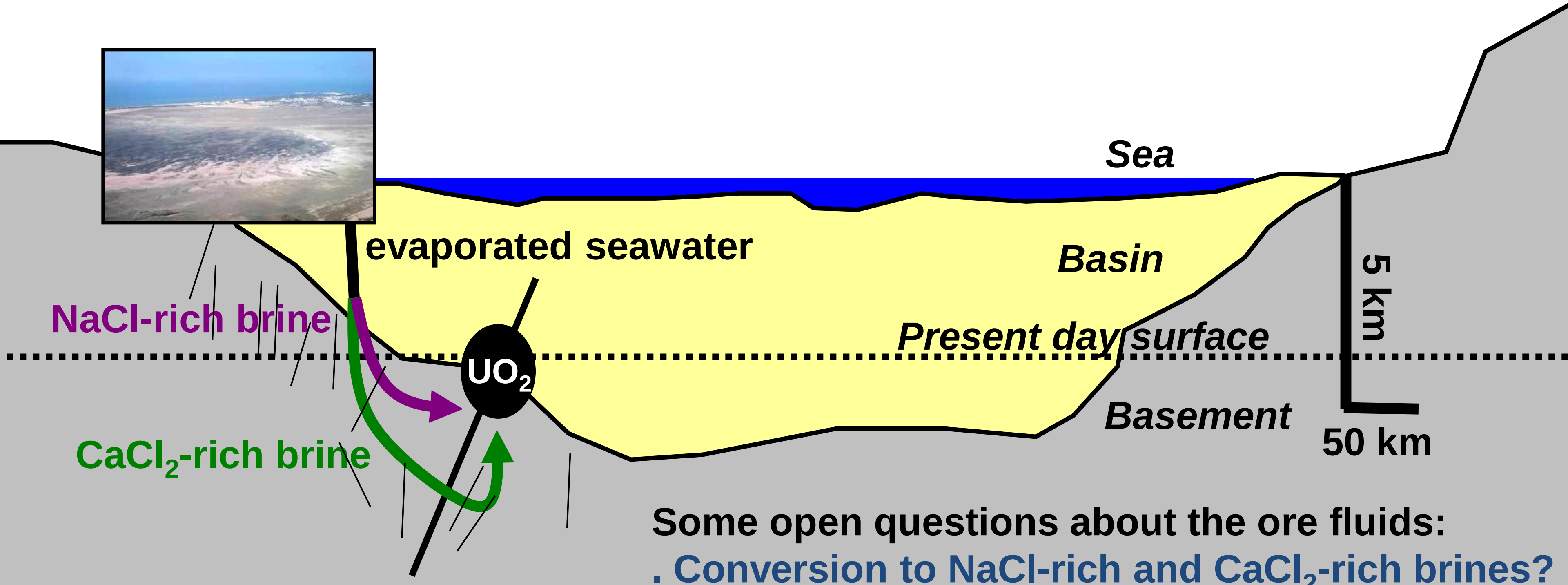


Mercadier et al. (2012) Geology 40, 231–234

. Halogens and B isotopes point to an evaporated seawater origin

Eaux de formation

U discordance



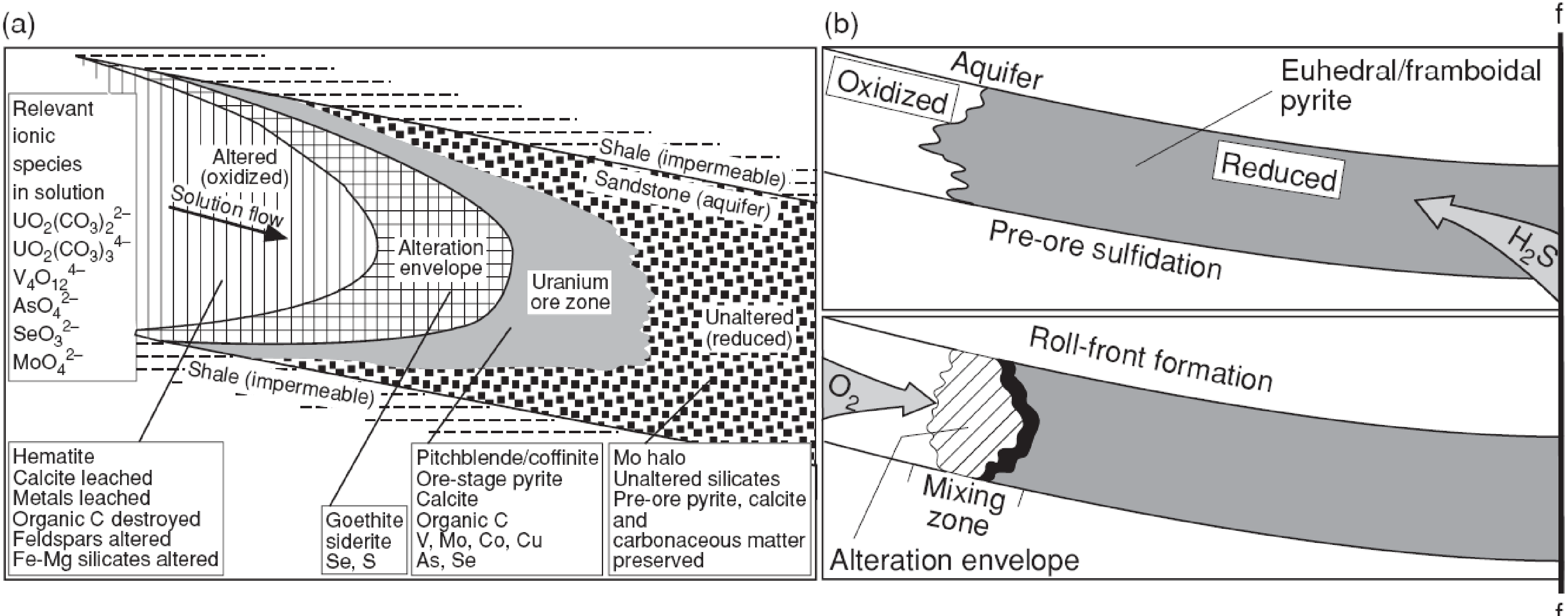
Some open questions about the ore fluids:

- . Conversion to NaCl-rich and $CaCl_2$-rich brines?
- . Why alteration + rock-buffering?
- . Origin of low pH?
- . Impact of brine mixing?
- . Origin of quartz dissolution?
- . Involvement of basement fluid?

Need for new work and new ideas on:
fluid chemistry, fluid-rock interaction, fluid dynamics and pathways!

Eaux de formation

U roll-front

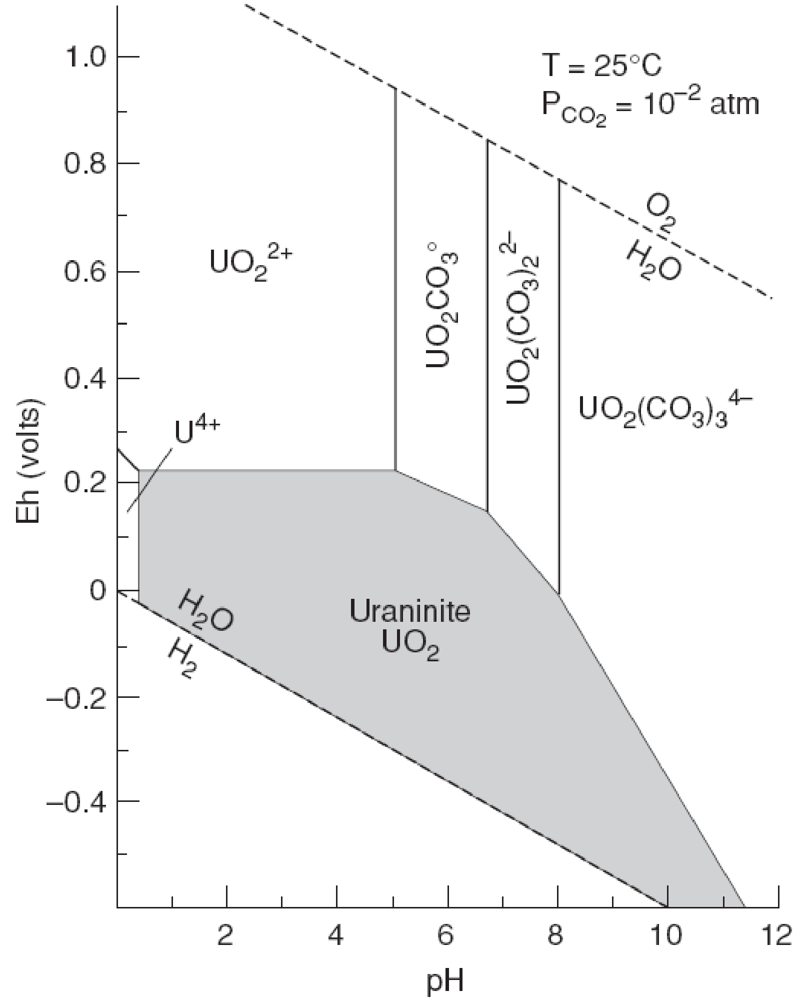


(a) Cross section through a typical roll front type sandstone-hosted uranium deposit, such as those in Wyoming, South Dakota, and south Texas. Uranium mineralization occurs at the **interface (or redox front) between the altered/oxidized and unaltered/reduced portions of the same aquifer** (after De Voto, 1978; Misra, 2000). **(b)** **A two-fluid mixing model** for roll front deposits. Initially a reduced fluid migrates up a syn-depositional fault (f) and sulfidizes the sandstone (top box). This is followed by down-dip migration of an oxygenated, uranium-bearing meteoric fluid and the precipitation of uranium ore at the redox front formed in the mixing zone (bottom box). This model is after Goldhaber *et al.* (1978).

(Robb, 2005)

Eaux de formation

U roll-front

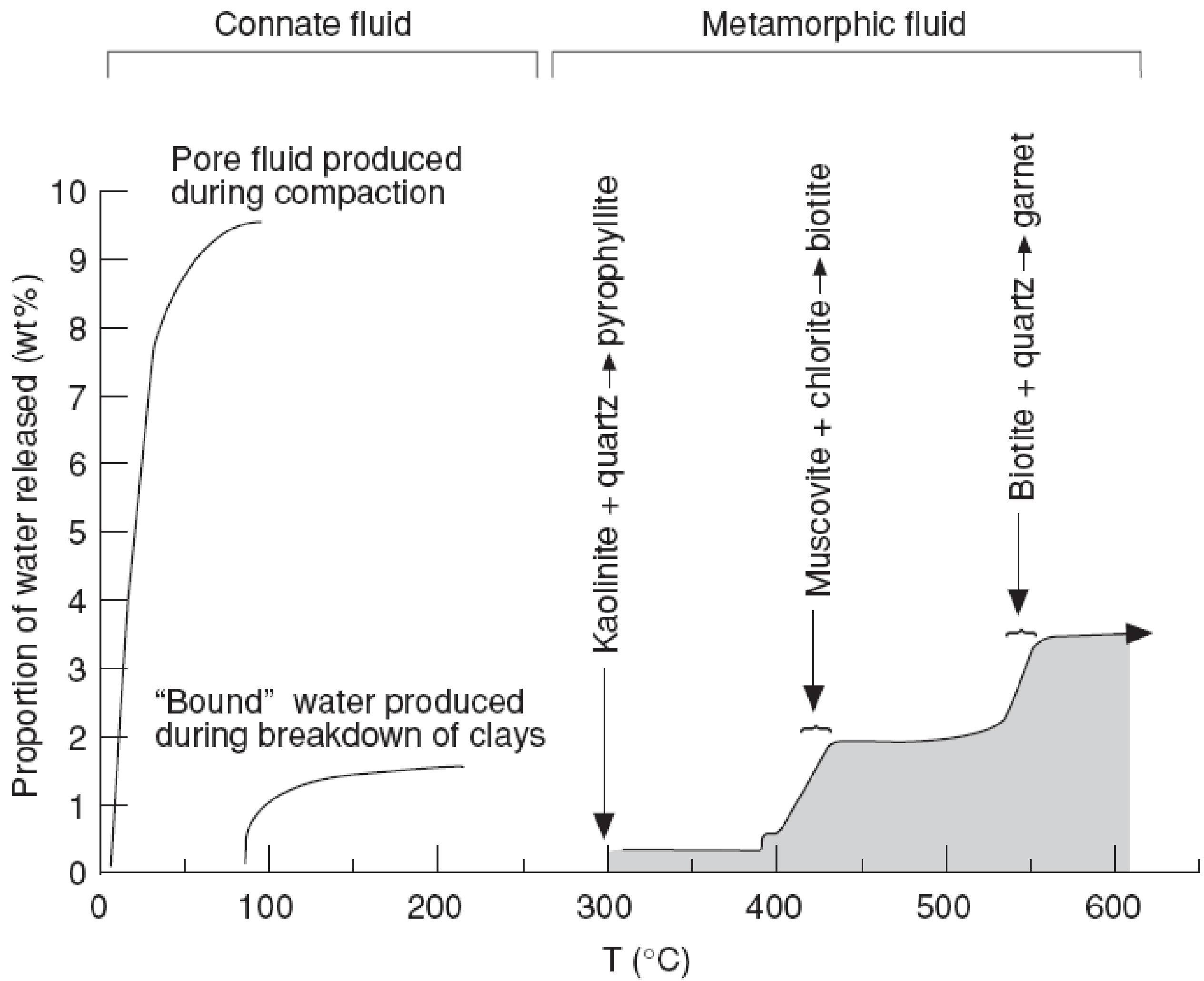


Eh–pH diagram showing relevant aqueous uranium species for the conditions specified. For most **meteoric waters in the near neutral pH range, the dominant aqueous species are likely to be U^{6+}-oxide or -carbonate complexes**. These will be **precipitated** from solution by a reduction of Eh to form **U^{4+}-oxide**, or **uraninite** (after Langmuir, 1978).

(Robb, 2005)

Gisements liés aux fluides métamorphiques

Eaux de formation et fluides métamorphiques



The relationship between connate fluid production during diagenesis and metamorphic fluid production due to **systematic dehydration reactions** involving the breakdown of one mineral assemblage to another containing less water. The conditions pertaining here were calculated specifically for the Witwatersrand Basin (after Stevens *et al.*, 1997).

(Robb, 2005)

Fluides métamorphiques

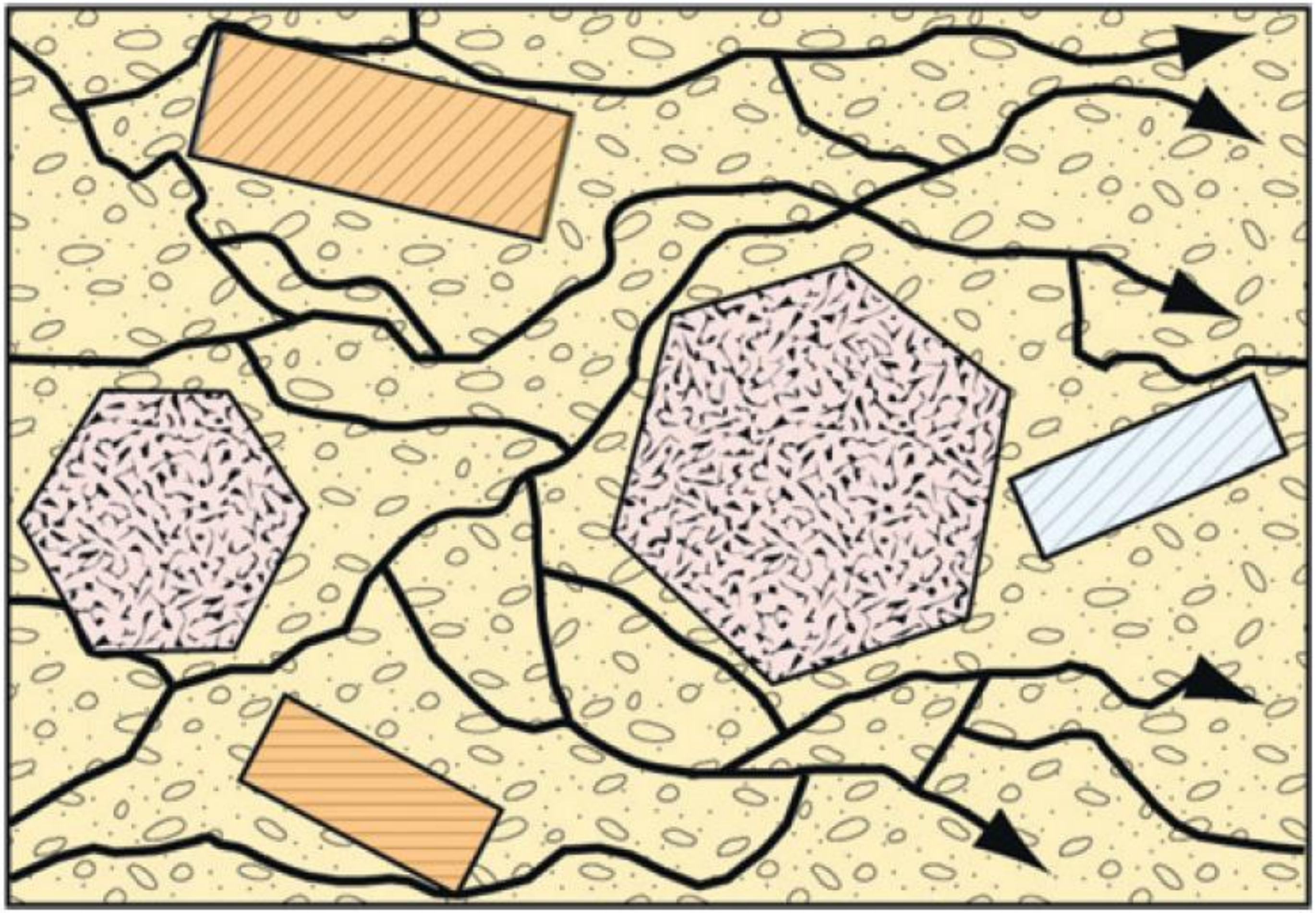


Figure 4 Schematic representation of metamorphic porphyroblasts and matrix illustrating concept of pervasive, grain-scale flow. Flow paths around grains denoted by black arrows.

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Fluides métamorphiques

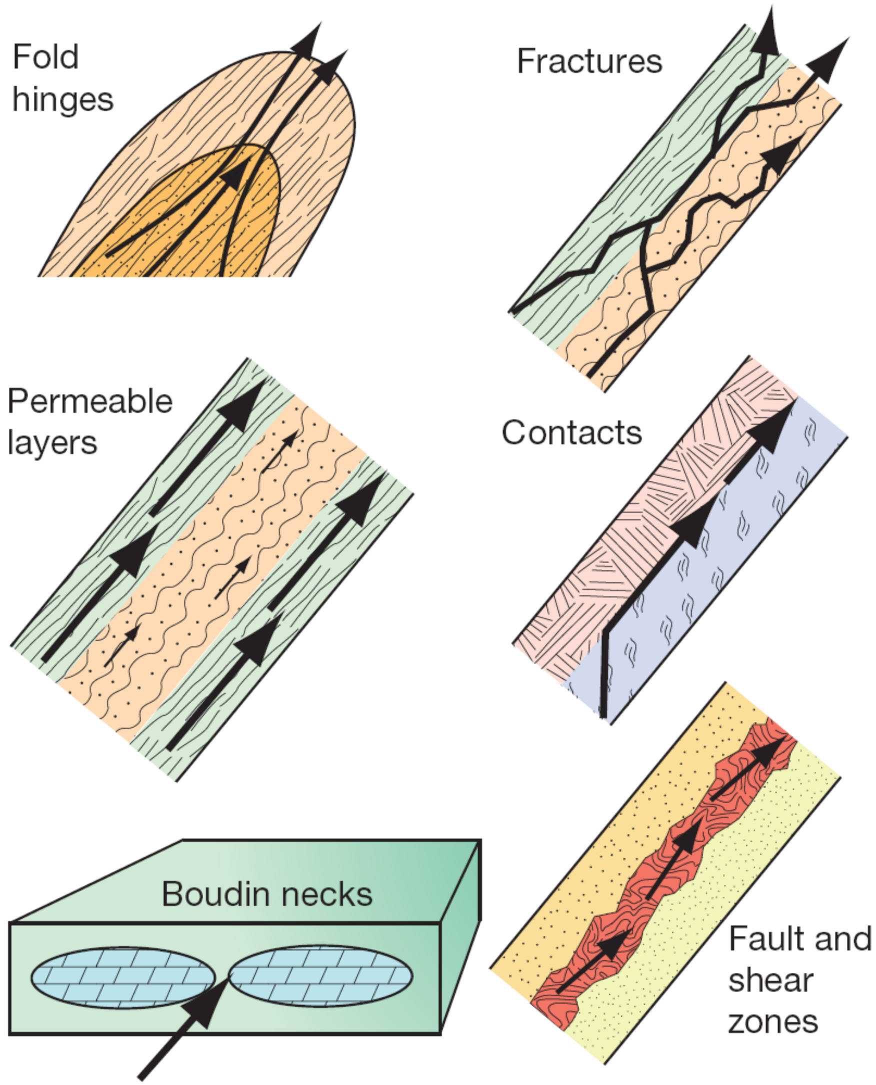

Figure 5 Examples of channelized flow.

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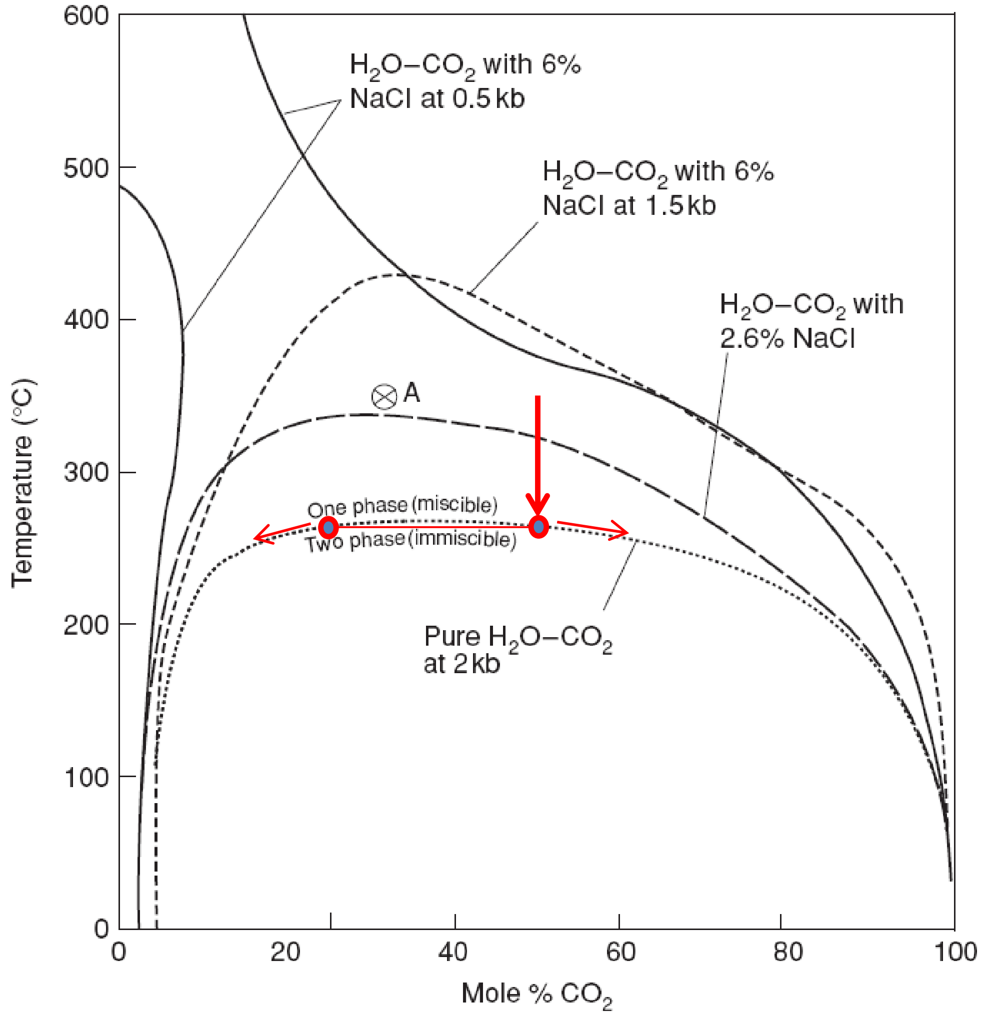
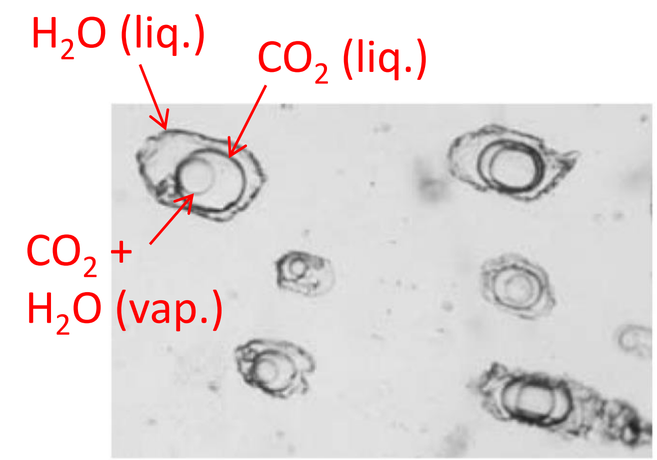
Fluides métamorphiques

Produits des réactions de déshydratation et décarbonatation: fluides à H_2O-CO_2+/-CH_4 +/-NaCl



Démixtions dans le trajet rétrograde



Inclusions fluides à H_2O-CO_2 à T° ambiante.

Various solvus curves for the system H_2O–CO_2; the solvus (i.e. the curve which defines where in P–T–X space H_2O and CO_2 unmix) moves to higher temperatures with decreasing pressure and increasing salinity of the mixture (compilations after Brown, 1998).

(Robb, 2005)

Fluides métamorphiques

Produits des réactions de dissolution des évaporites: fluides à H2O-NaCl

séquences ***sans*** *évaporite*

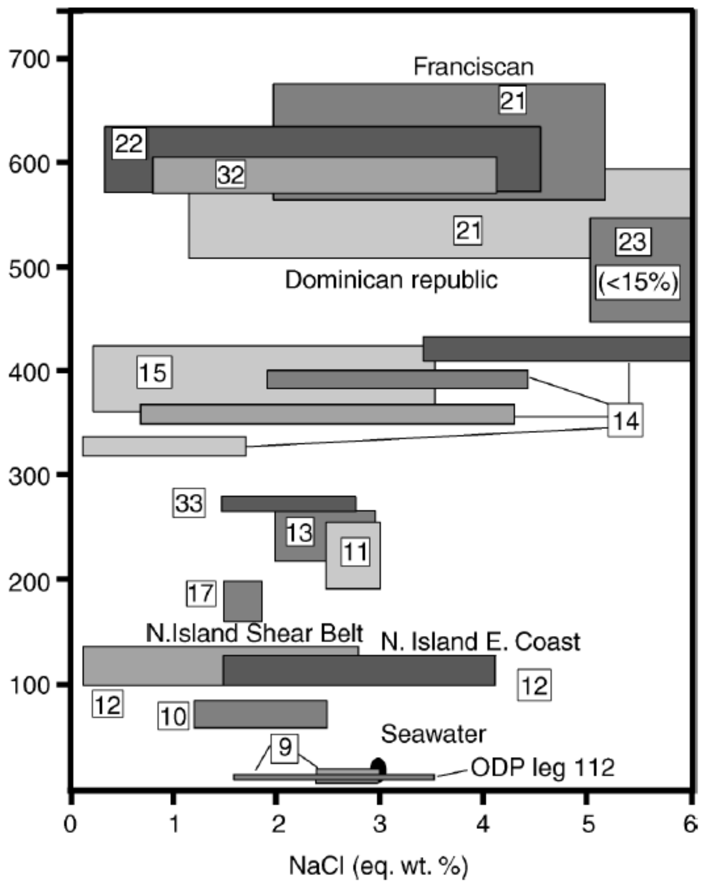


Fig. 1. Temperature–salinity plot for formation waters, spring waters and metamorphic fluids hosted by sequences of oceanic or accretionary prism origin. Boxes reflect the range of data from each of the numbered sources detailed in Table 1. Note the different horizontal scale to that of Fig. 2.

séquences **avec** évaporites

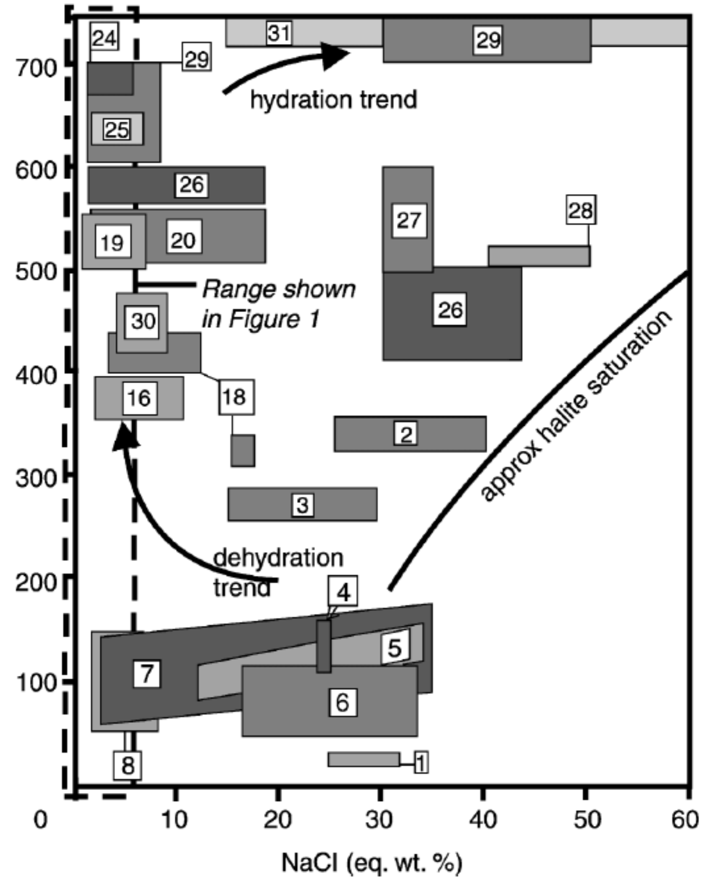
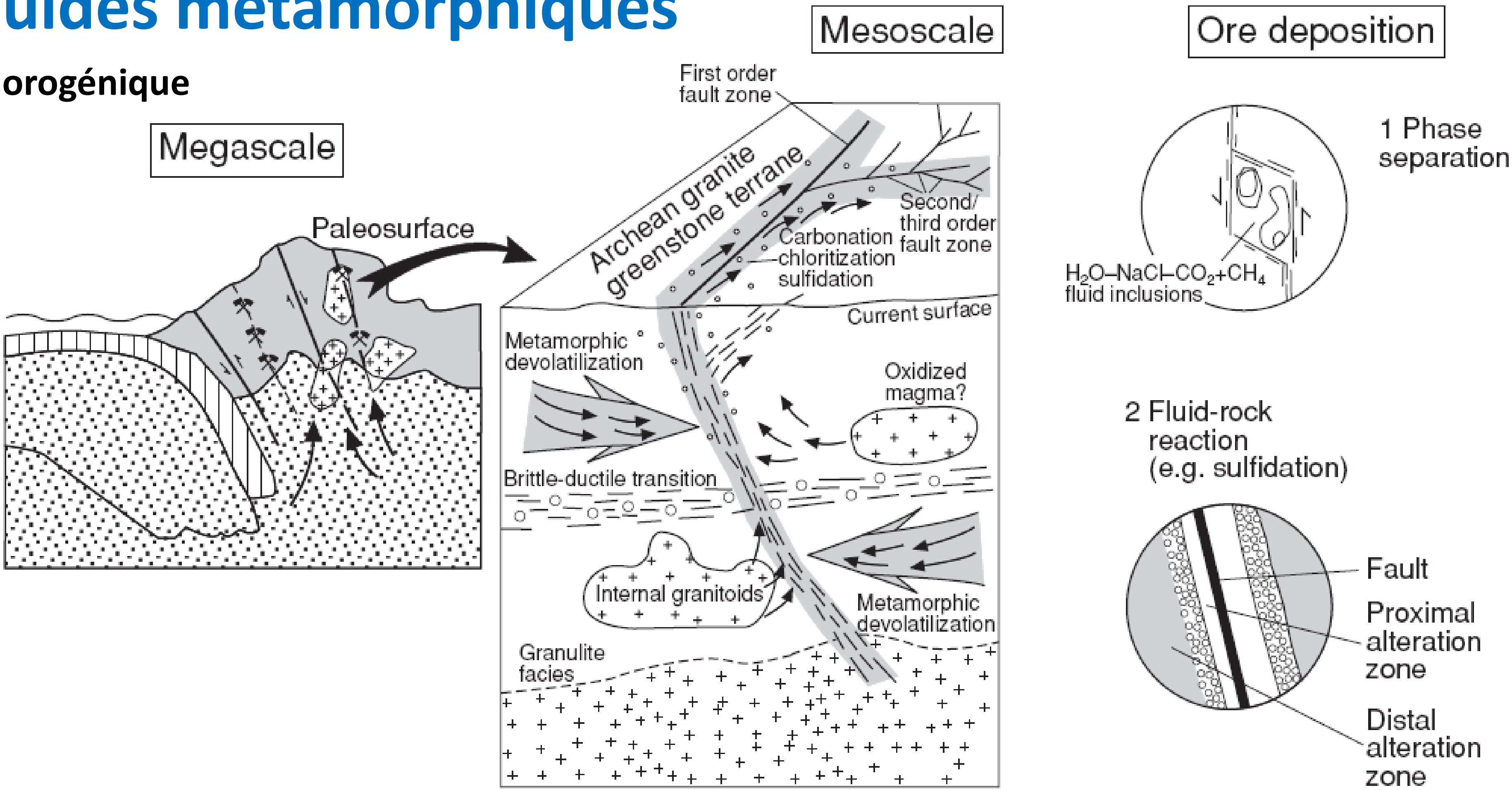


Fig. 2. Temperature–salinity plot for formation waters and metamorphic fluids hosted by sequences deposited in shallow seas and at continental margins. Boxes reflect the range of data from each of the numbered sources detailed in Table 1. The dashed box encloses the more restricted range of conditions plotted in Fig. 1.

(Yardley and Graham, 2002)

Fluides métamorphiques

Or orogénique



Schematic illustrations showing the principal features of Archean orogenic gold deposits – many of which also apply to Proterozoic and Phanerozoic examples. The main features at a megascale are that the deposits are associated with a **convergent plate margin** where metamorphism results in the production of fluids that are focused **along major structural discontinuities**. At a mesoscale **major shear zones** within or along the margins of **greenstone belts** represent district-scale hosts to mineralization that are accompanied by broad zones of **intense alteration**. Individual deposits occur along second- and third-order structures. **Ore deposition is a function of fluid rock reaction and/or H_2O–CO_2 phase separation** (after Hagemann and Cassidy, 2000). *(Robb, 2005)*

Fluides métamorphiques

Mélanges avec fluides météoriques: gisements d'Au orogéniques hercyniens

Mixing of metamorphic and surficial fluids during the uplift of the Hercynian upper crust: consequences for gold deposition

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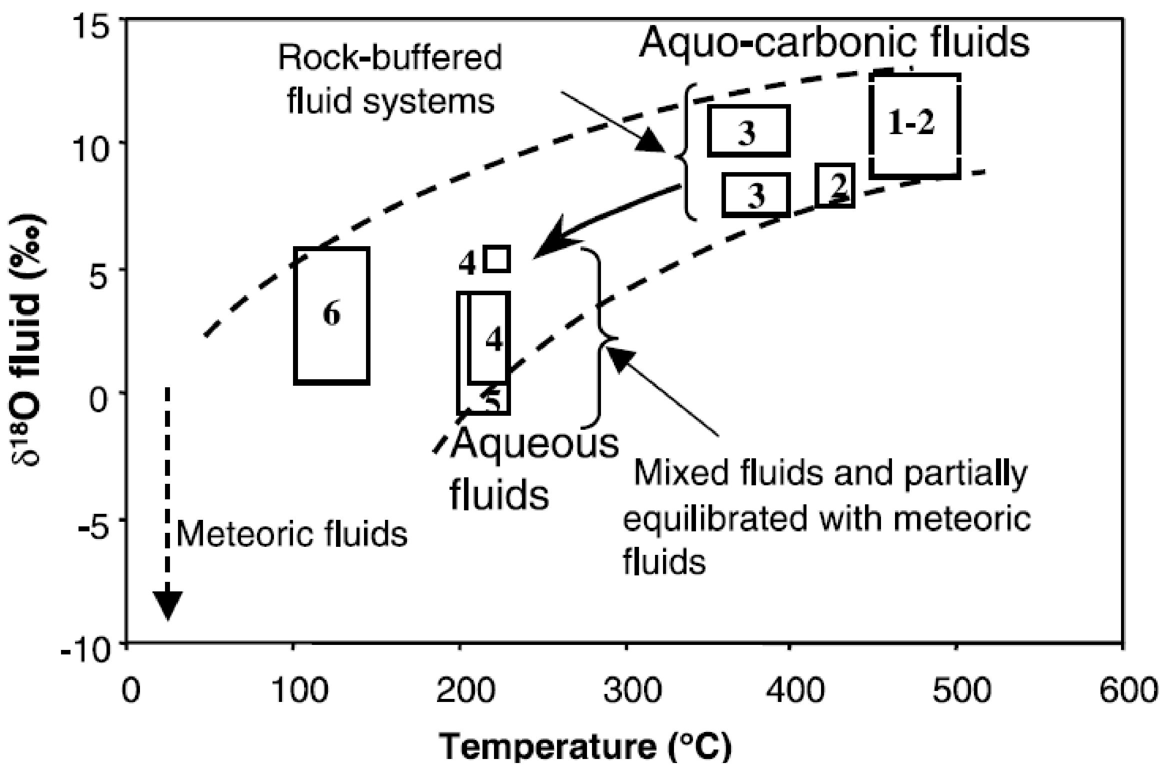
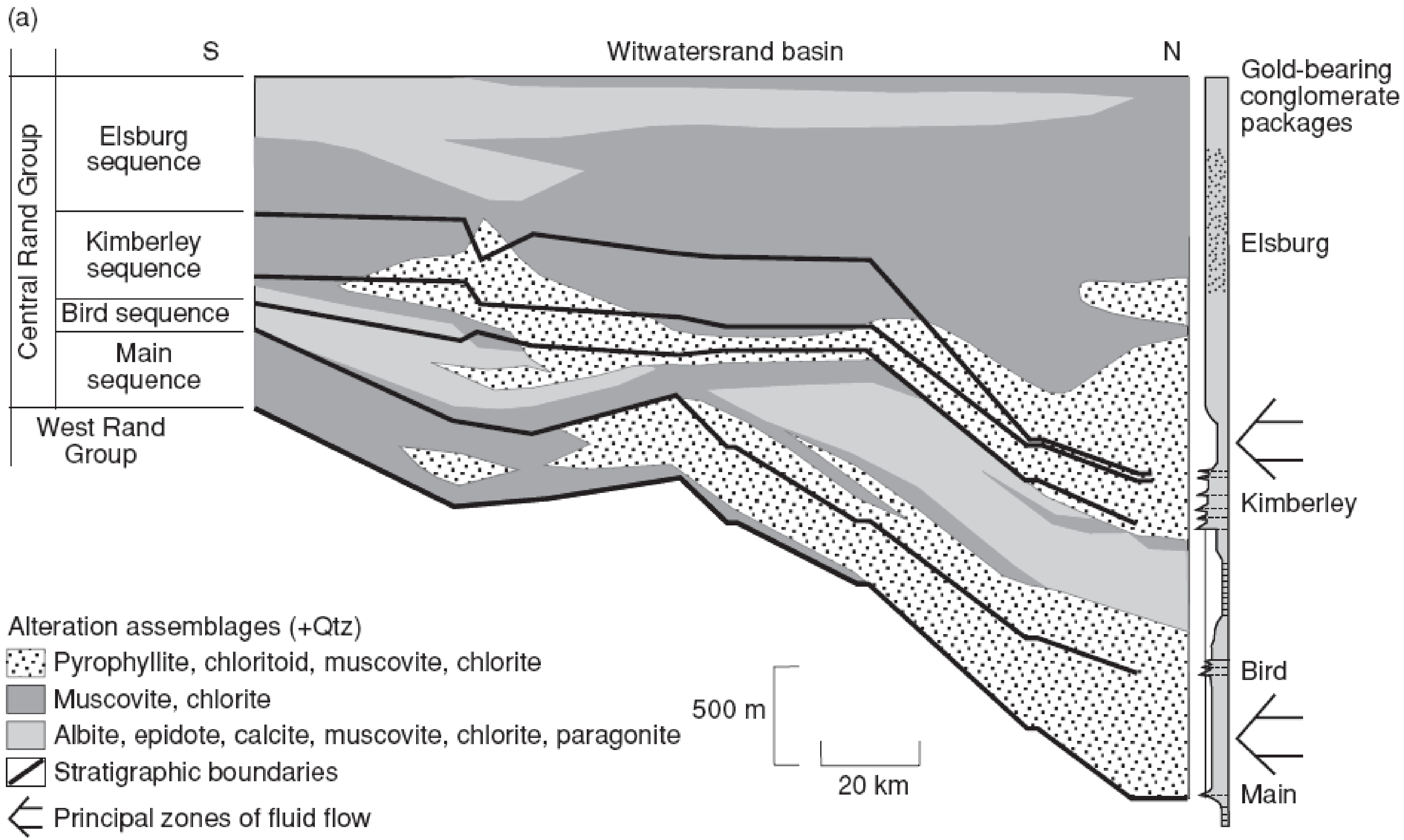


Fig. 8. Diagram showing the fields of $\delta^{18}O$ values (calculated from quartz isotopic data) and measured temperatures (fluid inclusions studies) for the successive stages of quartz growth and reequilibration identified in the gold-bearing quartz veins from the French Massif Central. (1) Milky quartz, (2) micro-crystalline quartz, (3) hyaline quartz, (4) clear quartz, (5) quartz–arsenopyrite, (6) late barren quartz (see Table 5).

Fluides métamorphiques

Or dans paléoplacers modifiés (ex: Wits voir « controverses métallogéniques »)



Simplified north–south section showing the pattern of alteration at a regional scale associated with gold-bearing conglomerate packages in the Central Rand Group of the Witwatersrand Basin (after Barnicoat *et al.*, 1997).

(Robb, 2005)