

Utilisation des éléments volatils en exploration minière : méthode d'analyse et exemples d'application

PROJETS CONSOREM

2013-08 et 2014-05

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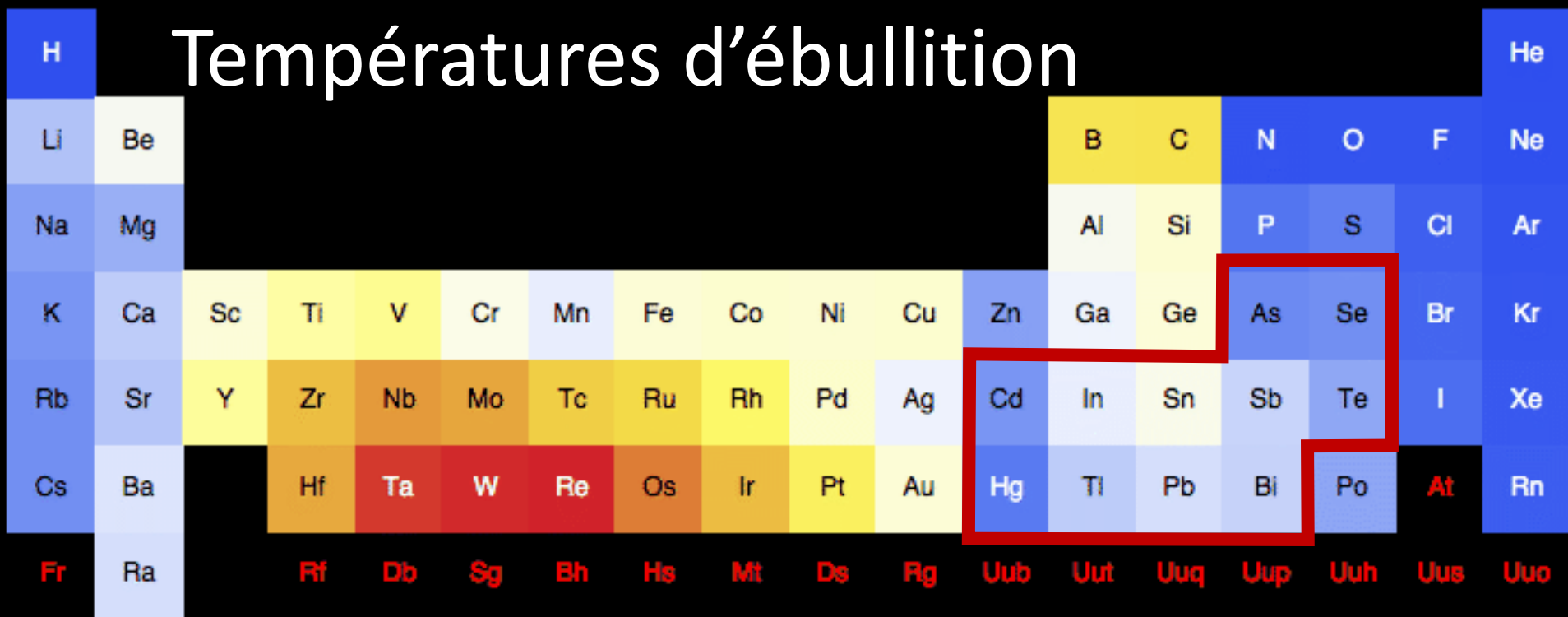


Éléments « volatils »

- Pas des volatils au sens strict du terme
- Volatilité: capacité d'un élément à se vaporiser
- Éléments qui présentent un point d'ébullition relativement bas
- Éléments qui sous certaines conditions vont être dispersés au-delà des zones minéralisées, voire même altérées.
- Éléments indicateurs SMV, SEDEX, Porphyre, Or Orogénique, etc.
- Dispersion dans l'environnement secondaire
- ... mais aussi les plus difficiles à analyser

| | | | | |
|---------------------|----------------------|-----------------------|----------------------|-----------------------|
| 30 Zn Zinc | 31 Ga Gallium | 32 Ge Germanium | 33 As Arsenic | 34 Se Selenium |
| 48 Cd Cadmium | 49 In Indium | 50 Sn Tin | 51 Sb Antimony | 52 Te Tellurium |
| 80 Hg Mercury | 81 Tl Thallium | 82 Pb Lead | 83 Bi Bismuth | 84 Po Polonium |

Températures d'ébullition



Fusion Li-métaborate: 1050°C

Boiling Point (°C)

Periodictable.com

Fusion

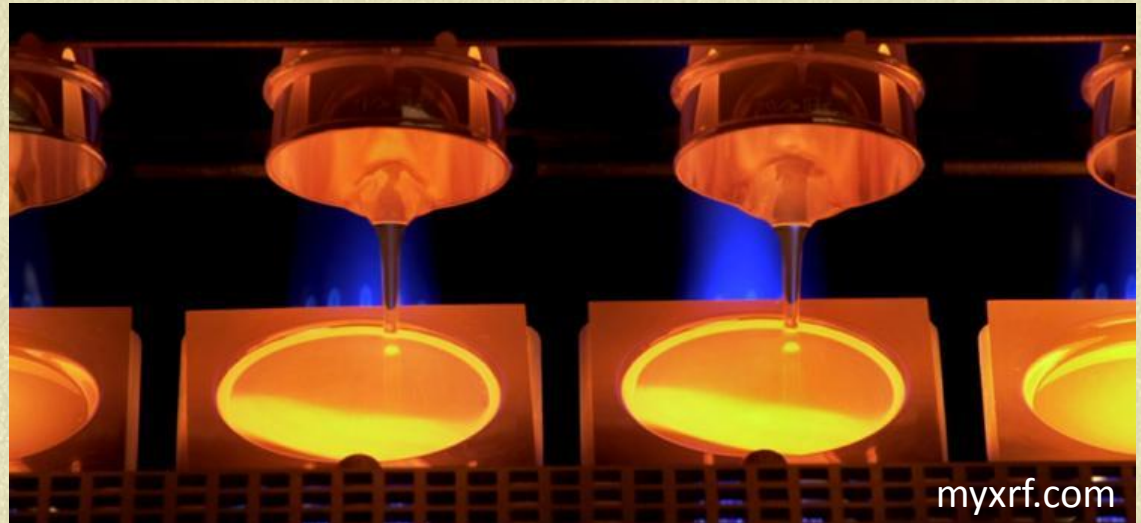
Digestion complète

Li-métaborate

- 1050°C
- Digestion efficace même des minéraux résistants
- Perte des volatils

Na-peroxyde

- 480-650°C
- Méthode pour sulfures et minéraux réfractaires
- REE, Sc, Y, HFSE
- Récupération basse Sn, Sb, Tl



Fusion

Digestion complète

Li-métaborate

- 1050°C
- Digestion efficace même des mx résistants
- Perte des volatils

Na-peroxyde

- 480-650°C
- REE, Sc, Y, HFSE
- Récupération basse Sn, Sb, Tl (50%)

Acides

Digestion partielle

Aqua Regia

- Dissolution partielle
- Sulfures
- Pas de perte de volatils

Exemple Zn:

Sphalérite ✓

Gahnite ✗

Exemple Tl:

Pyrite ✓

Séricite ✗

behr-labor.com



Fusion

Digestion complète

Li-métaborate

- 1050°C
- Digestion efficace même des mx résistants
- Perte des volatils

Na-peroxyde

- 480-650°C
- REE, Sc, Y, HFSE
- Récupération basse Sn, Sb, Tl (50%)

Acides

Digestion partielle

Aqua Regia

- Dissolution partielle
- Sulfures
- Pas de perte de volatils

HF-HClO₄-HNO₃-HCl

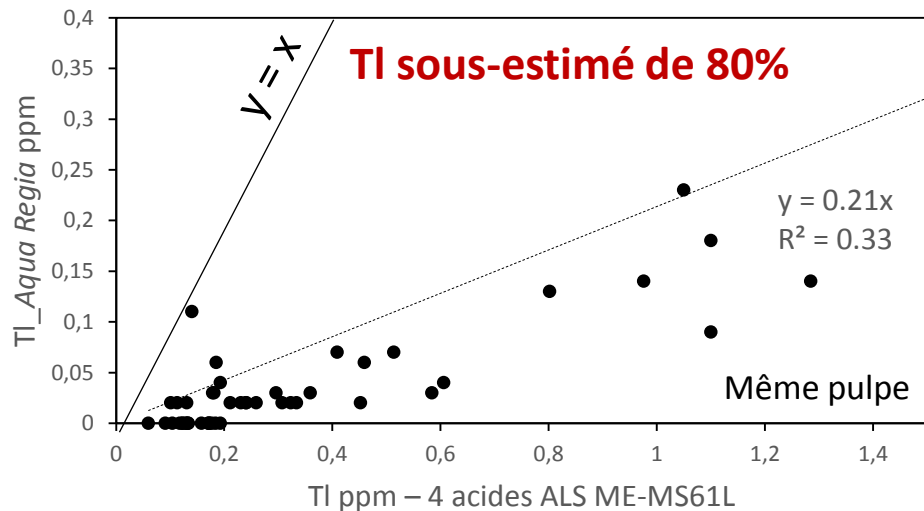
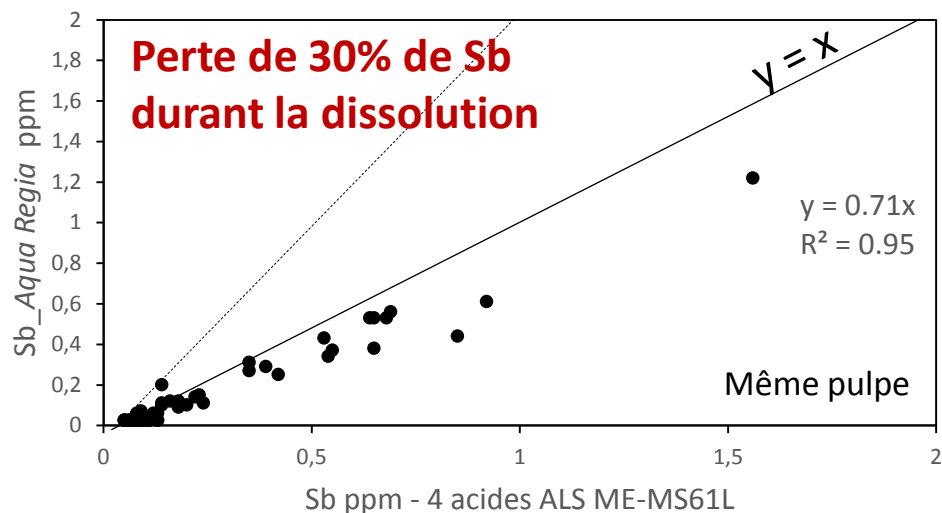
- Dissolution quasi complète
- Problème avec zircon, chromite, barite...
- Perte de certains volatils (F⁻)

Open vessel



Bomb reaction vessel





- Les nouvelles méthodes 4 acides permettent:
 - Conserver les éléments volatils durant le processus de dissolution
 - Abaisser significativement les limites de détection (ppm vs ppb)



- Forfaits multi-méthodes
- INAA, analyses en ppb/ppm, sans mise en solution

Irradiation dans un réacteur nucléaire. Mesure du rayonnement gamma émis.

| | | | | | | | | | | | | | | | | | |
|----|----|-----------------|-----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1 | | | | | | | | | | | | | | | | | 2 |
| H | | | | | | | | | | | | | | | | | He |
| 3 | 4 | | | | | | | | | | | 5 | 6 | 7 | 8 | 9 | 10 |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| 11 | 12 | | | | | | | | | | | 13 | 14 | 15 | 16 | 17 | 18 |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| 55 | 56 | 57 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | 86 |
| Cs | Ba | ¹ La | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| 87 | 88 | 89 | 104 | 105 | | | | | | | | | | | | | |
| Fr | Ra | ² Ac | Rf | Db | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | |
|------------------------------|----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|
| ¹ Lanthanide | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 |
| | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
| ² Actinide series | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 |
| | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lr |

| | |
|--|--|
| | No n-gamma radioactive isotopes |
| | Radioactive isotopes can be produced. Limitation is short half-life or flux energy |
| | Elements routinely determined by INAA ~20\$ |



CONSOREM

Consortium de recherche
en exploration minérale



Actif depuis 2000

Exemple d'application

Le camp minier de Flin Flon

Projet 2013-08

- Comment interpréter la présence d'amas SMV stériles aux premiers stades de l'exploration d'un secteur?

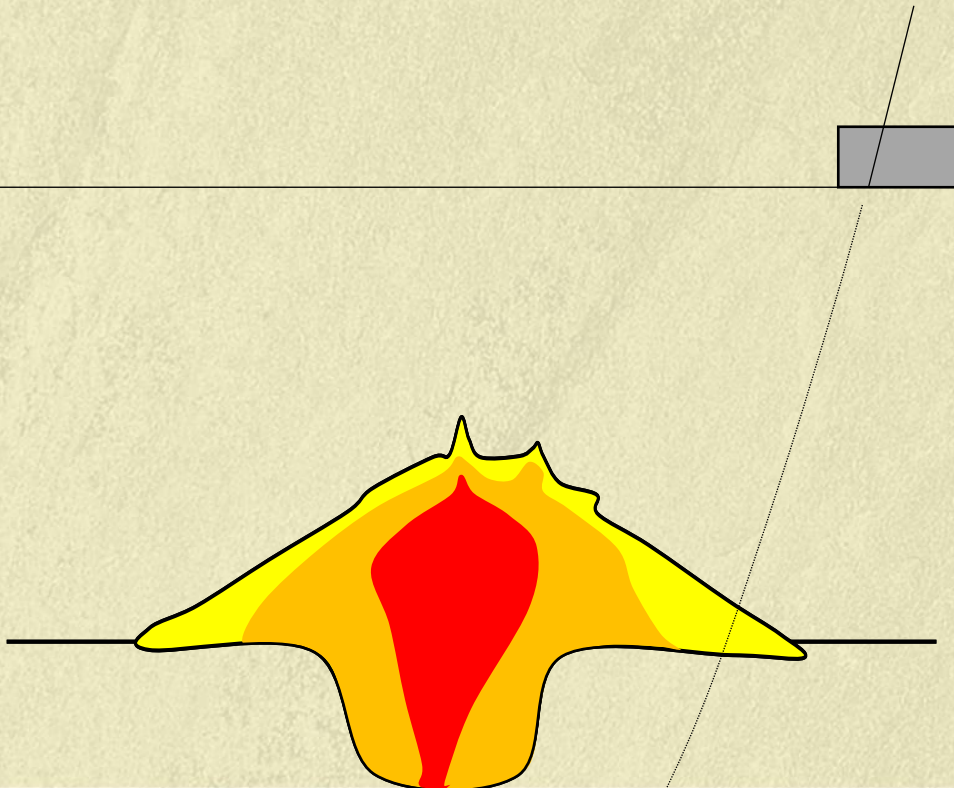


Figure A2.16b. Vamp Lake (Hudvam), diamond drill core CON36, 742 ft. Massive

Approche de la problématique

Qu'est-ce qu'on recherche?

- Des preuves de l'efficacité du système hydrothermal pour le transport des métaux économiques (Cu, Zn)
 - Recherche des éléments qui ont des comportements similaires, mais qui sont peut-être plus « mobiles » (dispersion plus large) et susceptibles d'être fixés dans les sulfures non économiques.

Application Flin Flon, Manito

40 dépôts
Bimodal mafique

Mines
Indices
(manque de volume)

Stériles
(manque de volume et teneurs)

Jonasson et al. 2009



 + VMS deposit (past/present producer),
sampled, not sampled
 • VMS occurrence, sampled, not sampled
 See "Legend.pdf" for geological legend.

Table 1. Summary of deposit and sample locations included in the Flin Flon belt database.

| Location | Status | Easting Nad 83 Zone 14 | Northing Zone 14 | Number of Samples |
|----------|--------|---------------------------|---------------------|----------------------|
|----------|--------|---------------------------|---------------------|----------------------|

Table A1: Flin Flon Area

| | | | | |
|---------------|------------------|--------|---------|----|
| Baker Patton | Occurrence | 332777 | 6071846 | 7 |
| Birch Lake | Past producer | 304312 | 6061329 | 10 |
| Callinan | Present producer | 314247 | 6075256 | 11 |
| Centennial | Past producer | 328322 | 6065079 | 5 |
| Coronation | Past producer | 306399 | 6052750 | 8 |
| Cuprus | Past producer | 325201 | 6067017 | 15 |
| Don Jon | Past producer | 334384 | 6071188 | 1 |
| Flexar | Past producer | 304674 | 6063047 | 14 |
| Flin Flon | Past producer | 314554 | 6072383 | 30 |
| Konuto Lake | Past producer | 302487 | 6061226 | 9 |
| Lakeview | Occurrence | 316402 | 6074096 | 1 |
| Mandy | Past producer | 317656 | 6068060 | 12 |
| North Star | Past producer | 334026 | 6071615 | 7 |
| Pine Bay | Past producer | 331862 | 6071731 | 18 |
| Schist Lake | Past producer | 317995 | 6067167 | 15 |
| Triple 7 | Present producer | 314790 | 6074114 | 8 |
| Trout Lake | Present producer | 319303 | 6078732 | 4 |
| West Arm | Past producer | 317012 | 6058816 | 12 |
| White Lake | Past producer | 324921 | 6065046 | 8 |
| Vamp (Hudvam) | Occurrence | 361129 | 6089875 | 8 |

Table A2: Snow Lake

| | | | | |
|-----------------|------------------|--------|---------|----|
| Anderson Lake | Past producer | 436296 | 6079569 | 7 |
| Chisel Lake | Past producer | 427947 | 6076770 | 5 |
| Chisel North | Present producer | 428353 | 6077865 | 19 |
| Ghost/Lost Lake | Past producer | 428545 | 6076599 | 13 |
| Osborne Lake | Past producer | 453599 | 6090808 | 10 |
| Photo Lake Mine | Past producer | 429534 | 6080154 | 13 |
| Rod No. 1 | Past producer | 441002 | 6078983 | 9 |
| Stall Lake | Past producer | 439455 | 6078749 | 9 |

Table A3: Subphanerozoic

| | | | | |
|-------------------------|------------|--------|---------|---|
| Archibald | Occurrence | 296179 | 6005951 | 9 |
| Fenton | Occurrence | 476962 | 6028306 | 6 |
| Harmin | Occurrence | 480087 | 6029232 | 6 |
| Hobbs Lake | Occurrence | 254820 | 6051700 | 4 |
| KOF Zone/ Farewell Lake | Occurrence | 432561 | 6037945 | 2 |
| Last Hurrah | Occurrence | 412778 | 6046488 | 4 |
| Limestone Bay | Occurrence | 419718 | 6007294 | 2 |
| Reed Lake Zone | Occurrence | 399904 | 6055620 | 7 |
| Sylvia | Occurrence | 424860 | 6029595 | 9 |

Table A4: Sherridon

| | | | | |
|----------------|---------------|--------|---------|----|
| Sherridon East | Past producer | 367546 | 6109796 | 11 |
| Sherridon West | Past producer | 365531 | 6111976 | 5 |

Table A5: Four Mile

| | | | | |
|--------------|---------------|--------|---------|---|
| Dickstone | Past producer | 404026 | 6079619 | 3 |
| Spruce Point | Past producer | 409446 | 6048716 | 2 |

Jonasson, I.R., Ames, D.E., and Galley, A.G., 2009. Sulphide ore geochemistry database for volcanogenic massive sulphide deposits of the Paleoproterozoic Flin Flon Belt and Sherridon area, Manitoba and Saskatchewan; Geological Survey of Canada, Open File 5432, 1 Cd-ROM.

- 400 analyses de roche totale des zones minéralisées de 40 gisements ou indices
- Sélection de 150 analyses de sulfures massifs (> 90%). Validée par les photos.
- Échantillons ne sont pas représentatifs des dépôts

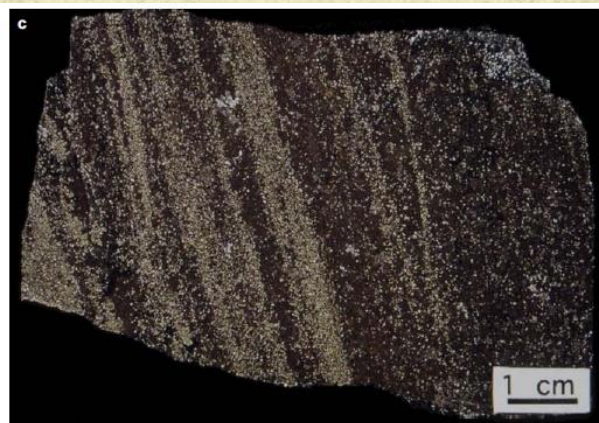


Figure A2.3c. Callinan deposit, 1600 m level, #7 lens. Massive sulphide composed of banded sphalerite/pyrite ore with siderite or ankerite, recrystallized mylonite. Sample 00GIA-CALL-531.1A3.

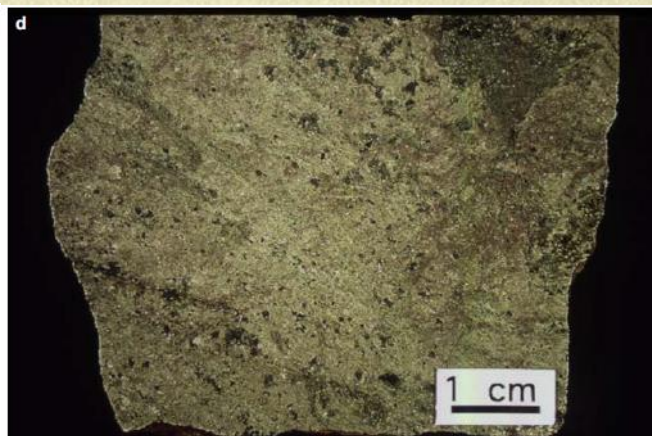


Figure A2.5d. Coronation deposit. Massive pyrrhotite/chalcopyrite/magnetite catclasite. Sample 00GIA-CRON-529D.

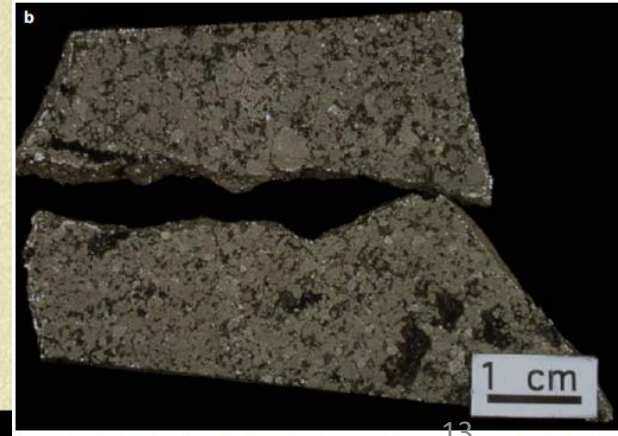


Figure A2.16b. Vamp Lake (Hudvam), diamond drill core CON36, 742 ft. Massive sphalerite/chalcopyrite buckshot pyrite; recrystallized pyrite/chlorite. Sample 00GIA-VAMP-554D.

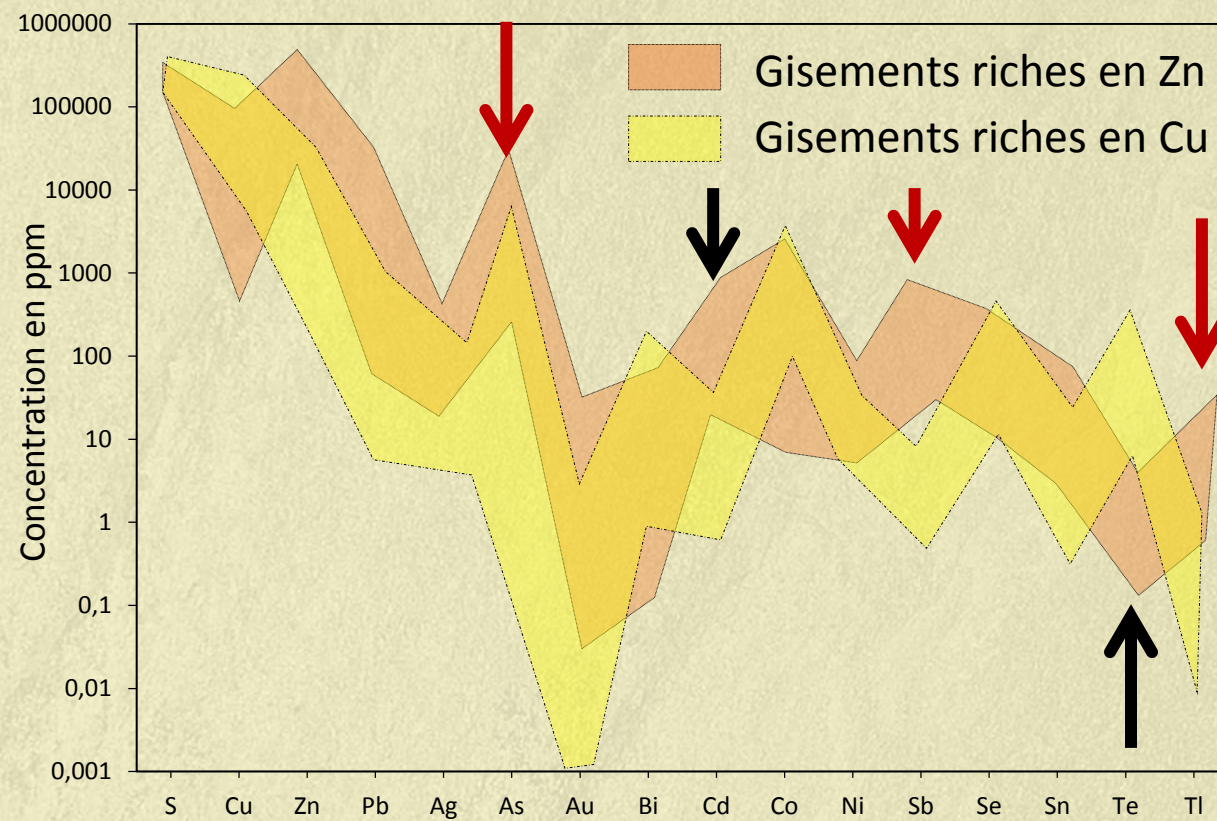


- 60 éléments analysés
- Méthodes d'analyses:
 - ICP-AES (majeurs) – Fusion Li-tétraborate
 - ICP-MS (mineurs et traces) – 4 acides
 - INAA (As, Au, Hg, Se)
 - S et CO₂

Table 2. Geochemistry methodology, source, and detection limits.

| Element | Method.Lab | Detection Limit |
|--------------------------------|---------------|-----------------|
| | | (%) |
| SiO ₂ | ICP. GSC | 0.5 |
| TiO ₂ | ICP. GSC | 0.02 |
| Al ₂ O ₃ | ICP. GSC | 0.2 |
| Fe _T | ICP. GSC | 0.04 |
| MgO | ICP. GSC | 0.04 |
| CaO | ICP. GSC | 0.01 |
| Na ₂ O | ICP. GSC | 0.03 |
| K ₂ O | ICP. GSC | 0.05 |
| Cu | ICP. GSC | 0.001 |
| Zn | ICP. GSC | 0.001 |
| Pb | ICP. GSC | 0.001 |
| Mn | ICP. GSC | 0.001 |
| CO _{2,T} | chemistry.GSC | 0.1 |
| P ₂ O ₅ | ICP. GSC | 0.01 |
| S _T | chemistry.GSC | 0.02 |
| Total | calculated | - |
| LOI | chemistry.GSC | - |

| | | |
|------------------|----------------|-------|
| Ag (ppm) | ICP. GSC | 0.5 |
| As | INAA. Act labs | 0.5 |
| Au (ppb) | INAA. Act labs | 5 ppb |
| Ba (ppm) | ICP. GSC | 20 |
| Bi | ICP. GSC | 0.2 |
| Cd | ICP. GSC | 0.2 |
| Co | ICP. GSC | 5 |
| Cr | ICP. GSC | 10 |
| Cs | ICP. GSC | 0.02 |
| Ga | ICP. GSC | 0.1 |
| Hf | ICP. GSC | 0.05 |
| Hg | INAA. Act labs | 1 |
| In | ICP. GSC | 0.05 |
| Mo | ICP. GSC | 0.2 |
| Nb | ICP. GSC | 0.05 |
| Ni | ICP. GSC | 10 |
| Rb | ICP. GSC | 0.05 |
| Sb | ICP. GSC | 1 |
| Sc | ICP. GSC | 0.5 |
| Se | INAA. Act labs | 3 |
| Sn | ICP. GSC | 0.5 |
| Sr | ICP. GSC | 10 |
| Ta | ICP. GSC | 0.05 |
| Te | ICP. GSC | 0.2 |
| Th | ICP. GSC | 0.02 |
| Tl | ICP. GSC | 0.02 |
| U | ICP. GSC | 0.02 |
| V | ICP. GSC | 5 |
| Y | ICP. GSC | 0.1 |
| Zr | ICP. GSC | 0.5 |
| La (ppm) | ICP. GSC | 0.1 |
| Ce | ICP. GSC | 0.1 |
| Pr | ICP. GSC | 0.02 |
| Nd | ICP. GSC | 0.1 |
| Sm | ICP. GSC | 0.02 |
| Eu | ICP. GSC | 0.02 |
| Gd | ICP. GSC | 0.02 |
| Tb | ICP. GSC | 0.02 |
| Dy | ICP. GSC | 0.02 |
| Ho | ICP. GSC | 0.02 |
| Er | ICP. GSC | 0.02 |
| Tm | ICP. GSC | 0.02 |
| Yb | ICP. GSC | 0.02 |
| Lu | ICP. GSC | 0.02 |
| REE _T | calculated | - |



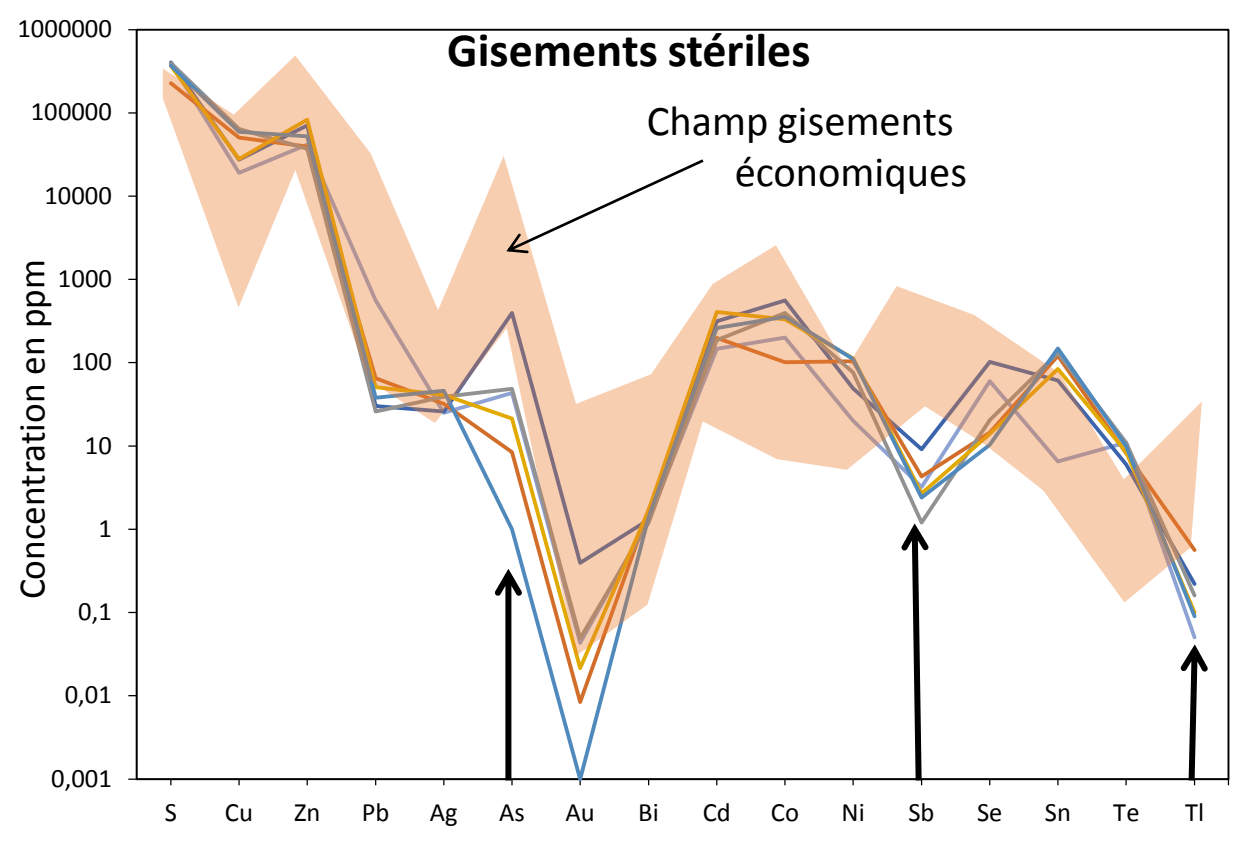
Pourquoi ces éléments?

Éléments présents en traces dans les pyrites des systèmes SMV

Ordre des éléments?

Basé sur le numéro atomique

Gisements économiques (mines) Flin Flon



Amas
Stériles
Flin Flon

Teneur en Zn

Vamp Lake
Hudvam

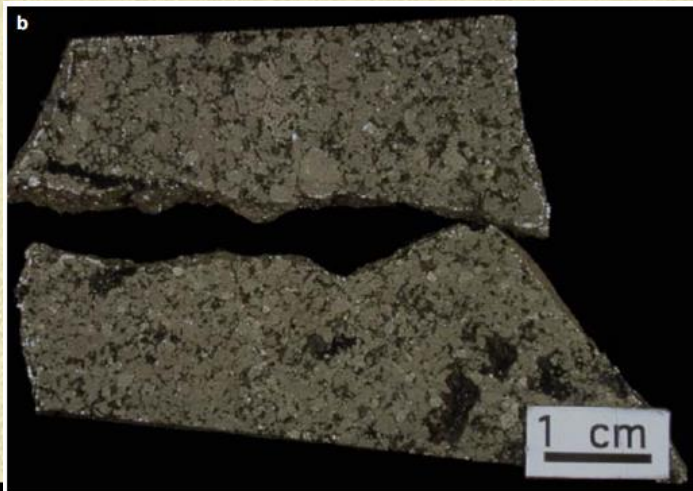
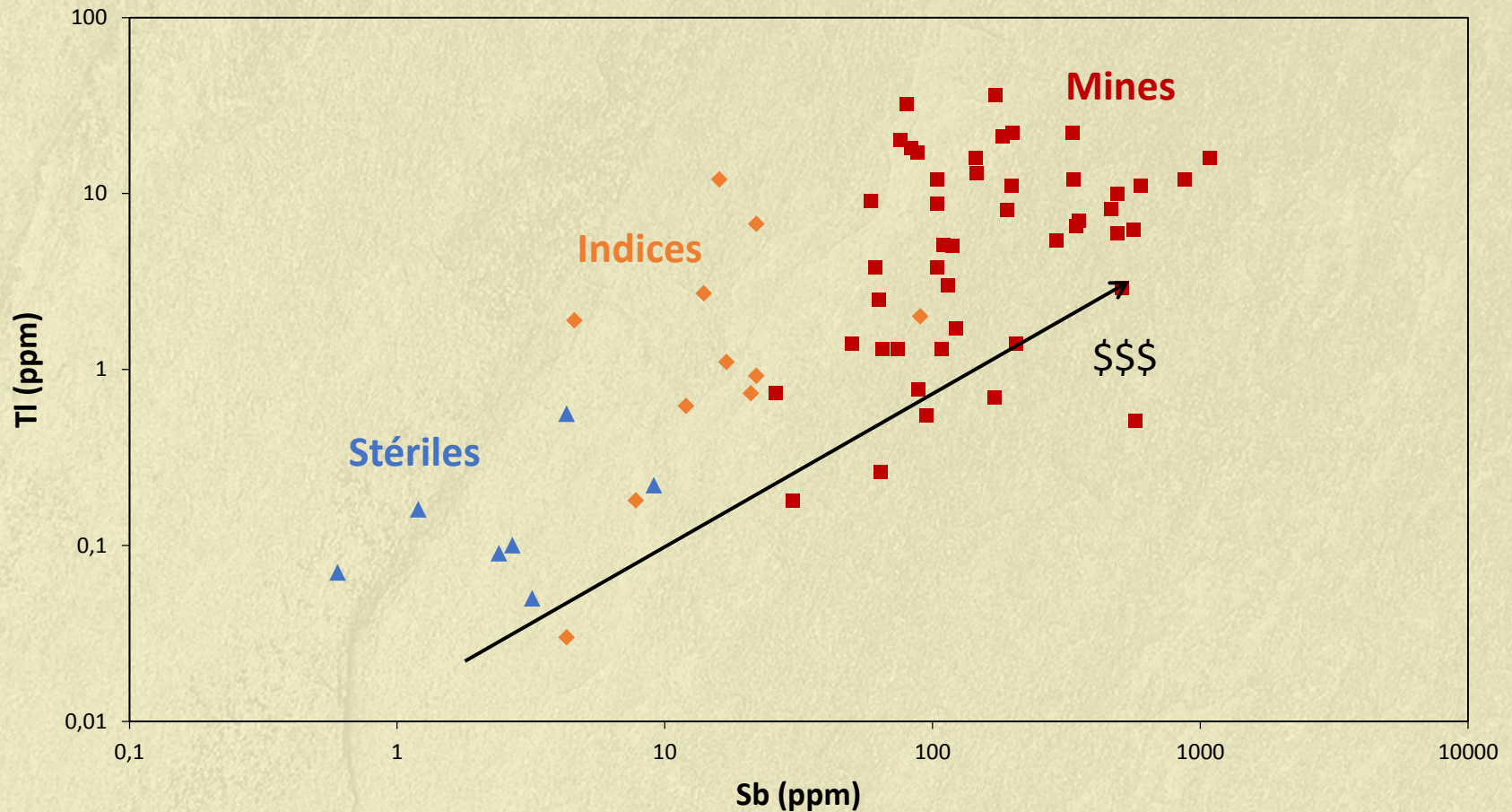
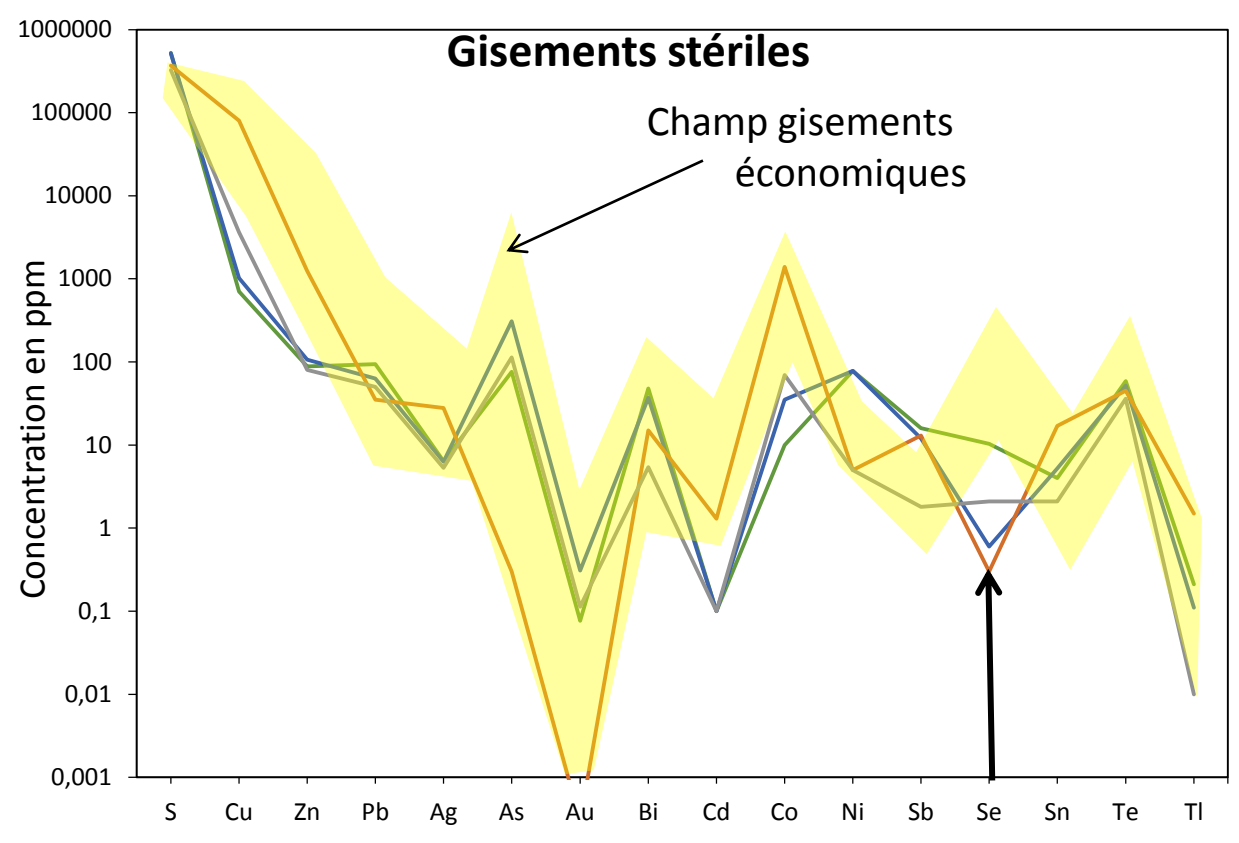


Figure A2.16b. Vamp Lake (Hudvam), diamond drill core CON36, 742 ft. Massive

Flin Flon – affinité zincifère





Amas
Stériles
Flin Flon

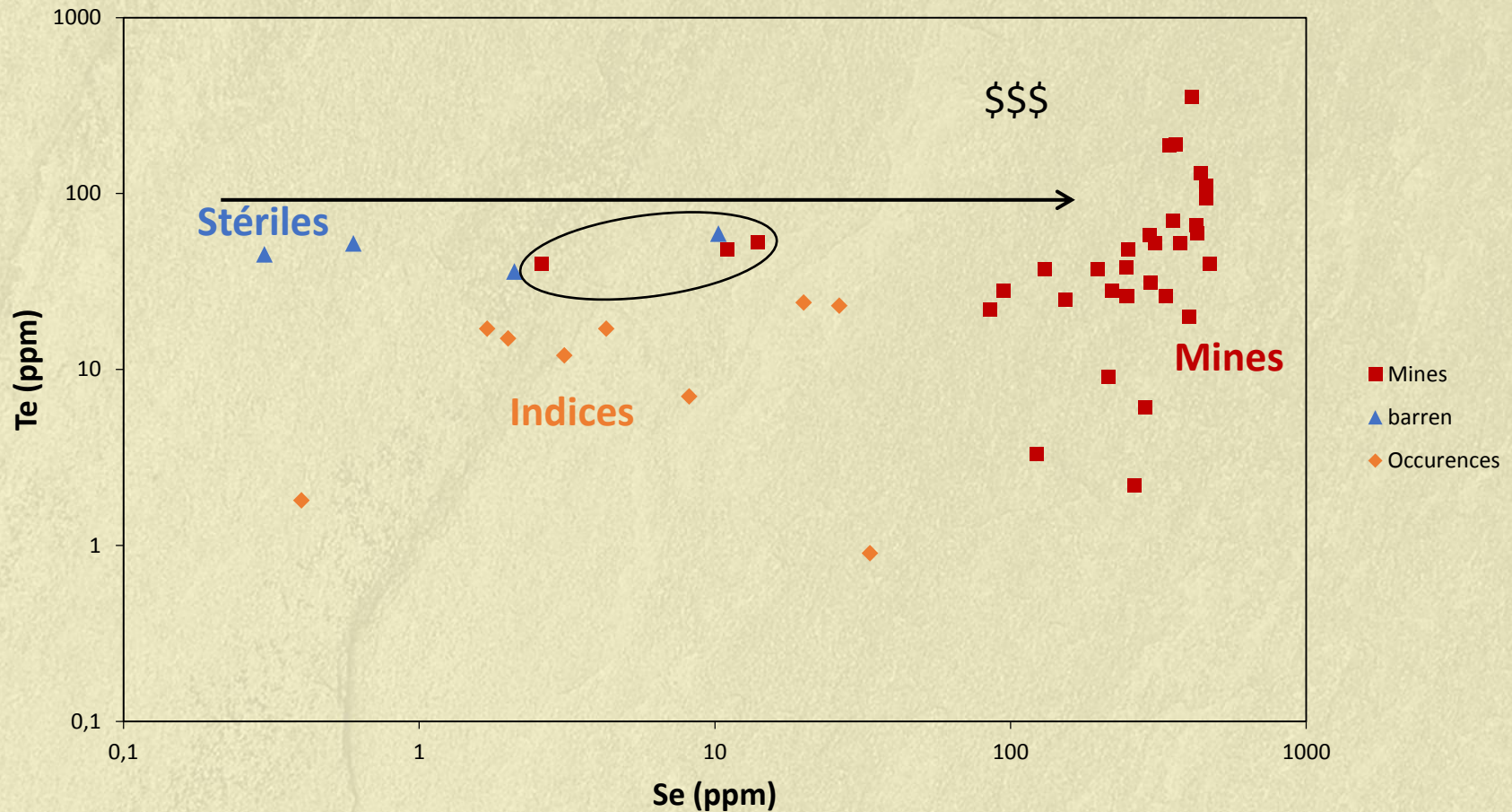
Teneur en Cu

Baker Patton
Sylvia
Reed Lake



Figure A2.1a. Baker Patton Cu deposit, surface trench sample. Very oxidized, pyrite-rich massive sulphide. Sample 06AV-501.

Flin Flon – affinité cuprifère



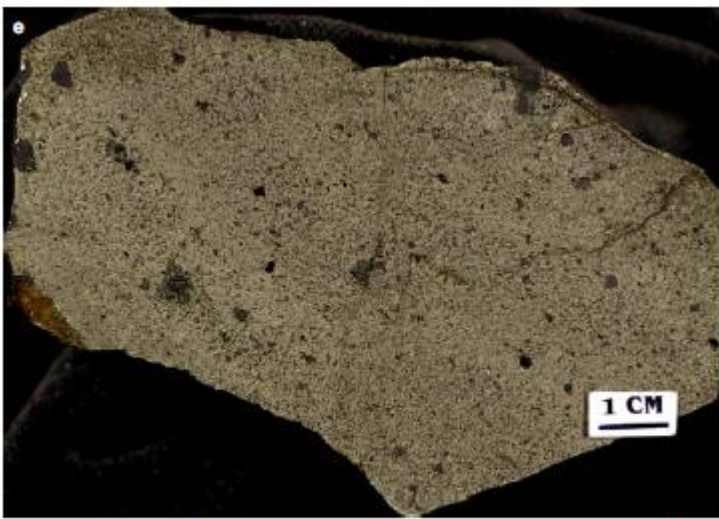


Figure A2.2e. Birch Lake deposit. Fine-grained massive pyrite-chalcopyrite massive sulphide. Sample 06AV-523.

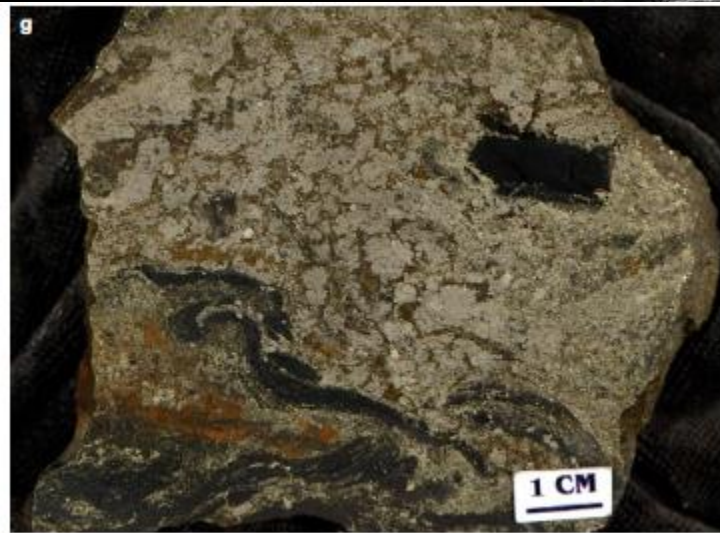


Figure A2.2g. Birch Lake deposit. Fine-grained pyrite-chalcopyrite massive ore with ~10% <1 cm diameter rock fragments. Sample 06AV-527.

Actif depuis 2000

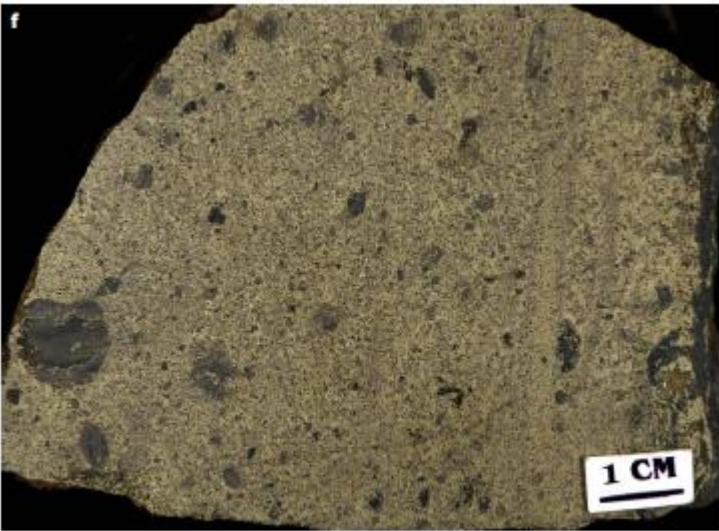


Figure A2.2f. Birch Lake deposit. Fine-grained chalcopyrite-pyrite ore with rounded fragments of wallrock. Sample 06AV-524.

Birch Lake deposit 1957-1960

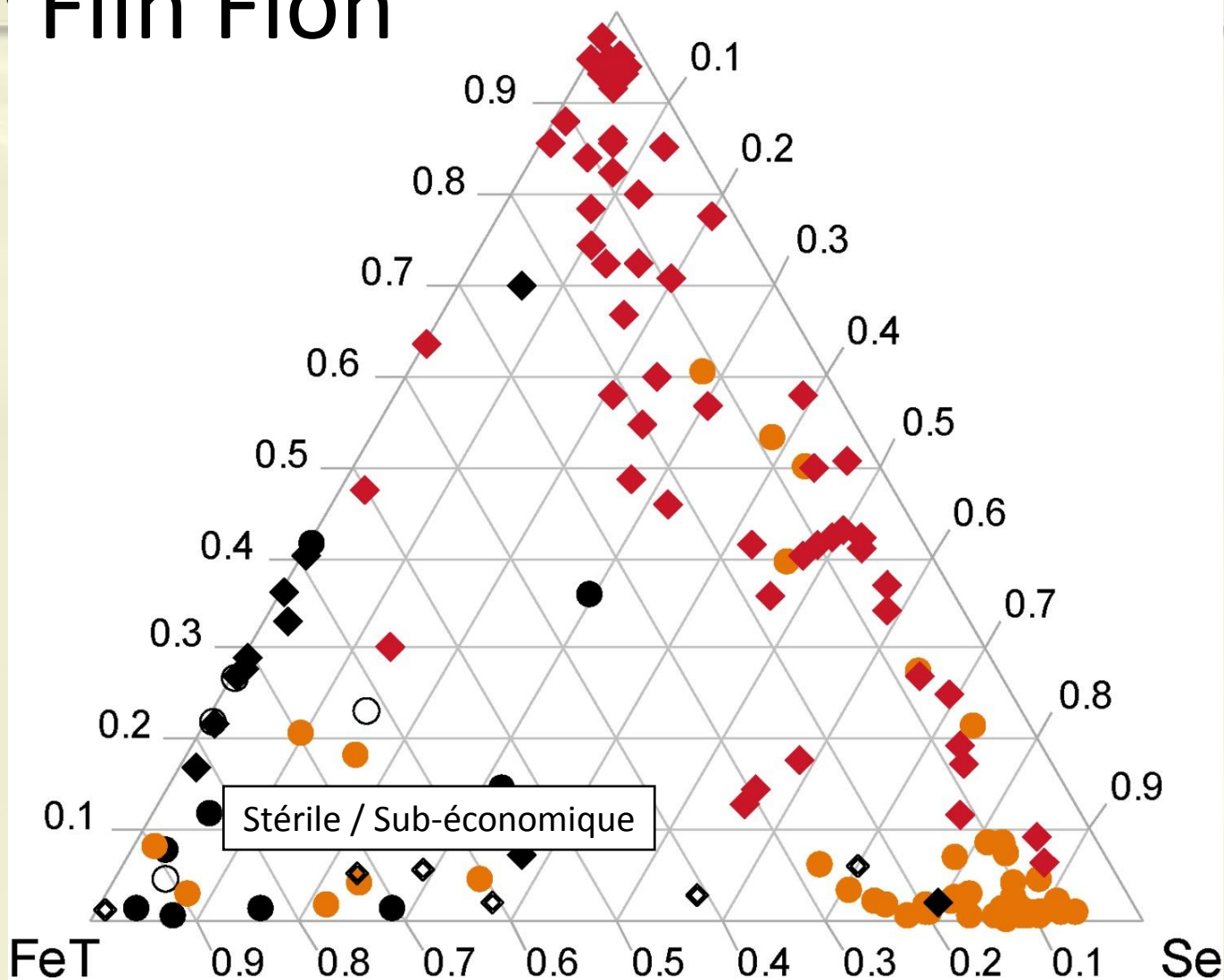
< 300 000 t

@ 4.11 ppm Ag, 6.21% Cu, tr Zn

- Pyrite fortement dominante

Flin Flon

Sb ou Tl



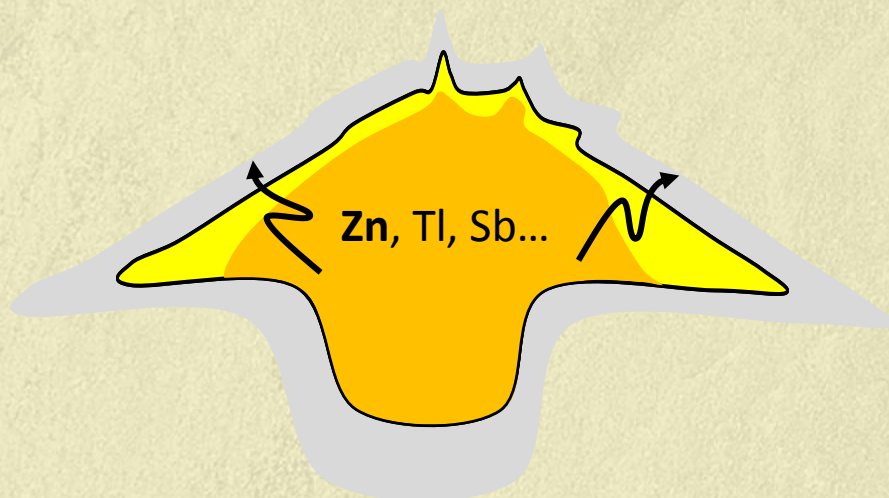
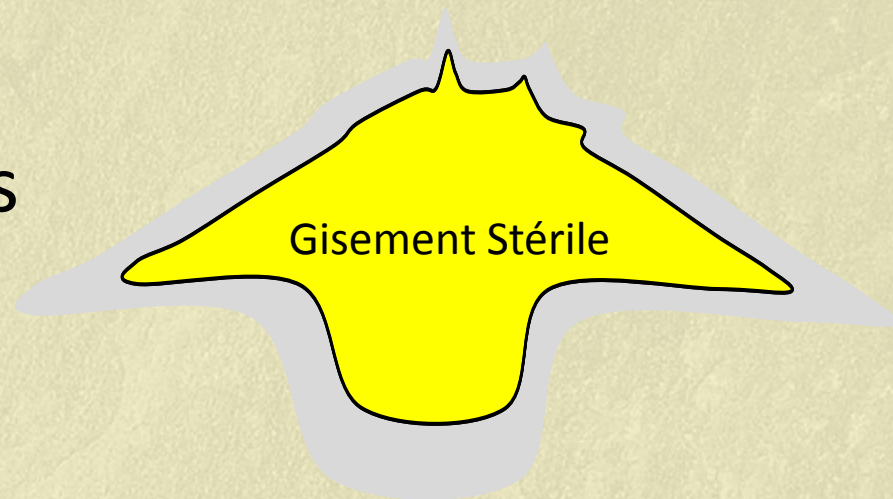
Indices et gisements stériles

- ◆ affinité zincifère
- affinité cuprifère

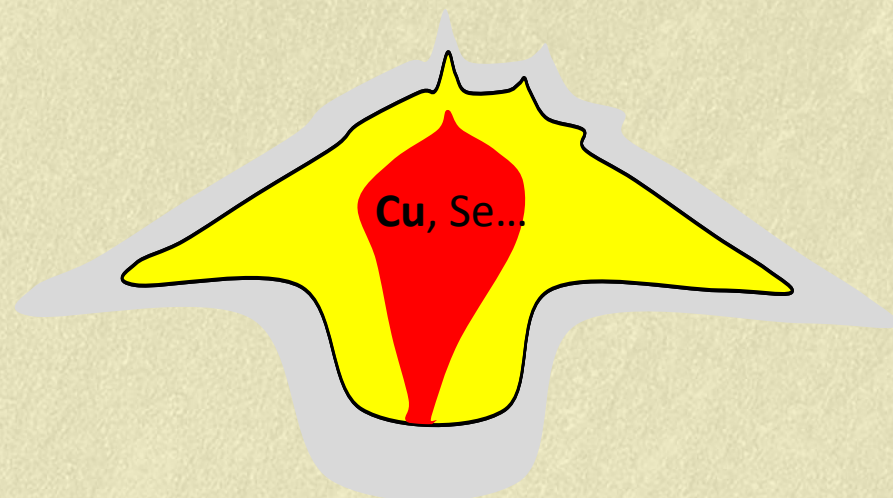
Gisements économiques

- ◆ riche en zinc
- riche en cuivre

Bilan empreintes hydrothermales



Gisement riche en Zinc

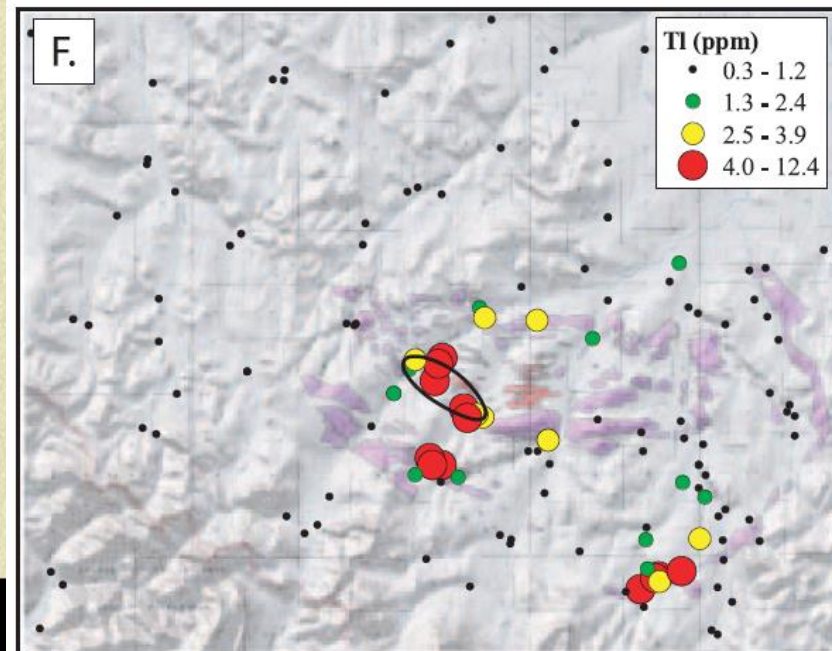


Gisement riche en Cuivre

Tl: un champion sous-estimé?

- VMS (Murao et Itoh, 1992; Large et al. 2001)
 - SEDEX (Slack et al. 2004; Graham et al. 2009)
 - Epithermal (Celenk et al. 1987)
 - Carlin (Ikramuddin et al. 1983, 1986)
-
- Bonne dispersion dans l'environnement secondaire!

Graham et al. 2009



Tl: un champion sous-estimé?

- Chalcophile **ET** lithophile
 - Tl → lithophile → séricite
 - Tl → chalcophile → sulfures

- Volatils
 - Grande dispersion (zone distale)
 - Problèmes analytiques
 - Ex: *Aqua Regia* sous-estime de 80%

Noll et al. 1996

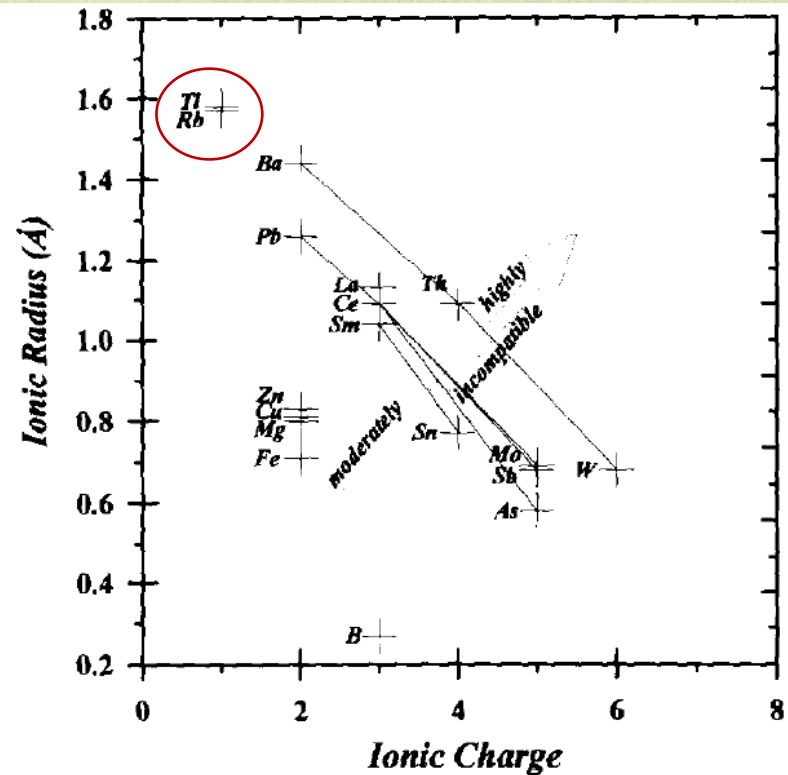
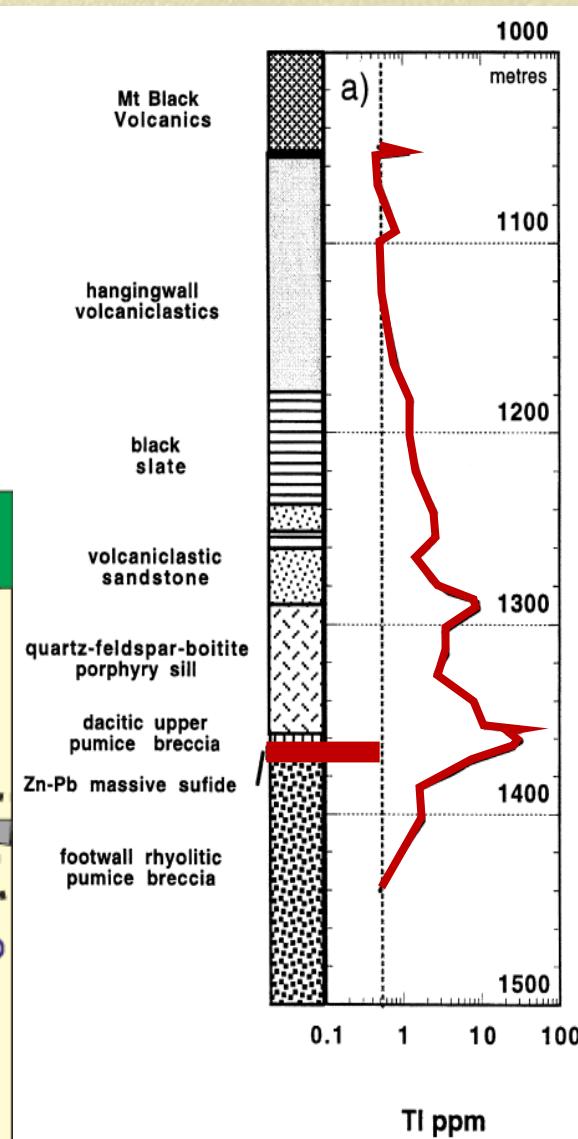
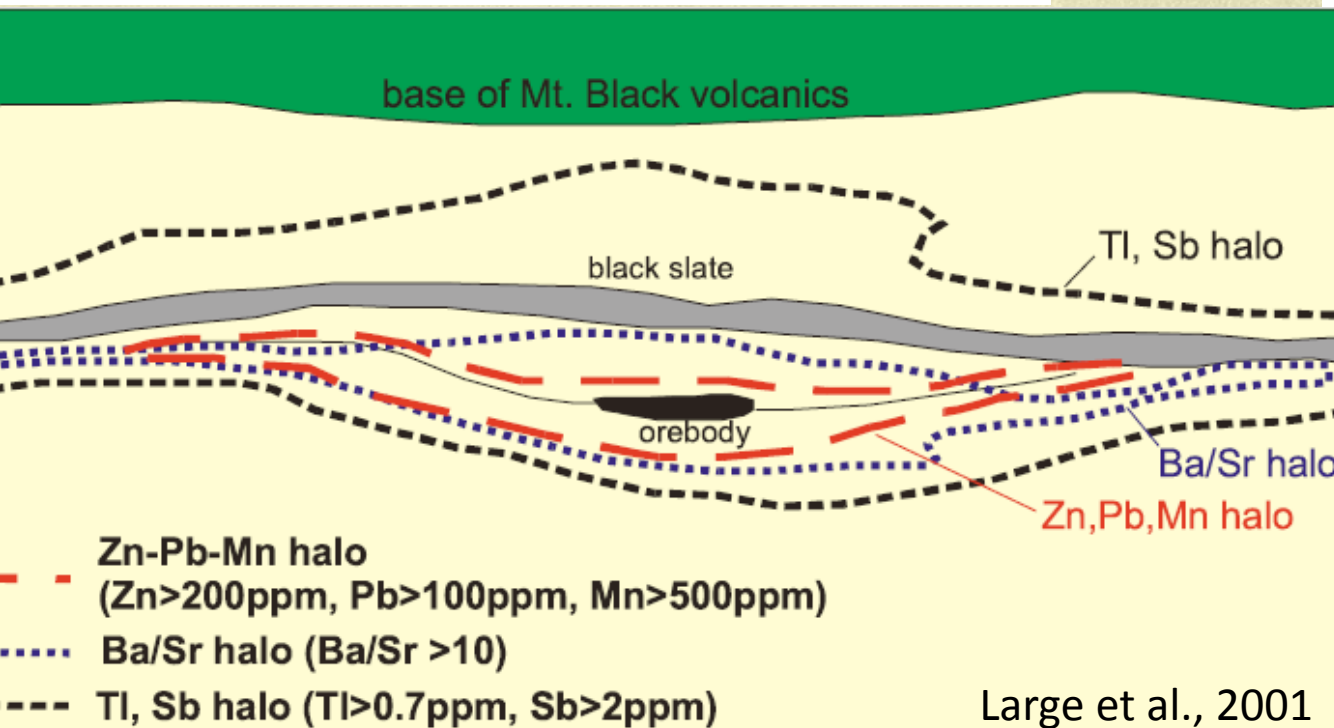
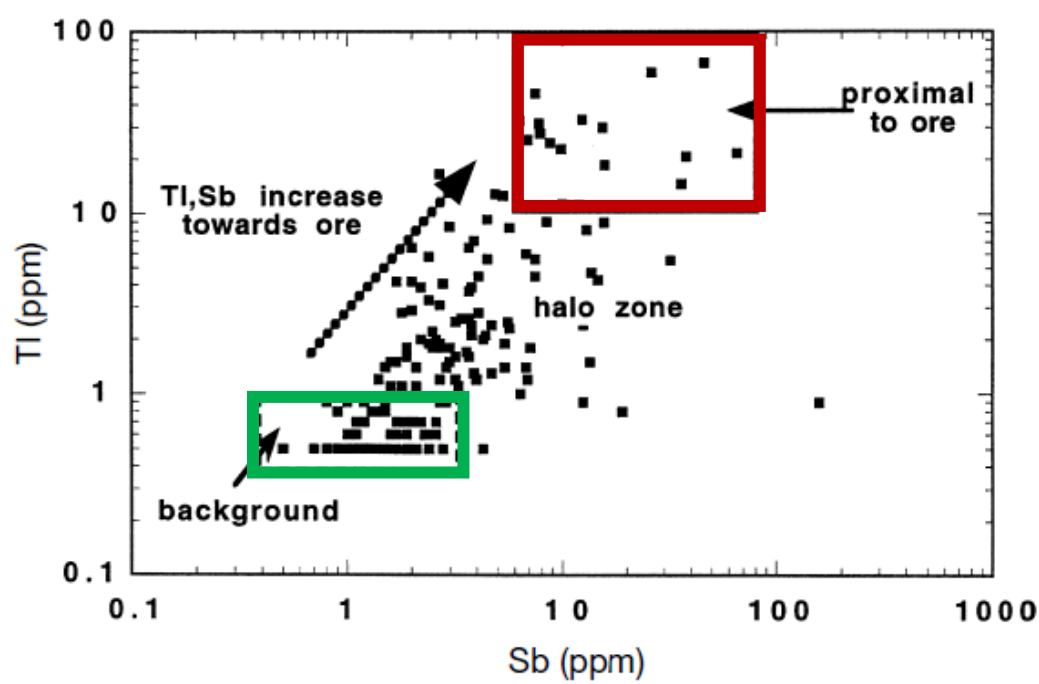
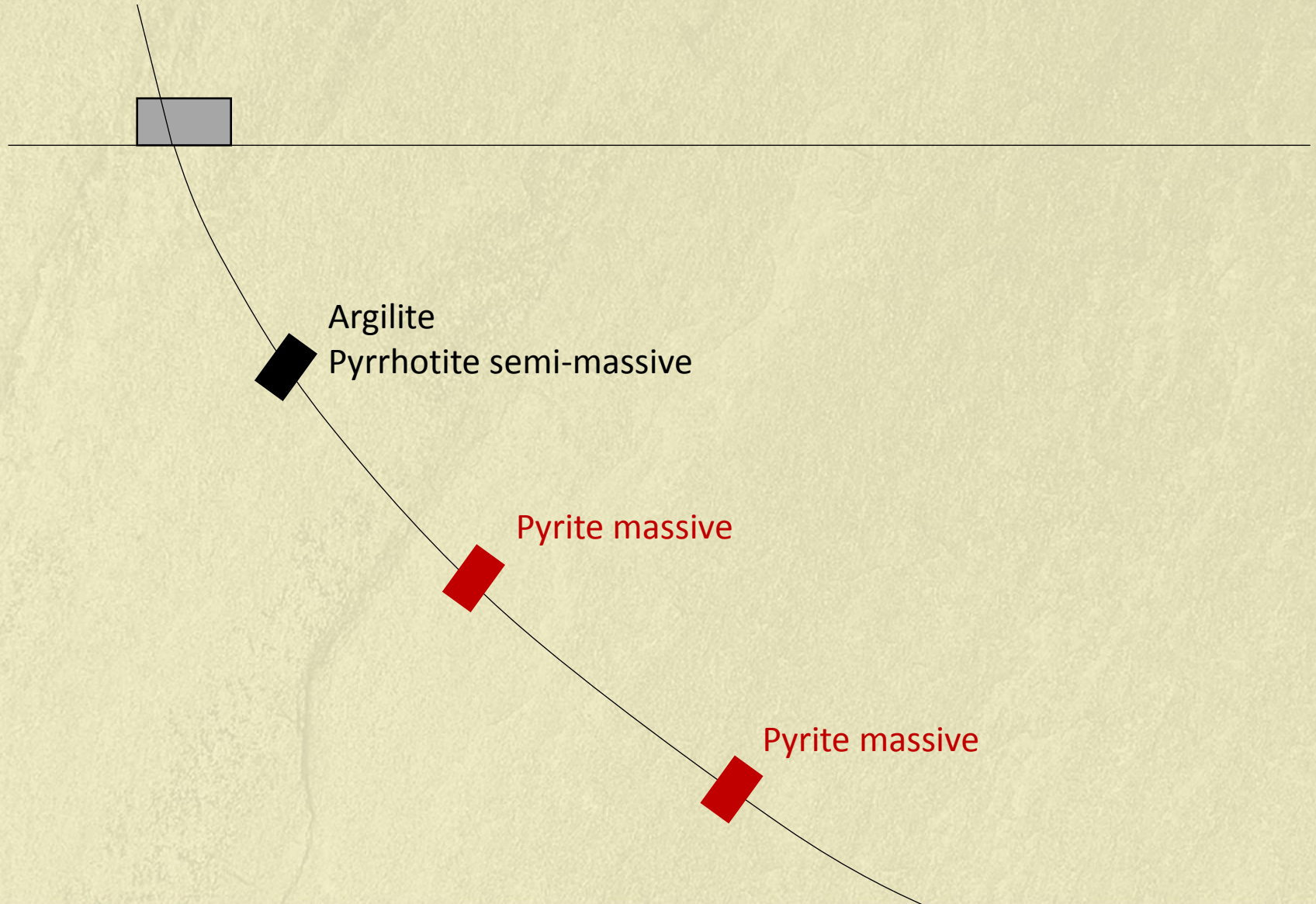


FIG. 1. Plot of ionic radius vs. ionic charge (after Jochum et al., 1993). Siderophile/chalcophile–lithophile element groups which have constant ratios form subparallel arrays. Incompatibility increases with increasing radius for a given charge and vice versa.

Affinité Tl-Sb et gisements SMV riche en Zn



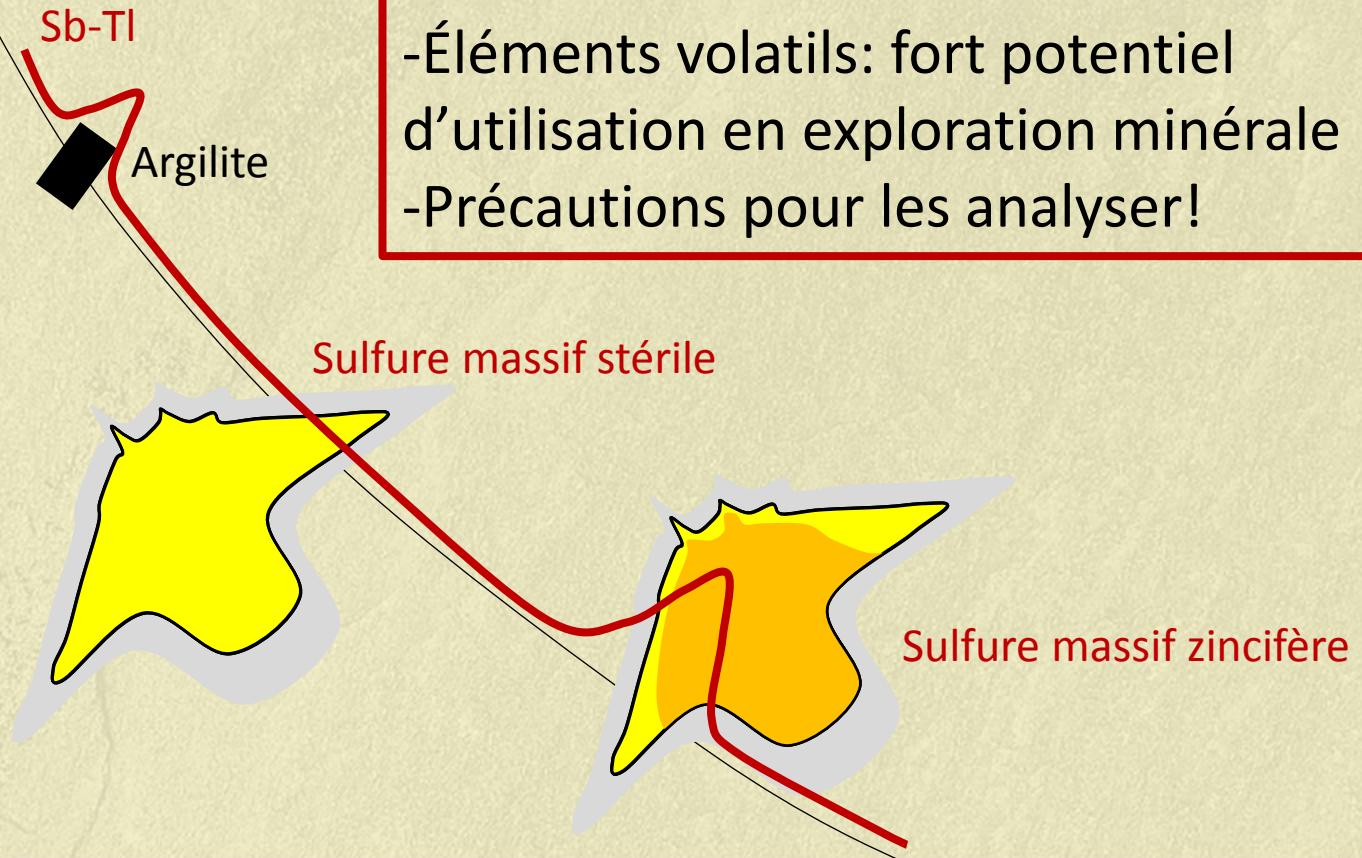
Large et al., 2001



Peut-on prédire la présence de minéralisation Zn grâce au Tl dans le halo d'altération?

Conclusions

- Éléments volatils: fort potentiel d'utilisation en exploration minérale
- Précautions pour les analyser!





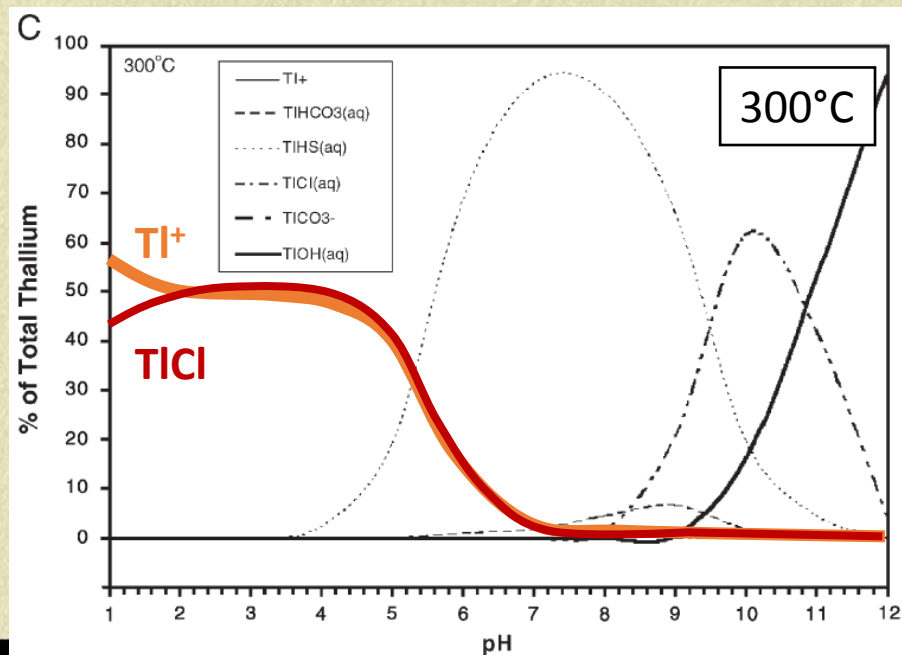
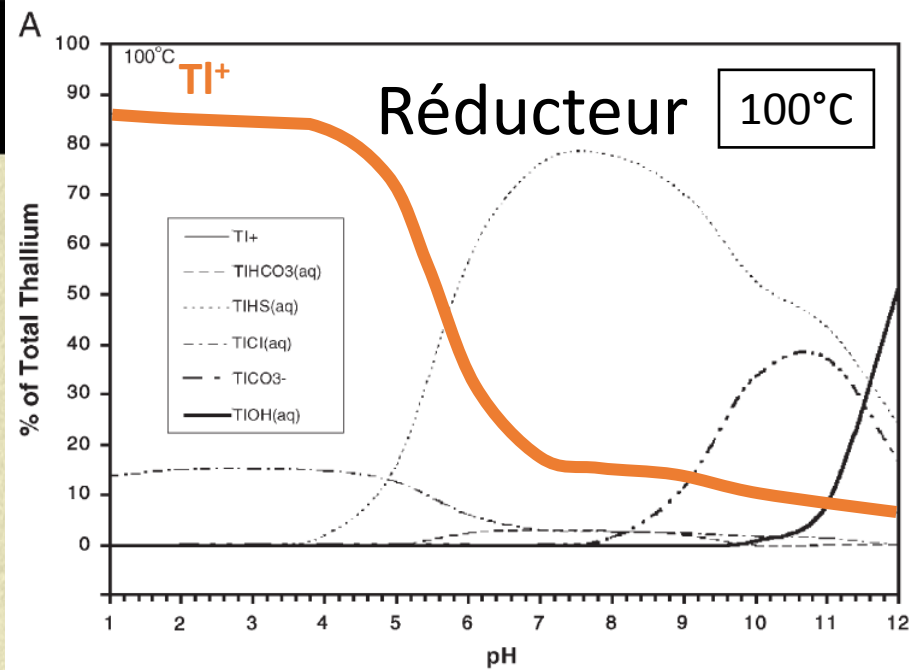
Merci pour votre attention



Solubilité du Tl

- Lessivage roche $>250^{\circ}\text{C}$
- Précipitation par neutralisation des fluides (mélange avec eau de mer)

Conditions identiques au transport et à la précipitation du zinc!



Limites d'utilisation

- Spectres développés à Flin Flon semblent bien fonctionner dans d'autres environnements VMS (Kuroko, Brunswick, Hackett-River, moderne...)
- Cependant, ils doivent être adaptés
 - Environnement géodynamique
 - Bruit de fond régional (influence sédiment...)
 - Niveau de métamorphisme (>schiste vert non testé)
 - Limites de détections et méthodes analytiques