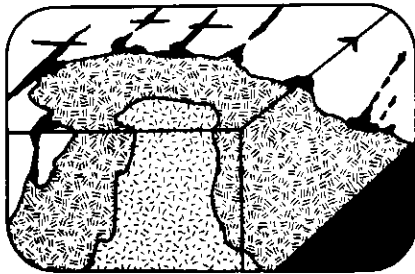


Articles



Ore Deposit Models - 5. A Model for Granophile Mineral Deposits

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Introduction

The aim of this paper is to outline a petrological-geochemical framework or "model" in which to consider mineral deposits that are associated with granitoid rocks. (I use the term "granitoid" rocks as only a textural term for the broad group of granite-textured or phaneritic intrusive igneous rocks which might have compositions from diorite to granite.) Although tin deposits are emphasized, the model should apply equally well to deposits of many other elements that are concentrated by the same processes. The paper does not aim to provide either detailed information on specific deposits nor any broad-scale metallogenic assessment, since this has been provided in a number of recent works (e.g., Ahlfeld and Schneider-Scherbina, 1964; Hutchinson and Taylor, 1978; Hosking, 1968; Ishihara and Take-nouchi, 1980; Jones, 1977; Stempok *et al.*, 1978; Strong, 1976; Taylor, 1979).

Mineral deposits associated with granitoid rocks may be conveniently grouped into two broad categories on the basis of a wide range of geological and geochemical features, some of which are summarized in Figure 1. Those of the first cate-

gory, *porphyry-type deposits*, have been described in the first paper of this series (McMillan and Panteleyev, 1980), and are characterized by Cu and Mo mineralization, in granitoid rocks of mainly intermediate composition, which were emplaced at shallow depths. The second category I term *granophile* deposits as they are typically hosted by quartz-rich leucocratic granitoids enriched in the so-called "granophile" elements. I would subdivide these granophile elements into three groups, i.e., the large highly charged cations Sn^{4+} , W^{6+} , U^{4+} , Mo^{6+} , the small variably charged cations Be^{++} , B^{3+} , Li^+ and P^{5+} , and the anions or anionic complexes CO_3 , Cl^- , F^- , which might be readily recalled under the respective

acronyms SWUM, BEBLIP and CCF. The SWUM group contains the economically important elements and may have others (e.g., Nb, Ta, Bi, Ag) concentrated with them. The BEBLIP group are concentrated in the mineral assemblages characteristic of greisens, produce geochemical anomalies useful in exploration, and may have associated concentrations of Na, Rb, Cs, REE, etc. The CCF group, possibly including sulphide and hydroxide complexes, are important in forming soluble complexes for transport of the SWUM and BEBLIP groups. Both the BEBLIP and CCF groups play a critical role in controlling the genesis of magmas and their subsequent solidification behaviour. The SWUM group on the other hand

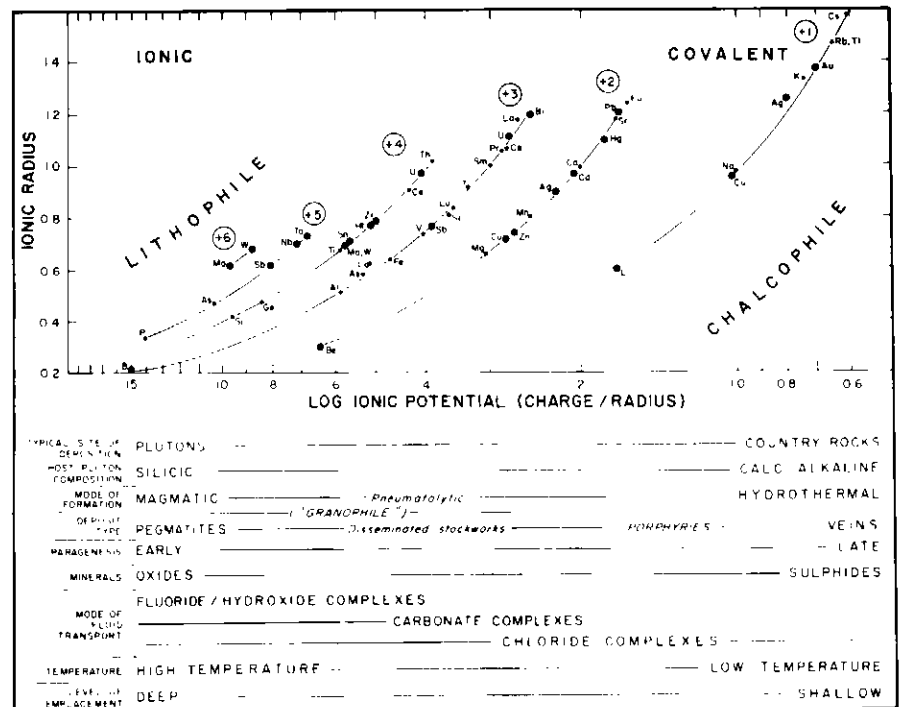


Figure 1 Schematic outline of the effect of two of the many variables which influence the geochemical behaviour of the elements which make up different types of granitoid mineral deposits. Some geological conditions controlling the formation of such deposits are crudely

summarized in the lower half of the diagram, indicating the common patterns of occurrence from the more lithophile or ionically bonded elements on the left to the more chalcophile or covalently bonded elements on the right (after Strong, 1980).

is passively controlled by these processes of magma generation and solidification.

Deposits of tin and other granophile elements have been classified using a variety of criteria such as tectonic setting or associated mineral assemblages (see Taylor, 1979), and a reasonably comprehensive and useful approach to classification is that of Varlamoff (1978) which relates deposit characteristics to depth of emplacement. This is shown in Figure 2, modified to include a number of different examples, and to expand the depth range which Varlamoff considered. Needless to say, no single deposit (including the examples given) will exhibit the full range of characteristics of a given category.

Porphyry Cu-Mo deposits, as reviewed by McMillan and Panteleyev (1980), are characterized by hydrothermal alteration assemblages which mainly result from

variable degrees of leaching by fluids consisting essentially of water. While granophile deposits may also display such effects as kaolinization or sericitization, they are more characteristically associated with greisens. *Greisens* can be described as the secondary mineral assemblage formed by alteration of either the granitic or country rock by the addition of elements such as Li, Be, B, F, H₂O, Si, to produce assemblages with variable combinations of white mica (commonly Li-rich), quartz, topaz, tourmaline, and fluorite. Greisen alteration patterns may be zoned, as shown in Figure 3, but they tend to be more irregular than those of porphyry Cu-Mo deposits, and may be telescoped, superimposed, or asymmetrical. There is often evidence for feldspathization preceding greisenization, and kaolinization following it (e.g., Badham *et al.*, 1976), reflecting changing fluid-rock

equilibria with falling temperatures.

Granophile deposits tend to concentrate towards the contact zones of related granitoids, and occur as disseminations or pegmatites in the pluton (endoccontact) and as veins and stockworks developed upwards or outwards from it (exoccontact). There is typically a zonation of elements, with Sn, W, As and U passing outwards through (U, Ni, Co) to Cu to Pb-Zn-Ag to Fe and Sb sulphides. This pattern, shown in Figure 4, is well-established in the Hercynian granites of western Europe, and is perhaps best-known for those of Cornwall. Such element zonation is known to occur on a very broad scale and can serve as a useful exploration guide in distinguishing between plutons of high and low mineralization potential (cf. Davenport, 1981).

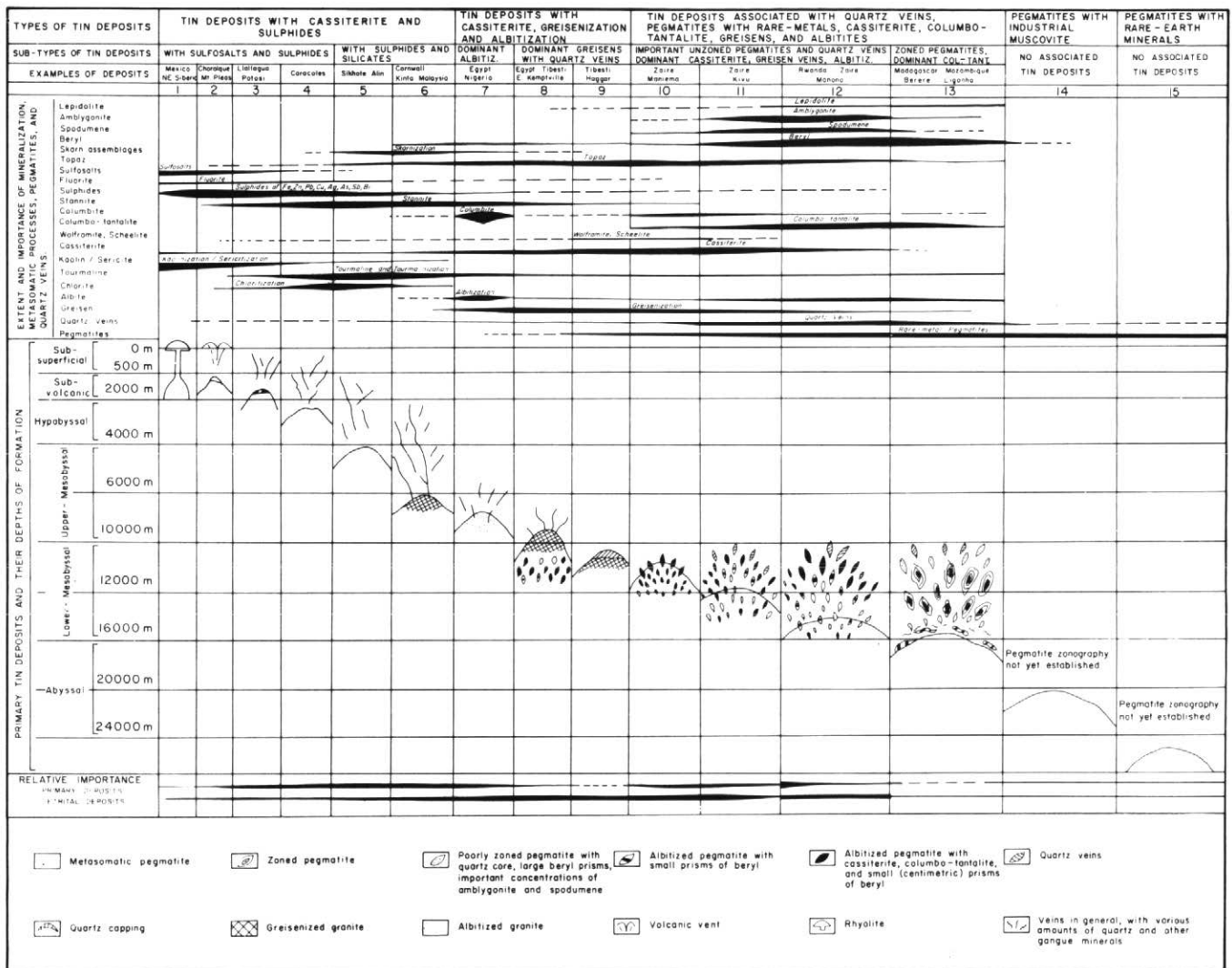


Figure 2 Classification of tin deposits relating general features of alteration and associated mineral assemblages to approximate depths of formation (modified from Varlamoff, 1978).

Granitoid Petrogenesis

There is no doubt that water is the single most important compositional variable in controlling both the physical and chemical behaviour of granitoid melts, and that it ultimately determines the characteristics of any related granophile mineral deposits, a theme most elegantly developed by Burnham (1967, 1969).

As shown in Figure 5, a range of rock types could melt at comparable temperatures under conditions of water saturation over a range of pressures, and the melt would be essentially granitic. In the absence of free water vapour (i.e., under-

saturation), melting would be governed by the breakdown of the hydrous phases, i.e., muscovite, biotite, or amphibole, at successively higher temperatures. Three important consequences of source-rock melting being controlled by the breakdown of hydrous minerals are:

1) The amount of water contained in the melt would be highest for muscovite breakdown and lowest for amphibole, i.e., more "primary" magmatic water would be available for mineralizing processes in muscovite-bearing granitoids or those derived from muscovite-rich source rocks such as shale.

2) More advanced melting of most source rocks at progressively higher temperatures and pressures would produce progressively less silicic "drier" melts (Brown and Fyfe, 1970).

3) These drier higher-temperature melts, i.e., biotite- or hornblende-bearing, would be capable of rising and intruding to shallower levels in the crust before they would reach their solidus curves and solidify, whereas primary muscovite-bearing magmas would tend to freeze at depths of about 12 to 16 km.

These predictions accord with the general observation that high-level, subvolcanic plutons tend to have calc-alkaline intermediate compositions, i.e., those associated with porphyry-type deposits. In contrast muscovite-bearing leucogranites, which generally host the SWUM deposits, are typical of metamorphic terrains and seldom break the surface. We thus have a natural link between the petrogenetic and metallogenetic history of granitoid rocks suggesting two extremes, i.e., large volumes of magmatic water, deeper levels of emplacement, primary muscovite-bearing silicic minimum melts and granophile deposits, versus water-poor intermediate composition, amphibole- or biotite-bearing subvolcanic (and therefore with access to groundwater circulation) intrusions with porphyry-type deposits. These two extremes provide us with a framework in which to focus on the similarities and differences between the range of deposits associated with granitoid rocks.

Granophile Metallogenesis

Figure 1 shows two of the properties which control geochemical behaviour of the elements of interest, i.e., ionic radius and "ionic potential" (a rough measure of the tendency to form ionic bonds - Taylor, 1965), which illustrates the grouping described above. Thus, the strongly lithophile group tend to form tetrahedral complexes ($(SnO_4)^{4-}$, $(WO_4)^{2-}$, $(NbO_4)^{3-}$, $(TaO_4)^{3-}$, etc.) and be strongly concentrated in silicic melts formed through either crystal fractionation or as initial partial melts. Those elements with very small ionic radii (Li, Be) may also form such complexes but can also be concentrated because of their exclusion from silicate structures because of their small radii. The strongly chalcophile Cu can either enter silicate lattices or form sulphides, and thus tends to be randomly distributed during cooling of a magma or partial melting. The other "lithochalcophile" elements, although comparable in ionic radii to silicate-forming ions such as Ca^{++} , have strongly covalent bonds with oxygen which exclude them from silicate lattices. They would thus be con-

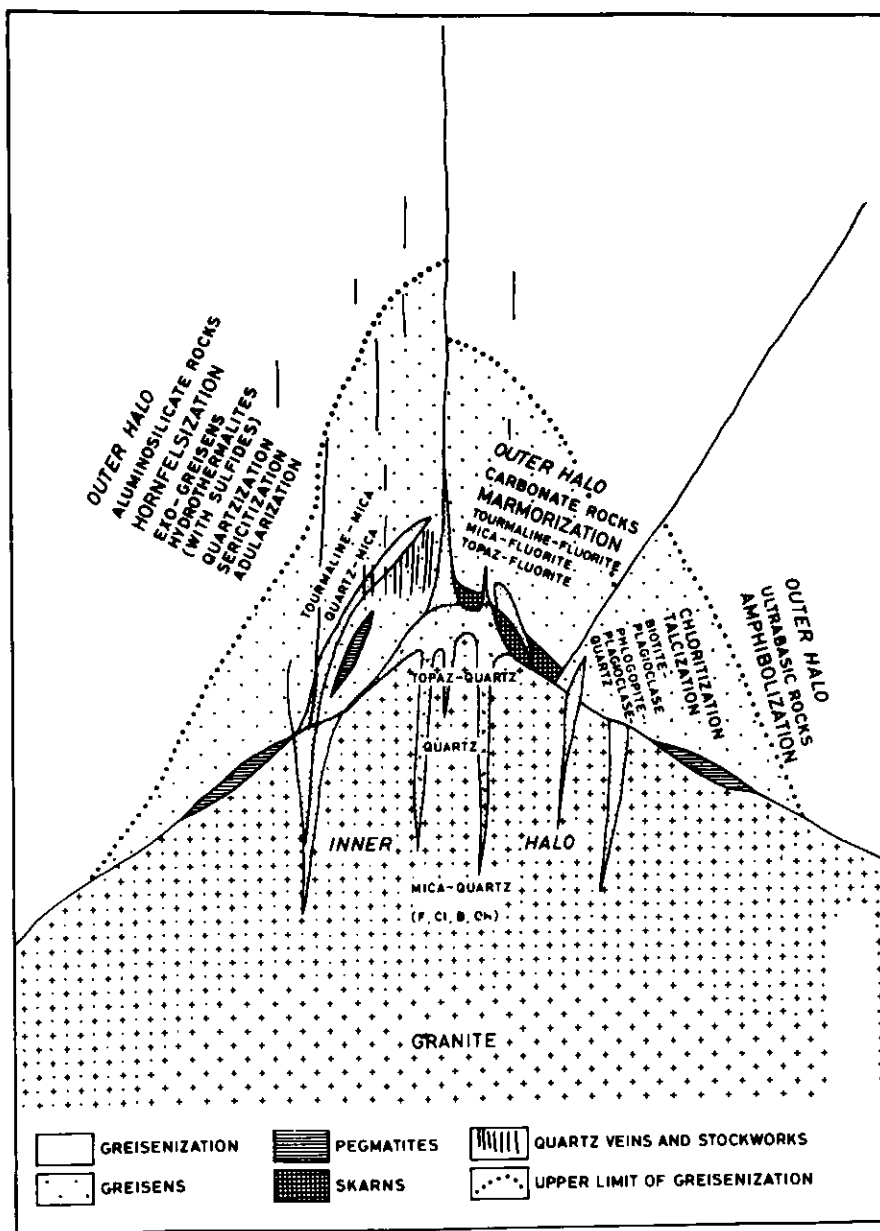


Figure 3 Alteration-zonation patterns of greisens in aluminosilicate, carbonate and ultramafic environments (after Taylor, 1979, redrawn from Scherba, 1970).

Gangue	Zone	Ore-minerals Latest minerals		Economically important elements	Composition of wolframite and sphalerite	Trace element data*	Wall-rock alteration		
Quartz Felspar Mica Tourmaline Chlorite Hematite Fluorite	7	Barren (pyrite)	Mesothermal and Epithermal Lodes Generally at right-angles to granite ridges	Fe Sb	↑ ↑ ↑ ↑ ↑ ↑ ↑	↑ ↑ ↑ ↑ ↑ ↑ ↑	Silicified granite. Silicified slate. Kaolinized granite (?). Hematitized slate. Hematitized granite. Chloritized granite: peach. Chloritized slate: peach. Tourmaline slate hornfels: capel. Tourmalized granite: capel. Quartz-sericite slate hornfels. Greensized granite.		
	6	Hematite Stibnite Jamesonite. Tetrahedrite Bournonite Pyragyrite? Siderite Pyrite (marcasite)		Ag Pb Zn U Ni Co Bi.					
	5b	Argentite Galena Sphalerite							
	5a	Pitchblende Niccolite Smaltite Cobaltite (Native bismuth bismuthinite?)							
	4	Chalcopryite Sphalerite Wolframite (scheelite) Arsenopyrite Pyrite		Cu				Fe increases in wolframite and decreases in sphalerite.	Bi and Sn decrease in galena.
	3	Chalcopryite (stannite) Wolframite (scheelite) Arsenopyrite Cassiterite (Wood tin)		Sn W As				Hypothermal Lodes Generally parallel to granite ridges and dykes	In, Mn, and Sn decrease, and Ge and Ga increase, in sphalerite.
	2	Wolframite (scheelite) Arsenopyrite (molybdenite?) Cassiterite							
1	Cassiterite, Specularite								
Greisen bordered veins		Arsenopyrite Stannite Wolframite, Cassiterite. Molybdenite.					Veins often in granite cusps		
Pegmatites		Arsenopyrite, Wolframite. Cassiterite Molybdenite							
		Earliest Minerals							

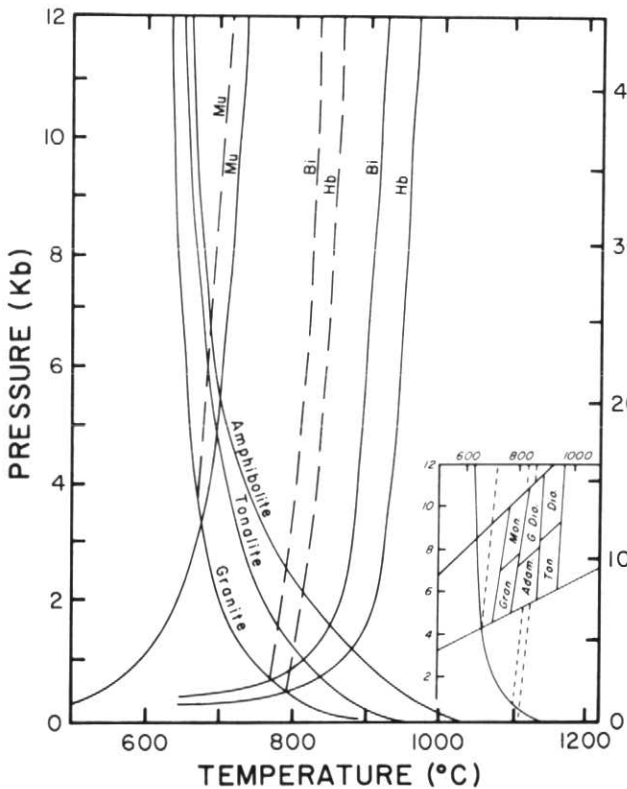


Figure 5 Pressure-temperature projection of some melting and reaction relations relevant to the genesis of granitoid rocks. The solid lines labelled "granite", "tonalite", and "amphibolite" are the solidi (beginning of melting) of these compositions as shown by Wyllie (1977). The

solidus (dashed) and liquidus (solid) curves for muscovite (Mu), biotite (Bi), and hornblende (Hb), are after Burnham (1979). Insert shows the approximate melt compositions formed under different P-T conditions (after Brown and Fyfe, 1970).

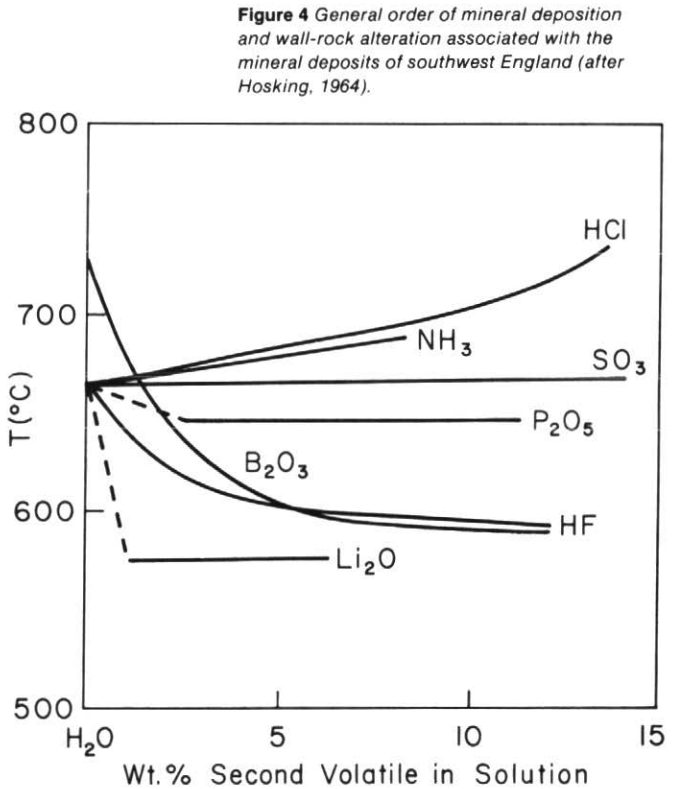


Figure 4 General order of mineral deposition and wall-rock alteration associated with the mineral deposits of southwest England (after Hosking, 1964).

Figure 6 The effects of different elements or compounds on the melting temperature of granitic compositions at 2.75 kbar. Modified from Luth (1976) to include the data for boron at 1 kbar from Chorlton and Martin (1978).

concentrated in differentiated liquids, unless sulphur activity were such that sulphides of certain elements like Mo can form and cause their early removal from magmas.

When aqueous fluids coexist with silicate magmas, the behaviour of the elements is critically dependent upon their fluid-melt partition coefficients, which depend upon a range of variables, particularly compositional. As can be seen from Figure 6, an important effect of our BEBLIP and CCF element groups is to lower or raise the melting temperature, reflecting their relative partitioning into the melt or aqueous solution, e.g., F or Cl. Thus, F, P, Li, or B would tend to stay with and concentrate in residual melts, lowering their viscosity and freezing temperature and prolonging their differentiation. Alternatively, they may lower the melting temperature of protoliths and promote magma generation in otherwise unfavourable situations. These effects would also permit the intrusion of muscovite-bearing granites to significantly shallower depths, as illustrated in Figure 7. Although the chemical processes are not well understood, there tends to be a strong correlation between these "solidus - lowering" elements and the SWUM group in both granites (Taylor, 1979) and silicic volcanic rocks (Hildreth, 1979), suggesting a genetic relation between them. The "solidus-raising" elements (Cl, CO₂) would, on the other hand, tend to concentrate in the aqueous phase and separate from the melt before significant differentiation, and not enhance the concentration of any elements in residual or early melts. Because chloride and possibly carbonate (Higgins, 1980) solutions are transition metal solvents, their separation and circulation would govern the nature of the base metal porphyry-type and other vein-type deposits.

In general, the formation of granitoid mineral deposits depends upon whether the element of interest is dispersed or concentrated during crystallization and partial melting. With dispersal, e.g., Cu in general or Mo in S-bearing melts, a stage of hydrothermal leaching is necessary to form economic concentrations. With magmatic concentration, hydrothermal vein-type deposits may be formed during cooling of a water-saturated melt if the element is preferentially partitioned into the aqueous phase, e.g., the lithochalcophile elements, thus not requiring particularly strong fractionation (i.e., not evolved granitoid compositions). With fractionation of a water-saturated magma, or if the element is preferentially partitioned into the silicate melt as are the SWUM and BEBLIP element groups, highly evolved magmas (and generally

high SiO₂, etc.) may be necessary to produce economic concentrations.

The Model

An attempt to summarize and integrate the above observations is shown in Figure 7. Figure 7a is an expanded and inverted version of Figure 5, to illustrate possible conditions of melt generation and behaviour, and Figure 7b illustrates the intrusive and mineralization phenomena which might be observed. Melts which formed by the breakdown of hornblende, biotite or muscovite at the arbitrarily chosen depths of regions I, II and III, would have the respective compositions of diorite, granodiorite and granite (Brown and Fyfe, 1970) and water contents of about 2.7, 3.3 and 8.4 wt. % (Burnham and Ohmoto, 1980). Alternatively, the more silicic melts might form by differentiation from the more mafic, with similar resulting water contents. These melts could ascend to a level where they encounter their respective solidi (e.g., points D, C and B), with the more mafic (driest) reaching shallower depths. Thus, muscovite-bearing melts would solidify at about 4 kb (12-16 km) whereas hornblende- and biotite-bearing melts would rise to very close to the surface. If the melts were sufficiently enriched in the BEBLIP group or F, either by differentiation or during partial melting, the solidus would be significantly depressed, allowing much shallower ascent, say to point A.

The line XYZ shows the H₂O-NaCl critical curve (Sourirajan and Kennedy, 1962), which intersects the water-saturated granite solidus at about 700°C and 1250 bars (point Z), and the BEBLIP-saturated solidus at about 650°C and 1100 bars (point Y). Assuming that XYZ applies for more complex aqueous systems containing the BEBLIP group elements, this line gives an indication of the maximum depth (about 5.5 km) at which the aqueous fluid (which has already boiled off the silicate melt - "resurgent" or "second" boiling) will boil again ("third" boiling).

It is generally assumed that the expansive evolution of gas during resurgent boiling is responsible for brecciation of the intrusion and host-rocks associated with high-level porphyry deposits. The "third" boiling would account for the preponderance of highly saline fluids and possibly induce further hydraulic fracturing during hydrothermal alteration. Note that the "third" boiling might occur if XYZ or its equivalent is encountered by either pressure-release (e.g. BEBLIP- or CO₂-rich fluid rising from point A) or temperature-drop (e.g., a Cl-rich fluid cooling from D or C). Although the phys-

ical effects of each may be similar in each case, it should be emphasized that the former depends on the prior enrichment of the melt in BEBLIP elements, results in alteration phenomena such as tourmalinization and greisenization, and is associated with SWUM deposits. The latter case results simply from post-magmatic cooling of a Cl-rich fluid which scavenges the intrusive or host rocks, with typical hydrothermal alteration and typical porphyry Cu-Mo deposits. Because of these basic differences, I term the former case "pseudoporphyries" to distinguish them from the true porphyries, recognizing, alas, that there are certainly gradations between these extremes.

Another implication of the model is that granitoid rocks intruded at depths between B and C (Figure 7a) would tend to be low in primary magmatic water, unlike those deeper than B, and would be unlikely to encounter groundwater systems, unlike those shallower than C. Hence, they would have little opportunity for, and low potential for, mineralization. I suggest that these are the large plutons of microcline-megacrystic biotite granite such as those which form most of the large Appalachian batholiths - and unfortunately tend to be barren. Of course, exceptions to this generalization may occur in the cases where such plutons can establish convection systems, e.g., in the rare cases where they intruded deep sedimentary sequences containing formation waters (cf. Plant *et al.*, 1980), or where cooling conditions allow efficient concentration of small amounts of magmatic water.

At this point the opportunity should be taken to point out the close correspondence between Figure 7a and the classic ideas of Fersman (1931), and to revive his very appropriate definitions of common terminology. He suggested that the order of mineralization in a cooling magmatic system could be described in the following successive stages:

- 1) *Magmatic stage*, at which equilibrium is maintained between silicate melt and crystalline phases, i.e., at temperatures above the solidi of Figure 7a.

- 2) *Pegmatitic stage*, throughout which the melt, crystalline phases and gas phases coexist, e.g., along the water-saturated or BEBLIP-saturated solidi of Figure 7a.

- 3) *Pneumatolytic stage*, characterized by equilibrium between crystals and supercritical fluid, i.e., between the solidi and line XYZ of Figure 7a.

- 4) *Hydrothermal stage*, in which equilibrium is maintained between crystals, aqueous solution, and aqueous gas, i.e.,

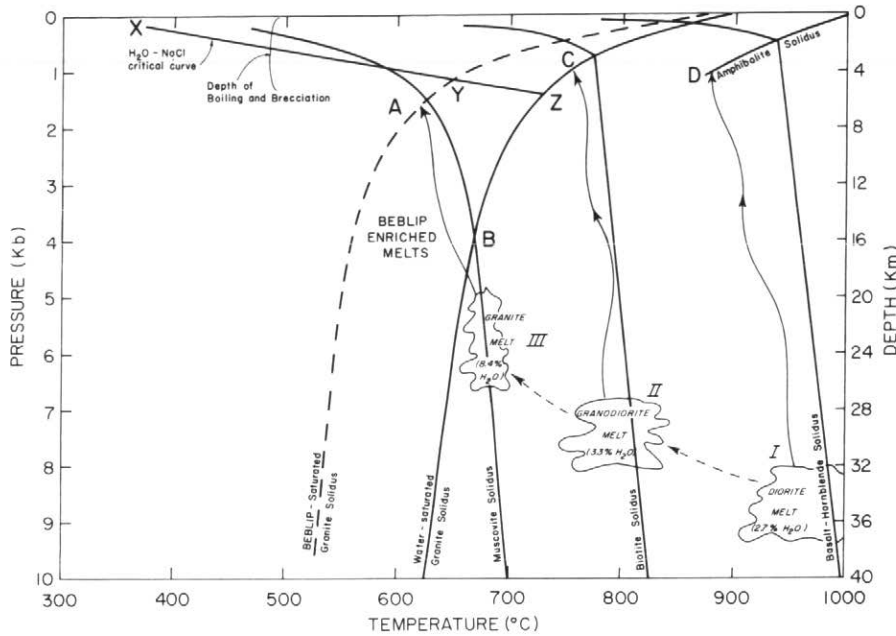


Figure 7a Approximate conditions of generation of granitoid melts and mineral deposits. The water-saturated granite solidus and mineral solidi are taken from Figure 5 or Burnham and Ohmoto (1980). The "BEBLIP-saturated granite solidus" is inferred from Figure 6, and the H₂O-NaCl critical curve from Sourirajan and Kennedy (1962). The compositions of melts forming at the arbitrarily chosen depths of I, II and III are inferred from the insert in Figure 5 (Brown and Fyfe, 1970), and the minimum water contents from Burnham and Ohmoto (1980). The solid arrows approximate paths of ascent, and dashed arrows represent differentiation of one magma from a more mafic one. See text for further discussion.

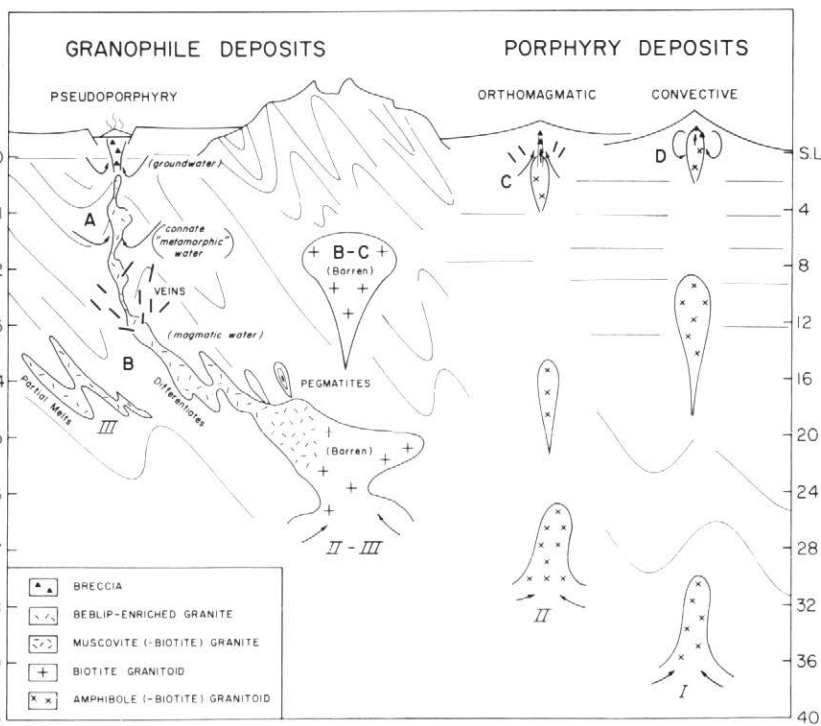


Figure 7b Schematic representation of features to be expected with types of deposits associated with different types of granitoid rocks formed as in Figure 7a. The more mafic calc-alkaline diorite and granodiorite melts formed at I or II could rise to shallow depths and discordantly intrude their volcanic carapace (letters correspond to those of Figure 7a). Low initial water contents in I may require augmenting by groundwater to generate a large porphyry-type deposit, e.g., the "convective" variety of McMillan and Panteleyev (1980). Larger initial water contents in II may be sufficient to form a large porphyry-type deposit, e.g., the "orthomagmatic" version of McMillan and Panteleyev (1980).

Intermediate composition granitoids formed between II and III and intruded between depths B and C (Figure 7a) are thought to represent the biotite-megacrystic granites-monzonites which form large discordant to concordant unmineralized batholiths of orogenic belts. They may be barren because of low initial water contents or lack of interaction with groundwater, lack of brecciation, etc. because of intrusion at too great a depth. Similar lithologies may form by differentiation of melts formed at sites I and II.

Muscovite-bearing granites may form as antecrystic melts at site III or as differentiates of the above, and may be concordant to discordant. They might be enriched in the BEBLIP group elements, typically in cupolas at the tops of larger plutons, which prolongs their time of crystallization and allows for greater SWUM-enrichment and shallower intrusion than for a normal water-rich muscovite-granite. This shallower intrusion permits second boiling and brecciation, forming "pseudo-porphyrates" with many physical features like those of Cu and Mo porphyry deposits. They may, however, form granophile deposits at deeper levels due to high initial H₂O content, or even set up convection cells with connate or metamorphic fluids at intermediate depths (as might biotite granites, but apparently very rarely). Pegmatites tend to be more abundant with these "type III" granites, as do greisens, with variations as illustrated in Figures 2 and 3. Dispersion of fluids and contained elements through the plutons and country rocks might result in veins with the characteristic zonation patterns shown in Figure 4.

after the supercritical fluid has intersected XYZ.

Further observations regarding Figure 7b are given in the caption.

It might be appropriate to conclude this discussion with the following statement from Hosking (1968) who wrote:

"As far as possible the writer has refrained from discussing those questions of relationship which require consideration of the sources of granitic magmas, granitising agents and ore-forming ones, and theories of the nature of these agents and the chemis-

try of ore genesis. He has adopted this line of action because he believes that a good exploration programme must be based essentially on facts, and that a programme founded largely on theoretical concepts, however sophisticated the latter might appear to be, is little better than one which requires only that a blind-folded person should stick a pin in a map in order to find a tin deposit."

Although there have been a number of recent studies which suggest approaches to tin exploration (e.g., Smith and Turek,

1976; Badham, 1980; Ivanov and Narnov, 1970; Flinter *et al.*, 1972; Tauson and Kozlov, 1973) one cannot go wrong by reading Hosking's numerous "factual" treatments of the search for tin (e.g., 1964, 1968, 1970). Meanwhile, I hope that the preceding more speculative model will provide a step towards understanding tin and other granophile deposits in their geochemical-petrological context, and lead to eventual removal of the blindfold.

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by D.H. McNeil and W.G.E. Caldwell
Geological Association of Canada
Special Paper 21, 1981

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