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., Anfield and Schneider-Scherbina, 1964; Hutchinson and Taylor, 1978; Hosking, 1968; Ishihara and Takeuchi, 1980; Jones, 1977; Stempel 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 category, 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 Sn⁴⁺, W⁶⁺, U⁴⁺, Mo⁶⁺, the small variably charged cations Be²⁺, B³⁺, Li⁺ and P⁵⁺, and the anions or anionic complexes CO₃⁻, 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 covalently 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 asymmetric. 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 (endocontact) and as veins and stockworks developed upwards or outwards from it (exococontact). There is typically a zonation of elements, with Sn, W, As and U passing outwards through (U, Ni, Co) 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).

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<th>Types of Tin Deposits</th>
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![Figure 2: Classification of tin deposits relating general features of alteration and associated mineral assemblages to approximate depths of formation (modified from Varlamoff, 1978).](image-url)
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 granophyric 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., undersaturation), 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 metallogenic 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 granophyric 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.

Granophyric 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)\(^{4-}\), (WO\(_3\))\(^{2-}\), (NbO\(_3\))\(^{5-}\), (TaO\(_3\))\(^{6-}\), 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\(^{2+}\), have strongly covalent bonds with oxygen which exclude them from silicate lattices. They would thus be con-
Figure 4 General order of mineral deposition and wall-rock alteration associated with the mineral deposits of southwest England (after Hosking, 1984).

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 solids (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 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).
centrated 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 sil-
clicate magmas, the behaviour of the ele-
ments is critically dependent upon their
fluid-melt partition coefficients, which
depend upon a range of variables, partic-
ularly 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 differ-
entiation. 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 signifi-
cantly shallower depths, as illustrated in
Figure 7. Although the chemical pro-
cesses are not well understood, there
tends to be a strong correlation between
these "solidus - lowering" elements and
the SWUM group in both granites (Tay-
lor, 1979) and silicic volcanic rocks (Hil-
dreth, 1979), suggesting a genetic re-
lation 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 ele-
ments in residual or early melts. Because
chloride and possibly carbonate (Hig-
gens, 1980) solutions and 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 crystalization 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 lithoalcal-
phile elements, thus not requiring partic-
ularly strong fractionation (i.e., not
evolved granoid 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 pro-
duce economic concentrations.

The Model
An attempt to summarize and integrate
the above observations is shown in Fig-
ure 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 pheno-
mena which might be observed. Melts
which formed by the breakdown of horn-
blende, biotite or muscovite at the arbi-
trarily chosen depths of regions I, II
and III, would have the respective composi-
tions of diorite, granodiorite and granite
(Brown and Fyfe, 1970) and water con-
tents of about 2.7, 3.3 and 8.4 wt.
% (Burnham and Ommoto, 1980). Alterna-
tively, 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 sur-
face. If the melts were sufficiently
enriched in the BEBLIP group or F, either
by differentiation or during partial melt-
ing, the solidus would be significantly
depressed, allowing much shallower
ascent, say to point A.
The line XYZ shows the H₂O-NaCl criti-
cal curve (Sourirajan and Kennedy,
1962), which intersects the water-
saturated granite solidus at about 700°C
and 1250 bars (point Y), and the BEBLIP-
saturated solidus at about 650°C and
1100 bars (point X). Assuming that XYZ
applies for more complex aqueous sys-
tems containing the BEBLIP group ele-
ments, 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 expan-
sive 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 pre-
ponderance of highly saline fluids and
possibly induce further hydraulic fractur-
ing 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 CI-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 enrich-
ment of the melt in BEBLIP elements,
results in alteration phenomena such as
tourmalization and greisenization, and
is associated with SWUM deposits. The
latter case results simply from post-
magmatic cooling of a CI-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 "pseudoporphries" to
distinguish them from the true por-
phyries, 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 sys-
tems, unlike those shallower than C.
Hence, they would have little opportuni-
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 unfor-
tunately 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 for-
mation waters (cf. Plant et al., 1980), or
where cooling conditions allow efficient
concentration of small amounts of mag-
matic water.
At this point the opportunity should be
taken to point out the close corre-
sence 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 follow-
ing successive stages:
1) Magmatic stage, at which equili-
rium is maintained between silicate melt
and crystalline phases, i.e., at tempera-
tures above the solidi of Figure 7a.
2) Pseudomagmatic 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 equili-
rium is maintained between crystals,
aqueous solution, and aqueous gas, i.e.,
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 chemistry 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,

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