MINERALIZED GRANITES AND THEIR ORIGIN

by

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Interpreting the relationship between the origin of granites and their metallogenic association leads to the establishment of criteria which enable scientists to differentiate mineralized granites from "barren" ones. This article reviews the recent field, analytical and experimental developments in this research area, particularly under the auspices of IGCP Project 26 - "Mineralization associated with acid magmatism". The author presents various models to account for the processes of transportation and deposition of tin and related metals which form mineral deposits of economic importance.*

Geotectonic position of mineralized granites

Granites with associated endogenous ore deposits occur in all the main metallogenic environments of the Earth - in orogenic belts, plate margins, cratons and areas of tectonic reactivation; they were emplaced in epochs ranging from the Precambrian to the Tertiary. Some of them display a general spatial relationship to ores such as Sn, W, Mo, Be, Nb and Ta, although so-called "barren" granites may also occur in the same metallogenic province. For other commodities and deposit types, the spatial dependence either continues to be a subject of scientific dispute, or is not as important as other regional geological factors.

Ore-bearing granites can be traced along major zones such as the Circum-Pacific belt or the tin belts around the Atlantic Ocean (Schuiling, 1967). Theories relating the role of plutonism to geosynclinal development place the origin of ore-bearing granitoids at moderate depths, whereas more recent concepts using plate tectonic models suggest an origin linked to the deepest part of the Benioff zone plunging under the continent (Mitchell and Garson, 1972). The fact that the emplacement of many ore-bearing granitoids is controlled by lineaments crosscutting the main structural units of a particular area may be explained by the reactivation of cratonic material in post-orogenic stages (Shcheglov, 1968), or even sub-crustal sources possibly associated with mantle plumes (Sillitoe, 1974).

Current theories point to an association of ore-bearing granites with deep mantle material. The geochemical cycle involves transport of metals derived from the deep mantle to metal-bearing provinces at relatively shallow depths in the earth's crust.

Ore-bearing granites may vary in size from small plutons (a few km²) with associated dykes, to large and complex plutons with outcrop areas of a few thousand km². Typically, these bodies are internally zoned and mineralization is related not so much to repeated forcible intrusion as to intense metasomatism.

The general dependence of tin, tungsten, molybdenum, niobium, tantalum, and beryllium deposits on their proximity to the granite contact is well known, illustrated most recently by Rundkvist (1977) in his study of 800 endogeneous mineral deposits (Fig. 1).

Petrology and geochemistry of granites

Classification of ore-bearing granitoids varies widely among current schools of petrology, so that the same rock, for example, may be termed by a variety of names. According to Ginsburg (1972), three major groups of ore-bearing granitoids may be distinguished:

Figure 1. The frequency distribution of tin and related mineral deposits in relation to granite contacts based on a sample of 800 deposits (Rundkvist, 1977). Crosses are granite; wavy pattern is country rock.

a) *Rare-element bearing, muscovite granites:* according to French petrologists, these may be synonymous with leucogranites, or partly synonymous with standard granites (Kovalenko, 1977). This group may include biotite, two-mica, aplite, amazonite, and alaskite granites.

b) *Lepidolite-plumasitic granites:* these may correspond to lepidolite-amazonite-albite apogranites (Beus, et al., 1962) or lithium-fluorine granites (Kovalenko, 1977).

c) *Riebeckite-arfvedsonite-aegirine granites:* these correspond to the alkaline (agpaitic) granitoids of Kovalenko (1977), and may be termed also as alkali-feldspar or per-alkaline granites.

The average compositions of common tin-bearing granites (biotite, muscovite and two-mica granites) are closely grouped over the low temperature minima of the feldspar-quartz cotectic of the Ab-Or-Q normative diagram (Stempok and Skvor, 1974). Compositions of the more unusual granites, such as the lepidolite plumasitic (lithium-fluorine) or the so-called "ongonites" (dyke equivalents of lithium-fluorine granites) plot closer to the Ab apex of the diagram (Fig. 2).

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Figure 2. The average normative composition of tin-bearing granites plotted on the Ab-Or-Q diagram for various provinces. 1 Alkaline granite (Kovalenko, 1977), 2 Averages of tin-bearing granites (Stemprok and Skvor, 1974), 3 Lithium-fluorine granites (Kovalenko, 1977), 4 "Ongonites", 5 Contours for the common granites (full lines), 6 Fields for mineralized granites, 7 Cotectic line feldspar-quartz at 500 kb. E_1 and E_2 eutectic points at 5 kb and 10 kb from Luth, Jahns, and Tuftle, 1964.

Granites are commonly subsolvus and their norms usually include low anorthite and some corundum. Texturally, they do not differ from normal granites and generally lack abundant miarolitic cavities considered previously as evidence of the presence of volatile constituents.

The mineral composition of the granites is strongly dependent on the secondary alterations which have been termed by various schools as late-magmatic, deuteric, autometamorphic, autometasomatic or post-magmatic. A general classification for the sequence of these alterations was presented by Beus and Zalashkova (1962) who distinguished between post-magmatic alterations or potash-feldspar metasomatism (I), and albitization (II). Later investigations in several provinces of the world (Central Europe, Nigeria) generally agreed with this scheme. These alterations may lead to changes in the normative composition of the granites as indicated by arrows on Ab-Or-An diagram of Figure 3.

Figure 3. The trends for change in normative composition of granites according to the indicated postmagmatic alteration processes (from Stemprok and Skvor, 1974).

Comparison of the averages of oxides in ore-bearing granitoids and in barren granites has not revealed significant differences. Simple calculations by Stemprok and Skvor (1974) and Tischendorf (1977) showed that tin-bearing granites appear to be silica and K_2O -rich but depleted in other oxides.

Trace elements offer some of the most reliable criteria for differentiating between a potential ore-bearing granite and one that is not. A classification of granites, based on trace element contents, was described by Tauson (1977) who listed selected ranges of amounts of trace elements present in different granite types (Fig. 4). Potential ore-bearing granites classified as agpaite, plumbite leucogranites, and granites of alkaline series have a significantly higher content of F, Li, Sn and Rb and a lower content of Sr and Be. Various models are invoked to account for these enrichments and depletions, some involving fractional crystallization, superimposed post-magmatic alteration and/or hydrothermal leaching.

Differentiation between ore-bearing and barren granites

Opinions on this topic vary from the optimistic (suggesting possibilities of finding ores according to the associated granite type), to the pessimistic (which state that

granite series	average Na ₂ O (wt%)	Na ₂ O (wt%)	ppm F	ppm Li	ppm Rb	ppm Ba	ppm Sr	ppm Zr	ppm Sn	ppm W	ppm Mo
plagiogranites of tholeiitic series	0.92	150	14.7	2.6	157	139	89	2.7	—	—	—
granitoids of andesitic series	0.63	700	10	100	150	260	115	2	—	—	1
granites of albitic series	0.52	600	21	125	1700	700	—	5	3	—	1.7
agpaite granites of rare metals	0.55	2100	104	270	140	12	2170	17.7	—	—	—
polygenic granites of calc-alkaline series	0.49	600	50	175	830	330	190	6.2	2.5	—	1.1
plumbite leucogranites of rare metals	0.45	2700	180	440	175	70	140	22	8.4	—	1.5
polygenic granites of alkaline series	0.49	300	27	140	1950	650	(1410)	3.8	(1.7)	—	1.5
granitoids of alkaline series of rare metals	0.47	300	52	270	500	170	—	5.7	2.1	—	1.8
ultramafic granites	0.36	160	11	140	2800	280	190	2.8	—	—	1.2
intervals according to Tischendorf (1977)		3700±1500	400±200	580±200	—	—	—	40±20	7±3	—	3.5±2

Figure 4. The average distribution of some trace elements in granites of various geochemical types according to Tauson (1977) compared to the averages for mineralized granites according to Tischendorf (1977).

ore-bearing granites can be identified only by the presence of ore deposits).

The following criteria have been presented by Tischendorf (1977) to identify potential ore-bearing granites:

- geotectonic (postkinematic, polyphase, intrusive complexes emplaced at hypabyssal levels and confined to the roof zone of a batholith),
- geochemical (excess of silica and potassium and the depletion of the other oxides; increase of trace elements, as shown in Figure 4, especially from the relatively older to younger intrusive phases),
- mineralogical (leucogranitic composition, early crystallization of quartz, strong post-magmatic alteration, common association of accessory minerals such as cassiterite, fluorite, topaz, tourmaline, columbite, tantalite, and others).

In the U.S.S.R., a distinction has been drawn between ilmenite-monazite and sphene-allanite granitoids, suggesting that the former are tin-bearing.

The presence, however, of these "ore-bearing" characteristics does not necessarily assure the presence of associated ore deposits. Additional factors reflecting other geological processes must be considered.

Why are only some granites ore-bearing?

The distribution of ore-bearing granites in major metallogenic belts has been interpreted by Koptev-Dvornikov and Rub (1964) as a result of the generation of granites in primary metal-rich zones in the crust and mantle. Intrusive primary magmatic rocks can concentrate those metals which are in excess over their "normal" content, such as tin, beryllium, tantalum, niobium. In order for these metals to be sufficiently concentrated so as to form economic ore deposits, further prerequisites are required. These include the existence of volatile constituents, suitable physico-chemical conditions for granite emplacement, favourable country rocks, tectonic setting, and crystal-chemical factors which may lead to dispersion or concentration of elements.

Another school of thought suggests that a granite does not have to have been originally rich in certain elements. Ovchinnikov (1970) and Ryabchikov (1975) believe that metals are capable of being concentrated in any granite magma through the action of water halogen-rich solutions and thus form ore deposits. For example, fluorine is considered to have been the main agent for the extraction, transport and concentration of tin, beryllium and certain other lithophile elements. This is further supported by the intriguing hypothesis that tin is derived from granite through partial melting of sediments along with a significant contribution of F, Cl, B and H₂O which are important agents for transportation and concentration of Sn (Chappell and White, 1974, White, Beams and Cramer, 1977).

Models for concentration of ore-bearing fluids

Four alternate models are currently used to describe the transport and deposition of ore-minerals.

(i) Emanation differentiation

This model postulates the transfer of metals in volatiles which would then accumulate in domes of the roofs of solidifying granite batholiths. Deposition would take place in fissures and faults in the granite or nearby country rock, or become dispersed in them. While the volatiles may become localized in an upper chamber, simultaneous crystallization of the magma in a lower chamber is considered (by Tauson, 1977) to be responsible for the superimposed hydrothermal aureole of a granite (Fig. 5-i).

(ii) Fractional crystallization

This model postulates fractional crystallization differentiation through removal of crystals from the system. Groves and McCarthy (1978) calculated the partitioning of Ba, Rb, Sr between the crystals and melts to develop their model for

crystallization of tin-bearing granites in South Africa, portrayed graphically in Figure 5-ii.

Ryabchikov (1975) calculated "compound" partitioning coefficients for tin and associated elements (Table I) and concluded that even at a value $K_{Sn}^C = 0.2$ the amount of residual tin passing into solution would be capable of producing economic ore deposits. For example, at a fractionation crystallization as high as $K_{Sn}^C = 0.999$ the corresponding K_{Sn}^{fl} of 0.001 (a minimum extraction capability) would yield at least 10³ tonnes of tin to the fluid phase for deposition in mineral deposits.

Table I

Estimated effective distribution coefficients for selected elements calculated based upon the distribution of elements in the phases of the Raunid granite massif, SW Pamir (Ryabchikov, 1975):

element	fractionation crystallization	equilibrium crystallization
Rb	0.3 - 0.5	0.3 - 0.5
Li	0.05 - 0.3	0.02 - 0.3
Sn	0.0 - 0.2	0.15 - 0.4
Be	0.05 - 0.3	0.25 - 0.5
W	0.0 - 0.2	?
Pb	0.55 - 0.65	?
Zn	1	?

(iii) Lateral secretion

This concept appears to account for the observed post-magmatic effects which followed solidification of a granite pluton. The lithophile elements captured by micas (mainly in biotite) and by feldspars (essentially in plagioclase) are redistributed in the post-magmatic stage by solutions permeating the solid rock. The graphical model for such autometamorphism/metasomatism is taken from Shcherba, et al. (1964) and presented in Figure 5-iii.

All three previous models are in agreement on the fluids being derived from the crystallizing magma. Recent isotopic data (Sheppard, 1977) indicate that during the evolution of mineralizing systems, the initial dominance of magmatic

Pine Creek Mine, California, U.S.A., largest operational tungsten mine in North America, is situated near contact of Cretaceous granite intruding grey limestone. Mine site is located in valley between darker meta-sediments (foreground, at right) and pale coloured limestone and granite (background).

Figure 5.

- i A postulated scheme according to Tauson (1977), for the crystallization of a hypabyssal intrusion with a high content of volatile constituents. 1 zone of high-temperature ore concentrations, 2 emanation aureole in country rock, 3 direction of movement of volatiles, 4 high-temperature ore-bearing fluids, 5 zone of cooling and incipient crystallization, 6 the chambers of melts, 7 country rock.
- ii Model for tin mineralization according to Groves and McCarthy (1978): a-initial crystallization of granite composed of hornblende, biotite, plagioclase, and quartz (need not be developed), b-continued crystallization of magma with progressive change in cumulus mineralogy; disruption of early crystals by melt to form a hornblende-free body, c-further disruption of early crystals during continuing crystallization, d-continuing crystallization with melt achieving water saturation; separation of a tin-poor vapour that collects in structural highs under roof to form barren pegmatite sheets, e-water-saturated melt crystallizes red or yellow-brown, miarolitic, muscovite-bearing granite; Sn, F- and/or B-rich vapours in late intercumulus liquid cause greisenization beneath roof zone; cassiterite-rich pipes may develop adjacent to greisenized granite; mineralization may occur along late fractures. 1 Tin mineralization in late fractures; 2 Greisenized granite-cassiterite-rich pipes; 3 Barren pegmatite sheet, 4 Red to yellow-brown muscovite-bearing granite, 5 Biotite-K-feldspar-plagioclase-quartz cumulate, 6 Hornblende-biotite-plagioclase-quartz cumulate, 7 Tin-poor vapour; 8 Water saturated melt, 9 Water-undersaturated melt; 10 Direction of crystallization; 11 Intrusion of granitoid magma.
- iii Autometamorphism of a cooling intrusion according to Shcherba, et al. (1964) caused by postmagmatic solutions. 1 Pegmatites, 2 Greisen, 3 Veins, 4 Stockworks, 5 Microcline granite, 6 Albitized granite, 7 Greisenized granite, 8 "Normal" granite, 9 Variably metamorphosed or altered country rock, 10 Direction of movement of post-magmatic solutions, 11 A Zone of microclinization, B Zone of albitization I, C Zone of weak greisenization, D Zone of microclinization II, E Zone of albitization II.
- iv Movement and concentration of mineralizing solutions from deep crust into roof zone of a granite body (after Stempok, 1963). 1 Country rock, 2 Solidified granite, 3 Source of the ore-bearing granite, 4 Stratified source of presumed alkaline-rich melt, 5 Zone of ore deposition, 6 Direction of movement of postgranitic solutions, 7 Direction of movement for the addition of mantle material.

hydrothermal solutions is lost as a result of the influx of meteoric, connate and sea water. For example, meteoric-hydrothermal water appears to have been a dominant or major component of the fluids involved in greisenization associated with Cornubian tin and tungsten deposits.

(iv) Undercrust sources

In this model the granites are not thought to be the direct source of the ore elements. Instead, both granites and ores are derived from a common deep-seated source (Stemprok, 1963). Peralkaline liquid, which is a very probable source material of some granites (Bailey and Schairer, 1962) may produce peraluminous granite with ore constituents which follow the paths of granite ascent (Fig. 5-iv) and subsequent strong alterations. Further support for this model is the development of tin deposits in Nigeria derived from mantle and crust (Bowden, 1979) in both the Palaeozoic and Mesozoic (Kinnaird, 1979). This may imply a sub-crustal source available through a long period of geological time.

Although none of the models proposed account for all the geological facts, each may be tested in future studies of specific deposits and metallogens.

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