Economic Geology: Lecture Notes

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Granitoids and Pegmatites

Lecture Contents

I. Origin of granitic magma

II. Factors affecting the mineralization of Granitic magma

III. Ore deposits in pegmatites

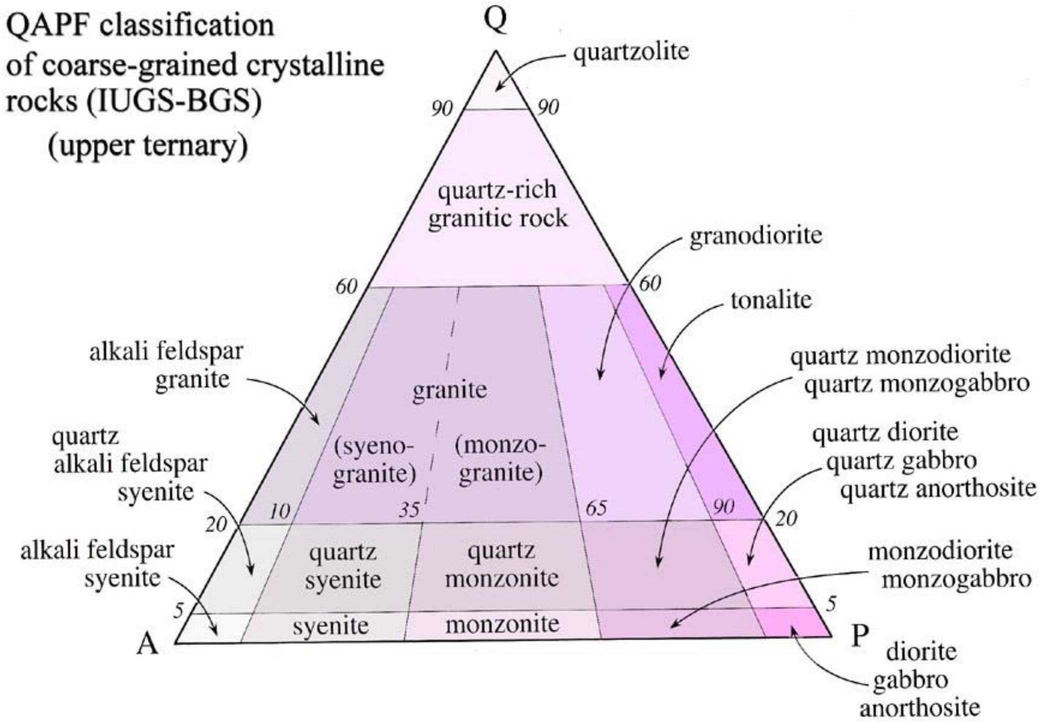
4. Granitoids and ore formation processes

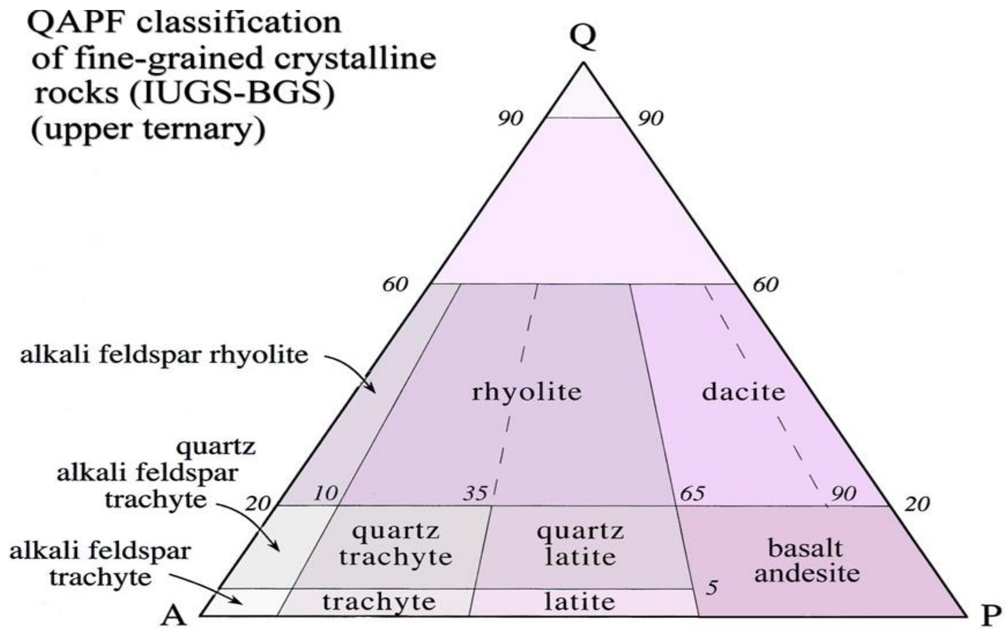
Granitoids are felsic plutonic rocks with more than 20 wt.% quartz.

The ore formation potential depends on origin and evolution of the parental granitoid.

Important controls are:

1. **the plate tectonic setting;**
2. **the nature of source rocks;**
3. **P/T-parameters of melting;**
4. **content of water and other volatiles;**
5. **the depth of intrusion;**
6. **coeval tectonic deformation;**
7. **partial pressure of oxygen (redox state) of the melt;**
8. **assimilation of country rocks and the evolution of the magma by fractionation;**
9. **cooling and crystallization including fluid segregation.**





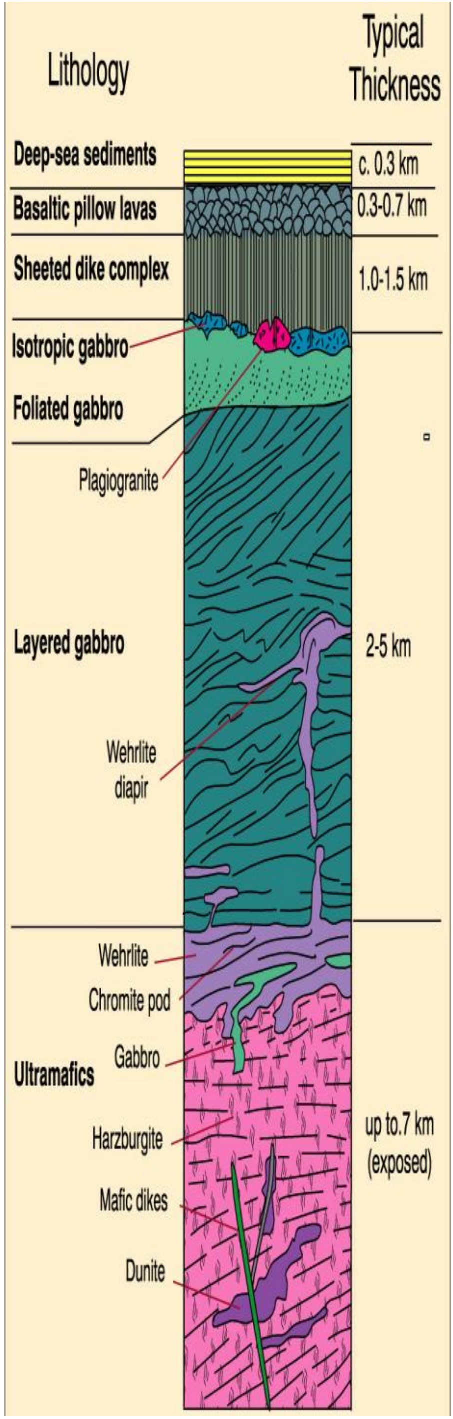
I. Origin of granitoid magma: Trace elements and isotopes in granitoids provide valuable information on the source rocks of granitoids:

1. **Peridotites of the Earth's upper mantle (asthenosphere, lithosphere).**

M-type granitoids are sourced in the mantle. They intrude the crustal rocks of ophiolites in the form of plagiogranite and quartz diorite. Typical ore deposits associated with M-type granitoids are copper-gold porphyries and hydrothermal gold.

2. **Magmatic and metamorphic rocks of the deep continental crust (infracrustal).**

I-type granitoids originated by melting of pre-existing infracrustal igneous rocks. I-type granitoids are the most common intrusive magmatic rocks. They display an abundance of hornblende and higher concentrations of Ca, Na and Sr compared with granites derived from sediments. Examples of the I-type granitoids are tonalites and granodiorites. The magma formed the I-type granitoids are undersaturated with water, which enabled them to rise to the surface, forming volcanic rocks (e.g. andesite and dacite).



Accessory minerals of I-type granitoids are often magnetite and titanite (magnetite-series magmatic rocks). This is due to a commonly higher oxidation degree of I-type magmas, although reduced I-type granitoids are known.

Characteristic ore deposits related to I-type granitoids are:

1. the iron oxide-copper-gold (U-REE) deposits (IOCG),
2. copper-molybdenum porphyries,
3. Mo-W Cu skarn,
4. hydrothermal lead-zinc and
5. certain gold and silver ores.

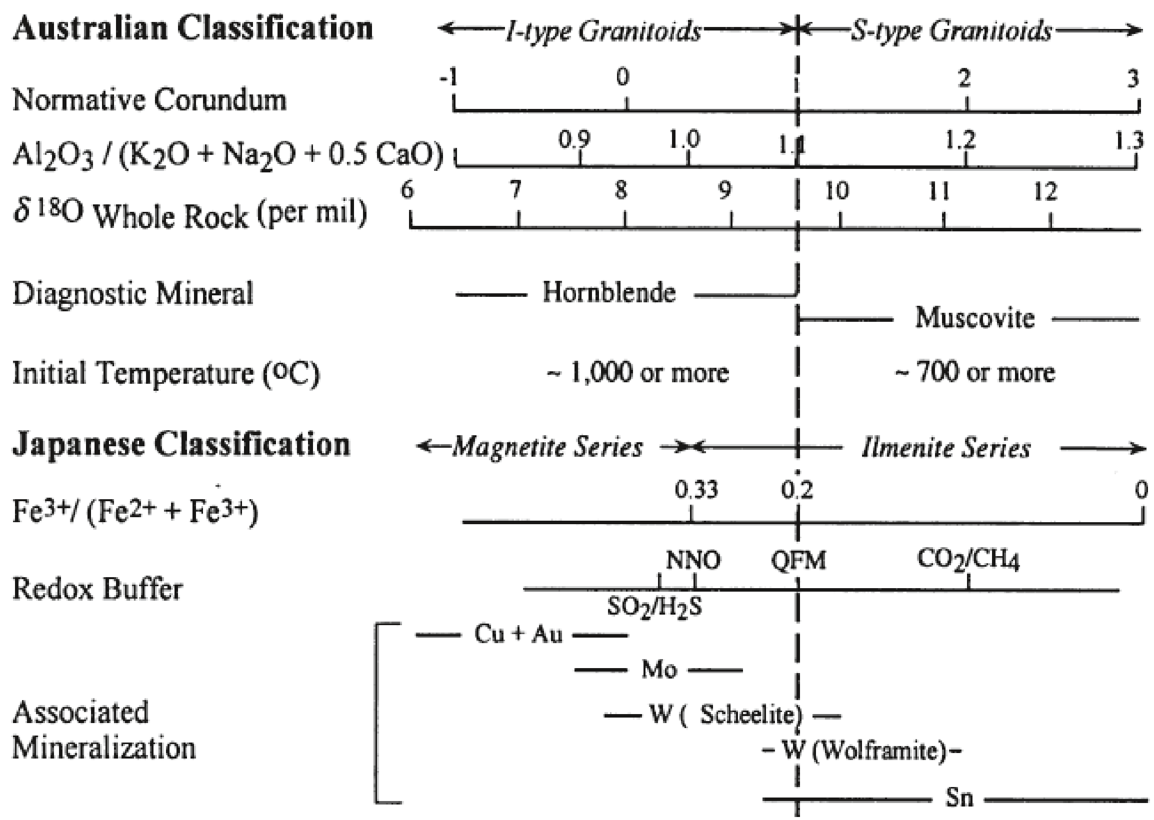
Tonalite

Granodiorite

3. Clastic meta-sediments and their metamorphic equivalents.

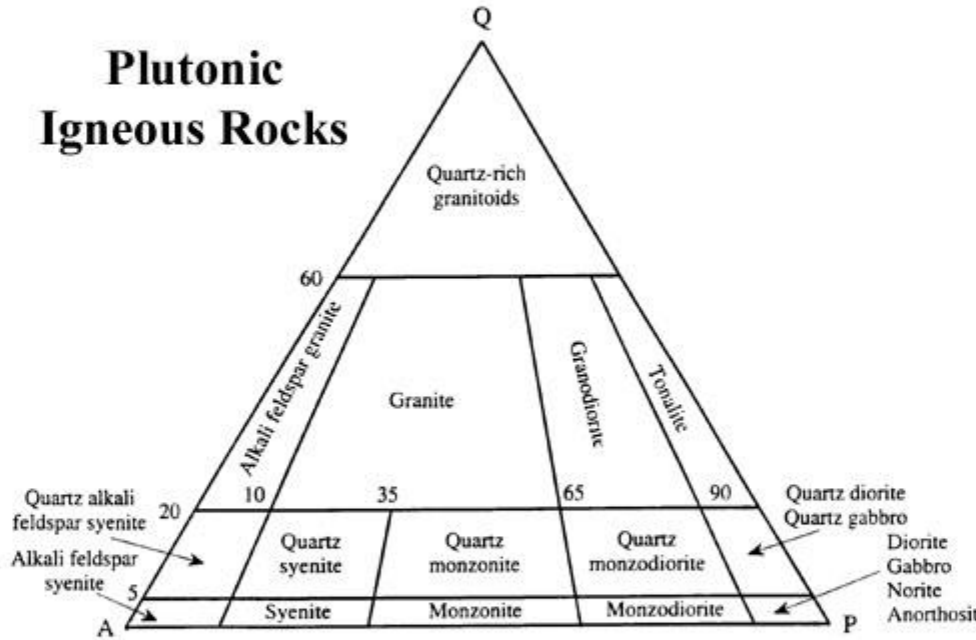
S-type granitoids originate by continental collision and deep subduction of sediments to great depths and high temperatures. Resulted melts are mainly leucocratic, SiO_2 rich rocks of a monzogranitic nature, often with muscovite and biotite. Accessory minerals include cordierite, garnet, kyanite and ilmenite (ilmenite-series magmatic rocks). The oxidation of these magmas is low, due to organic carbon in the source sediments. The water of the melts is derived by dehydration of muscovite in the metasediments. Highly fractionated intrusions could have the following ores: tin, tungsten and tantalum ore deposits.

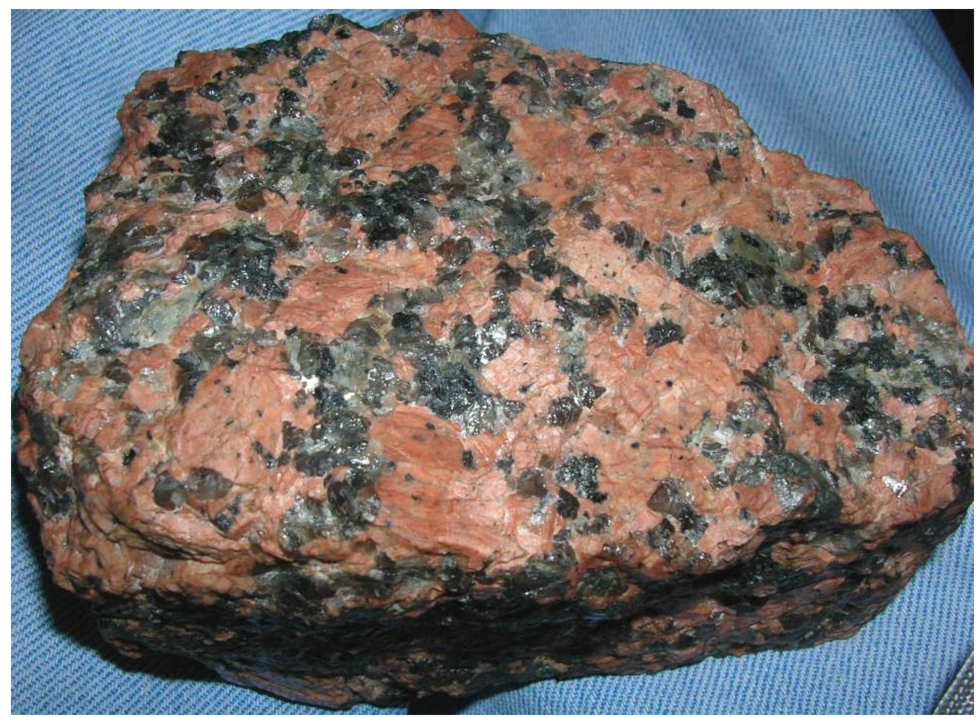
Generalized characteristics of I-type and S-type granitoids (after Ohrnoto 1986). Note that magnetite-series and ilmenite-series granitoids. as defined by Ishihara (1977) on the basis of modal compositions (relative abundance of magnetite vs. ilmenite) and bulk Fe203:FeO ratios, correspond only roughly to I-type and S type granitoids.



4. Restites of sediments and of magmatic rocks that have experienced earlier anatexis before a later melting event.

A-type granitoids "alkali rich, aluminous and anorogenic" are the product of repeated melt-extraction from the same source rocks. Some granites that have A-type characteristics may be derived by extreme fractionation of I- and S-type magmas. With every cycle of melting the source rocks acquire a more pronounced restite composition, marked by enrichment of less mobile substances. Another possible source of A-type magma is lithospheric mantle and not all A-granites are anorogenic. Typical A-type granites are the alkali granites of continental Rifts. Volcanic equivalents include tin-rich topaz rhyolites in fields of crustal distension.





Two different ore associations occur with A-type granitoids:

i. **Sodium-rich granites, contain concentrations of niobium, uranium, thorium, rare earth elements and some tin.**

ii. **Potassium- rich granites with abundant hydrothermal silicification, tourmalinization and acidity produce deposits of tin, tungsten, lead, zinc and fluorspar.**

Not all granites can be assigned to one of the source categories (SIAM) because of several reasons including complex mixtures of source rocks and extreme fractionation, which leads to increasing convergence of magma chemistry.

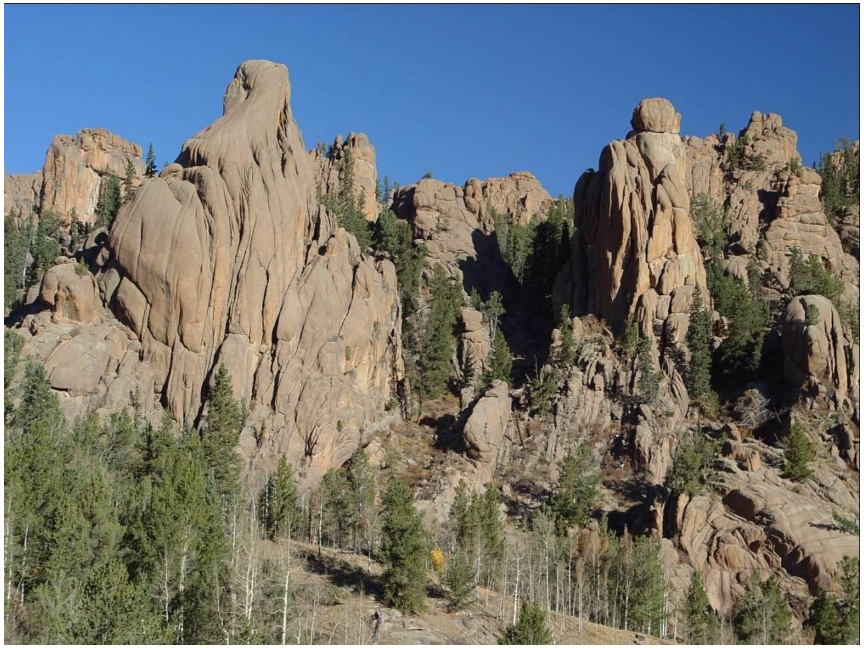
II. Factors affecting the mineralization of Granitic magma

A time-dependent chemical evolution of intrusions has been noted in many granite-related ore provinces:

i. Early batholithic intrusions are geochemically ordinary,
ii. later and smaller precursor granites are geochemically transitional to;
iii. small geochemically specialized granites;
iv. very small, mineralized granites which are intimately related to ore formation.

Compared with geochemically ordinary granites, precursor granites display higher content of K, SiO_2 and granophile trace elements (elements last to crystallize), and less Fe, Ti, Ca, Sr and Mg. Precursor intrusions always predate - come first - specialized granites, although they are genetically related.

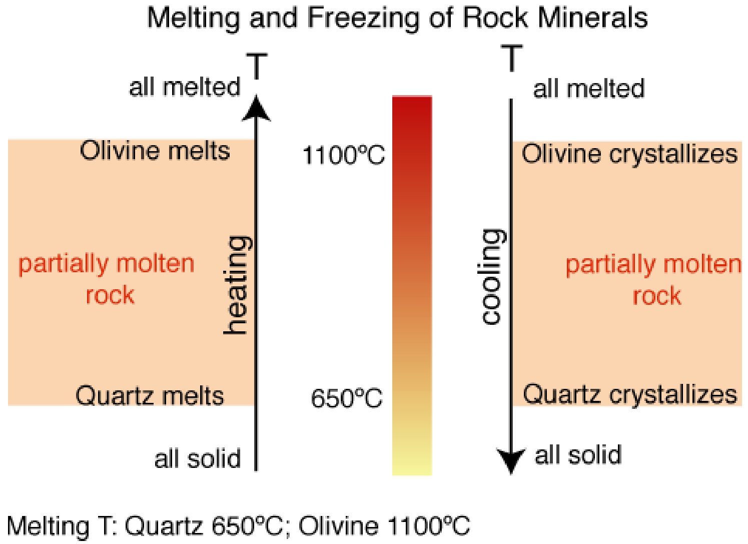
Specialized and mineralized (parental) granites are distinguished by geochemically elevated content of metals, such as Sn, W, Nb, Ta, Mo, U, Th, REE, Rb, Cs, Li, Be, often F (the latter include "topaz granites") and P. In specialized granites, rare elements are enriched in silicates and accessory minerals. Mineralized or parental granites, in contrast, stand out by their close relations to ore-grade concentration of rare elements.

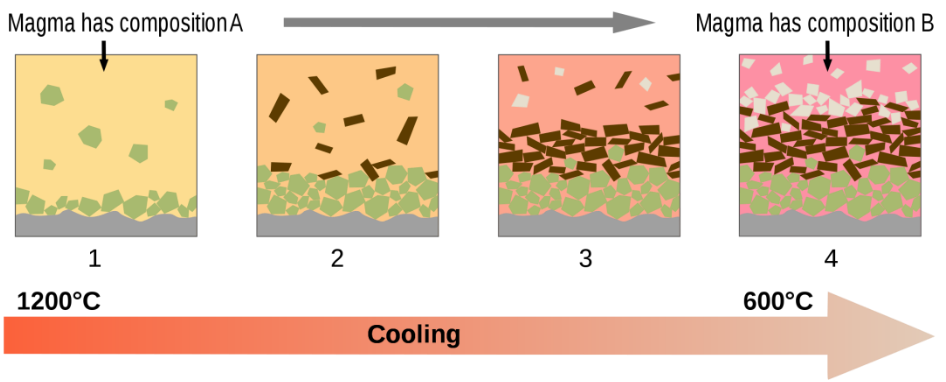


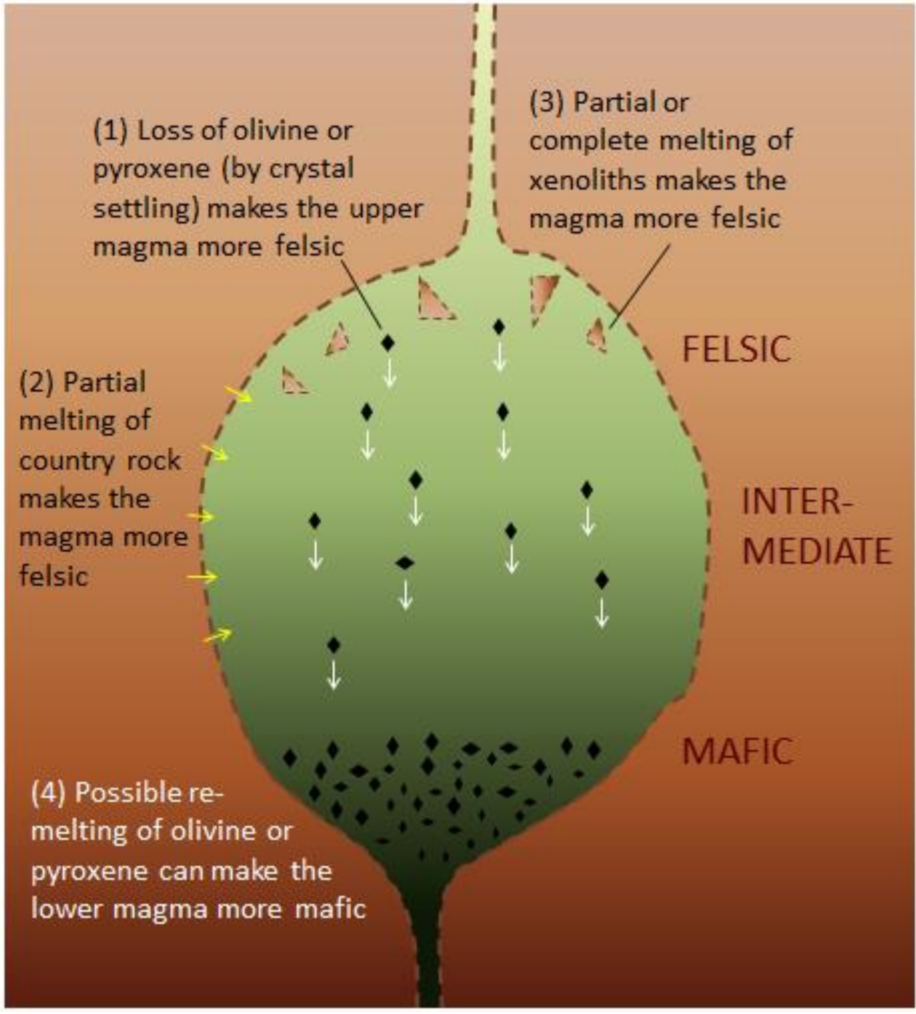
There are some trace elements found in granitic melt. These elements - because of their sizes, charges and/or chemical affinity - are strongly partitioned into the fluid phase and not to be crystallized with granitic silicate minerals. These elements are called "granophile trace elements". Eventually, they are concentrated to form mineral deposits related to granitic intrusions. These deposits are also called granophile mineral deposits. B and Be have very small sizes and can not substitute in the lattices of normal silicate minerals of granites. So, they form ore minerals such as tourmaline and beryl.

1. **The geochemical changes from ordinary to mineralized granitoids are mainly caused by a process system, which is generally termed "magmatic fractionation". Granites with extreme chemical fractionation are the source (and often the hosts) of deposits of rare elements including Sn, Li and Be.**

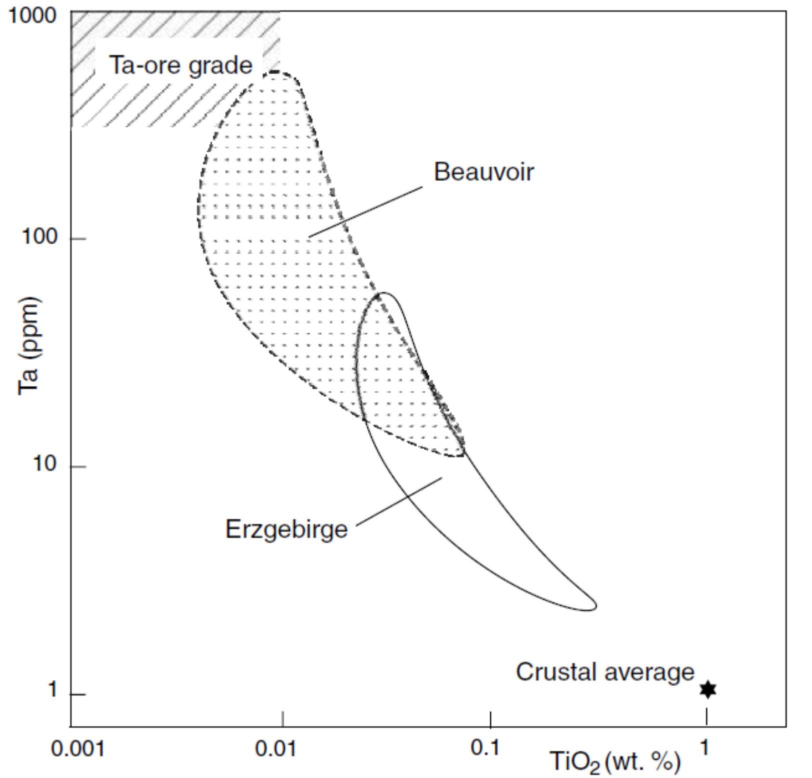
These granites are enriched in Large Ion Lithophile Elements (LILE) such as Rb and Cs, and high field strength elements (HFSE) such as P, Y, Zr, Hf, Nb, Ta, Th and U.







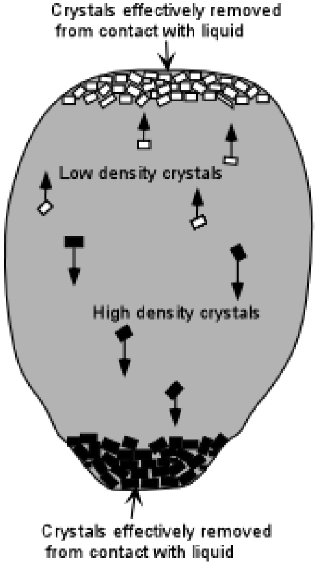
The increase of the magmatic differentiation shows how tantalum (Ta) (an incompatible element) is continuously enriched by increasing differentiation of successively more fractionated granite melt and finally reaches exploitable grades.



Ta/TiO2 variation of granites

The increasing differentiation of magmas is caused by fractional crystallization, early crystal settling and/or removal of liquid melt.

In some cases, melting of geochemically anomalous source rocks is considered to account for metal enrichment. Examples are magmas with a high content of the chalcophile elements Au, Ag, Bi, Sb, Hg and Tl, which are supposedly inherited from a pre-enriched melt region.



NB. a trace element is one whose concentration is less than 1000 ppm or 0.1% of the rock composition. Trace elements will either prefer liquid or solid phase. If compatible with a mineral, it will prefer a solid phase (e.g., Ni is compatible with Olivine). If it is incompatible with an element it will prefer a liquid phase. The measurement of this ratio is known as the partition coefficient. Trace elements can be substituted for cations in mineral structures.

Elements that partition preferentially into the solid phase (included in the silicate minerals during magma crystallization) are referred to as compatible because they are included in nascent rock-forming silicate minerals, for example europium in plagioclase. Incompatible elements concentrate in the liquid (melt) phase.

Lithophile or oxyphile elements are common in crustal silicates but are incompatible with minerals that have an important role in the formation of mantle magmas of basic and ultra-basic composition (e.g. olivine, pyroxene, spinel, garnet). Lithophile elements include Al, Si, O, alkalis, earth alkalis, rare earth elements and actinides, as well as metals such as Ti, Ta, Nb and W.

[Pyroxenes have the general formula $XY(Si,Al)_2O_6$ where X represents calcium, sodium, iron (II) or magnesium and more rarely zinc, manganese or lithium and Y represents ions of smaller size, such as chromium, aluminium, iron (III), magnesium, cobalt, manganese, scandium, titanium, vanadium or even iron (II). Although aluminium substitutes extensively for silicon in silicates such as feldspars and amphiboles, the substitution occurs only to a limited extent in most pyroxenes].

LIL elements (Large Ion Lithophile) such as Rb, Sr, K, Ba, Zr, Th, U and light REE are preferentially enriched in late, highly differentiated melt derived from restites, because these elements are less prone to partition into early water-rich liquids.

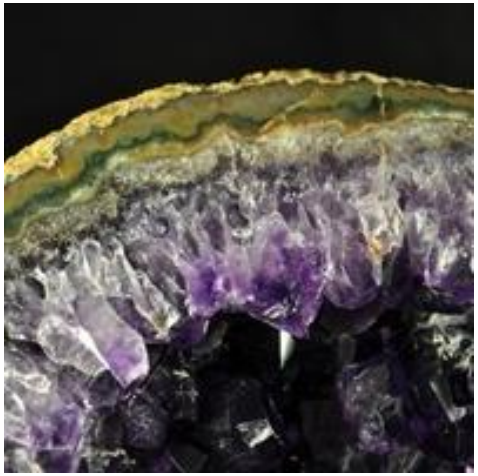
Cations with a high charge (3 to 6) such as Mo, Nb, Zr, Sn, W, Ta, U, Th, Y and REE are called High field Strength (HFS elements). HFS elements are normally abstracted (depleted/withdrawn) from the melt by incorporation in crystallizing biotite, amphibole, apatite, zircon, monazite and magnetite. However, this process is inhibited/prevented by high activity of complexing volatile compounds, which cause these HFS elements to collect/concentrate in late liquid and fluid phases.

2. The fertility of granitoids is closely related to differentiation, fractionation and the formation of exsolved magmatic volatile phases.

The composition of magmatic volatile phases is investigated by sampling volcanic exhalations, fluid inclusions in minerals (especially from miarolitic cavities) and volatiles included in volcanic glass.

Miaroles are crystal-lined cavities in granitoids that are thought to have formed from fluid pockets during the solidification of magma.

Fluid and melt inclusions preserved in miarolitic minerals reveal details about segregation, composition and evolution of mineralizing fluids.



Miaroles

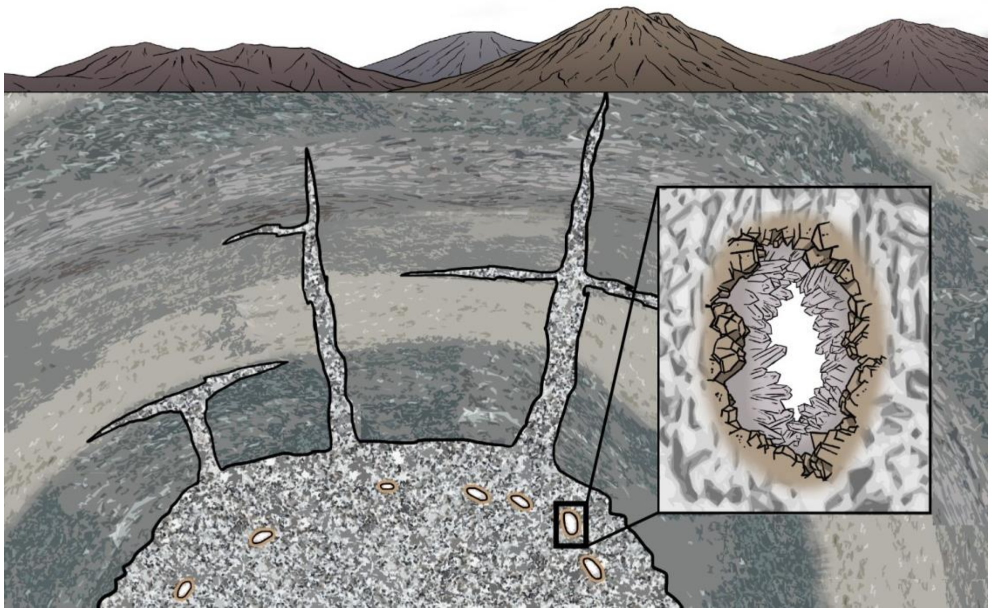


Diagram of great magma chamber. The voids – Miaroles - caused by discharge of the gases from the chamber magma crystallized quartz .

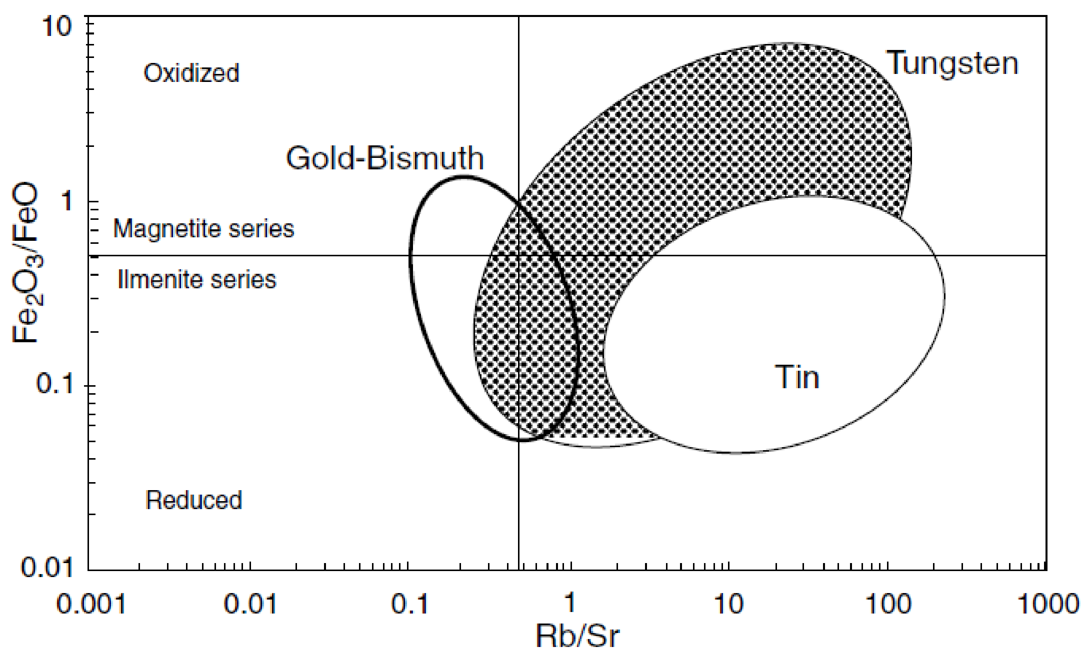
Fertile granitoid magmas are distinguished by high content of volatiles. Volatiles collect the rare elements that form ore, and also lower density, viscosity and solidus temperature of a melt increasing the melt mobility. Low magmatic temperatures and high salt concentrations favour the fractionation of metals into the fluid phase.

Water is the most common magmatic volatiles. In silicate melts, dissolved water reaches a maximum of 8 wt.% or 25 mole %. Water is followed in decreasing order by CO_2, H_2S or SO_2, HCl and HF, and small amounts of N_2, H_2, CO, P, B, Br, CH_4 and O_2.

3. Oxygen fugacity (pressure) in the melt is an important control for ore formation. High oxygen in granitic magma (oxidized environment) (magnetite series) causes depletion of tin (Sn) and tungsten (W) in the liquid and in late fluids (let them devoid of), because these metals are abstracted - taken - in dispersed accessory minerals already during main-stage crystallization.

Behaviour of copper (Cu) and uranium (U) is quite the reverse of tin (Sn) and tungsten (W). Oxidized magmas (of less sulfur) dissolve sulphur as an "anhydrite component", therefore the melt and its derived fluids may contain large non-sulfide Cu-Au deposits, i.e., mineralization could occur within the granite during crystallization.

In "reduced" granitic magmas (less oxygen and more sulfur) (ilmenite series), early sulphur saturation causes formation of dispersed sulphide droplets that collect copper and gold.



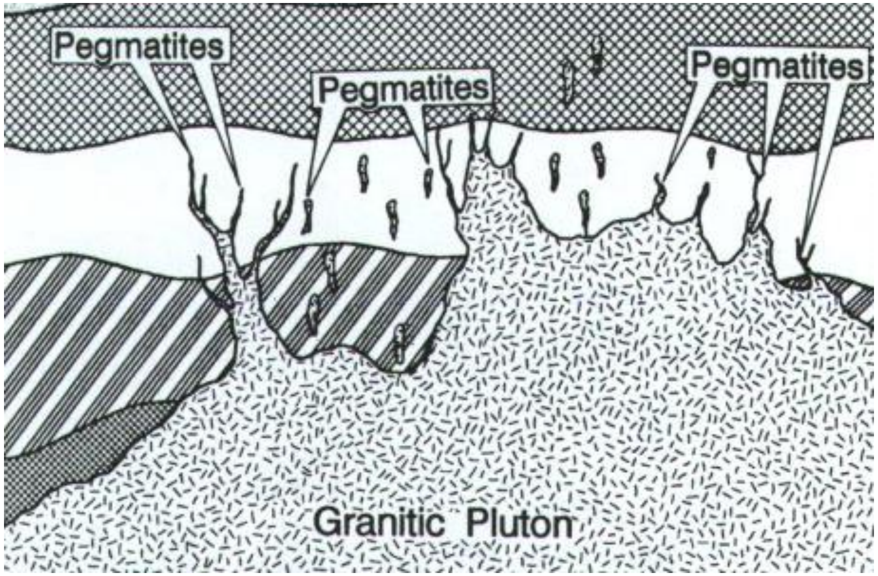
Typical fields of granites which are genetically associated with tungsten, tin and gold-bismuth deposits, in a plot of redox-state (vertical axis) versus increasing specialization (horizontal axis).

5. Ore deposits in pegmatites

Pegmatites crystallize from highly fractionated hydrous residual melt batches of felsic magma bodies that are enriched in volatiles and incompatible trace elements.

Pegmatites are characterized by:

1) coarsely crystalline textures,
2) occasionally by giant crystals,
3) miarolitic cavities,
4) minerals of rare elements.



Most pegmatites are related to granites and have a paragenesis of orthoclase (perthite), microcline, albite, mica and quartz. Common minor minerals include tourmaline, topaz, beryl, cassiterite and lithium minerals.

Felsic pegmatite melts intruding ultramafic rocks suffer de-silication resulting in plumasites that are characterized by corundum, kyanite and anorthite.

Gabbro pegmatites are derived from mafic magmas. **Gabbro pegmatites** are composed of anorthite, pyroxene, amphibole, biotite and titanomagnetite, occasionally including carbonates and sulphides. **Iron-rich ultramafic pegmatites composed of olivine.**

Rare syenite pegmatites with microcline, nepheline, apatite, niobium and rare earth element minerals are related to alkaline intrusions.

Anatectic pegmatites (metamorphic segregations) that are formed in the upper amphibolite facies are rarely mineralized. Yet, some mineralized pegmatites may have originated by partial anatexis at great depth.

Most pegmatites crystallize at intermediate crustal levels, at fluid pressures of 200 Mpa (2 kbar).

Gabbro pegmatites

Syenite pegmatite

Pegmatites are mostly Granitic and can be classified based on their emplacement depth which leads to differentiation of the following types:

1. **Abyssal pegmatites** are anatectic in migmatites of amphibolite and granulite facies metamorphic zones.

2. **Muscovite pegmatites** occur in amphibolite facies kyanite-mica schists and are commonly related to granites, but exhibit little fractionation.

3. **Highly fractionated rare element pegmatites** are derived from strongly differentiated fertile granites; host rocks typically contain cordierite and andalusite.

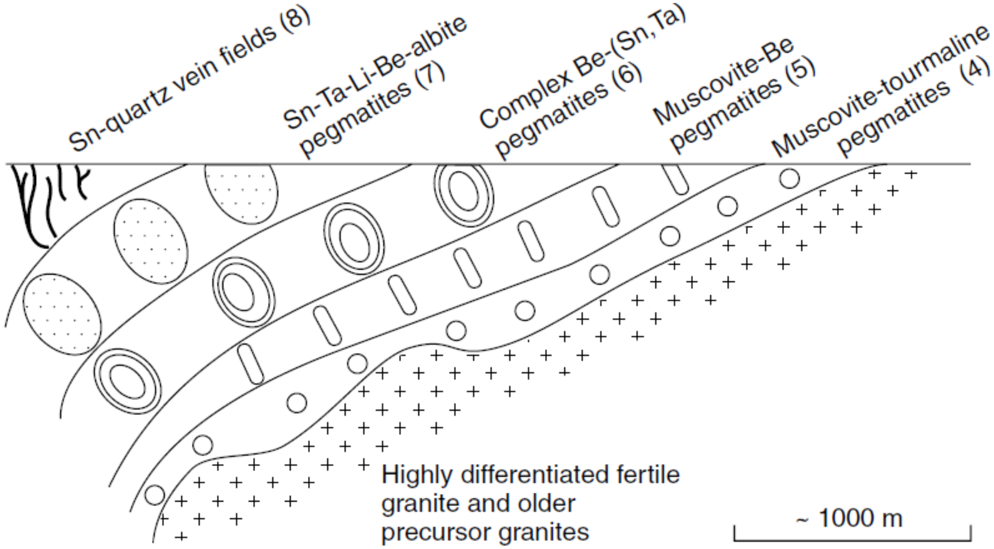
4. **Miarolitic pegmatites** form at low pressure (1.5–2 kbar) and are proximal to granites. They may contain quartz of optical quality, various gemstones and valuable crystals of many rare minerals.

Miarolitic pegmatites

Muscovite pegmatites

Granitic pegmatites occur in the form **of dykes, oval and lenticular bodies**. Most pegmatite bodies are relatively small with tens of meters thickness and a length of a **few hundred meters**. Some pegmatites occur at the roof of granite and form a thin shell between the intrusion and the roof rock.

Granitic pegmatites may be **isotropic (homogeneous)** (without a change of mineralogy or texture from wall to wall) OR **anisotropic (inhomogeneous - “zoned” or “complex” pegmatites)**.



External zonation of rare element pegmatites and cassiterite quartz veins near fertile granites in Central Africa

The **internal zonation** of complex pegmatites reflects crystallization from **the walls to the centre** of a pegmatite body.

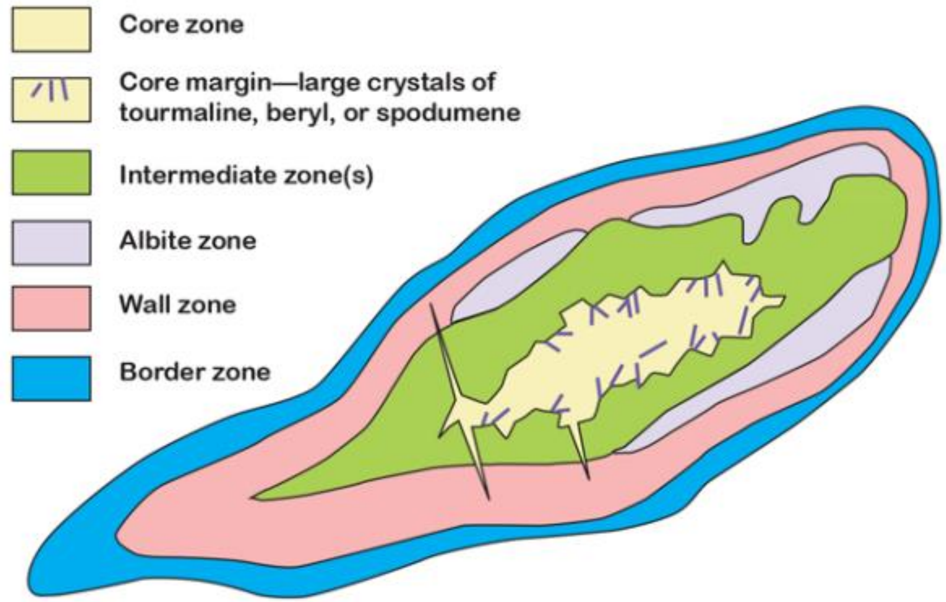
The following zones are distinguished:

1. **Border zone:** often fine-grained = aplitic, and very thin;

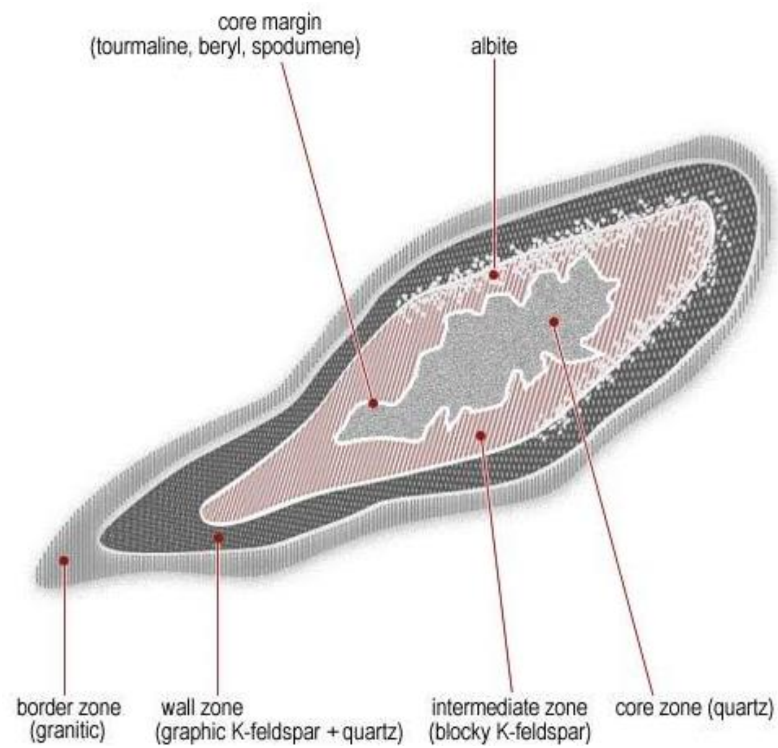
2. **Wall zone:** coarsely crystalline with exploitable muscovite and beryl;

3. **Intermediate zones:** albititic with microcline and contain the valuable minerals (cassiterite, columbite, spodumene, beryl, etc.);

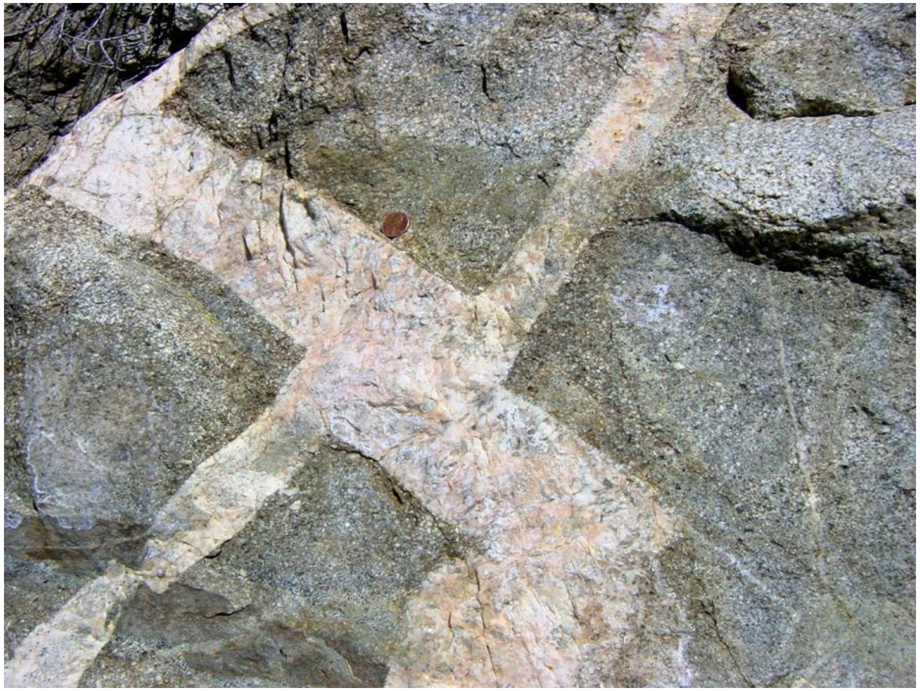
4. **Core:** which is commonly a solid mass of barren grey or white quartz, but may also contain feldspar, tourmaline and spodumen.



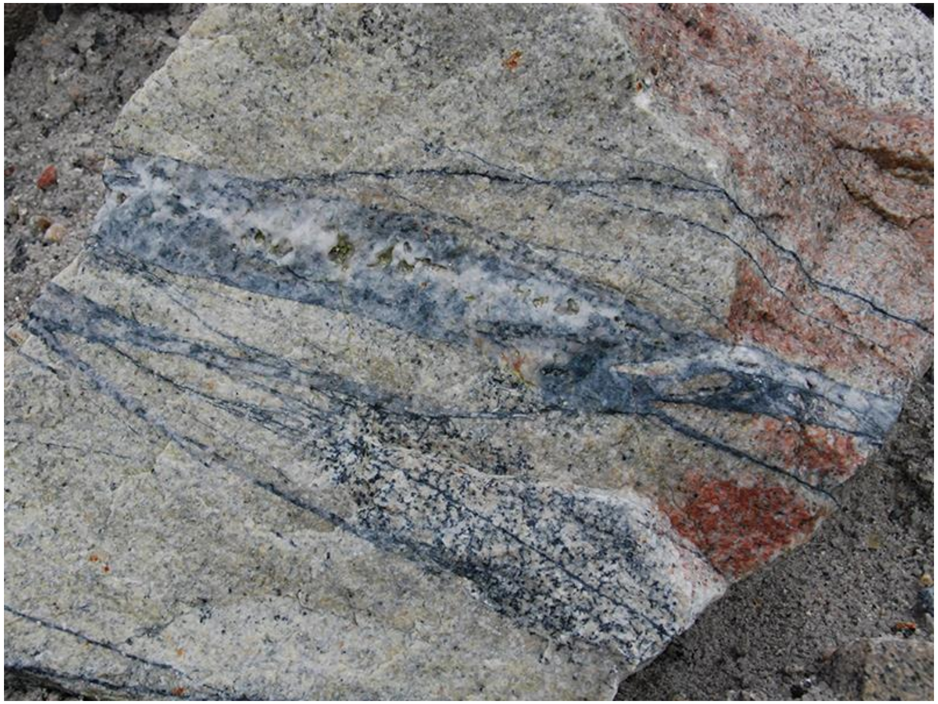
Deposit-scale zoning patterns in an idealized pegmatite



The internal zonation in complex pegmatites might have two causes: i) fractional crystallization in a closed system; or ii) repeated injection of new melt batches in an open system.



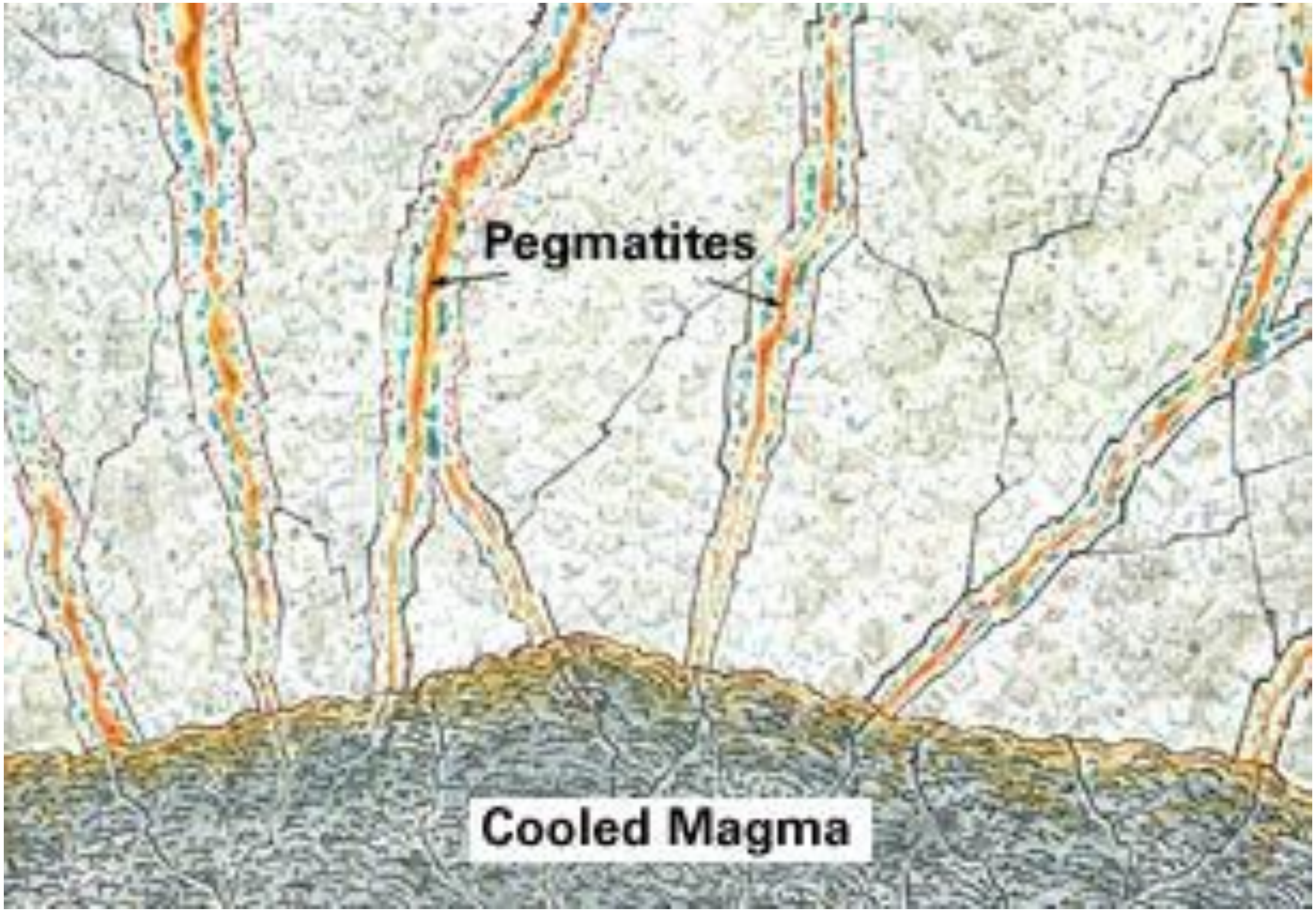
A chemical exchange directed from enclosing rocks to the pegmatite is possible. The wall zone could contain tourmaline-rich $(Ca,K,Na)(Al,Fe,Li,Mg,Mn)_3(Al,Cr,Fe,V)_6(BO_3)_3(Si,Al,B)_6O_{18}(OH,F)_4$ due to reaction of iron and magnesium mobilized from the host rocks with boron from the volatile phase of the pegmatite.



The pegmatite melts/liquids are ejected along with enrichment of water, B, F, P, Sn, Rb and other incompatible elements, while the main magma body crystallizes. Another possibility is that small pegmatitic melt batches rise directly from the source region of the “parent” granite.

Pegmatites may host many useful raw materials. These include ores of Be, Li, Rb, Cs, Ta > Nb, U, Th, REE, Mo, Bi, Sn and W, the industrial minerals muscovite, feldspar, kaolin, quartz, spodumene, petalite and fluorite, and gemstones as well as rare mineral specimens (emerald, topaz, tourmaline, ruby, etc.).

The derivation of pegmatites from I-, S- and A-type granites is probably the main control of the availability of specific elements for enrichment.



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