

9. Metasomatism and metasomatic rocks¹

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Introduction

A Study Group was set up under the leadership of N. Pertsev to consider the nomenclature of metasomatism and metasomatic processes. This paper reports the conclusions of that group.

Definition of metasomatism

The term metasomatism was introduced by Naumann (1826). *Metasomatism*, *metasomatic process* and *metasomatose* are synonyms although some authors use *metasomatose* as a name for specific varieties of metasomatism (e.g. Na-metasomatose, Mg-metasomatose, etc.). Metasomatism is defined as follows:

Metasomatism: *is a metamorphic process by which the chemical composition of a rock or rock portion is altered in a pervasive manner and which involves the introduction and/or removal of chemical components as a result of the interaction of the rock with aqueous fluids (solutions). During metasomatism the rock remains in a solid state.*

Metasomatic rocks, in general, have a granofelsic or granoblastic structure. They may be coarse- or fine-grained and may sometimes exhibit banding which may be rhythmic. They may demonstrably overprint earlier structures.

Metasomatism is separated from other endogenic processes by the following features (Zharikov et al., 1998):

1. *From the ion-by-ion replacement in minerals* (e.g. zeolites) by mechanisms in which the dissolution of minerals occurs synchronously with the precipitation of new minerals thus maintaining a constant volume and conforming with Lindgren's (1925) rule of constant volume during metasomatism. A good example of metasomatism is the pseudomorphic

¹ This paper is based on the report of the Study Group on Metasomatic rocks; it presents a systematic scheme and defines related terms. It is noted, however, that several of the terms have not been subject to extensive international usage and are therefore, under the SCMR rules, classified as restricted. Therefore the results of the paper are presented as provisional recommendations.

² It is with sadness that we record the death of Vilen Zharikov on 29th July 2006

replacement of a mineral crystal by another mineral (or by a mixture of other minerals) with preservation of the former shape and volume.

2. *From the group of processes including the infilling of cavities or cracks, magma crystallisation, and magma-rock interactions*, by the preservation of rocks in the solid state during replacement (the volume of solution filling pores is negligible in comparison with the total rock volume). The crystallisation of melts follows the eutectic law. However the main trend of metasomatic replacement, that is with a decreasing number of mineral phases from the outermost zone to the solution conduit is incompatible with the eutectic law. The chemical and mineral composition of magmatic rocks are uniform throughout the greater part of a magmatic body in contrast to the zonation pattern of metasomatic rocks. Magmatic rocks particularly residual melts are typically polymineralic in contrast to metasomatic rocks thus terms like *metasomatic granites* are incorrect according to metasomatic theory.

3. *From isochemical metamorphism* by substantial changes in the chemical composition by either the addition or subtraction of major elements other than H₂O and CO₂. Changes in the water and/or carbon dioxide concentrations are allowed in isochemical metamorphism, thus hydration/dehydration or carbonation/decarbonation reactions are not specific to metasomatism and terms such as *carbonate metasomatism* or *hydrometasomatism* are undesirable. Only H₂O and CO₂ are perfectly mobile (in a thermodynamic sense) during metamorphic processes, whereas during metasomatic reactions other rock- or ore-forming components may become perfectly mobile. The number of coexisting minerals in metasomatic zones is usually less than in a replaced rock unless the former rock was monomineralic.

4. *From magmatism and metamorphism* by the formation of a regular set of zones. These zones form a characteristic pattern (*metasomatic column*) across the metasomatic body. The zonal pattern represents chemical equilibration between two rocks or between a rock and a filtrating fluid (solution). In the case of diffusional metasomatism mineral changes across the zones are transitional whereas in the case of infiltrational metasomatism changes across zones occur in steps. The number of metasomatic zones in the column depends on the physico-chemical conditions of the interacting media. In the simplest cases it can be represented by a single zone. All zones in a metasomatic column are generated and grown contemporaneously, increasing their thickness along the direction of mass transport.

A **metasomatic column** (or metasomatic zone pattern) is the complete sequence of metasomatic zones characterising an individual metasomatic facies.

Types of metasomatic processes

There are two main types of metasomatism, namely, *diffusional* and *infiltrational* as determined by the prevailing nature of the mass transport (Korzhinskii, 1957). They are defined as follows:

Diffusional metasomatism is a type of metasomatism that takes place by the diffusion of a solute through a stagnant solution (fluid). The driving force of diffusion is the chemical potential (or chemical activity) gradients in the rock-pore solution.

Infiltrational metasomatism is a type of metasomatism that takes place by the transfer of material in solution, infiltrating through the host rocks. The driving force is the pressure and concentration gradients between the infiltrating and rock-pore solutions.

Diffusional metasomatic rocks form rather thinly zoned bodies (rims) along cracks, veins, and contact surfaces and the composition of minerals may vary gradually across each metasomatic zone. Infiltrational metasomatic rocks generally occupy much greater volumes and the composition of minerals is constant across each of the metasomatic zones.

The term *metasomatism* is conventionally limited by hydrothermal conditions (both sub- and super-critical) related to endogenic processes. Rock alteration under hypergenic (exogenic) conditions is strongly dependent on chemical kinetics, surface forces, and microbiological activity, which are less noticeable in the hydrothermal environments. Therefore hypergenic processes have to be related to *hypergenic metasomatism*.

Alteration at high pressures and temperatures in the mantle is connected with concentrated liquids whose properties are intermediate between fluids and magmas. The processes are quite specific, although the mechanisms are not clear. These processes are referred to as *mantle metasomatism*.

Korzhinskii (1953) stressed the relation of metasomatism to magmatism and distinguished two metasomatic stages namely: *metasomatism of the magmatic stage* and *metasomatism of the postmagmatic stage*. The first stage is connected with fluids emanating from a liquid magma body and metasomatising the solid host rocks. Metasomatic processes of the postmagmatic stage are retrogressive and are connected with hydrothermal solutions both emanating from the cooling magma and/or other heated exogenic sources, due for instance to the mixing of juvenile water with meteoric water.

The following common types of metasomatism can be recognised according to their geological position: *autometasomatism*, *boundary metasomatism*, *contact metasomatism*, *near-vein metasomatism*, and *regional metasomatism*.

Autometasomatism is a type of metasomatism that occurs at the top of magmatic bodies during the early postmagmatic stage. Typical autometasomatic processes, for example, are albitisation in granitic plutons and serpentinitisation of ultramafic rocks.

Boundary metasomatism is a type of metasomatism that occurs at the contact between two rock types

Contact metasomatism is a type of metasomatism that occurs at or near to the contact between a magmatic body and another rock. It may occur at various stages in the magmatic evolution. *Endocontact zones* develop by replacement of the magmatic rocks and *exocontact zones* are formed by replacement of the host rocks.

Bimetasomatism is a variety of the contact metasomatism, which causes replacement of both the rocks in contact due to two-way diffusion of different components across the contact.

Near-vein metasomatism: is a type of diffusional metasomatism, which forms symmetrical metasomatic zonation on either side of an infiltrational metasomatic vein (or a vein infilling).

Regional metasomatism occupies great areas developing in various geological situations. It commonly forms alkaline metasomatic rocks during the magmatic and early postmagmatic stages. Regional metasomatic rocks at moderate and even shallow depths form the outer zones of metasomatic rock associations accompanying ore deposits (*near-ore*) such as greisens, quartz-sericite rocks, propylites, and some others. The inner zones marked by intensive metasomatism are commonly rimmed by zones of weak alteration extending over great areas (Gryaznov, 1992; Plyushchev, 1981; Zhdanov et al., 1978). The weak alteration zones can be enclosed in turn by regional metamorphic rocks especially since the processes of metamorphism, metasomatism, and magmatism are intimately related.

Systematics of metasomatic rocks

General approach

The classification of metasomatic rocks is a much more difficult problem than that of magmatic rocks. Knowledge of the mineral and chemical composition as well as the structural features is insufficient for determining the type of metasomatic process, because the composition of a metasomatic rock depends not only on T, P, and replaced rock composition, but also on the type and stage of the metasomatic process and the composition of the fluid or solution.

So, for a genetic interpretation a hierarchical system may be constructed.

- 1) The basic unit is a rock with its mineral and chemical composition and structure (a *metasomatic zone* is taken as a specific rock with a single paragenesis).
- 2) An assemblage of rocks formed under specific physico-chemical conditions determines a *metasomatic facies*. Each facies is characterised by a specific type of metasomatic zonation or zonal assemblage.
- 3) A petrogenetic process (including magmatic, tectonic, and hydrothermal activity) commonly forms a number of metasomatic facies characteristic of that process. This facies-association forms a *metasomatic family*.

Some difficulties arise here because metasomatic rocks of similar composition can be produced by different hydrothermal metasomatic processes with different metallogenic associations, and so, they have to be separated.

Thus it becomes important to determine the distinguishing features of each petrogenetic process that results in the formation of a specific association of metasomatic rocks or facies. The nature of the 'metasomatising' solutions is one of the most important of these features.

The evolution of metasomatic systematics.

Metasomatic rock classifications were initially based on either the newly formed mineral assemblage (Lindgren, 1925; Schwartz, 1939) or on the input-loss chemical mass balance (Goldschmidt, 1921; Eskola, 1939; Turner, 1948; Barth, 1952). The facies approach was developed subsequently by Burnham (1962). However, neither of these approaches took account of the geological environment of the metasomatic rocks nor the nature of the metasomatic processes. The concept of associated groups of metasomatic facies or *families* ('metasomatic formations' in Russian publications) allowed the development of a more geologically based classification in which each metasomatic family (e.g. skarns, fenites,

greisens, beresites, propylites, secondary (or hydrothermal) quartzites, argillites, etc.) includes an association of rocks tied to a specific petrogenetic process. These ideas were first proposed in the fifties (Korzhinskii, 1953; Nakovnik, 1954; Zharikov, 1959). However, the facies approach remained the common method of classification for some time thereafter although proposals to base classifications on the family ('formation') concept continued in Russia during the period from the 60s to the 90s (Zharikov & Omel'yanenko, 1978; Zharikov, Omel'yanenko & Pertsev, 1992; Rundquist & Pavlova, 1974; Belyayev & Rudnik, 1978; Plyushchev, 1981; Shlygin & Gukova, 1981; Zhdanov et al., 1978, Gryaznov, 1992). A recent summary of some of this work is given in Zharikov et al. (1998).

The systematic scheme

Metasomatic zone: *is a metasomatic rock defined by a specific mineral paragenesis.*

Metasomatic facies: *is a regular set of metasomatic zones (a metasomatic column) developed under similar physico-chemical conditions (the compositions of the original rock and the metasomatised rock, the temperature and pressure conditions and the composition of metasomatising solutions or fluids).*

Metasomatic family: *is the totality of related metasomatic facies typical of a given petrogenetic process. The facies differ from each other by the appearance or disappearance of mineral parageneses or metasomatic zones reflecting a difference in one (or more) of the physio-chemical parameters.*

The underlying concept of the 'metasomatic families' is the acid-basic interaction of hydrothermal fluids and their general evolution as they cool through time from an **early alkaline** to an **acidic** and then to a **late alkaline** substage (Korzhinskii, 1953; Zharikov, 1976). The related metasomatic process involves a mass balance change as a result of input/loss of acid (SiO_2 , F, Cl, SO_3 , CO_2 , etc.) and alkaline/basic (K_2O , Na_2O , CaO, MgO, etc.) components. The acidic metasomatic rocks (or the products of acid leaching) show common enrichment with acid components and depletion of alkalies and alkali earths relative to the initial rocks. Alkaline and basic metasomatism produces the opposite mass exchange. Each of the metasomatic families that have been distinguished relate to a specific T-pH field: the most common metasomatic families are shown on Figure 9.1. All the fields plotted on Figure 9.1 may be divided into two general groups, namely: those with and those without quartz (acidic and neutral-alkaline). The acidic group may be further divided into three subfields forming bands of approximately equal acidity according to the stability of (1) clay minerals, (2) muscovite-hydromicas and (3) feldspars. The alkaline group is divided in the same way into subfields with stable parageneses containing (1) feldspars and (2) feldspathoids (nepheline).

Within most of the metasomatic families some facies may be distinguished on the basis of variations in the mineral assemblages related to the component activities in the hydrothermal solutions, the most important of which are variations of the F, Cl, S, CO_2 , K_2O , Na_2O , MgO, and CaO chemical activities.

The metasomatic families

The following is a brief description of some of the metasomatic families shown in Figure 9.1.

Fenite family

Fenites are high temperature metasomatic rocks composed mainly of K-Na-feldspars (perthite or antiperthite), albite, nepheline, alkaline pyroxenes (aegirine, aegirine-diopside, aegirine-augite), alkaline amphiboles (arfvedsonite, riebeckite, hastingsite, richterite); subordinate minerals include biotite-phlogopite micas, magnetite and ilmenite and the most common accessories are titanite and apatite (Brögger, 1921; Bardina & Popov, 1994; Evdokimov, 1982). In some cases fenites contain calcite. Fenites are related to alkaline-ultramafic magmatic complexes and may replace a wide range of rocks including ultramafic rocks and carbonatites formed in the early magmatic stages, as well as acid host rocks such as granite-gneisses and more rarely sandstones. The fenitisation process occurs in exocontact aureoles of nepheline syenites. Fenites are formed mainly or completely during the magmatic stage by silica-undersaturated alkaline magmatic fluids. The mass transport will modify the initial rock composition (the rocks have usually significantly less alkalis than the magmas and are silica-saturated) towards the magma composition through a series of metasomatic zones. The width of fenitisation aureoles may reach several kilometres.

The zonation of fenites depends strongly on the composition of the replaced host rocks and that of the magma. In the general case the first (outermost) zone is characterised by the disappearance of quartz. The next (intermediate) zone is commonly composed of pyroxene or amphibole + orthoclase (and/or albite). The innermost zone may contain nepheline, and sometimes may even be composed of monomineralic nephelinite. This last zone contains offshoots of alkaline magma.

The SCMR definition therefore is:

Fenite: *a high-temperature metasomatic rock characterised by the presence of alkali feldspar, sodic amphibole and sodic pyroxene; nepheline, calcite and biotite/phlogopite may also be present and typical accessories are titanite and apatite. Fenites occur as zoned aureoles around alkaline igneous complexes, forming in a wide range of host lithologies. They occur on the metre- to kilometre- scale.*

Fenitisation *is a metasomatic process leading to the formation of fenites.*

Skarn family

Skarn *is a metasomatic rock formed at the contact between a silicate rock (or magmatic melt) and a carbonate rock. It consists mainly of Ca-Mg-Fe-Mn- silicates, which are free or poor in water.*

Skarns (Goldschmidt, 1911) can form flat bodies along the contact (*contact skarns*) or occur as veins, pipes, etc. crossing the carbonate and/or the silicate rocks (*vein skarns*). Skarns formed from the magmatic or other silicate rock are termed *endoskarns* and skarns formed from the carbonate rocks are termed *exoskarns*. The outermost zone of endoskarns or the nearest zone of the exoskarn to the parental magmatic body may contain not only Ca-Mg-Fe silicates but also feldspar or scapolite and/or feldspathoid. For such rocks Korzhinskii (1953) introduced the special name *near-skarn rock*.

According to their composition and genetic features skarns have been divided into two major groups, namely: *magnesian skarns* developed at contacts with magnesian carbonate rocks (dolomites or magnesites), and *calc- (or lime-) skarns* formed at contacts with limestones and marbles poor in magnesium.

Skarns generally contain various metal ores. The theory of skarn genesis has been extensively studied (Korzinskii, 1953; Zharikov, 1959, 1968, 1970, 1991; Einaudi et al., 1981; Pertsev, 1977, 1991; Zaraisky, 1989; and others).

Subfamily of magnesian skarns

Magnesian skarns may develop in both the magmatic (prograde, in contact with magmatic fluids) and postmagmatic (retrograde) stages.

Magnesian skarn: *is a high-temperature skarn rock containing forsterite, diopside, spinel, periclase, clinohumite, phlogopite, pargasite and formed at the contacts of magmatic and calc-magnesian or magnesian carbonate rocks. Typically magnesian skarns may host ores of iron, base metals, Cu, Au, Fe-Mg- borates, and phlogopite.*

Magnesian skarns related to the magmatic stage are characterised by mineral assemblages of fassaitic pyroxene, forsterite, magnesian spinel, enstatite, monticellite, åkermanite, merwinite, and periclase. The typical zonation pattern (column) is: granite (or another silicate rock) → plagioclase (An₇₀₋₉₅) + diopsidic clinopyroxene → fassaitic clinopyroxene + spinel → forsterite + spinel → forsterite + spinel + calcite → dolomite (arrows show the direction of the zonal growth in the column). Orthopyroxene parageneses occur only when the chemical activity of CaO is low, for example, at the contacts with magnesite. Magnesian skarn facies of the magmatic stage, which are dependent on T-pCO₂ conditions and CaO activity, are: dolomite, periclase, magnesite, enstatite, forsterite-calcite, monticellite, monticellite-periclase, monticellite-spurrite, åkermanite, merwinite, merwinite-periclase and corundum-plagioclase (spinel occurs in each facies).

Magnesian skarns related to the postmagmatic stage are mainly developed as replacements (partly or completely) of former magnesian skarns developed during the magmatic stage. Their zonation and columns are less uniform and more complex. New characteristic minerals and parageneses appear along with the residual stable minerals of the magmatic stage. Spinel parageneses give place to phlogopite and pargasite. The main facies which are dependent on P-T conditions and the chemical activity of CO₂, K₂O, Na₂O, F₂, Cl₂, B₂O₃, FeO are: phlogopite-diopside, phlogopite-forsterite, magnetite-forsterite, diopside-monticellite, monticellite-brucite, monticellite-dellaite, monticellite-foshagite, pargasite-diopside, clinohumite, magnetite, ludwigite, kotoite, suanite, and others. The temperature range in which the subfamily is formed is about 750-450 °C at pressures of 0.5-10 kbar.

Magnesian skarns of both stages are commonly replaced in varying degrees by postmagmatic calc-skarns under moderate P-T conditions due to increasing CaO chemical activity with decreasing temperature and a corresponding decrease of CO₂ concentration in fluids (Pertsev, 1977). Low-temperature post-skarn alteration leads to the replacement of skarn minerals by serpentine, chlorite + actinolite, carbonates, and brucite.

Common ore mineralisation accompanying the formation of magnesian skarns is iron (magnetite) and borate (ludwigite, suanite and kotoite). A wide variety of ore mineralisation (Cu, Mo, W, Be, Sn, Pb, Zn, Au, B, and others) may be overprinted by lower temperature hydrothermal processes. The ores are formed along with postskarn hydrosilicates (actinolite, serpentine, talc, chlorite), carbonates, and some other minerals.

A rare facies of skarn is analogous to magnesian skarns except that the magnesium in minerals is completely replaced by manganese. Typical minerals are johannsenite, tephroite, glaucochroite, sonolite and galaxite. This facies is developed at the contacts of silicate rocks with manganese carbonates. Some investigators call them *manganesian skarns*. These metasomatic rocks appear to have formed at the postmagmatic stage and at low temperatures. Ca-Mn clinopyroxenes (johannsenite) as well as Ca-Mn pyroxenoids are characteristic of the manganese-bearing facies of calc-skarns. Normally, minerals of magnesian skarns do not contain noticeable Mn.

Subfamily of calc-skarns

Calc-skarn: *is a high (to medium) temperature skarn consisting mainly of granditic garnet, salite (to ferrosalite or/and johannsenite-rich pyroxene), wollastonite or Mn-rich pyroxenoids and formed at the contacts of magmatic (or other silicate rocks) with calcium carbonate rocks. It can replace former magnesian skarns (in hypabyssal or subvolcanic conditions). Typically calc-skarns may host ores of Fe, base metals, Cu, W, Mo, Be, B, U, REE.*

All (or almost all) calc-skarns belong to the postmagmatic stage. Typical minerals for the subfamily are granditic garnet, vesuvianite, clinopyroxene (salite up to hedenbergite or johannsenite), wollastonite, rhodonite and bustamite, epidote, scapolite, plagioclase, less common are more high temperature silicates with mole ratio $\text{Ca/Si} \geq 1.5$.

The typical facies succession, from the outermost endoskarn to the outermost exoskarn, is characterised by a bimineralic zone (where andesine or scapolite or K-feldspar is associated with salite or grossular or epidote), followed by a monomineralic (granditic garnet or calcic clinopyroxene) zone or bimineralic (garnet-clinopyroxene) zone, which may or may not be followed by a wollastonite zone. The specific mineralogies depend on both T-P conditions and the chemical activities of Na_2O , K_2O , F_2 , Cl_2 , SO_3 , FeO , O_2 , CO_2 and T-P conditions. These typical calc-skarns are formed in a temperature range of about 650-400 °C at pressures 0.5-4 kbar.

Some relatively low temperature skarns are enriched with Fe^{2+} and Mn^{2+} (hedenbergite or johannsenite molecules in pyroxenes, spessartite in garnets, rhodonite and bustamite). Some investigators call them *iron-calc* and *mangan-calc* skarns.

High temperature calc-skarn facies are marked by the appearance of zones containing Ca-rich silicates such as gehlenitic melilite, tilleyite, spurrite, rankinite, kilchoanite and merwinite. The temperature of their formation is 700-900 °C, at pressures of 0.5-1.5 kbar and $X_{\text{CO}_2} < 0.05$.

Magnetite ores can be formed in coexistence with skarn garnets and clinopyroxenes.

The formation of hedenbergite and johannsenite parageneses with quartz and quartz-garnet assemblages as well as amphiboles takes place during postskarn alterations along with or after the breakdown of skarn minerals. Different types of ores are formed at that time, namely: W, Sn, Be, Mo, B (danburite and datolite), Cu, base metals, Au, Ag, U, REE.

Rodingite family

Rodingites have mineral compositions resembling iron calc-skarns, namely: grossular (or hydrogarnet), clinopyroxene of the diopside-hedenbergite series (usually enriched with Fe^{2+} , Fe^{3+} and Al), vesuvianite, epidote, scapolite, and magnetite or haematite. The rock was originally described as magmatic (Bell et al., 1911) but later Grange (1927) showed that it was a metasomatic rock replacing a gabbro dyke. The physico-chemical conditions of

rodingite formation were experimentally studied by Plyusnina et al. (1993). The formation of rodingites requires the addition of CaO to the rock. Unlike skarns, rodingites do not demonstrate distinct zonation. Rodingites are commonly situated inside serpentinite masses presumably replacing bodies of basic rocks. Many investigators believe that rodingites appear during the serpentinisation of ultrabasic rocks, as a result of the alteration of basic dykes and/or inclusions. Other geologists suppose that rodingitisation is an autometasomatic process connected with postmagmatic fluids released from a cooling basic magma. Possibly, there are different types of rodingite formation as they may occur not only in serpentinites but also in basalts and even as rocks replacing amphibolites in gneiss terrains. Rodingites may, in places, contain iron and gold ores.

The SCMR definition therefore is:

Rodingite: *is a metasomatic rock primarily composed of grossular-andradite garnet and calcic pyroxene; vesuvianite, epidote, scapolite and iron ores are characteristic accessories. Rodingite mostly replaces dykes or inclusions of basic rocks within serpentinised ultramafic bodies. It may also replace other basic rocks, such as volcanic rocks or amphibolites associated with ultramafic bodies.*

Rodingitisation: *is a metasomatic process leading to the formation of rodingites.*

Greisen family

Greisens (Lempe, 1785) are quartz-muscovite rocks commonly with topaz, fluorite, tourmaline, and locally with orthoclase or amazonite. Small amounts of lepidolite, andalusite and diaspore may also occur. They may replace granites, sandstones, or micaceous schists. The greisen family of metasomatic rocks includes some facies related to varying activity ratios of F, Cl, CO₂, and B. Greisens are divided into two groups: greisens replacing Al-Si rocks (quartz, quartz-muscovite, muscovite-K-feldspar, quartz-tourmaline, and quartz-topaz facies) and those replacing Al-Si undersaturated rocks, for example those with ultrabasic or carbonate compositions (fluorite-muscovite and feldspar-fluorite facies). Under specific conditions greisens replacing leucogranite can form feldspar-muscovite, fayalite-quartz, siderophyllite-quartz and other acid zones. Greisens are either the products of pervasive greisenitisation in granite bodies, or form as veins, and vein borders. Rocks of this family relate to post-orogenic leucocratic granitic plutons at hypabyssal or subvolcanic depths. They may replace either the granites (*endogreisens*) or the country rocks (*exogreisens*), which are commonly metasediments. Pervasive greisenitisation occurs in the apical parts of granitic plutons and is commonly accompanied with skarn and quartz-feldspar metasomatic rock formation. Greisens are typically associated with Be, W, Mo, Sn, Ta mineralisation (Nakovnik, 1954; Rundquist et al., 1971; Schwartz, 1939; Zaraiskii, 1989).

The SCMR definition therefore is:

Greisen: *is a medium-temperature metasomatic rock characterised by the presence of quartz and white mica, commonly with topaz, fluorite, tourmaline and locally with amazonite, orthoclase, andalusite and diaspore. Typically greisens may host Be, W, Mo, Sn, and Ta mineralisation. They are associated with high-level late-orogenic leucogranites and form as replacements either in the granite body and/or in a wide range of country rocks. Zoning may be present.*

Greisenisation *is a metasomatic process leading to the formation of greisen.*

Beresite family

Beresite was originally a special Russian term for quartz-sericite-ankerite-pyrite metasomatic rocks and associated ore veins (Rose, 1837; Borodaevskii & Borodaevskaya, 1947; Rusinov, 1989). It originated by replacement of granite. The term was later widened to include the products of replacement of other rock types, of both igneous and sedimentary origin. These rocks are the result of acidic metasomatism under conditions of feldspar and kaolinite instability. The beresitisation process in ultrabasic rocks forms *listvenite* (quartz + Fe-Mg carbonate + fuchsite + pyrite) and in the silica saturated rocks it forms beresites. Subgroups of beresite are distinguished by the following parageneses (containing pyrite): quartz-sericite-ankerite, quartz-sericite-calcite, quartz-sericite, sericite-chlorite-calcite, and hydromica-quartz. Beresites are associated with a variety of Au, Au-Ag, Ag-Pb and U ore mineralisation.

The SCMR definition therefore is:

Beresite *is a low-temperature metasomatic rock characterised by quartz, sericite, carbonate (ankerite) and pyrite assemblages resulting from the replacement of both igneous and sedimentary protoliths. It may be associated with a variety of Au, Au-Ag, Ag-Pb, U ore mineralisations.*

Beresitisation: *is a metasomatic process resulting in the formation of beresite or listvenite.*

Propylite family

Propylites (the term was introduced by Richtofen in 1868) are metasomatic greenstones, which occur in various types of ore fields replacing volcanogenic and related rocks (Rusinov, 1972, 1989). They used to be classified as 'regional' metasomatic rocks, because they form an aureole around the ore deposits and can even occupy the whole extent of an ore field. Low temperature propylites consist of albite, chlorite, calcite, quartz, and pyrite. At higher temperatures epidote, actinolite, biotite, and magnetite (instead of pyrite) are formed. Propylites occur in various tectonic settings, but are commonly related to island-arc felsic or intermediate volcanism and to some post-orogenic hypabyssal granodiorite bodies. Propylite facies based on temperature variations may be distinguished, namely: low temperature calcite-chlorite-albite facies and high temperature epidote-actinolite-biotite facies. The facies are related to the postmagmatic stage with increasing acidity of the hydrothermal solution. The metasomatising solutions are nearly neutral. The CO₂ fugacity is higher than the stability field of pumpellyite and prehnite (prehnite can be formed only at very shallow levels, where CO₂ fugacity is low) and albite+calcite±chlorite assemblages are formed instead of these minerals. Ore mineralisation, directly related to post-propylite beresites, may overprint the propylite rocks. The ore mineralisation associated with propylites varies widely, with the possibility of Cu, Pb-Zn, Au, Au-Ag, Ag-Pb-Zn, Hg, Sb minerals.

The SCMR definition therefore is:

Propylite: *is a low to medium temperature metasomatic granofels formed by the alteration of basic volcanic rocks; low temperature varieties are principally composed of albite, calcite and chlorite; high-temperature varieties are composed of epidote, actinolite and biotite. They form at the postmagmatic stage.*

Propylitisation: *is a metasomatic process leading to the formation of propylites.*

Secondary (or hydrothermal) quartzite family³

Secondary (or hydrothermal) quartzites are metasomatic rocks consisting mainly of quartz (50-100 vol.%) with high alumina minerals, replacing granites, volcanic and less commonly sedimentary rocks. Some facies of the secondary quartzites are similar to products of advanced *argillisation* (see below). The main minerals of the secondary quartzites, apart from quartz, are sericite, pyrophyllite, diaspore, andalusite, corundum, alunite, kaolinite, pyrite, and haematite. Relatively common are fluorite, dumortierite, zunitite, rutile, tourmaline, topaz, svanbergite, and lazulite (Nakovnik, 1965; Schmidt, 1985).

Secondary quartzites relate to volcanic suites (rhyolitic or dacite-andesitic composition) and to subvolcanic granite-porphyry or monzonite-porphyry intrusions. Three groups of secondary quartzites are distinguished:

1.- a higher-temperature group, closely related to intrusive bodies, containing the following parageneses: corundum + andalusite, andalusite + pyrophyllite, diaspore + pyrophyllite, quartz + sericite, zunitite + sericite, and dumortierite + sericite. The quartzites of this group are commonly barren of mineral ores, except for some alaskitic granites with Mo-porphyry deposits (Climax type);

2.- a transitional group with quartz + sericite. This group is associated with copper-porphyry Au-bearing deposits;

3.- a low-temperature sulphate group commonly associated with dacite-andesite volcanic activity, and characterised by the following parageneses: quartz + kaolinite, kaolinite + alunite, alunite + hydromica, alunite + pyrophyllite, and an exotic quartz-barite facies. Quartzites of this group are associated with deposits of Cu, Sb, Hg.

The formation of 'secondary quartzite' is commonly accompanied by the redeposition of MgO and Al₂O₃, and also some bodies of chlorite-rich rocks and sericite-rich rocks.

The SCMR definition therefore is:

'Secondary quartzite': *is a medium- to low- temperature metasomatic rock mainly composed of quartz with subsidiary high-alumina minerals, such as pyrophyllite, diaspore, alunite and kaolinite. Common accessories include fluorite, dumortierite and lazulite. Secondary quartzites are associated with volcanic and subvolcanic rocks of rhyolitic to andesitic composition. Normally they form as replacements of acid igneous rocks and more rarely of sedimentary rocks. They may host mineral deposits of alunite, pyrophyllite, Au, Cu, Sb, Hg.*

Gumbeite family

Gumbeites are metasomatic rocks replacing granodiorites and associated with W- or Cu-bearing quartz veins and veinlets. The name comes from the Gumbeika ore deposit in the Urals, Russia (Korzhinskii, 1946). The typical mineral assemblage is quartz + orthoclase + carbonate (dolomite-ankerite series). Some sulphides and scheelite also occur. The outer zones of *gumbeitisation* commonly contain phlogopite or magnesian biotite.

³ This term is a translation from Russian: there is no suitable English name although such rocks are widespread, a suitable alternative might be *metasomatic quartzite*. It should be noted that 'quartzite' in this context implies that quartz is a dominant constituent of the rock but might not be $\geq 75\%$ of the mode as is normally required by the SCMR recommendations.

The following temperature-based facies are distinguished within the gumbeite family, from high to low T: biotite-orthoclase (440-400 °C), dolomite-orthoclase (400-300 °C), and phengite-orthoclase (<300 °C). The high-temperature facies is associated with W-Mo mineralisation (scheelite, Mo-scheelite, molybdenite, bismuthite and some other sulphides). The low-temperature facies (without biotite) is associated with some Au and Au-U deposits.

The SCMR definition therefore is:

Gumbeite: *is a medium to low temperature metasomatic rock mainly composed of quartz, orthoclase and carbonate. It forms as an alteration of granodiorite or syenite and is closely associated with W-Cu or Au-U bearing veins.*

Gumbeitisation: *is a metasomatic process leading to the formation of gumbeites.*

Aceite family

Aceites are low temperature metasomatic rocks consisting mostly of albite with subordinate carbonate and haematite; chlorite and quartz may also occur in some rocks. The name comes from the uranium mine at Ace, Canada (Omel'yanenko, 1978). The U-bearing fluorapatite is common in rocks with high CaO content, and locally in limestones it forms U-bearing apatite metasomatic rocks. The following facies, related mainly to the initial rock composition, are distinguished: quartz-albite, calcite-albite, chlorite-albite, ankerite-albite, albite-apatite, and apatite-calcite.

The process of aceitisation is an alkaline low-temperature metasomatism with input of Na₂O and with loss of SiO₂ (quartz is replaced by albite). The hydrothermal solutions are highly oxidised and enriched with Na-hydrocarbonate. TiO₂, P₂O₅, and ZrO₂ are mobile. Aceites occur exclusively with uranium mineralisation.

The SCMR definition therefore is:

Aceite: *is a low temperature alkaline metasomatic rock, mainly composed of albite with subsidiary carbonate and haematite. U-bearing apatite is a common accessory. Aceites are closely associated with U-mineralisation.*

Argillised rocks (argillisites) family

Argillisites are metasomatic rocks consisting of clay minerals (smectites, illite-smectites, chlorite-smectites, kaolinite group minerals, hydromicas, celadonite), zeolites, silica minerals (quartz, chalcedony, opal), carbonates (calcite, ferrous dolomite, ankerite, and magnesiosiderite), alunite, jarosite, and iron sulphides (pyrite, marcasite, mackinawite, greigite). They are products of hydrothermal argillisation, which is interpreted as a low temperature hydrothermal process resulting in the replacement of original intrusive, volcanic, or sedimentary rocks by clay mineral assemblages. Lovering (1949) applied the term *argillised rocks* to the products of wall-rock alteration near hydrothermal ore veins. Argillised rocks are also widespread in areas of volcanic hydrothermal activity (*sofataric argillisites*). These two genetic types of argillised rocks are distinguished on the basis that the solfataric argillisites form at the Earth's surface, and *hydrothermal argillisites* form at depth and are commonly accompanied by ore mineralisation (Rusinov, 1989; Shcherban', 1975, 1996).

Apart from these, two chemical groups of argillised rocks may be distinguished related to either strongly acidic or to neutral or slightly alkaline solutions. Acidic solutions leach base

components (mainly MgO, CaO, and Na₂O) and redistribute Al₂O₃, and add SiO₂. Slightly alkaline solutions produce zeolitisation. Some facies of argillites may be distinguished by their mineral assemblages, namely: *acid group* (quartz-kaolinite, quartz-kaolinite-carbonate, and quartz-hydromica); *subneutral group* (smectite-zeolite). Solfataric and hydrothermal argillites include both of the chemical rock groups.

Argillised rocks accompany uranium, stratabound massive sulphide Cu-Zn, and a wide range of epithermal deposits. Metasomatites closely associated with ore deposition occur around ore veins and veinlets and consist of berthierine, ferrous carbonates, adularia, mixed-layered minerals, and sometimes zeolites, fluorite, and tosudite.

The SCMR definition therefore is:

Argillite: *is a low temperature metasomatic rock that is mainly composed of clay minerals, also present may be silica minerals, carbonates and iron sulphides. The rock forms from the hydrothermal alteration of both igneous and sedimentary rocks.*

Argillisation: *is a metasomatic process leading to the formation of argillites.*

Alkaline metasomatites related to regional fault zones

Fault-related alkaline metasomatites are common in Precambrian shields. They consist primarily of albite, aegirine and riebeckite. The four most common groups of these rocks as distinguished within the Ukraine shield are: albitised granites, albitised gneisses, apojasperoids, and carbonatite-related albitites (Shcherban', 1996).

The *albitised granites and gneisses* are rather similar in their mineralogy and show the following metasomatic zonation (from initial rock to the inner zone of metasomatism): 0) initial rock (microcline + plagioclase + quartz + biotite); 1) microcline + quartz + chlorite + epidote; 2) microcline + albite + quartz + riebeckite + chlorite; 3) albite + riebeckite + aegirine. Sometimes the last zone is composed of albite + aegirine. Albitisation occurs in the upper part of granite plutons. It is commonly accompanied by greisenisation and mineralisation of Ta-Nb and Be.

The *alkaline metasomatites* after jasperoids (*apojasperoids*) differ from albitised granites through an absence of albite, because the alumina content in the initial rocks is too low. The metasomatic zonation in these rocks is as follows: 0) initial jasperoid (quartz + magnetite + carbonate + chlorite); 1) quartz + magnetite + carbonate + riebeckite + chlorite; 2) carbonate + riebeckite + quartz + magnetite; 3) riebeckite + aegirine + quartz + magnetite. The quartz content decreases from the initial rocks into zone (3), but quartz is still present in contrast to the situation with the albitised granites.

Albitites related to 'linear' carbonatite bodies in shear zones form rims around carbonatite lenses and veins and separate veins in the upper part of the alkaline-carbonatite rock bodies. Albitites of this type may form by the action of aqueous-CO₂ fluids replacing previously fenitised host rocks (gneisses or amphibolites).

Albitites in shear zones are commonly associated with gold mineralisation. Albitite forms a network of veinlets within ore shoots and occurs as rims around quartz-gold veins or veinlets. Albitite tends to associate with tourmaline, quartz, and sometimes ankerite.

Other metasomatic families could be described but those remaining are neither typical nor widespread. Also, many different metasomatic rocks have distinct parageneses and do not form part of a wider grouping.

The SCMR recommends that in cases where the relationship of a metasomatic rock to a specific family is not clear then the rock should be named by its main mineral composition, e.g. brucite metasomatic rock, cordierite- sillimanite-quartz metasomatic rock, corundum-plagioclase metasomatic rock (or metasomatite). In general the SCMR recommends that new names for metasomatic rocks, facies or families should be based on their mineral compositions and not on geographical or other criteria.

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Figure caption

Fig. 9.1. Diagram illustrating the general T-qualitative pH fields of the metasomatic families. The dot-dash line separates acidic and neutral-alkaline families (with and without quartz).

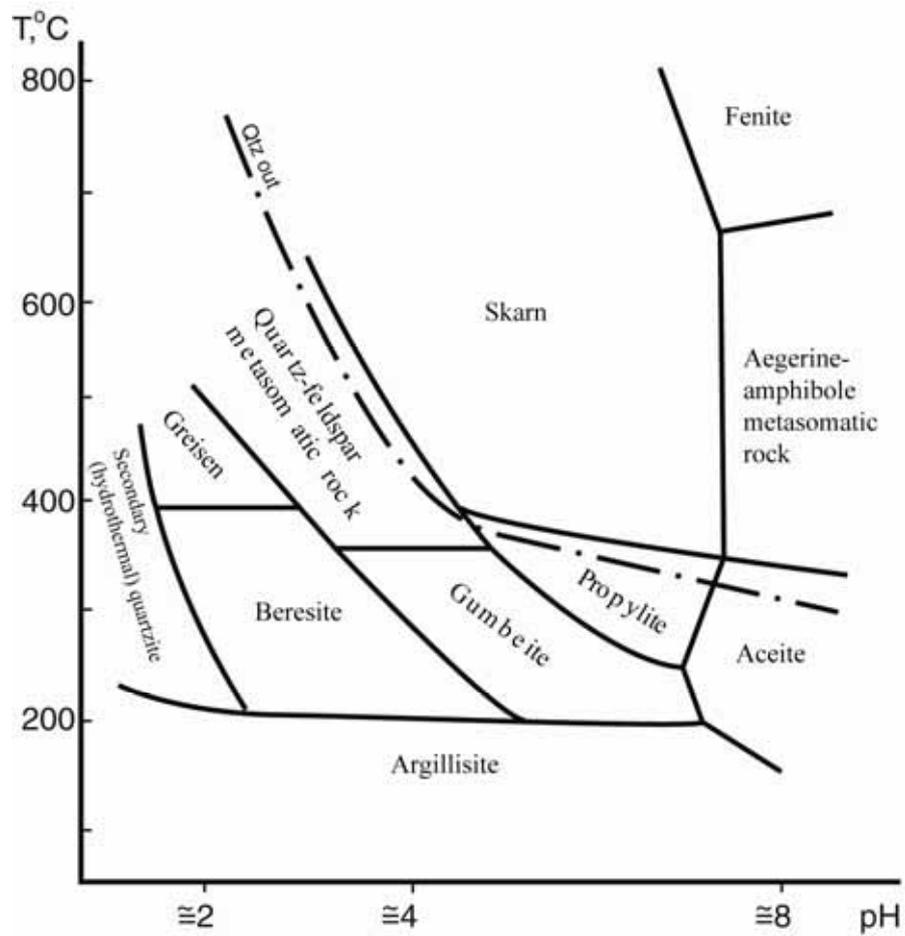


Fig 9.1