

ISSN 1526-5757

36. Experimental studies demonstrating metasomatic processes and their application to natural granitic environments

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April 27, 1999

Introduction

Experimental work of Tuttle and Bowen (1958) has been the foundation for most modern studies on the origin of granite. Their experiments convinced most petrologists that granite cannot form by granitization (elemental replacements involving solid-state diffusion and facilitated by introduced fluids) as was debated earlier by Read (1948) and Bowen (1948). Since 1958, the origin of all granite bodies of large size has been considered to be formed by magmatic processes. Arguments used to support a magmatic origin of granite have included the following (Best, 1982).

(1) Lowest temperature silicate melts in experiments have compositions at or near eutectic or cotectic points which are in equilibria with quartz and feldspars, and following crystallization, sub-equal proportions of quartz, K-feldspar, and albite are formed. These proportions result regardless of whether the melts are in last stages of fractional crystallization or in first stages of anatexis. Because these proportions match those found in natural granites of large size, it is logical that such granites have formed from magma. This logic is assumed on the basis that metasomatic fluids, which are believed to be variable in composition, should result in widely diverse quartz-feldspar proportions.

(2) Textures that include hypersolvus and subsolvus feldspars are more consistent with a magmatic origin than solid-state granitization. Textures in granites that were formed by granitization under solid-state conditions are supposed to result in a crystalloblastic (polygonal) fabric rather than hypidiomorphic-granular fabrics that are found in magmatic rocks.

(3) Field observations that felsic volcanic rocks in calderas overlie granites of the same chemical composition support a magmatic origin of the granite.

(4) Zoning in plutons is more consistent with an origin by magmatic processes than by granitization.

(5) Extensions of dikes into metasedimentary wall rocks and the incorporation of broken fragments (enclaves) in the granites are more consistent with a granite being magmatic than being metasomatic.

All of these arguments are quite valid, particularly when the problem that was being addressed in the 1940s and 1950 was whether granite was *all* magmatic or *all* metasomatic in origin. Granites having a diversity of origins (some being magmatic and some metasomatic) was not considered. Now, it is clear that most granitic rocks of large dimension are magmatic in origin, but the conclusion that all granites of large size are magmatic is not necessarily true. The experimental work of Tuttle and Bowen (1958) established what minerals and their proportions are stable at or near eutectic or cotectic points, but such work does not rule out that these compositions and proportions cannot be achieved by other means and at temperatures below melting, as long as the conditions are near the eutectic or cotectic points. Moreover, the assumptions that the textures that are produced by replacement processes must be crystalloblastic (polygonal) and that the solid-state diffusion during metasomatism is through long distances in unbroken or undeformed crystals are false.

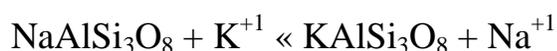
Following the classic experiments of Tuttle and Bowen, Orville (1962, 1963), also working in the Geophysical Laboratory of the Carnegie Institution of Washington, continued experimental studies on the origin of granite at temperatures *below melting conditions*. His experiments simulated replacements in an open system where natural rocks could have been subjected to a temperature gradient, but his work was done on artificial rocks in a specially designed closed system (described below). The results of his work could have had immediate far-reaching implications for the origin of granites. His accidental death, however, prevented him from following up on this work, which might have altered the history of geology. What follows is a brief description of Orville's experimental work and theoretical analyses.

Experimental work of Philip M. Orville

Orville (1962, 1963) did his experimental work in closed systems in which he examined how a temperature gradient would affect the compositions of

synthetic, pure, alkali feldspar grains. One closed system consisted of two separate chambers connected by a passage-way, 2.5 centimeters long, which permitted a vapor phase from one chamber to extend to the other. In each chamber, grains of both sodic plagioclase and K-feldspar were placed along with a small amount of alkali chloride solution. One chamber was heated to 600° Celsius; the other to 630° Celsius, and both chambers were kept at constant temperature. Thus, there was a temperature gradient, and elements (ions) released from the heated feldspar grains could diffuse in either direction in a static vapor phase from one chamber to the other. This experiment was conducted for several hundred hours, and the results of this and similar experiments provide the following five relationships that help to explain replacement processes.

(1) The vapor phase in equilibria with coexisting sodic plagioclase and K-feldspar grains becomes progressively poorer in K as the temperature is lowered, and in regions of the higher temperature, the amounts of K in the coexisting vapor phase are highest. On that basis, when vapor phases at higher temperatures, which contain high K-content, diffuse to regions of lower temperature, some of this K will replace a certain amount of Na-rich plagioclase to form K-feldspar as the vapor cools. In that replacement process, the K content in the coexisting vapor phase becomes less in order to achieve equilibria between the cooler vapor phase and the coexisting cooler feldspars. Conversely, at the same time, the Na that is displaced by the K will diffuse in the vapor phase back to the region held at higher temperature and replace the K-feldspar to form sodic plagioclase. These cross-current diffusions and replacements will continue in the closed system until equilibria is established between the vapor and solid phases as shown in the following equation.



(2) The effect of increasing anorthite content of plagioclase on the vapor phase in the closed system containing both plagioclase and K-feldspar is to increase the K-content of the vapor phase at higher temperature, paralleling the effect of increased temperature alone.

(3) Where the anorthite content of the plagioclase is variable (some grains being more calcic than others) and the plagioclase coexists with K-feldspar, equilibrium is achieved when the diffusion and replacements homogenize the plagioclase to the same anorthite content in all grains. During that homogenization process, the greatest K-replacements of plagioclase grains of different anorthite compositions occur where the plagioclase grains are most sodic, as in relationship

(1). The Na displaced by the K migrates to the more calcic grains, homogenizing their composition and making them more sodic.

(4) Where K-feldspar is absent but free quartz coexists with plagioclase grains that have variable anorthite content, equilibria between the coexisting crystals and dissolved elements in the volatile phases are achieved when all plagioclase grains are homogenized to the same anorthite content. In that process, greater amounts of silica and Na replacements of the more calcic plagioclase grains occur, homogenizing them to form a relatively more-sodic plagioclase and reducing the volume of quartz in adjacent sites. At the same time, Ca displaced by silica and Na migrates to those places containing plagioclase of lower anorthite content, causing this plagioclase to be homogenized and having the same anorthite content as in the other reaction. In that process silica is released, increasing the volume of free quartz in adjacent places. These equilibria reactions occur as is shown in the following equation.



(5) When both K-feldspar and quartz are present and coexist with plagioclase having variable anorthite content, a combination of reactions in (3) and (4) occurs. Diffusion of material in the vapor phase in the temperature gradient causes equilibria reactions among all three crystals so that the more sodic plagioclase grains are replaced by K-feldspar, and the Na, displaced by the K, replaces the more calcic plagioclase grains to homogenize them and make them more sodic. And, as above, Ca displaced by the Na will homogenize the remaining more sodic grains to a more calcic composition but equal in anorthite content to that contained in the other homogenized plagioclase grains (Orville, 1962).

Other variables and their consequences

On the basis of the above five relationships (referred to by number in later sections), replacement (metasomatism) by transfer of Na, K, and Ca is predicted, not only in closed systems where crystalline phases vary from place to place and where a temperature gradient is established, but also in systems where the temperature is kept constant. Orville did not do experiments at constant temperature, but he pointed out that changes in other variables would also cause the metasomatic reactions to occur and that instead of static vapors, there could be flowing solutions. For example, the metasomatic reactions could occur where pressure varies from place to place or where the system is opened so that more K can be added in solutions than is in the original system and/or more Ca and Na are

subtracted than are in the original system. In each of these variable conditions, or combinations of them, the amounts of dissolved K, Na, and Ca in a coexisting vapor phase (or solution) are likely not in equilibria with the coexisting feldspars and quartz, and, therefore, metasomatic reactions will occur. Orville (1962, 1963) showed that, in general, the results of a replacement process in a cooler environment will produce a rock that contains more K-feldspar than occurs in a hotter rock. Thus, K-metasomatism is a natural consequence of exchange reactions in a heterogeneous rock system, and such a system will achieve new equilibria as long as conditions are changed from that which occurred at the time when the rocks were originally formed. This conclusion is important and one which Tuttle and Bowen did not consider because their emphasis was to defeat the idea of granitization by long-distance solid-state diffusion *for all granites*. Orville promoted metasomatism, but he would have agreed with Tuttle and Bowen that *not* all granites are metasomatic. Orville thought that his experimental work would explain how K-feldspar megacrysts or augen might be formed in metasedimentary wall rocks of granite plutons crystallizing from magma.

Application of the five relationships for large-scale metasomatic reactions

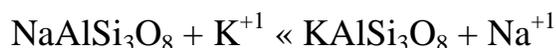
The above five relationships provide insights to explain the metasomatic origin of some large granitic bodies. The manner in which natural rock are affected by metasomatism, however, is different from that shown in Orville's experiments because these experiments were conducted in closed systems in which a temperature gradient was maintained. In natural environments the systems are open, and the temperature where the replacements occur is likely the same for both reactants and products because the replacement reactions occur commonly within a centimeter from each other. In nature a significant temperature gradient does not exist locally across a few centimeters but does occur across several hundreds or thousands of meters. On that basis, it is not a local temperature gradient that causes the metasomatism but changes in other variables that upset the equilibria. The following four factors probably determine when such large-scale metasomatism could occur in natural environments.

(1) A solid (or nearly solid) relatively mafic rock must be fractured or strongly deformed so that the system becomes open. In an open system, introduced fluids can move through and escape the system. Repeated movements and fracturing are needed to keep the system open.

(2) The fluids can consist of vapor phase and/or solutions that occur in fractures or as surface-films on grains. The fluids need not be static but can flow

and transport elements (ions, complexes). These fluids can come from distant sources and move to sites where the composition of the vapor phase or solution is not in equilibria with the crystal phases. The source of K and Si which causes the metasomatism can be local and/or from a distant source.

(3) The dissolved components in the vapor phase can diffuse along broken seals between grain boundaries and into fractures which extend through broken grains. More importantly, however, most Ca displaced by Na, and Na displaced by K can leave the system in escaping fluids. Because Ca escapes from the system, a more-sodic plagioclase is left behind that is more easily replaced by K, as indicated by the above relationships (1) and (5). Therefore, the escape of Ca and some Na will drive the equations of relationships (1) and (4) to the right, and, therefore, the replacement processes produce more and more K-feldspar as a residual, more-sodic, homogenized plagioclase is also formed.



(4) A large-scale pressure-temperature gradient exists between rocks that are at higher temperatures and pressures at great depth relative to rocks at lower temperatures and pressures found at shallower levels, perhaps many hundreds or thousands of meters higher up. The deeper rocks will likely contain relatively calcic plagioclase in which the associated vapor phase in fractures and surface films will contain high K-content (as indicated by Orville's experiments). Because of the pressure gradient that occurs from lower levels to higher levels in the crust, vapors (and solutions) carrying this high K-content will migrate upward through openings to regions of lower temperature and pressure where this high K-composition in the vapor is out of equilibria with the coexisting feldspars and quartz.

Observations by Orville and their applications

Orville (1962, 1963) pointed out that at lower pressures the stable plagioclase is one that has a more sodic composition than at higher pressure to cause plagioclase grains to become more sodic is small in comparison to the effect of lower temperature. Because of the relative speed of the metasomatic reactions in the experimental studies, Orville suggested that great volumes of moving fluids are not necessary to accomplish the metasomatism. The rate of diffusion of elements through a static vapor is quite sufficient to cause relatively rapid metasomatic reactions. Certainly flow of fluid, however, would accelerate the metasomatism

much beyond that achieved solely by diffusion through a static vapor. The fluid flow would replenish the introduced K, derived locally or brought in from deeper sources. This K would act to convert the plagioclase to K-feldspar, and repeated or continued flow or K-bearing fluids would cause the reactions to continue. Once the K-bearing fluids are introduced into the nano-sized fractures, however, flow of fluids is not necessary for replacements to occur within these fractures because diffusion of materials through static vapor will be quite sufficient and rapid to cause all of the replacement reactions, as noted by Orville (1962, 1963).

Composition of the fluids

On the basis of fluid inclusion studies (Smith, 1953; Roedder, 1963), fluids that move upward through deformed plutons likely contain, not only water, but also dissolved brines and various gases, including methane, hydrogen, nitrogen, and carbon dioxide. The principal cations in solution are Na^{+1} , K^{+1} , Ca^{+2} , and Li^{+1} , and the principal anions are Cl^{-1} , SO_4^{-2} , and CO_3^{-2} . The principal anions in these fluids can become the components of acids (HCl , H_2SO_4 , H_2CO_3) when and where the principal cations (Na^{+1} , K^{+1} , Ca^{+2}) are subtracted from the fluids during metasomatic reactions. The oxidation of methane, coming up from the mantle, to carbon dioxide and water, may be a primary source of carbonic acid that facilitates the metasomatic reactions. On that basis, the hot acids and water (acting as an acid) will dissolve much of the displaced Ca and other extracted metals and carry them out of the system.

Unrecognized Ca-removal

Although many investigators have considered the effects of transfer of Ca between feldspars in the formation of myrmekite (Collins, 1988), most investigators have not recognized that, not only are calcic plagioclase phases affected by metasomatic processes involving movement of Ca, but also all other Ca-bearing minerals in the original magmatic pluton. Such Ca-bearing minerals include clinopyroxene, hornblende, apatite, allanite, and sphene. These minerals will also break down and be replaced by quartz, and much of this displaced Ca and other metals will also be carried out of the system; see quartz sieve texture in hornblende in <http://www.csun.edu/~vcgeo05/Nr3Myrm.pdf>. However, the strong 4^{+} -bond of the Ti ion that occurs in sphene tends to make sphene one of the last Ca-bearing minerals to be replaced or removed by acid solutions; see <http://www.csun.edu/~vcgeo005/Nr18LyonMtn.pdf>. Hence, many metasomatic granites have euhedral sphene grains in them. Only where lower temperature conditions prevail may some of the escaping Ca be retained in epidote. In some

places this epidote may be subhedral to euhedral and, therefore, should not be used as a criterion for the formation of the granite at great depths (Zen and Hammarstrom, 1984), and certainly not when this euhedral epidote coexists with myrmekite.

Role of primary biotite

Where a primary gabbro, diorite, or tonalite is deformed and is biotite-bearing, the biotite is particularly susceptible to deformation because of its hardness of 3 and planar cleavage. Under deformational stress, the biotite breaks down and is replaced by quartz. In that process water, K, and other metals are released from the released from the biotite to the vapor phase or solutions. At high temperatures, a relatively high K-content can be expected in these fluids because such a relationship was found where K-feldspar coexists with relatively calcic plagioclase, as in relationship (2), and, therefore, even higher contents of K can be expected in the fluids where biotite is replaced by quartz. The upward movement in fractures of these K-bearing vapors and fluids containing acids and silica (it is everywhere) sets the stage for K-metasomatism at shallower levels in a deformed gabbro, diorite, or tonalite pluton where temperature-pressure conditions are less than at greater depth.

Deformation in the higher levels of a mafic, biotite-bearing pluton would also affect biotite and other higher-temperature ferromagnesian silicates (hornblende and pyroxenes) at these levels. Deformed grains of these minerals are unstable at temperatures below the eutectic and would break down and be replaced by quartz. Therefore, biotite at these higher levels also contributes K that can cause metasomatism of the adjacent coexisting plagioclase.

Role of zoned plagioclase

Generally, in a primary, intrusive, mafic pluton, the plagioclase at higher levels is zoned with relatively calcic cores and more sodic rims. Thus, plagioclase phases of differing anorthite content exist in these rocks on a millimeter scale, and they can be affected by metasomatism in the same manner as in relationships (3), (4), and (5). At the low temperature conditions that are present in the solidified rock, the relatively calcic cores of the zoned plagioclase grain are the most unstable. Where these zoned grains are deformed and broken, vapor can penetrate to the more calcic core along nano-sized fractures. Diffusion of Ca out of the cores in such vapor produces interior sites that are increasingly more sodic and unstable because of the electrical imbalance of residual ions. The Na would tend to remain

behind, as the Ca leaves, because sodic plagioclase is the more stable phase in the lower temperature-pressure condition, as in relationship (4). It is this altered plagioclase interior that has become more sodic that is most susceptible to being replaced by K to form K-feldspar, as in relationship (1). Therefore, generally the K-replacement progresses from altered interior sites in the plagioclase outward as Ca is increasingly removed from the plagioclase; see illustrations of progressive removal of Ca from zoned plagioclase interiors in <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf>. In that process, in most places entire plagioclase grains are eventually converted to K-feldspar. It is only in those parts of altered plagioclase grains where Ca cannot escape, because of unbroken adjacent boundary seals, that an imbalance in the residual elements occurs such that myrmekite is formed; see <http://www.csun.edu/~vcgeo005/Nr1Myrm.pdf>; <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf>; <http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf>, and Collins (1988) and Hunt *et al.* (1992). During the K-replacement stage, the residual Na is also displaced, and this Na can then move to other altered plagioclase grains (depleted in Ca but not all), causing their anorthite compositions to be homogenized. In this case, however, the homogenization is not to anorthite values that would be the average of the original compositions in a closed system, as in the experiments done by Orville (1962, 1963). Instead, the An-values of the homogenized plagioclase approach a value about half that of the original average (Collins, 1988; Hunt *et al.*, 1992). This is because much of the displaced Ca is carried away in escaping fluids.

Because the replacing K-feldspar is in equilibrium with elemental materials in the interstitial vapor and because this vapor composition is also in equilibrium with nearby quartz as well as the homogenized plagioclase, the composition of the newly-formed replacement K-feldspar will have a certain amount of dissolved Na that remains in its lattice, which is equivalent to what would be expected at that particular temperature, as determined experimentally (Bowen and Tuttle, 1950). Likewise, the homogenized plagioclase will also tend to have a certain amount of K remaining in the crystal lattice, characteristic of the equilibria and temperature at which the metasomatism occurred. Consequently, at still lower temperatures, the Na retained in the metasomatic K-feldspar lattice will exsolve to form perthite lamellae in the same way that perthite lamellae are produced in magmatic K-feldspar that crystallized from a melt. Therefore, the presence of perthite lamellae in the K-feldspar cannot be used as a criterion to say that the K-feldspar crystallized from magma, and thereby making the granite magmatic. Instead, the coexistence of such perthitic K-feldspar *with homogenized plagioclase and bordering myrmekite* is a clue that the rock has formed by replacement processes.

This coexistence contrasts with magmatic rocks lacking wartlike myrmekite and containing perthitic K-feldspar with adjacent zoned plagioclase.

Characteristics of metasomatic granitic plutons

The final result of the K-replacement of plagioclase and of the Si-replacement of ferromagnesian silicates in an original, magmatic, mafic pluton is to produce a rock richer in K-feldspar and quartz and a texture that is completely interlocking. The intergranular vapors and fluids permit complete recrystallization by diffusion of elements and growth of grains which eliminate the former fractures through which the fluids once moved. Therefore, in final stages of metasomatism the rock may lack any outward evidence of deformation, both in outcrop and in this section. Even extensive cataclasis may be almost completely annealed by the recrystallization and replacements, and the granite may be massive and uniform in composition. This uniformity occurs because the original magmatic rock also had a uniform composition. Only the existence of myrmekite, the occasional remnant veins of K-feldspar penetrating broken plagioclase, and/or the occurrence of rare islands of plagioclase in parallel optical orientation with a plagioclase grain outside the K-feldspar will indicate this former deformation. One other clue, however, can be deduced from the fact that the anorthite composition of the plagioclase in advanced stages of the replacement is *homogenized*, eliminating the former zoning. Even though the granite has formed by metasomatic processes, outwardly it still may look magmatic in origin because this granite will inherit nearly all of the structural features of the original magmatic rock, such as mafic enclaves, dikes, flow banding, and an outer contact-metamorphic aureole in sedimentary wall rocks. The texture of the granite will consist of a hypidiomorphic-granular fabric rather than crystalloblastic fabric because the former is inherited from the original magmatic rock as the K-feldspar replaces solid crystals from the interior outward, and, thereby, retaining the same fabric as a pseudomorph. The sub-equal proportions of quartz, K-feldspar, and albite are achieved because most of the ferromagnesian silicates are replaced by quartz and the original more-calcic zoned plagioclase is replaced by about equal proportions of K-feldspar and homogenized more-sodic plagioclase. See <http://www.csun.edu/~vcgeo005/Nr19Myth.pdf> in this web site for additional contrasting characteristics of metasomatic and magmatic rocks.

Terranes that show the normal and predictive behavior of metasomatism

Any high-grade metamorphic or solidified magmatic rocks that have been subjected to strong deformation or cataclastic granulation and are at temperatures

near and below the eutectic or cotectic points for granitic compositions (about 500 to 650° C) are potential terranes for metasomatic alteration and recrystallization. Such terranes include solidified plutons that are still actively rising because of density differences, strong shear zones or deep fault systems, and rocks in limbs of folds that are being squeezed tightly to become nearly isoclinal anticlines and synclines.

(1) Examples of plutons exhibiting metasomatism include the Vaaraslahti pyroxene granitoid in Pielavesi, Finland (Lahti, 1995). This pluton is rectangular in outline and bordered by a high-temperature metamorphic aureole. It consists of an older intrusive quartz syenite phase and a younger, myrmekite-bearing granitic phase. The quartz syenite is strongly brecciated. During metasomatism K and Si have replaced those parts of the brecciated syenite which are strongly crushed, converting them to granite, but islands of uncrushed syenite were impervious to replacing vapors and solutions and remain scattered with sharp contacts in the metasomatic granite. Additional examples of granitic plutons that have resulted from replacements of former, more-mafic, magmatic rocks are the Donegal plutons in Ireland (<http://www.csun.edu/~vcgeo005/Nr10Donegal.pdf>), some Scottish plutons (<http://www.csun.edu/~vcgeo005/Nr23Scotland.pdf>), and the megacrystal granitoids of Twentynine Palms, California (<http://www.csun.edu/~vcgeo005/Nr9Twenty.pdf>), and Nakusp, British Columbia (<http://www.csun.edu/~vcgeo005/Nr34Caribou.pdf>).

(2) Examples of strong deformation that has led to metasomatism along major deep faults or shear zone include the K-feldspar augen-bearing Ponaganset gneiss along the Hope Valley Shear Zone extending northward through Rhode Island into Massachusetts (<http://www.csun.edu/~vcgeo005/Nr22Ponaganset.pdf>), the eastern boundary of the Waldoboro complex in Maine ([article 6](#)), the plate contact area between the Precambrian Grenville and older Huronian rocks near Killarney in Canada (Hunt *et al.*, 1992), the deformed Precambrian Popple Hill gneiss and megacrystal Herman granites in northern New York (<http://www.csun.edu/~vcgeo005/Nr28Popple.pdf> and <http://www.csun.edu/~vcgeo005/Nr30Grenville.pdf>), the thrust system that includes the Hall Canyon and Skidoo plutons in the Panamint Range of California (<http://www.csun.edu/~vcgeo005/Nr15Hall.pdf> and <http://www.csun.edu/~vcgeo005/Nr16Skidoo.pdf>), the granitic rocks involved in the nearly horizontal thrust sheets of metamorphic core complexes in California and Arizona (e.g., <http://www.csun.edu/~vcgeo005/Nr33BillW.pdf>), and several muscovite-bearing granitic plutons in the Mojave Desert area (<http://www.csun.edu/~vcgeo005/Nr14Mojave.pdf>).

The Sierra Nevada batholith is dominantly magmatic in origin, but north-south deformation zones in several places have created metasomatic granites, as in the rocks near Lake Isabella (Collins, 1988). In some of these zones, metasomatic, myrmekite-bearing K-feldspar megacrysts (2-3 cm long) have formed, as in the Rosy Finch shear zone in the Mono Creek granite (Lockwood, 1975; Tikoff and Teyssier, 1992).

The strong deformation on the eastern side of the Southern California batholith has also permitted metasomatism, changing many mafic pluton rocks into more granitic compositions (e.g., the Temecula area, described in articles <http://www.csun.edu/~vcgeo005/Nr2Myrm.pdf> and <http://www.csun.edu/~vcgeo005/Nr3Myrm.pdf>, and the Rubidoux granite near Riverside, described in <http://www.csun.edu/~vcgeo005/Nr13Rubidoux.pdf>).

In completely exposed glaciated surfaces in southern Greenland, massive diorite and gabbro make a gradual transition to strongly banded gneisses in a zone of severe deformation (Myers, 1978). Where the original mafic rocks are biotite-bearing, the granitic bands along strike contain K-feldspar and myrmekite (personal communication with Myers).

An example in Australia includes the Oonagalabi gneiss complex (Sivell, 1986). Here, garnet-bearing quartzofeldspathic gneisses and migmatites are characterized by abundant myrmekite, and these gneisses and migmatites are interlayered with mafic granulites and amphibolites. The mafic rocks are described as being progressively depleted in Ca and Al and replaced by K and Rb.

An example in Africa occurs in the Heerenveen and Mpuluzi batholiths (Anhaeusser and Robb, 1983). European and Asian examples include a granite in the Aiguilles Rouges and the megacrystal Bergell granite in the Alps (Laurent, 1973; Wenk 1982), the megacrystal Kavala granodiorite in Greece (<http://www.csun.edu/vcgeo005/Nr29Greece.pdf>), and many myrmekite-bearing granites in the Himalaya Range along the border of India and China (Misch, 1949). In thrust sheets and nappes of the Himalaya Range, the repeated deformation and metasomatism likely has created granitic rocks that have been re-melted and mobilized, and then subjected to other cycles of metasomatism. In that way these granitic rocks have become progressively more and more felsic. In later stages, the alaskitic, metasomatized granites in the Himalaya Range are so felsic that myrmekite is not formed, and probably most petrologists would consider them entirely magmatic in origin (Collins, 1988).

(3) Metasomatic rocks that are found in isoclinal folds occur in the Central City area of Colorado (Collins and Davis, 1992), the Hibernia anticline in the Dover area of northeastern New Jersey (Collins, 1988), and the Gold Butte anticline in Nevada (<http://www.csun.edu/~vcgdo005/Nr11Gold.pdf>). The Cooma granodiorite is associated with metasedimentary rocks that exhibit multiple isoclinal folds in which the granodiorite is mobilized in the limb of one of these folds (Collins, 1996).

Large-scale Na-metasomatism

If Orville's (1962, 1963) experiments are valid indications of large-scale replacement processes in natural environments, then the reverse of the equation in relationship (1), in which Na migrates in solutions to a region of higher temperature and replaces K-feldspar should be found in a few places on a plutonic scale.



An example is in the granite gneisses near Ausable Forks, New York; see <http://www.csun.edu/~vcgeo005/Nr18LyonMtn.pdf>. See also an example of Ca-metasomatism of deformed and broken primary K-feldspar in Finland (<http://www.csun.edu/~vcgeo005/Nr4CaMyrm.pdf>).



It is easy to recognize that such large-scale Na-metasomatism has occurred, not only because of the replacement of deformed and broken primary K-feldspar by sodic plagioclase but also because of the formation of coexisting species of sodic amphiboles and pyroxenes. Generally, such large-scale Na-metasomatism is accepted by most petrologists because of the occurrence of newly-formed sodic ferromagnesian silicates that replaced former more calcic species. If large-scale Na metasomatism is accepted, the aforesaid discussion in this article should make it plain that large-scale K-metasomatism in some places should be equally accepted.

Rb-Sr and U-Pb systematics

It is worth repeating here some observations recorded in Collins (1988) that in rocks that become granitic because of metasomatic processes, Sr leaves the system with Ca as Rb tends to stay behind with K. This differential flow of elements will disrupt the Rb-Sr systematics. Moreover, the replacement of biotite and other ferromagnesian silicates will likely release U, Th, and Zr ions which then

may be deposited as overgrowths on early-formed (older) zircon crystals. Thus, the U-Pb systematics may be modified to produce discordant curves so that two different ages are apparent. These observations are something that should not be overlooked in considering isotopic studies of some granite bodies.

Other implications

Because nearly complete replacement and recrystallization accompany the formation of metasomatic granite, such make-over of the rock and annealing eliminate much evidence for former strong cataclasis. On that basis myrmekite gives a clue to a past history of strong deformation in such a rock which otherwise might be totally overlooked. Recognizing this implication may result in a completely different interpretation of the structural history of a given terrane, particularly when the granite is now massive and seemingly undeformed.

The formation of metasomatic granites may also help to explain why calcite (from trace amounts to one percent or more) is ubiquitous in many granites. The transfer and removal of much Ca in fluids carrying carbon dioxide can be expected to be incomplete in many places and, therefore, leave a residue of calcite filling a former crack.

Conclusion

Orville (1962, 1963) pointed out how large scale metasomatism is just a matter of transporting elements (ions, complexes) from a distant source where the chemical potentials are high to a zone of replacement and recrystallization and where the chemical potentials are low. In the replacement reactions, some mineral phases grow, disappear, or change in composition. In that process some diffusion of material takes place directly in crystal lattices, but the total amount of solid state diffusion is likely much less than a fraction of a millimeter or half the distance between two closely spaced nano-sized fractures, which is unlike the large distances of solid-state diffusion suggested or implied by the early granitizers. Other diffusion that supplies material to the grains being replaced occurs through volatile-rich phases or surface films that border the crystals or in nano-sized fractures cutting through the grains. All diffusion will occur along gradients or activities (concentrations) of the diffusing substances. The volatile phases that facilitate the diffusion can be static or moving in solutions through broken rock. Where migrating solutions occur, replacements are accelerated because the material that is deposited is constantly being replenished as displaced and subtracted materials (Ca, Na, Mg, Fe, and other elements) are carried away.

Perhaps only a small weight proportion of a nonvolatile constituent may be in solution at one time, but the cumulative transfer of material from less stable to more stable phases and from more stressed grains to less stressed grains will cause a complete overhaul of the rock constituents. The reason why replacement occurs is because the components dissolved in the fluid phase are not in equilibria with the coexisting crystals. All of these relationships explain how and why deformed biotite-bearing gabbro, diorite, and tonalite are converted to metasomatic granite on a plutonic scale.

The stability of sub-equal proportions of quartz, K-feldspar, and sodic plagioclase at the eutectic and cotectic points for granite and at temperatures in a short range *both above and below these points* is the reason why both magmatic and metasomatic processes arrive at the same granitic compositions. Tuttle and Bowen (1958) did the experimental work that applies to magmatic processes, and Orville (1962, 1963) did the experimental work that applies to metasomatic processes. Equilibrium among all phases in granite (vapor, solutions, melt, and solids) has to be attained. How the system gets there can be by diverse means.

Acknowledgments

This article is dedicated to Philip M. Orville whose careful work in 1962 and 1963 provided the needed experimental and theoretical support to overcome the current misplaced belief that all granites are magmatic in origin. Also, I thankfully acknowledge the many thoughtful suggestions and editorial criticisms offered by my wife, [Barbara](#), which have markedly improved the clarity of the article.

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