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52. E granite, a new kind of "evolved" granitic plutonic rock that is formed where K and Si are mobilized

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ABSTRACT

Examples of how silicate minerals in plutonic igneous rocks are modified by mobilized K and Si in the temperature range of about 350-550ºC have not been described elsewhere, whereas modifications above and below this range have been thoroughly documented. The modifications described herein require open systems that are created by deformation that allow K and Si to move by flow in fluids or by diffusion through water vapor. Metastable ferromagnesian silicates and relatively-calcic plagioclase formed at temperatures above 550ºC are replaced volume-for-volume by stable orthoclase or microcline, relatively sodic plagioclase, and quartz to create E granites that range in size from a few cubic meters to whole plutons. The process is a kind of retrograde metamorphism (metasomatism) in which solidified relatively mafic magmatic rocks of all types (S, A, I, and M) can "evolve" to more granitic compositions.

INTRODUCTION

Much is known about the mobility of K across a broad continuum of temperatures and in large volumes of rocks. At low temperatures of 25-150ºC, any K-feldspar that is slightly broken in near-surface granitic rocks or strongly mylonitized is converted to K-free kaolinite, and released K is removed by through-going water (Higgins, 1971). At temperatures of about 100ºC, mobilized K has formed metasomatic authigenic K-feldspar (adularia) in Precambrian gneisses and overlying Paleozoic rocks, extending across thousands of square kilometers throughout Missouri, Wisconsin, Iowa, Illinois, Indiana, and Ohio (Liu et al., 2003). In the temperature range of 130-300ºC, the mobility of K is indicated by the local removal of K from biotite to form wedges of K-free chlorite in large volumes of many plutonic igneous rocks. (This temperature range is based on chlorite studies in volcanic rocks by Cathelinean and Nieva, 1985.) At higher magmatic temperatures (above 550ºC), mobilized K and Na, coming from alkaline and carbonatitic magmas, have fenitized (metasomatized) wall rocks through large volumes to form albite, alkaline feldspar, and Na-bearing ferromagnesian silicates (e.g., Morogan, 1989). The high mobility of K is additionally supported by evidence for K-metasomatism in the mantle and lower crust (Morris and Pasteris, 1987; Montanini and Harlov, 2006). Finally, the first melts to form from solidified plutonic rocks consist of mobilized Si, K, and Al that form quartz and K-feldspar – the reverse of Bowen's reaction series (Winter, 2001).

What is missing from this temperature continuum for K mobility is a model for K-metasomatism in the range of 350-550ºC. In this range, higher-temperature silicate minerals crystallized above 550ºC but now in solidified plutonic igneous rocks would be metastable. Where rocks containing these minerals are deformed to create an open system, K could be mobilized to replace these minerals similar to the large scale K-metasomatism that occurs in Precambrian gneisses to form metasomatic adularia. Another argument that supports this hypothesis is the fact that Na-metasomatism has been observed across thousands of square kilometers in northern New York (Postel, 1952; Collins, 1997f). Because K has chemical properties similar to that of Na, K-metasomatism should be expected to have a similar large-scale replacement capability.

BASIC PRINCIPLES

There are a number of basic principles and observations about rocks that could be subjected to K-metasomatism at 350-550ºC.

1. The earth is not static everywhere, and a temperature of 350-550ºC is also a range in which minerals could be affected by the mobility of K and Si as occurs at temperatures above and below this range.

2. The most commonly replaced mineral by K-feldspar is adjacent, microfractured, relatively-calcic plagioclase, which is metastable at temperatures below 550ºC (Collins, 1988; Collins 1997a, 1997b, 1997c).

3. The source of K for this K-metasomatism at 350-550ºC generally comes from the break-down of nearby deformed biotite, but because of the high solubility and mobility of K in hydrous fluids in open systems, additional K could come from biotite at depths below the volumes being replaced by K-feldspar.

4. The resulting K- and Si-metasomatism of plagioclase, biotite, hornblende, and pyroxenes that crystallized at temperatures above 550ºC in solidified diorite, quartz diorite, tonalite, and gabbro result in a special kind of retrograde metamorphism (metasomatism) to produce quartz, K-feldspar, and relatively sodic

plagioclase. The K-feldspar can be either orthoclase, which is stable down to about 500ºC, or microcline, which is stable from about 500ºC to 350ºC or lower (Smith, 1974).

5. In early stages, the recrystallization of the solid rock can be by nearly isochemical auto-metasomatism in which the ferromagnesian silicates show little to no replacements or alterations, and the volume of newly-formed secondary K-feldspar is small (trace amounts to 5%). But in more advanced stages, the process is non-isochemical. The K- and Si-metasomatism require the removal of much Ca from the unstable plagioclase and much Fe and Mg from the unstable ferromagnesian silicates that are replaced by quartz. In plutonic igneous rocks undergoing K- and Si-metasomatism, much of the Na remains behind in recrystallized more-sodic plagioclase.

6. Finally, pressure is a factor during K-metasomatism at 350-550ºC, but its range is unknown. The allowable pressure is at whatever depth where crystal-boundary seals can be broken, openings can exist along nano-sized fractures in crystal lattices, and a porosity can occur inside both K-feldspar and plagioclase crystals without plastic collapse (Putnis et al., 2007).

E GRANITES

Because early proposals for large scale K-metasomatism were described as solid-state "granitization" of sedimentary rocks and had faulty concepts that were not consistent with data obtained from experimental studies (Read, 1948; Bowen, 1948; Tuttle and Bowen, 1958; Eiler, 2007), a new name is needed to describe the above kinds of large scale K- and Si-metasomatism. The name "E granite" is proposed. An E granite is a rock that has "evolved" from older relatively-mafic plutonic igneous rocks by K- and Si-metasomatism. The compositions of E granites vary from granodiorite to quartz monzonite to monzonite to granite, depending upon the amount of newly-formed secondary K-feldspar and quartz and upon the ratio of K-feldspar to residual more-sodic plagioclase in the replaced and recrystallized rock.

K- and Si-metasomatism that forms E granites can occur in rocks subjected to different degrees of deformation: (1) by just cracking grain boundary seals, (2) by fracturing crystals without translation, or (3) by shearing that causes broken-crystal translations. Because each of these degrees of deformation can be on scales that range from a few cubic meters in an outcrop to cubic kilometers in plutons, E granites exist in all sizes. E granites are produced by only slight chemical and mineralogical modifications of former plutonic rocks to almost complete make-overs, and the primary plutonic rocks being modified by K- and Si-metasomatism can range in compositions from granodiorite to diorite, quartz diorite, tonalite, or gabbro, but the final E granite is always more granitic than its starting, unaltered, relatively-more-mafic composition.

Where former mafic rocks are strongly fractured and open to fluid movements, released and displaced Fe^{+3} can also move with K into altered plagioclase crystals and form tiny hematite crystals. In this way metasomatic K-feldspar can be created in massive pink granite throughout large volumes of the crust. Thus, such hematite does not form by exsolution of Fe^{+3} in high-temperature orthoclase (Putnis et al., 2007).

E granites form only where an open system is present that allows movement of fluids in and out of rocks that are being transformed. Such open conditions are commonly created in: (a) diapiric plutons which were at one time still actively rising to deform the relatively-mafic solidified margins, such as the Ardara pluton in northwest Ireland (Pitcher et al., 1987; Collins, 1997e) and the Papoose Flat pluton in eastern California (Sylvester et al., 1978; Dickson, 1996; Collins and Collins, 2002b) and (b) broad shear zones such as occur in the Hope Valley shear zone along the boundary of Connecticut and Rhode Island (Gromet and O'Hara, 1985; Simpson and Wintsch, 1989; Collins, 1997g) and sheared Precambrian diorites and tonalites along the Quetico-Wawa subprovince junction in the Canadian shield (Krugh, 1990).

Because recrystallization may eliminate evidence of former deformation, thin section and field studies may not show evidence for cataclasis that would have allowed metasomatism to occur. Possible clues to this necessary deformation, however, include (1) the loss of Sr that causes "errorchrons" in Rb-Sr age-dating measurements. The loss of Sr occurs because its chemistry is similar to Ca. Because Ca is removed from the system during K-metasomatism, much of the Sr goes out with the Ca. At the same time, introduced Rb coming in with K is retained, and the differential movements of both Sr and Rb from place to place create variable Rb/Sr measurements (Collins, 1988a, 2004). And (2), the presence of rim or wartlike myrmekite on borders of microcline and orthoclase (Collins, 1988a, 1997a, 1997b, 1997c; Hunt et al., 1992). Rim and wart myrmekite have never been made experimentally in closed systems and can only form in open systems where K, Na, Ca, and Al are mobilized in deformed rocks.

The rim myrmekite indicates early-stage, interstitial, secondary K-replacements of plagioclase crystals where grain boundary seals have been broken adjacent to zoned plagioclase crystals. The wartlike myrmekite represents incomplete replacements of microfractured plagioclase crystals from their interiors outward in which portions of altered plagioclase recrystallize with excess silica that forms tapered quartz vermicules narrowing toward the K-feldspar (Collins and Collins, 2002a). Such myrmekite occurs on the borders of the secondary K-feldspar (microcline or orthoclase). Not all E granites necessarily contain myrmekite, however, because where the primary rocks contain sodic plagioclase, the K-feldspar replacement of albite or sodic oligoclase does not produce any myrmekite.

The problem for recognizing the existence of former cataclasis or deformation is compounded for petrologists studying rocks by using only the petrographic microscope. Viewing thin sections under cross-polarized light may not reveal internal nano-sized cracks in plagioclase crystals and early stages of replacement. Therefore, additional studies using cathodoluminescence or electron microprobe and transmission electron microscopy may be necessary to see evidence for subtraction or addition of elements (Collins 1988a; Putnis et al., 2007).

When petrologists find wartlike myrmekite in rocks, it must be remembered that not all wartlike myrmekite is formed by processes that create E granites. Other kinds of wartlike myrmekite are formed either (a) by Ca- and Na-metasomatism of outer borders of primary orthoclase crystals or along inner walls of fractures that extend through broken orthoclase crystals or (b) by Ca-metasomatism of borders of relatively Na-plagioclase. Examples of (a) include a site in southern Finland where aggregates of myrmekite replace interiors of entire orthoclase phenocrysts (Collins, 1997d) and in large areas of northern New York (Postel, 1952; Collins, 1997f). Examples of (b) include deformed areas in anorthosite masses (e.g., Dymek and Schiffries, 1987). In both (a) and (b) types of replacements, the quartz vermicules inside myrmekite are not tapered to the margins but have nearly uniform widths and are contained totally inside the myrmekite.

E granites are also characterized by relative losses of Ca, Mg, Fe, and some Al when chemical compositions of the E granites are compared to the chemical compositions of unaltered primary mafic igneous rocks that have not been subjected to K-metasomatism. Proportionately, the altered rocks that are recrystallized as E granites are enriched in residual Si because of the loss of relatively heavy “oxides” of Ca, Mg, and Fe (as reported in chemical analyses). On that basis, large volumes of added Si are not necessary to account for all the proportionately increased weight percentages of residual SiO_2 in the E granites. Nevertheless, because Si is ubiquitous, Si-metasomatism accompanies the K-metasomatism and brings in extra Si. In E granites the Si-metasomatism of primary biotite, hornblende, and pyroxenes results in the formation of secondary quartz to various degrees. In many places, hornblende and pyroxenes may be completely replaced by quartz, but generally remnants of biotite remain (Collins, 1997c).

OTHER CONSIDERATIONS

Megacrysts of orthoclase or microcline in plutonic igneous and metamorphic rocks have generally been regarded as primary phenocrysts that have crystallized during late stages from melts (Vernon, 1986), particularly if the megacrysts are zoned. Undoubtedly, many K-feldspar megacrysts have a primary melt origin as phenocrysts, but such may not always be true. They can also be formed by secondary replacement processes under subsolidus conditions. Where K-feldspar megacrysts grow in rocks subjected to repeated deformation that periodically re-opens the system to fluid movements, each episode of deformation may allow fluids with slightly different compositions of Ba and Rb to be introduced with the K (Dickson, 1996; Collins and Collins, 2002b). Therefore, each successive overgrowth layer on a growing megacryst could contain different Ba- and Rb-zonal compositions. Also, different parts of a pluton may have large primary orthoclase phenocrysts while other parts that have already solidified may undergo subsolidus deformation so that secondary K-feldspar megacrysts are formed by replacement processes. In other places, primary orthoclase phenocrysts may have overgrowths of secondary K-feldspar that simultaneously replaces groundmass minerals along the rim. In still other places K-bearing fluids may move out from magma in the core of a pluton into solidified pluton borders and form secondary K-feldspar megacrysts in both the outer portions of a granitic diapir and in the country rock so that the K-metasomatism crosses rock boundaries (Dickson, 1996; Collins and Collins, 2002b). In any case, where K- and Si-metasomatism occurs in only small volumes or throughout whole plutons, E granites are created, and the presence of megacrysts does not negate metasomatism.

E granites can have all the outward characteristics and internal chemistry of different kinds of magmatic S, A, I, or M igneous rocks that undergo K- and Si-metasomatism. That is, the E granites could inherit mafic inclusions (enclaves), cross-cutting dikes within the pluton and extending into the wall rock, comb layering, and compositional layering because of crystal settling from a liquid. E granites can also have the trace element characteristics of the primary S, A, I, or M igneous rocks that are being modified because the original chemical compositions will also be inherited. Primary zircons may not be altered when E granites are formed, but these zircon crystals may exhibit secondary overgrowths because of the release of Zr, U, Th, and other elements from replaced plagioclase and ferromagnesian silicates. E granites can be massive or foliated, but a foliation is commonly found in E granites because they generally form where rocks have undergone deformation in which lateral translations of crystals occur. If the E granites recrystallize in environments lacking directed stress and the deformation merely breaks grain-boundary seals or cracks the crystals without lateral translation, a former foliation may be eliminated by recrystallization or not even form. The E granite will then have a massive appearance. E granites can have uniform compositions extending through large volumes if the original igneous rocks also had uniform compositions throughout large volumes.

Some plutonic igneous rocks become more granitic because of slight modifications by K- and Si-metasomatism, while others are strongly modified, resulting in a complete mineralogical make-over. Other plutonic igneous rocks are modified to form E granites only in restricted areas so that gradations in composition occur through narrow or wide zones between the two rock types (Collins and Collins, 2002a). Still other E granites exhibit sharp contacts against magmatic rocks because deformation and replacements occur up to a sharp contact against undeformed volumes of the magmatic rocks (Collins, 1988a, 1988b). E granites can form in metasedimentary wall rocks where K-feldspar augen or megacrysts of either orthoclase or microcline can be formed by recrystallization and replacements (Collins, 1993; Dickson, 1996; Collins and Collins, 2002b). Finally, if temperatures rise again above solidus conditions, some magmatic granite can also result from the re-melting of rocks that have been modified previously by K- and Si-metasomatism to form E granites.
Granites that have been modified by Na-metasomatism to form secondary albite or sodic oligoclase, as in northern New York (Postel, 1952; Collins, 1997f), or by boron-metasomatism to form tourmalized granites, or by any other kind of metasomatism are excluded from granitic rocks that are called E granites. These other types of metasomatism should have their own names and descriptions.

CONCLUSIONS

Both small- and large-scale K- and Si-metasomatism exist in silicate rocks because deformation creates an open system in which K and Si ions can be mobilized in both small and large volumes of rock (e.g., Mariano and Woodard, 2006). Such metasomatism is a special kind of retrograde metamorphism that forms mineral assemblages which are stable at about 350-550ºC. Microcline (or orthoclase), quartz, and relatively sodic plagioclase are generally the dominant phases. Their modal percentages and chemical compositions plot on and near the eutectic as also occur for magmatically derived granitic rocks. In the open systems, ions can move by flow of hydrous fluids or by diffusion in water vapor so that K and Si can come in and Ca, Mg, Fe, and some Al can go out. Na tends to remain behind. Metasomatic rocks formed during this process can be called E granites because they have “evolved” by retrograde recrystallization and replacements of former rocks that crystallized at temperatures higher than about 550ºC.

Although Rb-Sr “errorchrons” and myrmekite are evidence for E granites, the best evidence is observed in transition zones from unaltered plutonic igneous rocks to places where these rocks undergo various degrees of deformation and in which plagioclase is progressively replaced by K-feldspar volume-for-volume. Cathodoluminescence and transmission electron microscopy may be needed to demonstrate the metasomatism. Unfortunately, no published articles are available (with one exception) that provide textural illustrations of such metasomatism which could be cited. The exception is Putnis et al. (2007). On that basis, many cited articles had to come mostly from the electronic journal "Myrmekite" (ISSN 1526-5757), and in this journal are many other articles that could have been cited. See http://www.csun.edu/~vcgeo005/index.html.

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