ISSN 1526-5757

6. MYRMEKITE AS A CLUE TO METASOMATISM ON A PLUTONIC SCALE: ORIGIN OF SOME PERALUMINOUS GRANITES

Lorence G. Collins

email: lorencecollins@gmail.com

February 3, 1997

Waldoboro and Friendship, Maine, U.S.A.

In this presentation questions are raised about a melt-restite unmixing model proposed by Barton and Sidle (1994) for the myrmekite-bearing Waldoboro granite complex along the southeastern coast of Maine (USA). This complex consists mostly of granite/granodiorite gneiss and granite, but smaller masses of quartz diorite, aplite, pegmatite, leucogranite, tourmaline granite, and granite porphyry occur. A mylonite zone extends through the granite porphyry on the east side of the pluton and through wall rock consisting of mafic igneous rocks of the Benner Hill sequence. On the west side, the granite complex is bordered by paragneisses of the Bucksport Formation. The granite pluton is poorly exposed in an area covering >340 km^2, but relationships between rock types are readily apparent in wave-cut shorelines south of Friendship and along other shorelines on islands and the mainland.

Assumptions and problems

There are a number of problems associated with the interpretations of the Waldoboro granite complex made by Barton and Sidle (1994), which call into question their melt-restite unmixing model.

1. Barton and Sidle suggest that the Waldoboro terrane is an ideal place to test the melt-restite unmixing model because the transitions from country rock (paragneisses) of the Bucksport Formation to granite/granodiorite gneiss, to granite, and then to leucogranite are preserved. These investigators point out that the Bucksport Formation consists of muscovite schists (metapelites), amphibolites (metavolcanics), and biotite feldspathic gneisses (metagraywackes), with the bulk of the formation being metagraywackes. Calculations are provided (their Table 7)

to show that the granite gneiss consists of a mixture of 55% melt - 45% restite and that the granite consists of 76% melt - 24% restite, but the supposed restite left behind in the Bucksport Formation from which their model is dependent is not described. Its narrow range of chemical composition suggests that it could be nothing more than layers of primary amphibolite. What criteria do the investigators use to distinguish amphibolites, from which no melt has been separated, from mafic restite material from which large volumes of melt has been separated and which is the basis for their restite-melt unmixing model? Or was the restite chemical composition chosen merely because it fit the restite-melt unmixing model without regard to considering this problem?

2. Additional calculations are then made for the melt-restite unmixing model to show that the mass-balance for trace elements is in agreement with that shown for major oxides for the granite gneiss *but not for the granite*. In the granite, mass-balance calculations for the trace elements require 85% melt - 15% restite instead of 76% melt - 24% restite. This difference is attributed to "*inhomogeneous distribution of minor phases and the effects of metasomatism*." High K_2O, Rb, Ba, Cs, Li, B, K/Rb, K/Ba, Rb/Sr, and Th/U are identified as evidence of metasomatism. These investigators, however, admitted inability to identify anything in thin sections which they could interpret as evidence for metasomatism. Therefore, they would not know whether metasomatism could have been more extensive. Could metasomatism also explain the progressive chemical changes from wall rock to granite gneiss to granite and then to leucogranite? Furthermore, could there have been subtraction of some elements in a linear fashion, such as Fe, Ca, Mg, and some Al (as shown in their Figures 5 and 6) which could be associated with the metasomatism? Could this subtraction of elements also account for enrichments in K, Rb, and Ba?

3. If a melt-restite unmixing model applies to country rocks and adjacent granitic rocks on the west side of the Waldoboro granite complex, it would be logical to assume that there should be some effect on the east side, also. Attempts by Barton and Sidle to apply this model to the megacrystal granite (the granite porphyry) and the adjacent Benner Hill sequence, however, totally failed. The presence of magnetite and hornblende in the megacrystal granite was supposed to represent restite, but the lack of fit of the chemical data to the melt-restite unmixing model was again attributed to *effects of metasomatism*. Nevertheless, the "granite porphyry" was suggested to be a "magmatic phase" of the granite complex on the basis that migmatites in the adjacent country rock supposedly indicated that melting temperatures were achieved.

4. Barton and Sidle (1994, p. 1247) then attribute the granite porphyry and adjacent country rock to be a product of deformation and recrystallization, "accompanied by metasomatism (leading to feldspar blastesis, replacement of early formed minerals by perthite, albite, and tourmaline, and to formation of myrmekite around feldspar megacrysts)." If myrmekite and K-feldspar blastesis are evidence here for metasomatism, why is it not also evidence for metasomatism in the gneissic granite/granodiorite and granite where these investigators report that both myrmekite and feldspar porphyroblasts occur? If Barton and Sidle (1994) suggest that K-metasomatism can produce a granitic composition in a distance of 10 to 100 meters, how can they know that it cannot happen for larger distances? At what distance is there a cut-off which then makes granite magmatic and not metasomatic?

Barton and Sidle (1994), although indicating that they were testing models of granite genesis, restricted their modeling of the granitic complex *entirely to magmatic processes* involving partial melts, even though they *admitted* that the granite porphyry and wall rocks on the eastern side as well as in the main masses of the granite/granodiorite gneisses and granite have been *modified by later metasomatism*. This metasomatism may, however, be more extensive than they realized, because the field and microscopic relationships are *not* entirely consistent with magmatic processes.

Field relations, eastern Waldoboro granite complex

On the eastern side of the complex, biotite-rich tonalite and diorite layers of the Benner Hill sequence are deformed and grade into a megacrystal rock, which then, along strike, gradually grade into the "magmatic" granite porphyry. Lenticular and elongate remnants of the tonalite and diorite are preserved in the megacrystal granite. Field relationships between the Benner Hill diorite can be seen in beach exposures at low tide 500 m south of the last lobster fisherman's dock on the east coast of the promontory, extending south of Friendship, Maine (Fig. 1a, Fig. 1b, and Fig. 1c). Here, wedge-shaped zones of megacrystal rock taper to narrow digitate projections into the diorite. At the narrow ends the K-feldspar megacrysts (2 cm long) gradationally and nearly abruptly disappear along strike into the diorite.

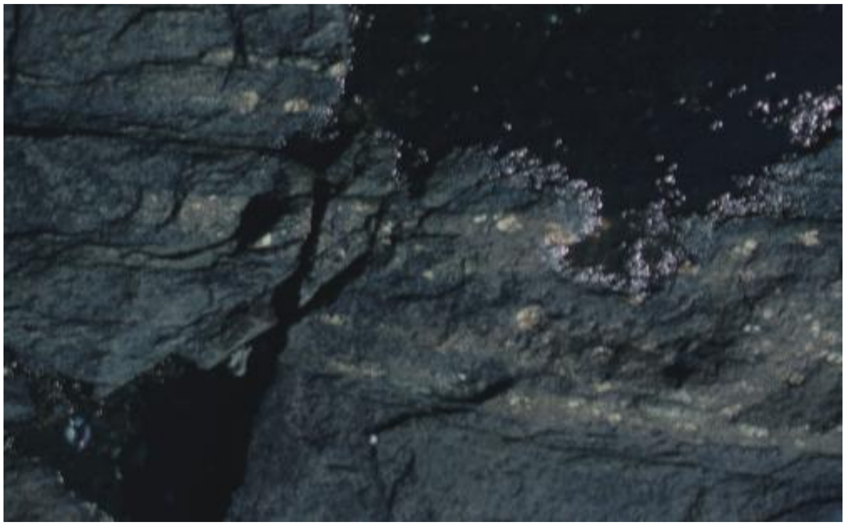

Fig. 1a. Beach exposure of a wedge of megacrystal rock, about 60 cm wide at its widest exposure and tapering to narrow digitate projections into diorite (dark). The wedge extends 10 m and is bounded by diorite. At the digitate end (shown here), the K-feldspar megacryst crystals (2 cm long) gradationally and nearly abruptly disappear along strike (left side of photo). Black areas are puddles of water.

Fig. 1b. Beach exposure 60-cm-wide end of area shown in Fig. 1a.

Fig. 1c. Another nearby wedge of megacrystal rock replacing diorite and disappearing into diorite along strike.

In other places, the diorite, containing K-feldspar crystals (2 cm long), grades to foliated, megacrystal biotite granite in which the K-feldspar crystals range from 2 to 4 cm long (Fig. 2). Excellent exposures of diorite grading into megacrystal granite are also found on Friendship Long Island (Fig. 3 and Fig. 4).

Fig. 2. Megacrysts of K-feldspar in diorite (black, right half) adjacent to the more felsic megacrystal granite (left half) of the Waldoboro granite complex (same locality as in Fig. 1abc). In the darker, less-replaced rock, megacrysts range from 1 to 2 cm long, whereas in the granite, megacrysts range from 1 to 4 cm long.

Fig. 3. Megacrystal Benner Hill sequence layers on promontory on west coast of Friendship Long Island west of Lobster Pond. Deformed (foliated and relatively unreplaced) diorite layers (dark) alternate with lighter layers containing less biotite and plagioclase and more quartz and K-feldspar megacrysts. These rocks are on strike with layers shown in Fig. 1abc.

Fig. 4. K-feldspar-bearing, deformed diorite interlayered with megacrystal granite (same locality as in Fig. 3).

Descriptive petrography

Relatively undeformed diorite in the Benner Hill sequence contains normally zoned plagioclase, biotite, hornblende, and minor quartz. Sphene, allanite, epidote, apatite, magnetite, and zircon are accessories.

K-feldspar (microcline) is absent in relatively undeformed diorite,, but it gradationally appears as deformation increases. First appearance of K-feldspar (Figs. 1a, 1b, and 1c) occurs along fractures in broken plagioclase crystals or as interior islands in deformed plagioclase, and this K-feldspar lacks myrmekite borders. Where the rock has undergone more severe deformation, K-feldspar occurs as individual, undeformed crystals, increases in abundance, and is locally bordered by myrmekite. Where myrmekite first appears, volumes of myrmekite exceed volumes of K-feldspar. In the deformed rocks, K-feldspar crystals gradually become megacrysts and greatly exceed the volume of bordering myrmekite. The large K-feldspar crystals enclose remnant fragments of broken plagioclase, quartz, and biotite crystals in the diorite and may also enclose earlier formed myrmekite. Ghost myrmekite (quartz bleb clusters) in the K-feldspar megacrysts may coexist with the myrmekite. Where K-feldspar megacrysts are the largest (4 to 11 cm long), and the granite is most felsic (Fig. 2, volume percent of biotite is greatly reduced as quartz shows a corresponding volume increase/

Where the adjacent diorite contains andesine, the quartz vermicules in myrmekite in the associated megacrystal rock are relatively coarse (Fig. 5, and where the adjacent diorite (or tonalite) contains oligoclase, the quartz vermicules in myrmekite in the associated megacrystal rock are less coarse. In the main Waldoboro granite pluton, where the plagioclase is even more sodic, quartz vermicules in the associated myrmekite are quite tiny.

Fig. 5. Myrmekite (center, with branched vermicules) bordering K-feldspar megacrysts (gray, upper left). Quartz is light gray and white. Biotite is brown.

Metasomatism on the eastern side of the complex

Barton and Sidle (1994) interpret the megacrystal granite and adjacent Benner Hill wall rocks on the eastern side of the Waldoboro pluton complex to be the result of metasomatism. Field and microscopic studies confirm this conclusion. Deformation could have permitted K- and Si-bearing fluids to enter and produce the wedge-shaped areas in the biotite-rich diorite facies of the Benner Hill sequence which contain K-feldspar crystals that increased in size to become megacrysts. This could have been an on-going process which, in later episodes, could have continued to deform and become mylonitic, giving the illusion that the metasomatism was a late process when, in fact, it could have produced the granite long before the mylonitic stage occurred.

Outcrops in the shore line on the mainland (Figs. 1a, 1b, 1c, and 2 show that diorite is replaced by K-feldspar megacrysts. Along strike of the foliation to a 100-m-wide shear zone on Friendship Long Island, the same diorite containing abundant K-feldspar megacrysts (Figs. 3 and 4) then gradually grades into megacrystal biotite granite. It is clear from these relationships that *the megacrystal granite is not formed from the crystallization of magma but by large-scale K- and Si-metasomatism*.

During the K-replacement process, as suggested by Barton and Sidle (1994), some minerals must lose elements as they gain other elements. The loss of Ca and Na from replaced plagioclase and loss of Ca, Fe, Mg, and Ti from biotite and sphene result in a residual enrichment in K, Na, Al, and Si. Some Na tends to remain behind to replace and recrystallize some of the deformed plagioclase as albite or oligoclase while K replaces other deformed plagioclase crystals to form microcline. The residual excess Al is crystallized in muscovite and minor garnet. Quartz increases as biotite and hornblende disappear. The correlations between andesine or oligoclase compositions in the diorite and the sizes of the quartz vermicules (coarse to intermediate) in myrmekite in the associated megacrystal rock correspond to what is expected where K-metasomatism of plagioclase occurs (Collins, 1988; Hunt et al., 1992).

Discussion

Although Barton and Sidle (1994) have limited analyses of the Benner Hill rocks, comparisons between chemical analyses of the two rock types show that large losses of Ca, Mg, Fe, and some Al must have occurred as K and Si were introduced (Barton and Sidle, 1994; data from their Table 4). The fact that these chemical changes occur in the megacrystal granite suggest that such changes also likely took place in the deformed paragneisses of the Bucksport Formation. This is because the biotite-rich gneisses of the Bucksport Formation exhibit the same kinds of microscopic features that occur in the Benner Hill rocks. That is, hornblende and biotite are deformed and contain quartz sieve textures, and deformed plagioclase is associated with undeformed K-feldspar, more sodic plagioclase, and myrmekite. All of these alterations, if also resulting from metasomatism, could result in large losses of Ca, Mg, Fe, and some Al and provide the same kinds of linear chemical changes that were proposed in the melt-restite unmixing model. Moreover, the same changes would strongly affect trace element abundances because new minerals that were formed during introduction of K and Si do not accommodate the trace elements in the same way as the original minerals did at higher temperatures in the former rocks of the Bucksport Formation.

Magmatism versus metasomatism

Early metasomatism in the Waldoboro terrane might have produced granite, leucogranite, and aplite without magmatism. For example, in strong shear zones in which the rocks become mylonites, the final product could have been a fine-grained leucocratic cataclasite (aplite), containing broken fragments of microcline, albite, quartz, muscovite, biotite, and myrmekite in which almost all of the dark minerals have been removed (replaced). Such a cataclasite could have formed below melting temperatures and recrystallized as fine-grained granite, leucogranite, or aplite in which evidence for cataclasis would no longer be present. Nevertheless, because the composition of the resulting granite lies near the eutectic minimum for melting, temperatures likely were hot enough in many places so that partial melting (anatexis) or complete melting occurred. Coarse muscovite-bearing pegmatites, cutting through the granite and wall rocks (Bucksport Formation and Benner Hill sequence), testify that melting occurred in some places. On the basis that anatexis or complete melting occurred following metasomatism, when the resulting melt solidified as granite, the main body of the granite did not become coarse grained (1) because of continued deformation while plastically rising in the crust as a pluton, (2) because the magma was water saturated, increasing the number of nucleation sites, (3) because of undercooling and rapid nucleation, or (4) because of pressure quenching. Water saturation of magma might be expected to be the cause of the fine-grained nature of the granite if metasomatism has occurred prior to melting because of the large volumes of water that were likely moving through the deformed rocks and enabling the introduction and subtraction of the elements (ions) in the rocks. The melting and crystallization (solidification) could have been followed by renewed deformation and K- and Si-replacement stages. This same sequence could go through several cycles in the main body of the Waldoboro granite complex. Each time, renewed metasomatism would make the granite residue more felsic. In the final solidified stage, however, deformation and further replacement by K- and Si-bearing fluids could occur, and this last deformation and replacement stage is indicated by the occurrence of myrmekite with very tine quartz vermicules associated with the albite. At any rate, the final replacement products of the rocks in the Bucksport Formation and the Benner Hill sequence are modified magmatic rocks that consist of strongly-peraluminous fine-grained granite or pegmatite containing muscovite and garnet.

Development of peraluminous granites

Barton and Sidle (1994) describe gradational contacts with rocks in the Bucksport Formation on the western side of the pluton and attribute the peraluminous nature of the Waldoboro granite to partial anatexis and assimilation of these rocks as well as to the partial anatexis and assimilation of the Benner Hill sequence on the eastern side of the pluton. Although this anatexis and assimilation may be true in some terranes, Garcia and others (1994) show that peraluminous granites likely do not result from anatexis of aluminous shales but originate from igneous rocks in the calc-alkalic suite. These authors show that the shale-sandstone continuum has a characteristic trend for their Al_2O_3, TiO_2, and Zr compositions (hereafter, called Al-Ti-Zr) which crosses the trend for these same components in the calc-alkalic suite as well as for strongly peraluminous granites (Fig. 6). Because the peraluminous granites do not project to the aluminous shales is the reason why the shales do not seem to be an appropriate precursor parent.

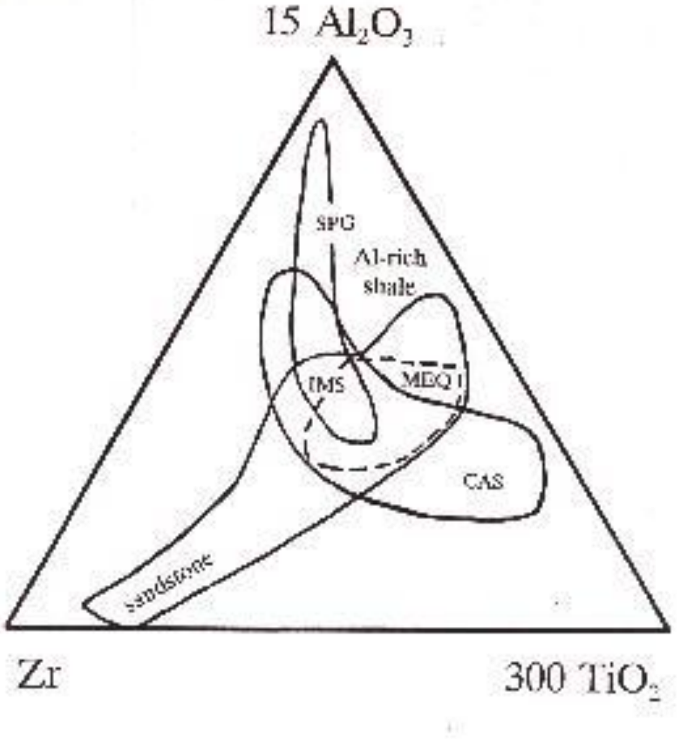

Fig. 6. Trends in the Al-Ti-Zr projection for Al-rich shales through sandstones, including immature sandstones (IMS) and for fields of calc-alkalic suites (CAS) and strongly peraluminous granites (SPG); from Garcia and others (1994). Data from shales, slates, schists, and high-grade gneisses from the Littleton Formation in New Hampshire (MEQ) are outlined by dashed contour (Shaw, 1956).

Low- to high-grade metamorphosed equivalents of the shale-sandstone continuum show the same Al-Ti-Zr trend as for the unmetamorphosed rocks, which is what would be expected (Fig. 6) and is confirmed by the same Al-Ti-Zr trend of the metapelites and metapsammites in the Cooma complex (Collins, 1996). Significantly, however, aluminous gneisses containing garnet, sillimanite, and cordierite, which are derived by K- and Si-replacements of diorites and gabbros, show Al-Ti-Zr trends that follow the trends of the calc-alkalic suite (Collins, 1998).

When the Al-Ti-Zr compositions of the Waldoboro granites and their wall rocks are plotted (Fig. 7), the trends for the Benner Hill sequence (Bh) and its associated megacrystal granite (Wgp) and the trends for the Bucksport Formation (Bgs) and the associated facies of granite (Wg), granite gneiss (Wgn), leucogranite (Wgl), aplite (Wga), and pegmatite (Peg), produce a field which is similar to the Al-Ti-Zr trends for strongly peraluminous granites on Fig. 6 (Collins, in press).

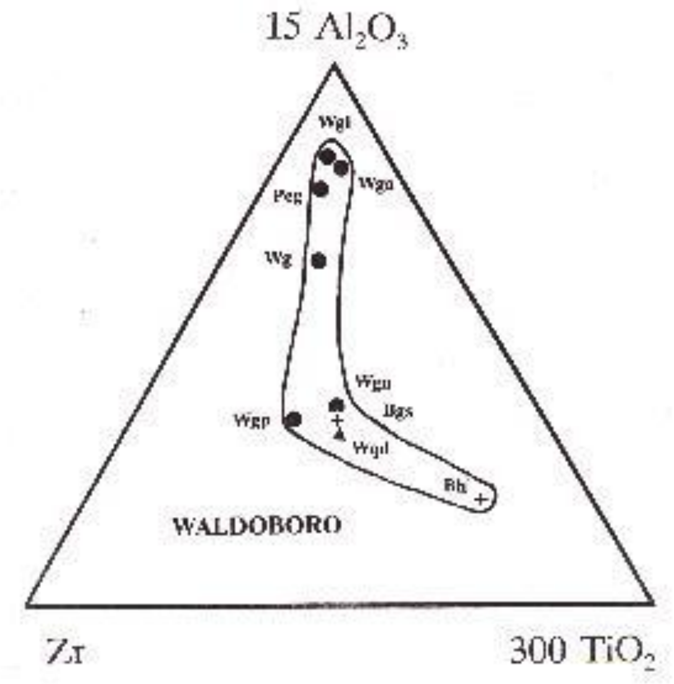

Fig. 7. Example in the Al-Ti-Zr projection of seven granitoid units from the Waldoboro Pluton Complex in mid-coastal Maine and two adjacent country rocks from the Bucksport Formation and Benner Hill sequence (Baron and Sidle, 1994). Data points represent average values. Granitic rocks (solid circles; including WGp granite porphyry, Wng granodiorite gneiss, WG granite, Wga aplite, Wgl leucogranite, and Peg pegmatite); quartz diorite (solid triangle); and country rock (pluses; including Bgs Bucksport Formation and Bh Benner Hill sequence).

This similarity of Al-Ti-Zr trends on Figs. 6 and 7 suggests that strongly peraluminous granites may reach their final compositions because of a history of metasomatism of former mafic, biotite-rich igneous rocks, subtracting Ca, Mg, Fe, and Ti while enriching the residue in Al prior to melting. On that basis, the hornblende quartz diorite (Wqd, Fig. 7), that occurs within the eastern part of the Waldoboro granite complex may be a remnant facies of a former biotite-rich diorite pluton that once occupied the whole area (>340 km^2) as well as the area now mapped as the Bucksport Formation and the Benner Hill sequence (see Myers, 1978). If so, the rocks in the hornblende-bearing facies were relatively undeformed and preserved (as in the quartz diorite enclosure in the pluton) or deformed to become the mafic wall rock gneisses, whereas the biotite-rich facies was the one that was readily deformed and replaced to become the various granites in the Waldoboro granite complex.

The above relationships and the occurrence of myrmekite form the basis for suggesting that metasomatism can operate on a plutonic scale to produce some large granite masses. The modifications of former mafic magmatic rocks that have been deformed below melting temperatures and modified by hydrous fluids that move through these rocks and enrich them in K and Si while subtracting Ca, Mg, Fe, and Ti must occur at temperatures below melting because if melting temperatures were reached, the delicate intergrowth of quartz vermicules in myrmekite would have been destroyed.

Such an idea for large-scale metasomatism has application to the Donegal granites in Ireland, the megacrystal quartz monzonite in the Twentynine Palms area of the United States, the granites in the basement rocks of the Great Plain in Hungary (Szalay, 1983), and many other localities.

References

Barton, M., and Sidle, W. C., 1994, Petrological and geochemical evidence for granitoid formation: The Waldoboro pluton complex, Maine. Journal of Petrology, v. 35, p. 1241-1474.

Collins, L. G., 1988, *Hydrothermal differentiation - A clue to many geological puzzles*. Athens: Theophrastus Publications, 387 p.

Collins, L. G., 1996, The metasomatic origin of the Cooma complex in southeastern Australia. Theophrastus Contributions to Advanced Studies in Geology, v. 1, Athens: Theophrastus Publications, p. 105-112.

Collins, L. G., (1998), Metasomatic aluminous gneisses at Gold Butte, Nevada, U.S.A.: A clue to formation of strongly peraluminous granites; in

Theophrastus Contributions to Advanced Studies in Geology, v. 2, Augustithis, S. S. and others (eds.): Athens, Theophrastus Publications, p. 33-46.

Garcia, D., Fonteilles, M., and Moutte, J., 1994, Sedimentary fractionations between Al, Ti, and Zr and the genesis of strongly peraluminous granites. Journal of Geology, v. 102, p. 411-422.

Hunt, C. W., Collins, L. G., and Skobelin, E. A., 1992, *Expanding Geospheres - Energy And Mass Transfers From Earth's Interior*. Calgary: Polar Publishing Co., 421 p. Order from: http://www.polarpublishing.com

Myers, J. S., 1978, Formation of banded gneisses by deformation of igneous rocks. Precambrian Research, v. 6, p.43-64.

Shaw, D. M., 1956, Geochemistry of pelitic rocks, Part III: Major elements and general geochemistry. Geological Society of America Bulletin, v. 67, p. 919-934.

Szalay, A., 1983, Metasomatic alteration of metamorphic, granitoid rocks in the basement of the Great Plain, Acta Geologica Hungarica, v. 26, p. 359-374.