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PETROCHEMISTRY OF PRECAMBRIAN GRANITIC ROCK FROM NORTHEASTERN WISCONSIN

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ABSTRACT

Precambrian granitic rock from northeastern Wisconsin appears to have been emplaced mesozonally between 1.6 and 1.9 Ga. Granite to quartz diorite are represented, yet mineralogy is quite similar. The rock is calc-alkalic in nature and displays a relatively high K_2O/Na_2O ratio which supports a syntectonic to late tectonic origin.

The close correlation between the results of this study and experimental results for the system Ab-Q-Or-H_2O and Ab-An-Or-H_2O imply that the granitic rock has formed through crystallization of a magma derived from the melting of downfolded crustal rock, possibly along a subducting zone. Most rock units appear to have formed between 670 °C and 750 °C and from 1 to 3 Kbar pressure.

INTRODUCTION

The main purpose of this study is to provide information, primarily of a petrological and chemical nature, about granitic rock from a twenty thousand square kilometer area in northeastern Wisconsin (fig. 1). Because of the enormous size of the area and the relative scarcity of outcrop detailed fieldwork was not attempted. It is hoped, however, that much of the information presented here will be of use to future investigators involved with more detailed studies. The data are published separately (Mursky and Bailey, 1988) as Wisconsin Geological and Natural History Survey Open-file Report WOFR 88-2.

PREVIOUS STUDIES

The first detailed investigations of granitic rock in the region was done by Cain (1962) and Wadsworth (1962). Cain described several granitic units of the Athelstane area, including the Amberg granite, Newingham granodiorite, Hoskin Lake granite, and the Dunbar gneiss. Cain and Banks dated several of these units, and obtained zircon ages of between 1.85 and 1.95 Ga. Wadsworth (1962) studied the chemistry and petrology of the Twelve Foot Falls quartz diorite pluton located at Pembine, and Myles (1972) investigated the area near the contact of the Wolf River batholith and the Athelstane quartz monzonite, mainly through chemical analyses of both rocks and minerals. Cudzilo (1978) studied approximately the same region as Cain, concentrating primarily on the chemical relationships of the units described by Cain. Petrochemical work in east central Wisconsin was also done by Anderson, and others (1980). Recently, the geologists from the Wisconsin Geological and Natural History Survey have been doing large scale mapping in northeastern Wisconsin and in 1984 the Survey published a geological map of the area (Greenberg and Brown, 1984).

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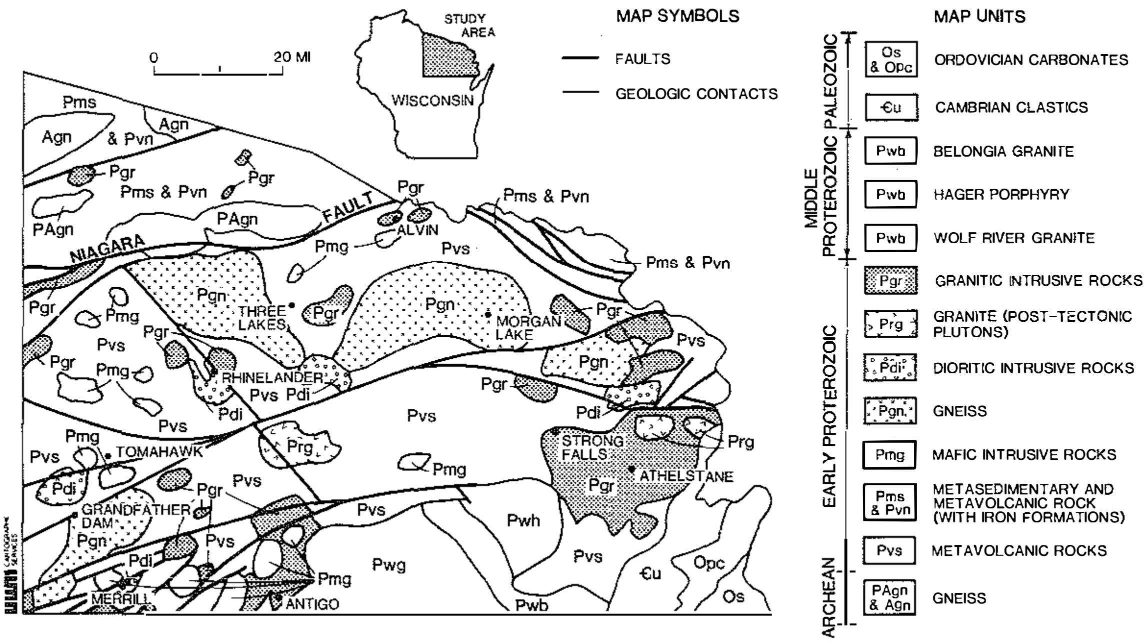


Figure 1. Geologic map of northeastern Wisconsin showing locations of granitic rock units from this study (simplified from Greenberg and Brown, 1984).

METHODS

Eighty thin sections were made, at least one for each outcrop. The anorthite content of plagioclase was determined with the aid of four axis Zeiss universal stage according to Michel-Levy method. Modal analyses were obtained from rock slabs after staining of feldspar according to the method of Bailey and Stevens (1960) and Hutchison (1974). Whole rock chemical analyses for Si, Al, K, Ca, and Fe were determined using a Phillips PW 1410 X-ray spectrometer (XRF) whereas Na and Mg were determined by atomic absorption. X-ray spectrometry (XRF) was carried out according to the procedure described by Jenkins (1976) and atomic absorption techniques were similar to those advanced by Andigo and Billings (1972).

GENERAL GEOLOGY

The majority of plutonic rock in the study area ranges in composition from granite to quartz diorite but mineralogy is quite similar (fig. 2). The predominant alkali feldspar is microcline, ranging from nonperthitic or slightly perthitic in the more basic rock to very perthitic in some of the true granite. Orthoclase was occasionally observed. Quartz is ubiquitous, occuring in large amounts even in some quartz diorites (up to 35 percent). Plagioclase ranges between oligoclase and andesine in composition, and is almost always altered more than the other major minerals. Biotite is invariably pleochroic in dark brown and yellow and hornblende in dark green and yellow. The most common accessory mineral in the more basic rocks is sphene and in the more acidic, zircon. Apatite was frequently observed and epidote, allanite and various opaques were occasionally seen.

Although primary textures, due to cataclastic effects, are commonly obscured, most rock is medium grained, hypidiomorphic granular to allotriomorphic granular. Microcline and quartz are usually anhedral, but microcline is more commonly interstitial and quartz is often polycrystalline. Plagioclase is usually zoned, subhedral and polysynthetically twinned. Biotite and hornblende are commonly subhedral. The paragenetic sequence of minerals for each area is shown in figure 2.

Most of the granitic rock can be tentatively classified as mesozonal, because features associated with katazonal or epizonal emplacement were not readily observed. For instance, migmatization and high-grade regional metamorphic rock associated with greater depths and pressures were lacking.

Metamorphic effects in the samples are not uncommon, but it is nearly always low grade, and commonly retrograde. For instance, many samples contain saussuritized plagioclase, and potash feldspar in the granite is commonly kaolinized or sericitized. In a few extreme cases granite has been metamorphosed to the low-grade mineral assemblage quartz, muscovite, albite, chlorite, and epidote, but still retain the original granitic texture.

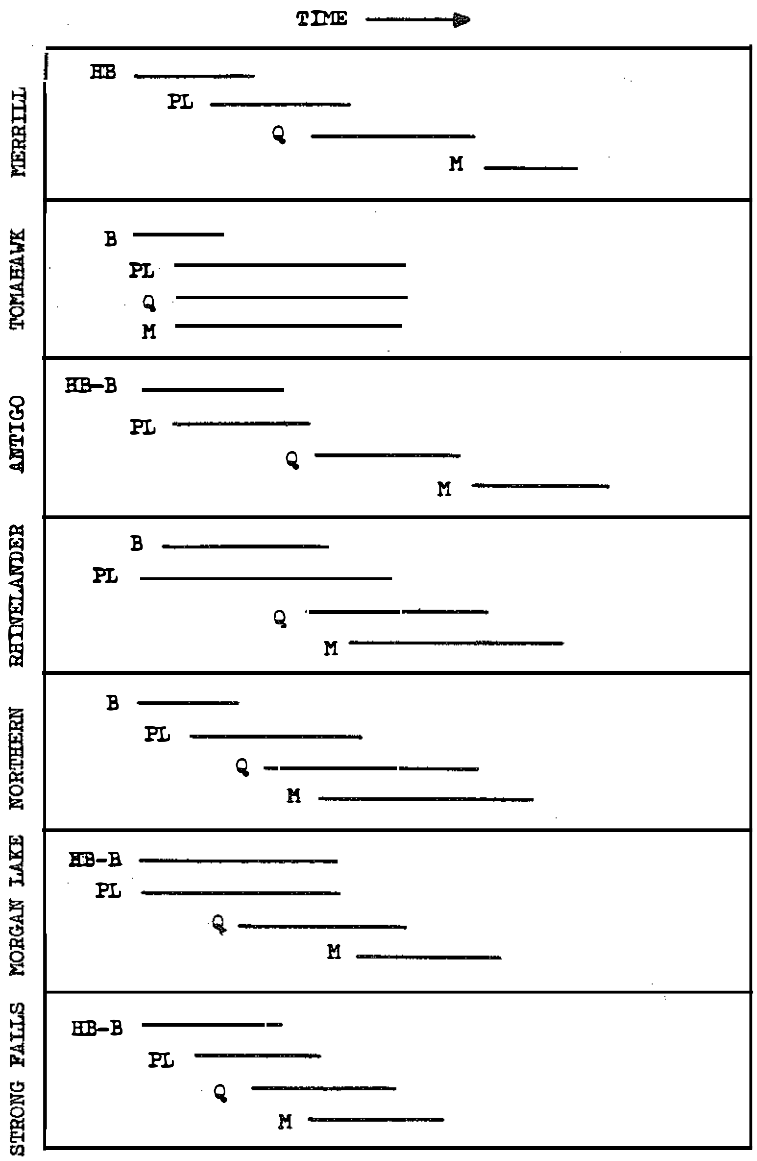
Samples which have been metamorphosed to higher grades are relatively few. Quartz diorite samples of the Twin Lakes area have been changed to amphibolite, and the rock collected at Argonne contain almandine garnet and are possibly paragneissic. The other Twin Lake rock may also be metasedimentary, but this is uncertain since strictly metamorphic minerals were not observed and the texture, though granular, was not necessarily relict. Contact metasedimentary rock found at Grandfather Dam is part of a roof pendant which has been metamorphosed to the sanidine facies.

In some cases, the original texture of the rock has been modified and obscured by cataclastic effects. Although pronounced changes can be seen in hand specimen, they can be most easily observed under the microscope. As strain increases, textural changes appear in a progressive sequence. Initially, trains of inclusions and undulatory extinction appear in quartz, and occasionally twin lamallae of plagioclase are bent. As strain increases, mortar texture is observed around quartz grains until finally quartz is apparently transformed into polycrystalline aggregate and feldspars appear as lenticles outlined by micas. Complete mylonitization was not observed.

PETROGRAPHY

Antigo Area

The samples for this area were collected on Highway 64 west of Antigo and on county roads in the vicinity of Antigo. The rock commonly shows exfoliation, and vary from fine to coarse grained and from granite to quartz diorite. Color is also quite variable. The mineralogy of most of the samples is typical of granitic rock. Quartz (25 to 45 percent), slightly perthitic to nonperthitic microcline (0 to 10 percent), biotite (20 percent), zoned



B=biotite, HB=hornblende, M=microcline, PL=plagioclase, Q=quartz

Figure 2. Mineral paragenesses in granitic rock from northeastern Wisconsin.

plagioclase An_{15-35} (25 to 65 percent) and hornblende (trace to 30 percent) are the primary minerals. Apatite, sphene, zircon, and allanite are accessories.

Athelstane Area

Athelstane area has been studied previously (Cain 1962, Cudzilo 1978); however, new outcrop, particularly along external contacts, is being looked at for the first time. The unit underlies about 200 squre kilometers of northeastern Wisconsin and has been dated at 1810 50 Ma (Van Schmus, 1973). Typical Athelstane area rock is medium- to coarse-grained granite to granodiorite composed of anhedral quartz (25 to 35 percent), anhedral and perthitic microcline (20 to 40 percent) and subhedral to anhedral plagioclase (20 to 40 percent) with anorthite content varying from An_{25} to An_{35}. Ubiquitous albite twinning in plagioclase is very fine and often obscured by a dusty appearance or saussuritization. Biotite is pleiochroic in red brown to dark brown and yellow, and hornblende in green and yellow (5 to 15 percent). Typical accessories include apatite, zircon, and strings of anhedral sphene. Overall, the texture is hypidiomorphic granular and occasionally slightly porphyritic.

Rhinelander Area

The samples studied were collected in and around the city of Rhinelander. They are generally altered granitic rocks which vary slightly in texture and color, from medium to coarse grained and from pink to beige. The Rhinelander rock varies considerably in mineral abundance. Plagioclase varies from An_5 to An_{35} and makes up 15 to 50 percent of the rock. Quartz (30 to 50 percent), nonperthitic microcline (0 to 30 percent), biotite (5 to 15 percent), and a little orthoclase are the primary minerals. Metasomatism was observed at the contact with mafic porphyry indicated by microcline development in the porphyry and depletion of potassium in the adjoining granite.

Northern Area

Although the samples from this area are further apart than the rock of the other areas, they are uniformly beige medium-grained, biotite granite. However, in the far north of the area pegmatite was observed intruding granite gneiss, probably near contact with country rock. The northern rock consists of quartz (25 to 35 percent), zoned and corroded anhedral to subhedral plagioclase (15 to 25 percent), slightly perthitic microcline (35 to 40 percent), and biotite and muscovite (10 percent). Myrmekite is a common constituent and may be due to reaction between contacting K-feldspar and plagioclase. The pegmatites are composed almost entirely of quartz and microcline with a little almandine garnet.

Grandfather Dam Area

Outcrop from this area was found on Highway 107 between Merrill and Tomahawk in the Grandfather Dam area. The rock varies from granite to diorite and most is foliated. The rock varies from fine to coarse grained and locally is cut by quartz veins about 5 cm thick. The diorite consists of 50 percent pale green uralite, formed from the alteration of clinopyroxene, and 50 percent plagioclase (An_{40-45}). Chlorite and epidote occur as alteration products of the clinopyroxene. Quartz rich tonalite is composed of biotite and hornblende (15 percent), quartz (45 percent), plagioclase An_{25-30} (20 to 30 percent) and microcline (10 percent).

Tomahawk Area

Rock was collected on town roads a few kilometers north of Merrill. All are granitic in composition varying from predominantly red, coarse-grained granite to subordinate tan, fine-grained granite in contact with and commonly contains greenstone inclusions. The coarse-grained, red granite contains quartz (30 to 35 percent), anhedral to subhedral saussuritized plagioclase An_{10-15} (20 to 25 percent), slightly perthitic microcline (40 to 45 percent), biotite (5 to 10 percent), and minor hornblende. Sphene, apatite and epidote are the accessories. The finer grained granite phase is similar to the above, but is less strained. Accessories include epidote, zircon and allanite. Myrmekite was present in all the samples from this unit.

Three Lakes Area

The rock from this vicinity is mainly foliated, east-west striking medium-grained quartz diorite gneiss. There is a distinct change in the petrology to more mafic diorite gneiss in the southern part of the area, possibly representing a separate unit. The quartz diorite gneiss is composed of quartz (25 to 30 percent), plagioclase An_{30-35} (55 to 60 percent) a little microcline (5 percent) and less than 15 percent biotite and hornblende. Accessories include chalcopyrite. The more mafic samples contain about 50 percent hornblende, and 50 percent plagioclase (An_{40-45}) and had been metamorphosed to the amphibolite facies.

Morgan Lake Area

The Morgan Lake rock samples were collected from a very small area and are almost identical petrologically. They are beige, medium- to coarse-grained granite composed of quartz (25 to 35 percent), altered, and zoned subhedral to euhedral plagioclase An_{20-25} (15 to 30 percent), slightly perthitic microcline (25 to 45 percent), brown biotite and muscovite. Zircon is the major accessory, prominently appearing in a variety of shapes. The Morgan Lake rocks display fewer characteristics of strain than the rock from most other areas.

Strong Falls Area

As with the Morgan Lake granite, samples were collected in a very small area. They are pink, coarse- to medium-grained granite consisting of quartz (20 to 30 percent), anhedral to subhedral plagioclase An_{10-15} (20 percent), microcline perthitie (35 percent), biotite (15 percent) and a little hornblende intergrown with biotite. Very distinctive zircon, displaying variable appearance is the major accessory.

Merrill Area

The rock underlying this area is medium-grained quartz diorite. Locally, this unit is foliated in an east-west direction and is cut by pegmatite dikes. Mineralogically, the Merrill rock is composed of plagioclase An_{40-45} (50 to 60 percent), hornblende (20 to 30 percent), quartz (20 to 30 percent) and a trace of interstitial microcline. Texturally, it varies from massive to foliated. Small clumps of hornblende crystals wrap around larger grains of plagioclase in the foliated samples. Chlorite, epidote, and apatite are present as accessory minerals.

Miscellaneous

The miscellaneous grouping includes those areas about which there is limited information. The Alvin area rock is granite with mineralogy and texture similar to those found in many other areas of this study. Those granite gneisses cropping out north of Argonne, however, are paragneisses with a granoblastic texture. The mineralogy includes plagioclase, microcline, biotite, quartz, hornblende and almandine garnet. Diorite located at Laona Junction has locally been metamorphosed to the greenschist facies. The rocks of the Carter area are granites which vary in color gradually between grayish green and pink and under the microscope it appears that they were formed by metamorphism and possibly metasomatism of medium grained sandstone. It is probably significant that Carter is only two miles north of the contact with the Wolf River batholith. The areas about ten miles west of Strong Falls and at Armstrong, are underlain by quartz monzonite similar petrologically to the majority of other granites in this study. For a more detailed petrography of these rocks, see Appendix II in Mursky and Bailey (1988).

CHEMISTRY

Introduction

Forty-eight rock samples were chemically analyzed for seven major elements: Fe, Ca, Si, Al and K were analyzed by X-ray fluorescence; and Na and Mg by atomic absorption. In most cases the results were reasonable and satisfactory, but the oxide sum was uniformly low for the more mafic rocks. One possible explanation for this is that H_2O and TiO_2 are not accounted for. Another reason may be that some divitrification of the glass discs, used in X-ray fluorescence, took place, resulting in heteorgeneity of the samples (Jenkins, 1976). However, for the purposes of this comparative study the results seem to be satisfactory.

The chemical analyses were used to calculate Niggli molecular norms and to calculate and plot variation diagrams and fractionation indices. Norms for the bulk of the rocks were calculated with a program written in BASIC for a Sinclair ZX81 computer. These norms were then compared with the modal analyses.

Variation diagrams were used to compare the chemical trends. Among the diagrams prepared were Harker diagrams (Harker, 1909), (Na + K) - Fe - Mg and Na - K - Ca triangular diagrams, the Peacock Diagram, Ab - Q - Or, Ab - An - Or triangular diagrams, and K_2O vs Na_2O.

Molecular Norms

Niggli molecular norms (figs. 3 and 4) are corundum normative (peraluminous) and quartz normative but comparison of norms with modes discloses some discrepancies. Orthoclase, in particular, is usually higher in the mode than in the norm. This is possibly due to incorporation of Na in the alkali feldspar not accounted for by the normative calculations. Quartz is usually higher in the norm than in the mode, and this is probably due to the presence of other silicate minerals in the analysis. Minor errors in these norms can be accounted for by the limited number of elements analyzed for.

Norms were used to calculate the Differentiation Index (DI) (Bowen and Tuttle 1958), which gives some clue to the stage of fractionation of a rock. In this scheme the DI of the average granite = 93, average granodiorite = 67, average diorite = 48.

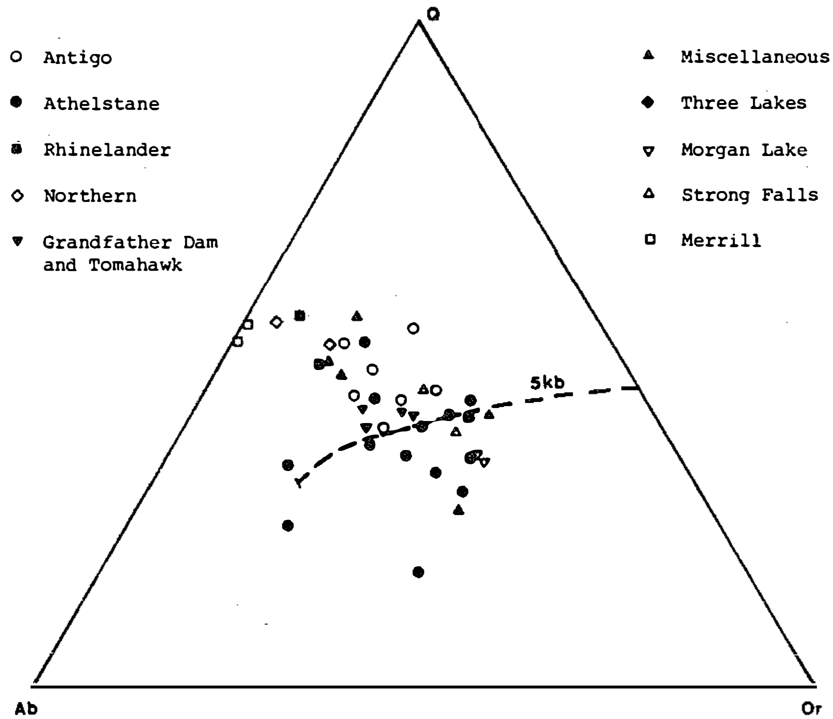


Figure 3. Ternary diagram of the normative components albite (Ab)-quartz (q)-orthoclase (Or) for the individual sample areas with the approximate position of the cotectic line drawn in.

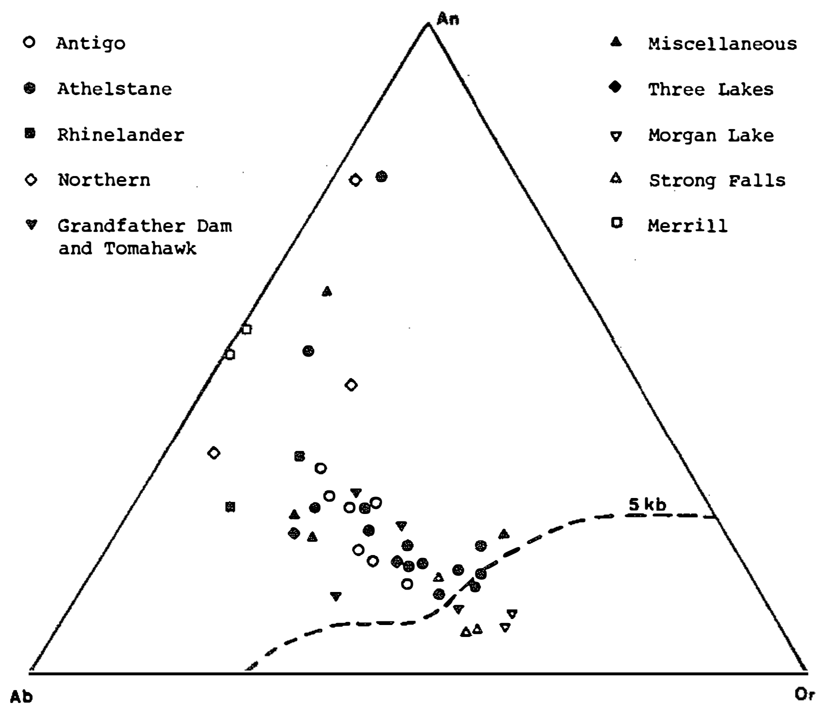


Figure 4. Ternary diagram of the normative components albite (Ab)- anorthite (An)-orthoclase (Or) for the individual sample areas with the approximate position of the cotectic drawn in.

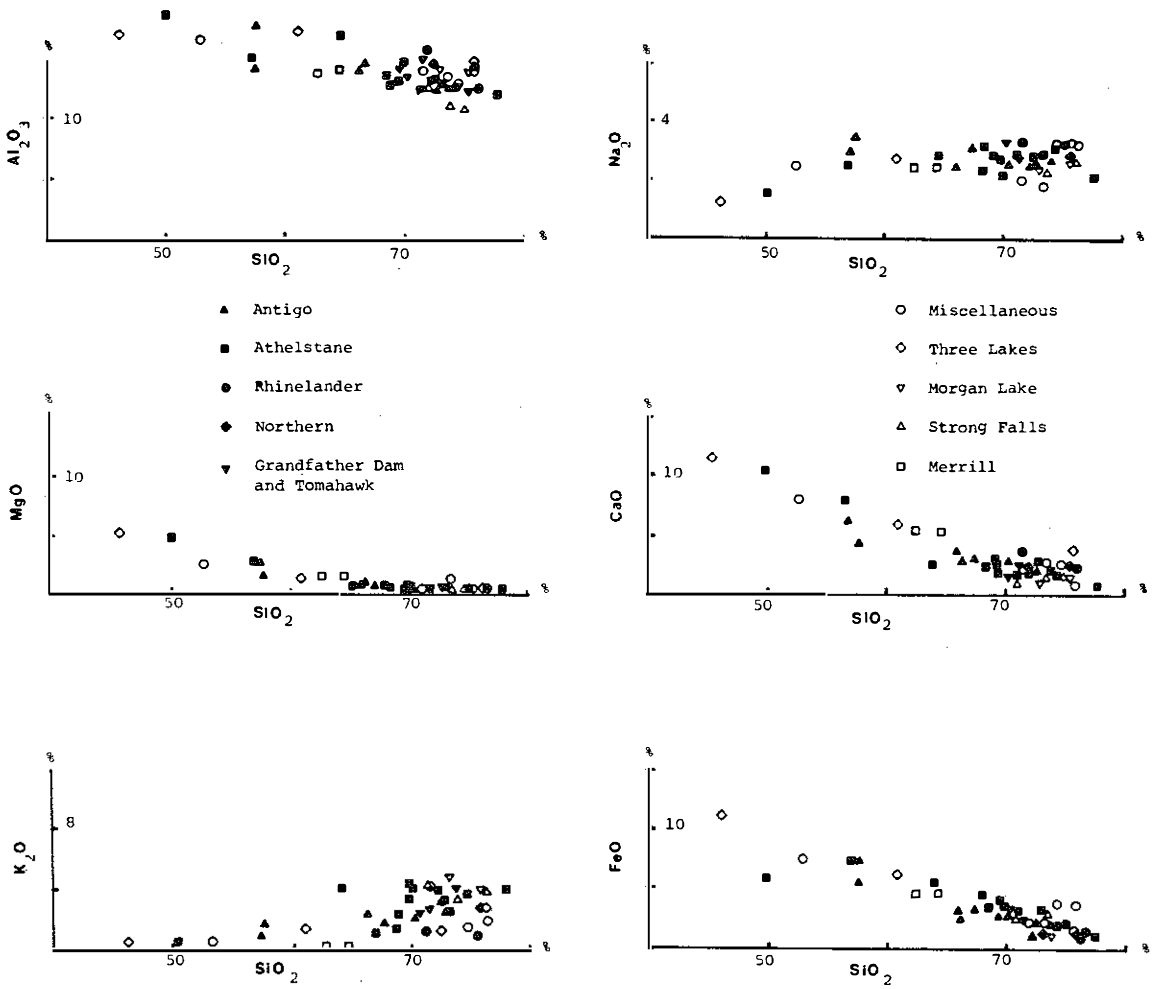


Figure 5. Harker variation diagrams for granitic rock from northeastern Wisconsin.

Variation Diagrams

Harker Diagrams are displayed in figure 5 and their study discloses several interesting trends. In the sodium diagram the points define a line nearly parallel with the silica axis. This implies that there is no correlation between sodium and silica content. However, on the calcium and iron curves, which nearly coincide, one can see a definite increase with decreasing silica. The same trend can be seen on the alumina curve, but not as pronounced and with greater point scatter. The magnesia curve maintains a correlation with silica with little point scatter, however, this latter condition is probably due to the small amounts of magnesia in the silica rich rocks. On the potassium diagram one can observe the greatest amount of scatter and a definite increase of potash with increased silica. The scatter possibly implies greater mobility of the potassium than the other oxides.

It is instructive to compare the trends from the individual geographical areas on the same diagrams. For example, on the calcium curve the Athelstane and Antigo group of rocks define slightly different trends, as does the combination of Three Lakes, Merrill and the miscellaneous samples nearest Cavour, all of which are diorites or quartz diorites. This may be due to the derivation from different magmas, or heterogeneity within the same magma.

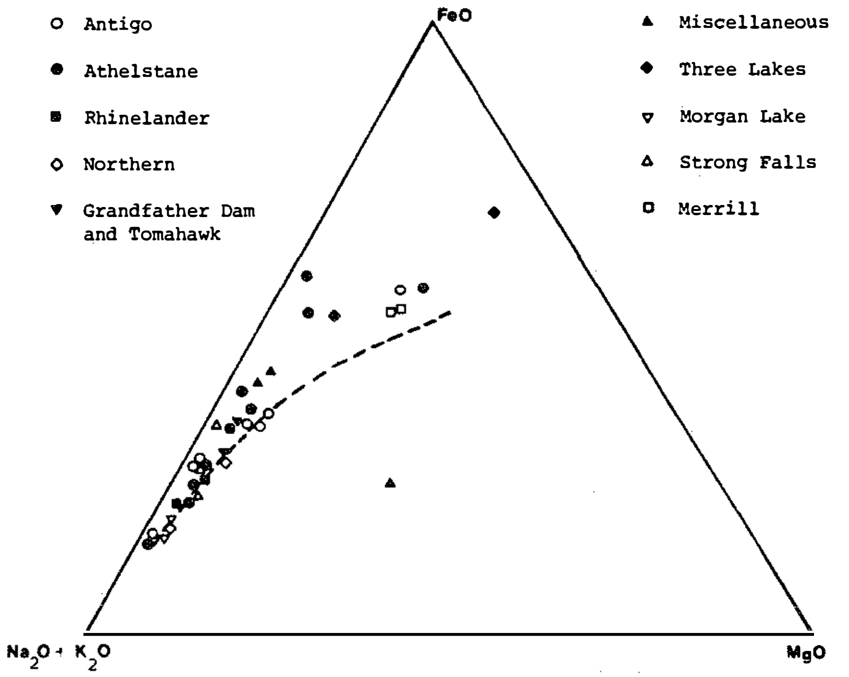


Figure 6. Ternary diagram of the components FeO (total iron) – MgO – Na_2O + K_2O) in weight per cent for the individual sample areas also showing the trend of the Southern California batholith (Nockolds and Allen, 1953, dashed line.

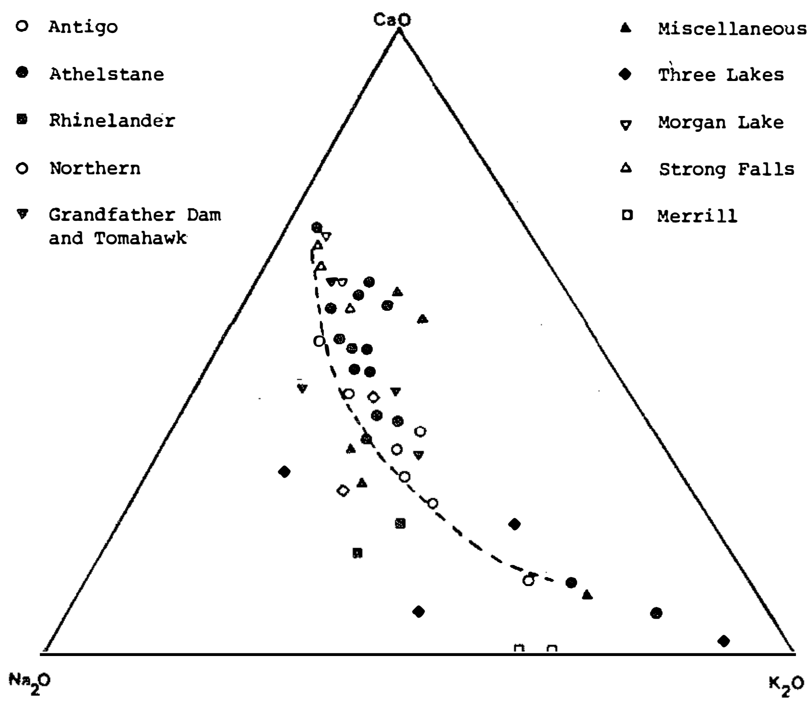


Figure 7. Ternary diagram of the components Na_2O-K_2O-CaO in weight percent for the individual sample areas including the trend for the Southern California batholith (Noxckolds and Allen, 1953, dashed line).

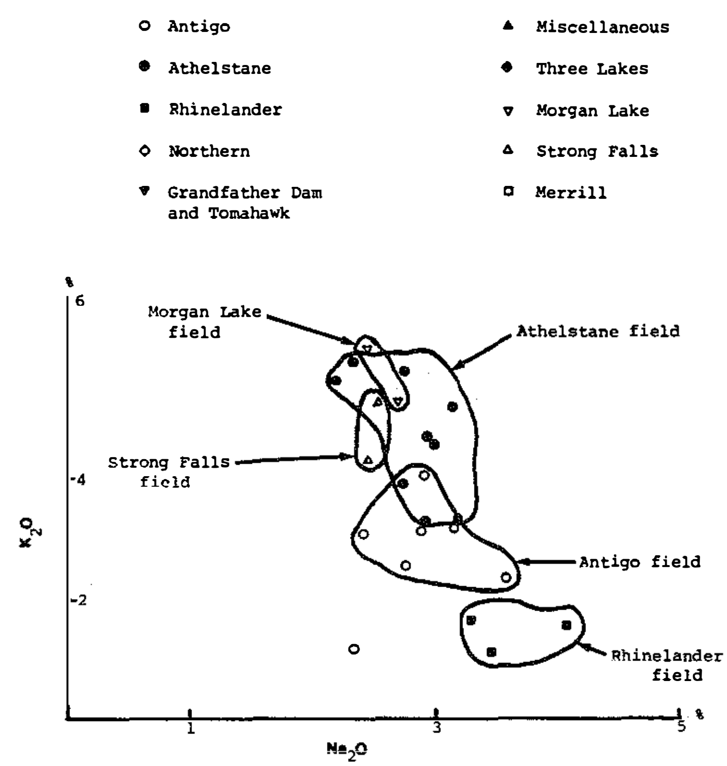


Figure 8. Plot of Na_2O versus K_2O showing the separate fields delineated for the individual sample areas.

On the iron curve the trends are very similar to those of the calcium curve, but on this plot the Athelstane rocks have slightly more iron than the Antigo rocks. Because of the small amount of Mg in the more acidic samples, distinction between different trends cannot be made.

The points on the potassium curve show the most scatter, particularly in the silica rich samples. This could be due to metasomatism or assimilation. Comparing potassium to sodium for acid rocks in any of the areas discloses discloses that these rocks are high in potassium which is typical of late tectonic granites (Barth 1962), although the Rhinelander rocks are noticeably deficient in potassium.

In figure 6 one can see a distinct trend, defined by the position of the plotted points from the recalculated chemical analyses. The trend of this curve and distribution of the individual points are similar to that for calc-alkalic suites, that is. The Southern California Batholith (Nockolds and Allen 1953). Areal trends are also evident. The points representing the Athelstane quartz monzonite traces out the main curve, as do those representing the Antigo samples. However, it is not possible to separate the individual trends with confidence for other areas.

The data in Na_2O - K_2O - CaO (fig. 7) defines a trend similar to those observed for calc-alkalic suites of rocks. On this diagram the points nearest the K_2O corner are the most granitic, while those at the top are the most mafic, and the Athelstane rocks are more potassic than the Antigo rocks for a given Na_2O/CaO ratio. The Merrill rocks do not lie on the main trend, but are scattered near the bottom of the diagram.

Another ternary diagram useful in differentiating units or, in interpreting conditions of formation is one whose corners are normative albite (Ab) - quartz (Q) - orthoclase (Or) (fig. 3). The Athelstane and Antigo samples can be distinguished as separate units in this diagram because the Athelstane samples have a higher Or content for a given Q/Ab ratio. The points from the Merrill, Morgan Lake, and Strong Falls rocks all group as individual units also. The Athelstane points which do not group nicely represent samples near external contacts. The other areas cannot be differentiated as easily from this diagram.

If normative Ab-An-Or are plotted as components on a ternary diagram (fig. 4) the Strong Falls rocks (low An, Ab/Or ratio = 1) and the Rhinelander rocks (low Or, Ab/An = 1.5) can be distinguished as separate units. The Athelstane and Antigo area rocks are not as easily distinguished in this diagram due to variable An content.

Figure 8 is a plot of Na_2O versus K_2O and it has been used to assist in differentiating the plutons of far northeastern Wisconsin (Cudzilo 1978). The samples from many of the areas delineate separate fields. The Rhinelander rocks have the highest Na_2O/K_2O ratio, the Morgan Lake and Athelstane rocks the lowest.

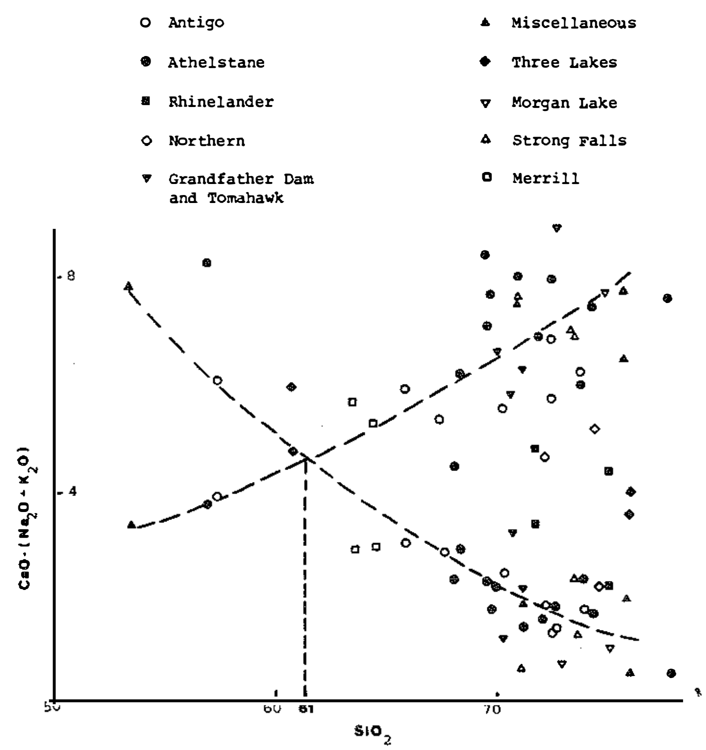


Figure 9. Peacock diagram of individual sample areas with inferred trends (dashed lines).

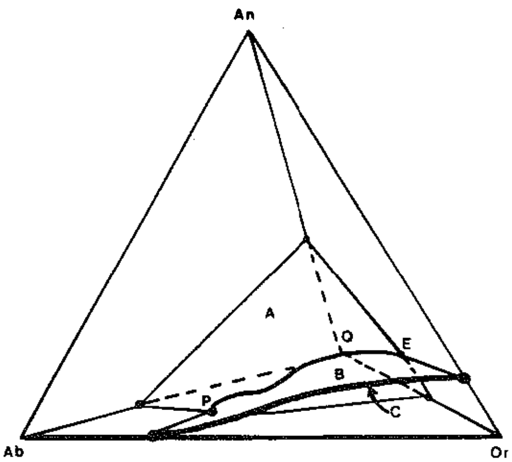
The Peacock diagram (fig. 9) can be used to identify the rock series to which a cogenetic group of rocks belongs (Hyndman 1972). The plot defines two intersecting concave upward lines and the SiO_2 value at the point of intersection defines the type of magma from which the rocks were derived. Inspection of the plotted points for the rocks of the study area in figure 9 makes it apparent that some interpretation is necessary to determine the position of the two lines. The dotted lines appear to be the best choices and intersect at a SiO_2 value of 61.0 which indicates a borderline calcic or calc-alkalic rock series. Such series are usually associated with orogenic areas. Note should be made that the Rhinelander and Three Lakes samples are relatively deficient in alkalis.

CONCLUSIONS

The majority of rocks in this study were probably emplaced during the Penokean Orogeny about 1.6 to 1.9 Ga. The Athelstane quartz monzonite has been dated at 1810 50 Ma (Van Schmus 1973) and many of the other units show evidence of a similar age. For example, some units are foliated in a direction approximately parallel to the tectonic axis of the Penokean mobile belt (that is Merrill, Grandfather Dam and Three Lakes) and some units contain greenstone inclusions presumably belonging to the belt. Therefore, these units are mainly late tectonic and syntectonic. The calc-alkalic to calcic chemistry of the units, the relatively high K_2O/Na_2O ratio, and apparent mesozonal emplacement of these units support a mainly late tectonic origin. Detailed radiometric dates would be useful to substantiate the probable relationship to the Athelstane quartz monzonite and the previously studied plutons of northeastern Wisconsin.

Many of the plutonic units of this study can be classified as I-type granites (compositionally expanded), as opposed to S-type (compositionally restricted)(Pitcher 1979). I-type granites are thought to be mainly derived from anatexis of upper mantle rocks formed over a subduction zone at an oceanic plate and continental plate boundary similar to the geological setting on the west coast of South America (Pitcher 1978). Analogously, the study area was probably an ancient continental margin underlain by subducting oceanic crust. Some of the granites in the study area may be of crustal origin and this would be similar to S-types. Furthermore, many features of an I-type granite geological setting (Pitcher 1978) are not present in this study. Initial $^{87}Sr/^{86}Sr$ ratio would help to resolve this question.

From experimental studies of the Ab-An-Or-Q-H_2O system (Winkler, 1979), the relationship of the phases with changing temperature at constant pressure has been clarified (fig. 10). The important features of this diagram are the cotectic line PE, the cotectic surfaces A, B, and C, and the spaces beyond each of these surfaces. In fusion studies of paragneisses, containing the components Ab-Or-Q-An, and enough H_2O to maintain constant pressure throughout fusion, melting begins on the cotectic line PE, and upon raising temperature the melt composition moves up the line until all the alkali feldspar in the paragneiss is melted, then it moves onto one of the cotectic surfaces. Finally, after raising the temperature even higher, one of the remaining phases completely melts, and the composition of the melt moves into one of the spaces above or below the cotectic surface. From the experimental studies it was found that the position of the cotectic line changes only



Explanation

PE = cotectic line

A = cotectic surface separating quartz space from plagioclase space

B = cotectic surface separating plagioclase space from alkali feldspar space

C = cotectic surface separating quartz space from alkali feldspar space

Figure 10. Phase relations in the system Ab-An-Or-Q at a given H_2O pressure (after Winkler, 1979).

slightly with regard to pressure and a change in the composition of the paragneiss. Providing the initial material contains the preceding major components the above sequence is followed upon melting.

As discussed previously, the rocks of this study have been projected onto the triangular diagrams Ab-Q-Or and Ab-An-Or of the tetrahedron in figures 3 and 4. Most of the Athelstane samples plot on or close to the cotectic line and because of their low An content may represent a "minimum melt" derived from anatexis of paragneisses with an Ab/An ratio of between 2.5 and 8 at H_2O pressures of less than 3 kb and temperatures of about 670 to 700 C or as late differentiates under the same pressure- temperature conditions. The Strong Falls and Morgan Lake units could have been formed in essentially the same way and the Antigo, Rhinelander and Northern units possibly formed at temperatures 50 to 80 °C higher as later melts, or earlier differentiates. Most of the points on the diagram can be interpreted as originating in either of these two ways and it is possible that nearly all the rocks could have originated mainly by partial melting of rocks of appropriate composition, followed by crystallization from a magma.

Conclusions regarding the temperatures and pressures of formation of the rock units, based on figures 3 and 4, indicate that most units formed between about 670 and 750 °C from 1 to 3 Kbar H_2O pressure. Support for this hypothesis includes the mineralogy of the samples. The primary minerals found in these rocks are stable within this range, and maximum microcline in particular indicates formation near the low temperature limit proposed. The roof pendant, at Grandfather Dam, which belongs to the sanidine facies, was probably metamorphosed near the upper temperature limit, possibly by underlying dioritic magma.

The study area is not unique among Proterozoic areas of the world. Mobile belts and associate plutons of this age exist in several places, but the one best studied is the Svecofennide Province in southwestern Finland and Sweden (Read and Watson 1975).

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