RELICT PLAGIOCLASE PHENOCRYSTS FROM METAVOLCANIC ROCKS MANTLING A GRANITE DOME AND THE PETROLOGY OF THE ASSOCIATED ROCKS IN THE GRENVILLE PROVINCE OF SOUTHEASTERN ONTARIO

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ABSTRACT OF THE THESIS

Relict Plagioclase Phenocrysts from Metavolcanic Rocks Mantling a Granite Dome and the Petrology of the Associated Rocks in the Grenville Province of Southeastern Ontario

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A granite dome mantled by metavolcanic rocks, metaconglomerate and other metasedimentary rocks occurs near Plevna Lake in the Madoc-Bancroft area of southeastern Ontario. The Madoc-Bancroft region contains the only low-grade metamorphic rocks and unequivocal metavolcanic rocks of the Grenville Province. A major emphasis of this study is the effects of metamorphism on relict calcium-rich plagioclase phenocrysts in the metavolcanic rocks and the petrology of the associated rocks.

Apparently anomalous field relationships between metaconglomerate with granitic clasts and the underlying granite are clarified by evidence that (i) while the clasts closely resemble the granite megascopically, modal analyses show that most of them are unrelated plutonic rocks and (ii) there is a border zone of the granite that is mineralogically and texturally distinct which is a chilled zone.

The metaconglomerate is not derived from the granite but rather the latter was intruded into the sequence of metaconglomerate, metavolcanics, paragneiss and marble. A temperature gradient between granite and country rock is indicated by a chilled zone and a contact metamorphic zone in the adjacent metamorphic rocks.

The metaconglomerate appears to be at or near the base of the known section in this area but the clasts represent an even earlier time of plutonic activity.

The composition of the granite closely approximates the system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2 - H_2O . Differentiation trends in the chilled zone show the position of the low-temperature trough in this system and demonstrate that the granite is epizonal and was emplaced at a P_{H_2O} of less than 1000 bars.

Prior to the intrusion of the granite, the metasedimentary metavolcanic sequence was regionally metamorphosed to either the staurolite-almandine subfacies or the kyanite-almandine subfacies of the almandine-amphibolite facies. Plagioclase compositions are greater than An_{20} ; no albite is present. Kyanite occurs locally in the metaconglomerate matrix. The amphibole of the metavolcanics is tentatively identified on the basis of X-ray diffraction and optical work as being in the tremolite-actinolite series.

The metavolcanic sequence includes both pyroclastic rocks and porphyritic andesite-basalt flows; many are so completely recrystallized that the original rock type is unrecognizable.

Most of the plagioclase phenocrysts have been completely recrystallized; there is a marked correlation between deformation and recrystallization of the phenocrysts.

Plagioclases were studied by five-axis U-stage techniques, the Tsuboi method and electron microprobe analyses. The relict phenocrysts are in an ordered structural state, all original compositional zoning has been destroyed and the secondary groundmass plagioclase grains have compositions in the same range as that of the phenocrysts. Three samples containing relict phenocrysts were studied in detail and have the following plagioclase compositional ranges (groundmass and phenocrysts); An_{24-28} , An_{30-38} and An_{39-41} . These relict phenocrysts reacted with the remainder of the rock and changed composition by solid state diffusion without recrystallizing. Original twin planes and re-entrant angles are preserved and the twin planes have reoriented themselves to the new composition and structural state. The assemblages are disequilibrium assemblages; relict amphibole phenocrysts occur in all three samples. The sample having the most sodic plagioclase composition has more secondary amphibole developed and was closer to equilibrium. The preservation of the phenocrysts was due to their size, a lack of deformation and to a low volatile content in the center of the metavolcanic mass during metamorphism.

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INTRODUCTION

This is a study of a granite dome and the surrounding metasedimentary and metavolcanic rocks which occur in the Grenville Province near Plevna Lake in southeastern Ontario. The Grenville Province is a northeast-trending structural subdivision of the Canadian Shield approximately 1000 miles long and 200 miles wide encompassing parts of Ontario, Quebec, Labrador and New York State. The province was named by M. E. Wilson (1918) and features which have come to be considered characteristic of the province, although not ubiquitous, are crystalline limestones and anorthosites.

Radiometric dating by the Geological Survey of Canada (Stockwell, 1961, 1963a, 1963b, 1964) has shown relatively consistent potassium-argon ages of 950 ± 150 million years, which represents the last metamorphic event, and it is on this basis that the Grenville Province is currently defined (Wynne-Edwards, 1967a). Structural relationships with the adjacent provinces are not everywhere clear, but it is known that rocks from these older provinces enter the Grenville Province where they acquired new radiometric ages and characteristics of the Grenville Province.

The metamorphic grade throughout the Grenville Province is uniformly high with the exception of the Bancroft-Madoc area in southeastern Ontario where the only known greenschist facies metamorphic rocks and the only unequivocal metavolcanic rocks in the Grenville Province are found. Early workers in the area, principally from the Geological Survey of Canada, regarded the less metamorphosed rocks, which includes conglomerates, as a separate series (Hastings Series) deposited on the older, more highly metamorphosed rocks of the Grenville Series. This concept has influenced the interpretation of the regional geology as well as becoming a source of controversy. However, mapping by Wilson (1933, 1940), Smith (1958), Moore (1967) and Lumbers (1967a) has shown that the metamorphic grade of stratigraphic units varies along strike and that supposed Hastings-type rocks are overlain in part by Grenville-type rocks. The term Hastings Series is now generally regarded as invalid.

Lumbers (1967b) has summarized the regional geology as follows:

> "The Bancroft-Madoc area is underlain mainly by a Proterozoic metasedimentary-metavolcanic sequence about 27,000 feet thick, whose base is unknown and in which the oldest dated rocks are about 1310 ± 15 m.y. old. This sequence is divided stratigraphically into two groups: (1) a predominantly metavolcanic group containing some metaconglomerate and metasandstone which, for the most part, were derived locally from tectonically active volcanic areas within the original basin of sedimentation; and (2) a marble-rich metasedimentary group. The volcanic rocks were extruded into a dominantly marine environment in which was deposited the metasedimentary group, whose lower part interfingers with, or is equivalent to, the upper part of the metavolcanic group.
>
> "The stratified rocks were subjected to complex, Proterozoic, plutonic, metamorphic, and tectonic events, and a large variety of plutonic rocks form two principal age groups: (1) an early sodic group, about 1250 ± 25 m.y.; and (2) a late potassic group, about 1125 ± 25 m.y. Metamorphic zoning... developed in two stages between 1310 ± 15 and 1125 ± 25 m.y. ago. Culmination of a low to moderate regional metamorphism preceded the main plutonic activity, but postdated the development of the principle northeasterly trending fold pattern.... A period of intense deformation and metamorphism accompanied the emplacement of the late potassic plutonic rocks and culminated before the emplacement of not only some of these plutonic rocks, but also a late (1050 ± 20 m.y.) generation of hydrothermal veins and pegmatites."

The dates mentioned by Lumbers (1967b) were not obtained by the potassium-argon method. Macintyre _et al_. (1967) have shown that potassium-argon ages are in general systematically lower than uranium-lead or strontium-rubidium ages in the Madoc-Bancroft area.

One of the more remarkable features of the Madoc-Bancroft area is the Clare River syncline (Wilson, 1933; Burns, 1951; Ambrose and Burns, 1956). Recent mapping by Reinhardt (1963) indicates that the northeast-trending belt of Precambrian rocks near Carlton Place, Ontario may be a northeast extension of the Clare River syncline. Thus, it may be possible to trace this relatively narrow belt of metasediments and metavolcanics for over seventy miles until they disappear from view beneath a cover of Paleozoic sediments.

The preservation of primary sedimentary and volcanic features in the Bancroft-Madoc Area is also notable. Cross bedding, graded bedding and conglomeratic units are found in metasedimentary rocks and metavolcanic rocks with pillow structures, vesicules, amygdules, agglomerate textures and original phenocrysts are found.

The purpose of the present study is to add to the existing knowledge of the metamorphism of plagioclases of basic volcanic rocks. The effects of metamorphism on relict phenocrysts has received relatively little attention with the exception of a study by Noble (1966) on relict calcium-rich phenocrysts in lower and middle greenschist facies rocks. The area of the present study at Plevna Lake includes metavolcanics with relict phenocrysts in the almandine-amphibolite facies and provides an opportunity to extend the present knowledge concerning metamorphic effects on these relict phenocrysts. Other metavolcanic units in the region were studied and sampled before an area for detailed study was selected at Plevna Lake in Barrie and Clarendon townships, Frontenac County, Ontario.

This area also offered an opportunity to study an unresolved structural and stratigraphic problem concerning the origin of a metaconglomerate with granitic clasts overlying a granite. Neither the relationship between the granite and the metaconglomerate nor the relationship between the metaconglomerate and the surrounding metavolcanic and metasedimentary rocks was clear.

Figure 1, after Smith (1958), shows the stratigraphy and structure of a portion of Frontenac County which includes the study area.

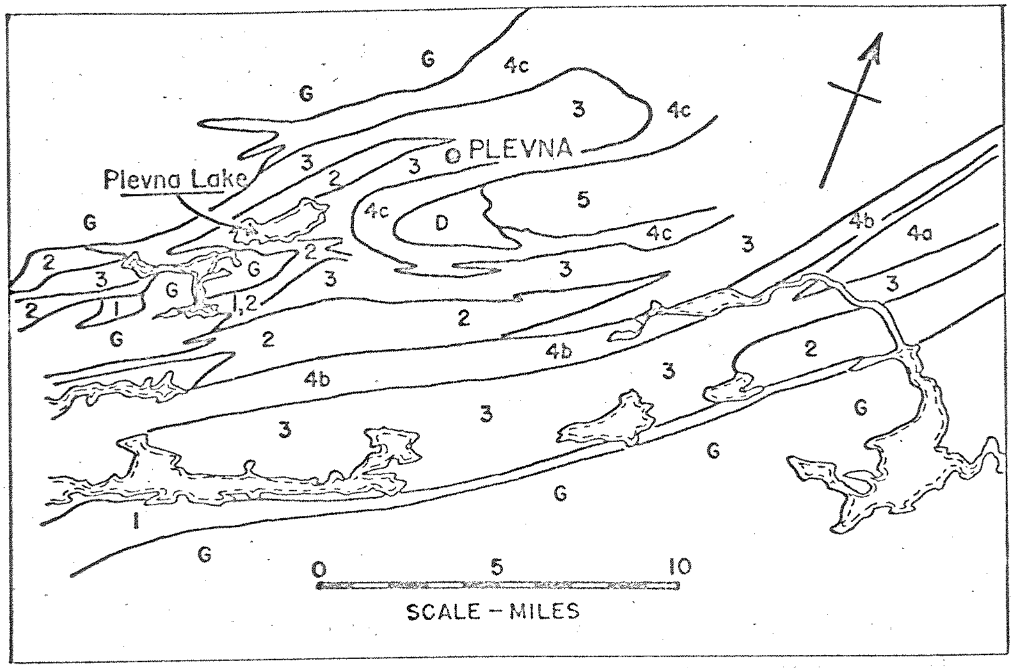

FIGURE 1. Key map showing location of Plevna and Plevna Lake. The numbers 1 through 5 represent an interpretation of age relationships from oldest to youngest; 1 = metavolcanics; 2 = mostly paragneiss; 3 = marble; 4a = metasedimentary rocks of the Ompah syncline; 4b = metasedimentary rocks correlated with 4a; 4c = Plevna syncline rocks believed to be approximately equivalent stratigraphically to rocks of the Ompah syncline; 5 = marble. D represents metadiorite and G represents granitic and granodioritic rocks. Stratigraphic interpretation slightly modified after Smith (1958, inset map no. 1956-4).

STRUCTURE AND STRATIGRAPHY

Smith (1958) has pointed out the occurrence and called attention to the significance of a metaconglomerate with granitic clasts overlying granite near Plevna Lake. The clasts of the metaconglomerate are predominantly (greater than 99 percent) granitic pebbles, cobbles and boulders. Figures 2 and 3 are typical exposures of the metaconglomerate. In hand specimen these clasts have a striking resemblance to the underlying granite and suggest that the metaconglomerate might overlie the granite from which it was derived. However, the metaconglomerate is overlain in turn by paragneiss, metavolcanics, and marble - as shown in Figure 4 - and field evidence was described by Smith (1958) indicating that the granite might be intrusive into these rocks.

Detailed mapping has verified the previously published stratigraphic sequence and has shown that the structure is anticlinal plunging to the northeast (Figure 4). Reconnaissance to the west - in Barrie township - indicates that the same sequence, including the metaconglomerate, is present and that the plunge becomes southwesterly so that the pluton has the shape of an elongate dome. Metaconglomerate interfingers with paragneiss, and metavolcanics are interlayered with both paragneiss and marble. It is clear that there was concurrent volcanism and sedimentation. The metavolcanics consist of both flows and pyroclastic rocks. Feldspar phenocrysts and agglomerate textures are well preserved.

FIGURE 2. Metaconglomerate dipping to the north on the north side of the pluton.

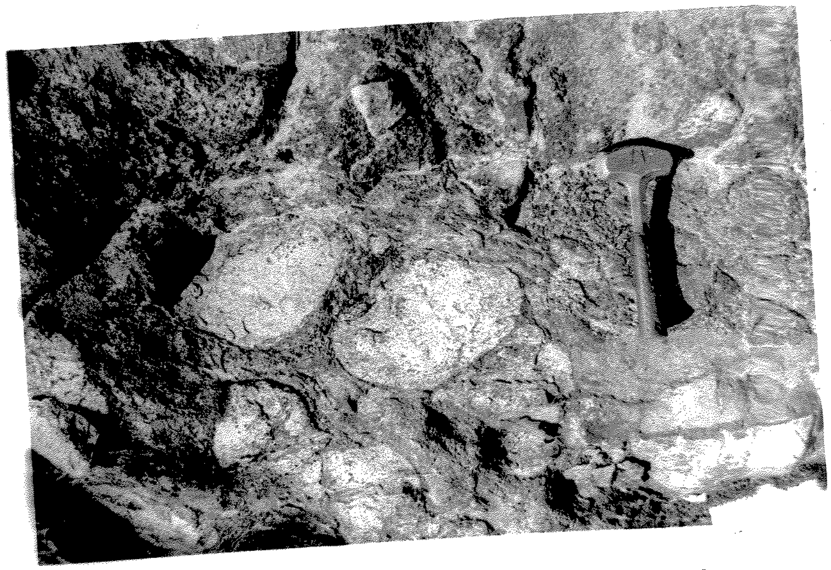

FIGURE 3. Metaconglomerate

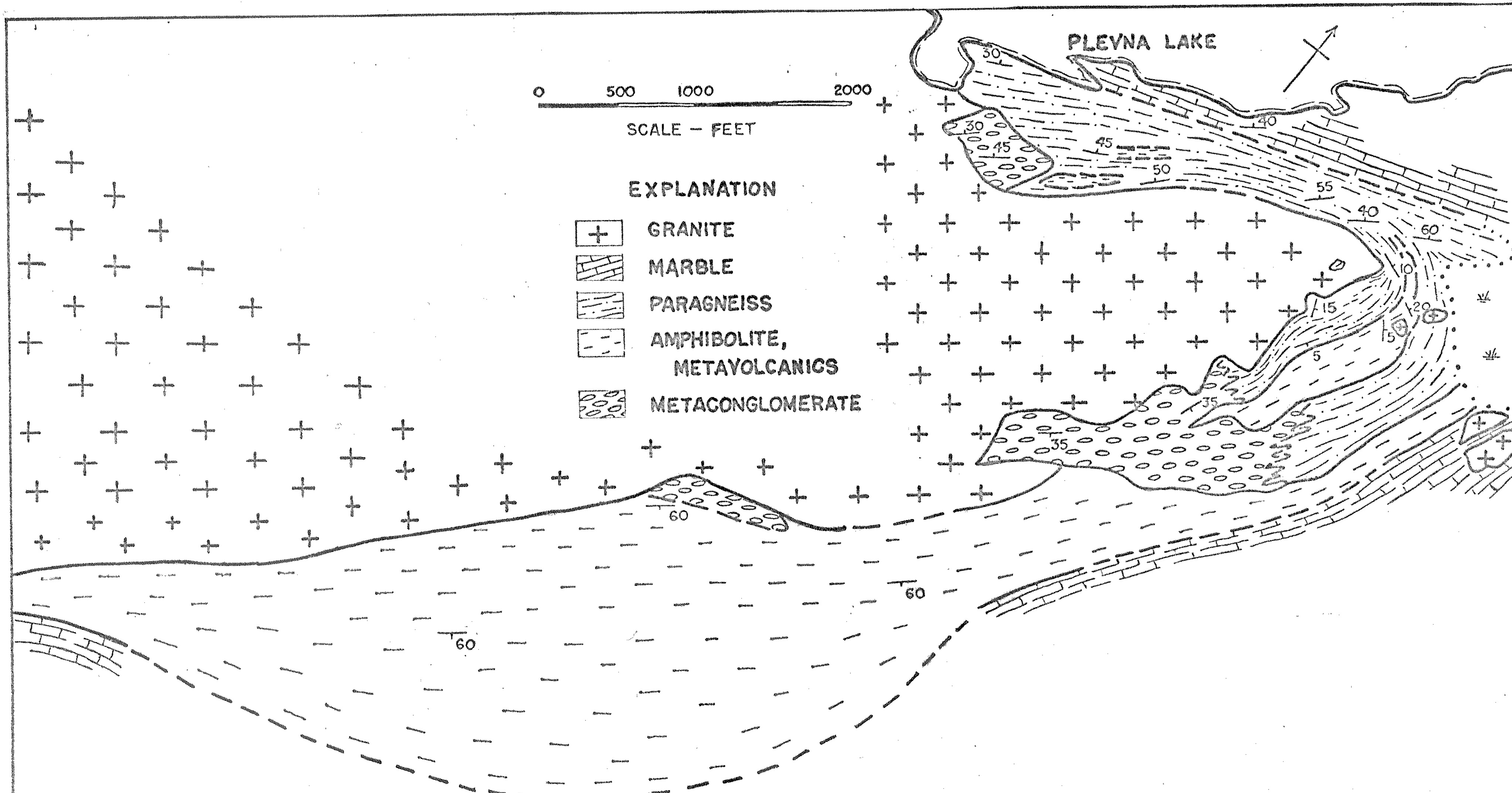

FIGURE 4. Geology of an area south of Plevna Lake.

Granite and Metaconglomerate

Evidence that the granite was intruded, at least in part, as a liquid into the other rocks includes the occurrence of sills and dikes in the paragneiss and metavolcanics. Near the contact with the granite there is local intimate veining along the foliation planes of the paragneiss. The intrusive relationship is also indicated in Figure 4 by the fact that the two larger metaconglomerate bodies are partly surrounded by granite. On the northern side of the pluton, near the lower contact of the metaconglomerate, it appears that, locally, the granite has intruded along the foliation planes of the metaconglomerate matrix and this has resulted in the appearance of granitic clasts surrounded by fine grained granite. The detailed mapping also verifies that there is a contact metamorphic zone near the granite contact (Smith, 1958). Local contact effects around sills and dikes were also noted. The contact of the granite with the country rock is a chilled contact and is discussed in detail in a later section.

The pink, medium grained granite is monotonously homogeneous with no foliation, xenoliths, flow structures or pegmatites noted. The only inhomogeneities observed were scattered areas within the pluton of finer grain size which the writer interprets as being due to chilling of the magma. These were noted in the northeastern portion of the granite mass near the fold nose and are interpreted as portions of the roof zone, either in place or perhaps broken off and displaced downward by sinking in the magma.

Modal analyses of thirty three ramdomly selected clasts are compared with modal analyses of the granite in Figure 5 in terms of quartz, microcline and plagioclase. Other minerals (muscovite, biotite, carbonate and opaques) average about five percent in the granite, 12 percent in the clasts. Of the three clasts whose composition falls within the compositional range of the granite, two contain accessory garnet (not found in the granite). In a few stained slabs, zoning was observed in the clasts and introduction of potassium from the matrix is indicated in the margins of the clasts. To minimize possible effects of such zoning, thin sections were cut only from the central part of the clasts.

Several possible origins for the metaconglomerate were considered in this study. Brecciation in the border zone of the intrusive is ruled out by the interfingering relationship with the paragneiss and the compositional differences between granite and clasts.

Another possibility considered was that the conglomerate was derived from the underlying granite and was subsequently buried and metamorphosed with local remobilization of a low melting granitic material during metamorphism giving rise to the observed crosscutting relationships. However, the evidence is preponderously against this. The following observations are crucial in this respect. The granite has a contact metamorphic aureole surrounding the body (discussed in detail in the section on metamorphism), a chilled contact zone and the surrounding metasediments and metavolcanics are in the lower almandine-amphibolite facies. If this were a case of remobilization

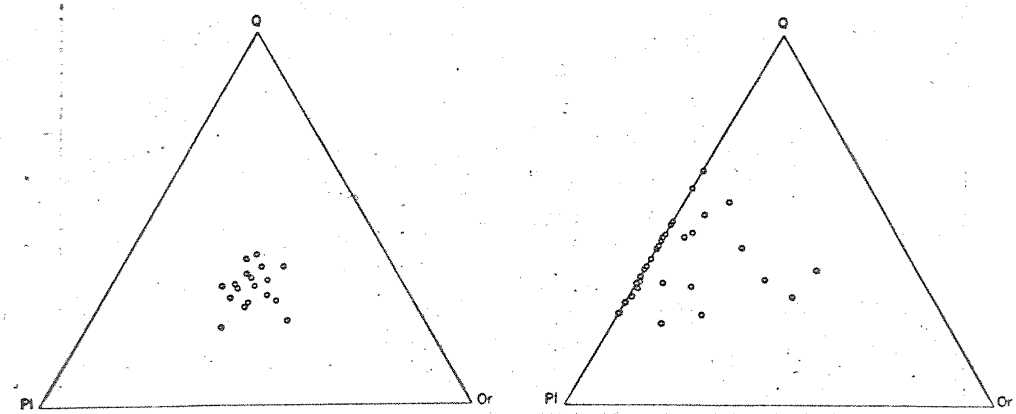

FIGURE 5. Modal analyses of granite (5A) and clasts from the metaconglomerate (5B) compared in terms of quartz, plagioclase and microcline.

the steep thermal gradients, chilled contact and the contact aureole would not be developed. In addition, a higher degree of regional metamorphism would be developed. Nor does it seem likely that potassium would be preferentially removed from the clasts during metamorphism and remobilization. In addition, the granite post-dates the regional metamorphism as shown by the co-existing albite and free carbonate.

The metaconglomerate was not derived from the granite but rather the latter intruded into the sequence of metaconglomerate, paragneiss, metavolcanics and marble. The metaconglomerate appears to be near the base of the known geologic section in Barrie and Clarendon townships (Smith, 1958; this study) but the clasts represent and even earlier plutonic event.

CHILLED ZONE IN GRANITE

The border zone of the granite differs from the homogeneous interior of the granite in several aspects which can be seen in the field. The most apparent differences are that the granite immediately adjacent to the contact is finer grained than the interior of the pluton and also small free quartz veins are abundant in a narrow zone on either side of the contact. This was tentatively identified in the field as a chilled contact and later laboratory work has verified this.

Feldspars from the border zone were compared to those from the interior and showed significant differences. The microcline of the marginal zone contains less albite and the plagioclase contains less anorthite. Microcline composition was determined by the methods of Orville (1963, 1967) and plagioclase determinations were made by the Tsuboi method (Tsuboi, 1923; Vogel, 1967).

Plagioclase in the marginal zone ranges in composition from 2 to 9 percent anorthite, averaging 4 percent. Samples from the interior range from 4 to 15 mole percent anorthite, averaging 8 percent. Although this difference in composition between margin and interior is small, it appears to be a systematic one.

The microcline from the marginal zone has a total albite content (exsolved plus that in solid solution) which ranges from 18.5 to 22.0 mole percent albite. This compares with a range of 30.0 to 49.0 mole percent albite in samples from the interior of the pluton. In both the margin and the interior, almost all the albite is exsolved with only two to four mole percent in solid solution. The low amount of albite in solid solution would indicate that these are in a highly ordered structural state, and this is confirmed by the delta values (Dietrich, 1962; Orville, 1967) which range from 0.91 to 0.98 - i.e. highly ordered - with no discernible variation from the contact zone to the interior.

It is apparent from the delta values that the potash feldspars have been completely re-equilibrated. Instead of the sanidine or orthoclase that would be expected in a chilled margin, an almost completely ordered microcline is present. This, as well as the almost complete exsolution of albite from the potash feldspar, is readily explained as a subsolidus reaction taking place after the initial crystallization. Late stage volatiles leaving the granite mass may have played a part in this recrystallization and may also be the cause of the quartz veining in the contact zone.

The composition of coexisting feldspars from the interior of the pluton as opposed to those of the border zone are explained by subsolidus reactions after the initial crystallization. A temperature gradient was present between the interior of the pluton and the surrounding metasedimentary-metavolcanic rocks. As a result, the coexisting feldspars from the interior of the pluton exsolved and equilibrated at a higher temperature than did those of the border zone and thus contained more albite in solid solution.

Figure 6 shows a plot of modal analyses from a detailed traverse in the border zone of the granite. Sample A is a modal analysis of

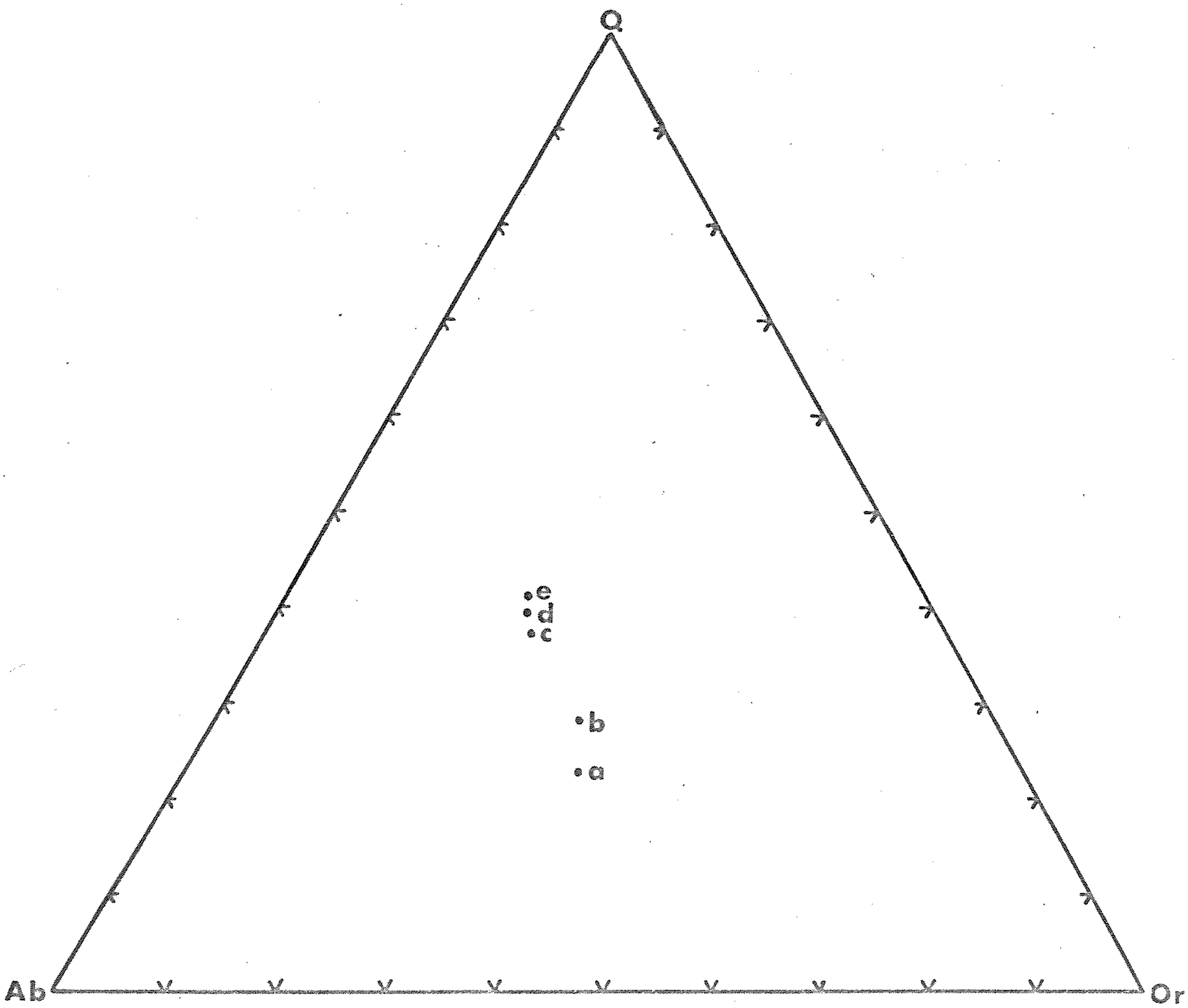

FIGURE 6. Modal analyses of samples from the chilled zone showing the differentiation trend. Sample A lies at the contact between granite and metavolcanics and sample E was taken from a point 16 feet within the granite.

the granite at the contact with metavolcanics and B, C, D, and E lie successively further out into the granite. Each modal analysis has been corrected for the amount of albite contained in the potash feldspar and has been recalculated so that quartz, albite and potash feldspar total one hundred percent. It is apparent from this plot that magmatic differentiation has taken place in this zone and that the liquid has changed composition toward the quartz apex of the triangle. As the magma came into contact with the relatively cool surrounding rock it was quenched and disequilibrium crystallization took place. As the magma was quenched to the point where the liquidus was reached, the first phase to crystallize out was an alkali feldspar or possibly two feldspar phases crystallized out simultaneously. Heat was conducted away from the magma faster than equilibrium between liquid and crystals could be established and, as the melt crystallized rapidly inwards, the net result was to enrich the magma in silica and volatiles, along with other components. The net result of this enrichment was to lower the liquidus temperature, perhaps on the order of 100° C. If the magma was not originally saturated with respect to H_2O (as the lack of pegmatities would suggest), the additional volatile material would also have lowered the liquidus temperature. Even though the modal analyses reflect the quenching and fractionating of the magma for a distance exceeding sixteen feet from the contact, the textural differences (i.e. grain size) are apparent for a distance of only about three feet from the contact. This is almost certainly due not only to heat flow from the interior of the pluton and slower crystallization but also to the lowered liquidus temperature and perhaps to the increasing mobility of migrating ions as the volatile content of the residual magma increased.

The system $KAlSi_3O_8$-$NaAlSi_3O_8$-SiO_2-H_2O has been studied in detail by Tuttle and Bowen (1958). Their work, in which the system was always saturated with respect to water, showed that the eutectics in the system $KAlSi_3O_8$-SiO_2 and $NaAlSi_3O_8$-SiO_2 are joined in the ternary system by a sloping cotectic line and that a temperature minimum exists on this cotectic line (Figure 7). Both the cotectic line and the temperature minimum are affected by a change in pressure: the temperature minimum shifts toward the Ab corner with an increase in pressure. This was further clarified by the work of Luth, Jahns and Tuttle (1964) at pressures of 4 to 10 kilobars. Not only does the progressive shift toward the Ab corner continue but at P_{H_2O} exceeding approximately 3.6 kilobars the temperature minimum becomes a ternary eutectic and at pressures exceeding 5 kilobars the phase field of alkali feldspar on the liquidus is replaced by a two phase field of feldspar solid solutions (an orthoclase solid solution and an albite solid solution). Figure 8, taken from Luth, Jahns and Tuttle, shows this progressive shift with increasing P_{H_2O}.

Phase relationships become considerably more complex when the addition of anorthite to the system is considered. Experimental work in the system $CaAl_2Si_2O_8$-$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O at two kilobars has been carried out by H. v. Platen (1965) and is discussed by Winkler (1965). It can be seen in Figure 9 that the addition of a

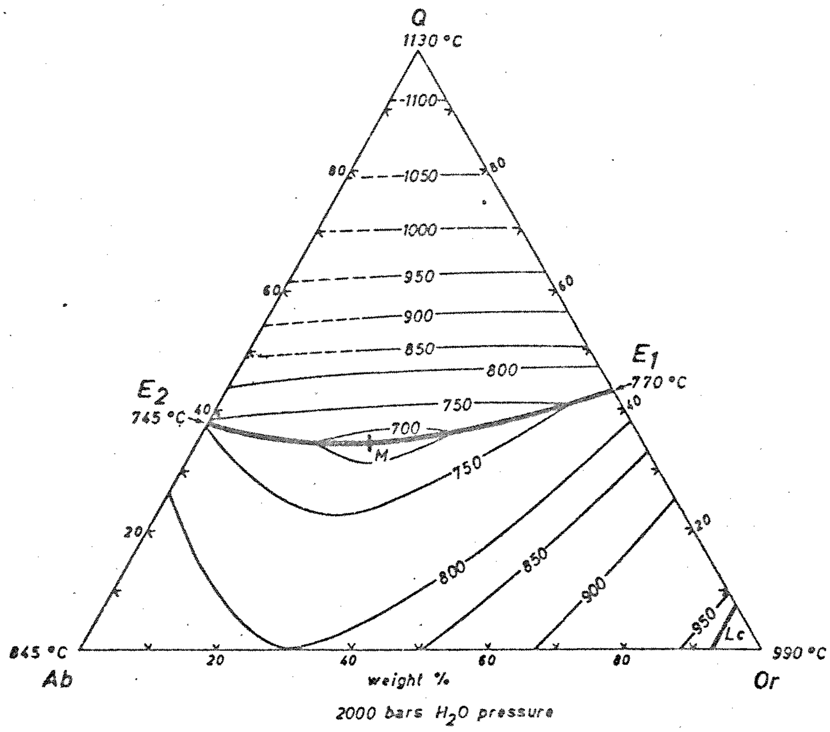

FIGURE 7. The system Ab-Or-Q-H_2O

(Tuttle and Bowen, 1958).

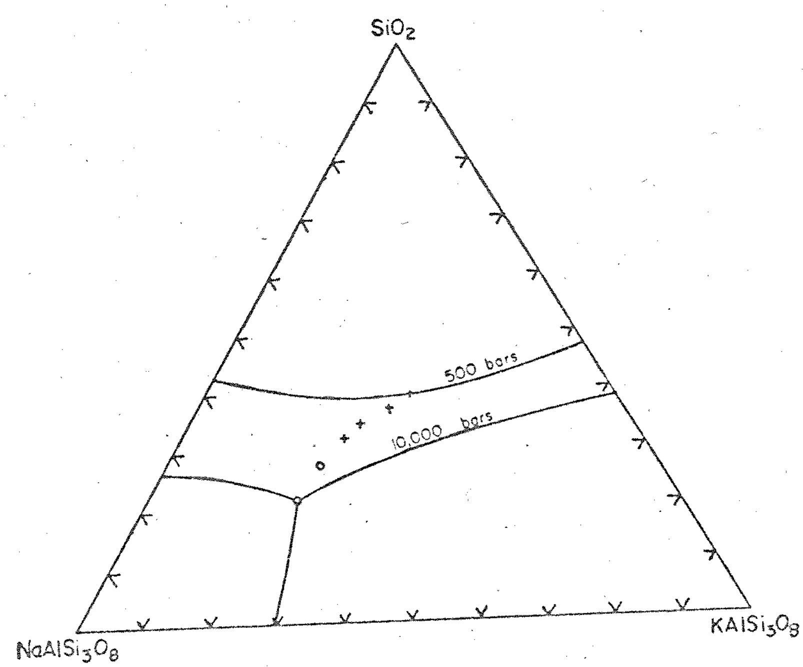

FIGURE 8. The system Ab-Or-Q-H_2O at P_{H_2O} of 500 to 10,000 bars.

(Luth, Jahns and Tuttle, 1964).

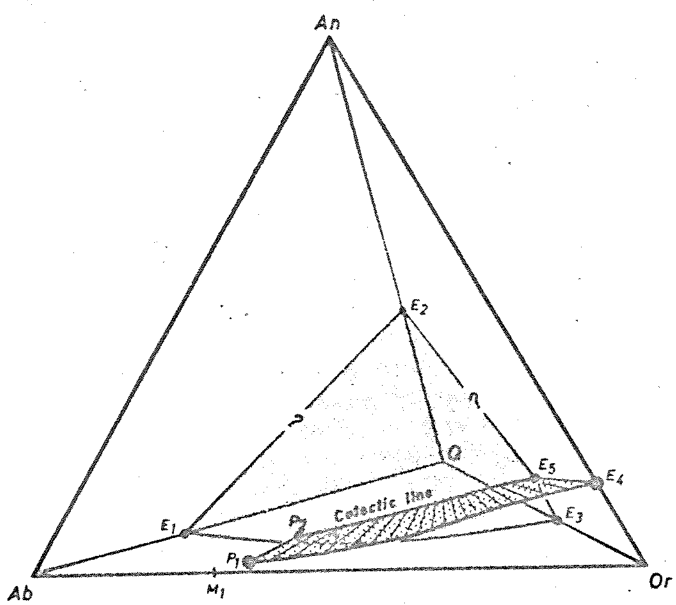

FIGURE 9. The system Ab-Or-An-Q-H_2O at P_{H_2O} of approximately 2000 bars. (Winkler, 1965).

small amount of the anorthite molecule to the system results in the splitting of the alkali feldspar into a two-phase region: an alkali feldspar + plagioclase in place of a single alkali feldspar. The exact position of point P_1 in Figure 9 and therefore of the cotectic line P_1-P_2 is not known at this time. The positions of the cotectic lines and the temperature minimums are shown in Figure 10 projected onto the Q-Or-Ab base of the tetrahedron for various Ab:An ratios. It is apparent from this work that the cotectics and temperature minimums shift toward quartz with increasing An content.

The effect of compositional variables other than An content are largely unknown at this time; in particular the effects of CO_2 and other volatiles are not completely understood. H. v. Platen (1965) has shown that the presence of HCl during anatexis in the system Q-Ab-An-Or-H_2O-HCl lowers the minimum melting temperature somewhat and shifts its position so that the minimum melting composition is poorer in Q and richer in Or.

The differentiation path followed by the magma of the granite at Plevna Lake during its crystallization provides good evidence on the location of the low temperature trough in this system. A comparison of this crystallization path can be made with the experimental work of Tuttle and Bowen on disequilibrium crystallization. Figure 11 is taken from Tuttle and Bowen (1958) and shows the disequilibrium curves at P_{H_2O} = 1000 bars. The thermal valley in the alkali feldspar field is still present just as it was for conditions of equilibrium crystallization. The previously mentioned plagioclase determinations give an Ab:An ratio ranging from approximately 12:1

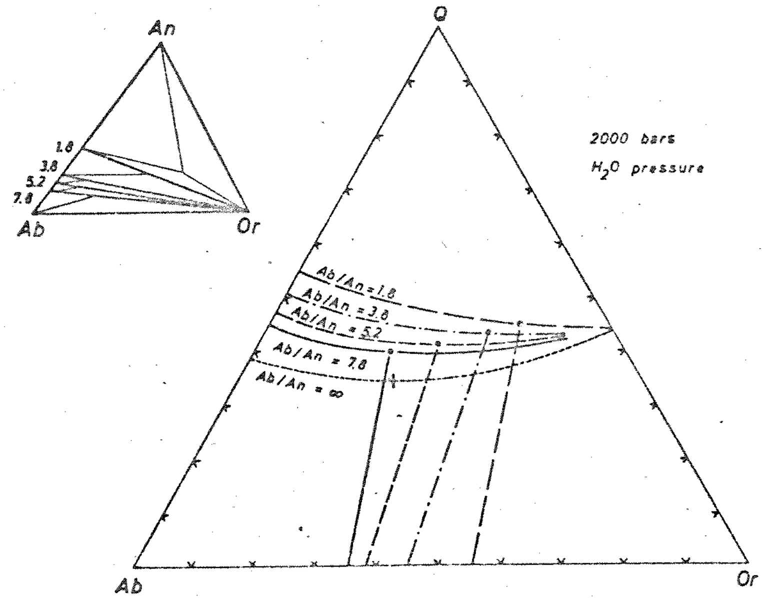

FIGURE 10. The system Ab-An-Or-Q-H_2O with various Ab/An ratios, at P_{H_2O} = 2000 bars.

(v. Platen, 1965).

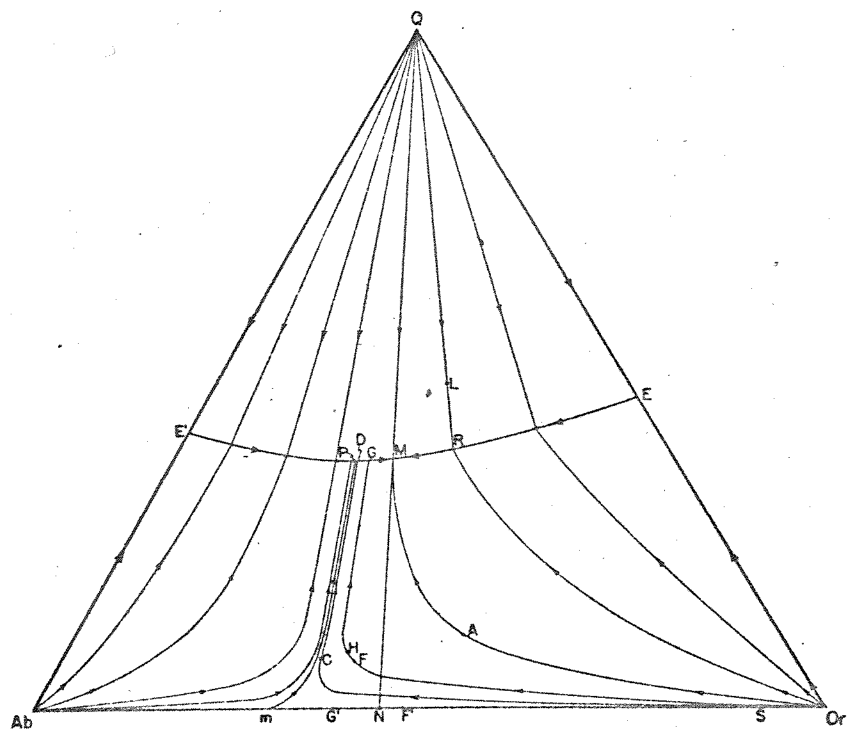

FIGURE 11. Isobaric fractionation curves for P_{H_2O} = 1000 bars in the system Ab-Or-Q-H_2O. (Tuttle and Bowen, 1958).

to 49:1. As can be seen from Figure 10 this will have only a slight effect on the position of the cotectic line and subsequently on the position of the minimum temperature trough. Therefore, one can determine with some assurance the approximate pressure during crystallization. Because of the high Ab:An ratio, the system is very closely approximated by the Ab-Or-Q-H_2O system. A review of the modal analyses of the chill zone shows that the position of the differentiated magma and therefore of the low temperature trough was displaced well toward the quartz apex in the system Q-Ab-Or-H_2O. Applying the results of Tuttle and Bowen (1958) and Luth, Jahns and Tuttle (1964), it is clear that the P_{H_2O} and presumably P_{Total} was very low, probably less than 1000 bars. The temperature of the magma was between 800 and 900° C. Evidence tending to confirm this, although not in itself conclusive, is seen in thin section examination. The plagioclase feldspars and the potash feldspars tend to occur together and the quartz grains also tend to be grouped. The plagioclase is largely untwinned. Both are suggestive that this may have been a single feldspar granite at the time of crystallization with later exsolution into separate potash feldspar and plagioclase grains. Luth, Jahns and Tuttle (1964) have shown that single feldspar granites can form only at P_{H_2O} less than 5000 bars. Buddington (1959), in a review of the emplacement of granites, has discussed features commonly found in epizonal plutons. Features noted include the presence of chill zones, contact aureoles in the surrounding country rock, sharp contacts with the country rock, tourmaline commonly occurs in the aureoles and distinct pegmatite veins are rare or minor. All of these features occur here and the evidence seems conclusive that this granite was emplaced at a high level in the crust.

METAVOLCANIC ROCKS

The metavolcanic rocks consist of both flows and pyroclastic material. These rocks vary in thickness along strike and occur for the most part in the southern limb of the fold. The exposures in the northern limb are thin and consist of amphibolite interbedded with paragneiss. Their origin is generally recognizable only by a higher content of mafic minerals and their stratigraphic position with respect to known metavolcanic rocks.

In the southern limb, the metavolcanic rocks vary from rocks containing original volcanic textures to what have been called "turkey-track" amphibolites. This descriptive term refers to the appearance of the rock caused by acicular amphibole crystals set in a matrix of light-colored plagioclase. Agglomerate textures are well preserved and structures interpreted as pillows have been found (Meen, 1944). Many of the flows contain recognizable relicts of plagioclase phenocrysts and, rarely, the original unrecrystallized plagioclase grains are preserved. These phenocrysts are the subject of a major portion of this study and are discussed in a later section.

The agglomerate textures are mainly seen as clots of mafic minerals commonly ranging up to two or three inches in length with occasional clots up to eight inches in length. The form is generally ellipsoidal with the long dimension in the foliation plane. Greenish, elliptical inhomogeneities, common in the metavolcanics of this region, occur at scattered stratigraphic levels throughout the sequence. These are also generally two to three inches in length but in one outcrop they reach a length of up to two feet and are almost perfectly elliptical. The exact nature of these striking features is not known to the writer but some workers in this region have attributed them to probable epidotized volcanic bombs (Hewitt and James, 1956). A chemical analysis for calcium on similar material from metavolcanics in the greenschist facies in western Barrie township showed a higher calcium content in the inhomogeneity as opposed to the bulk composition of the host rock (pillow-lavas). The writer is not aware of a definitive study of these features. They are, however, widespread as Miyashiro (1953) has commented on apparently identical features in metamorphosed basic rocks in Japan. Although Miyashiro did not deal with the problem of their origin, he was able to show that the calcium-rich lenses and bands are metamorphosed progressively with the surrounding metamorphic rocks and that their formation therefore must be before or during the metamorphism of the surrounding rocks. He also showed that diffusion of materials through the metamorphosed basic rocks surrounding the calcium-rich lenses and bands appears to be strikingly little as they frequently contain calcium-rich minerals that are incompatible with the mineral assemblages of the surrounding rocks and sometimes even incompatible mineral assemblages at different parts within a single lens. The not infrequent occurrence of quartz and microcline in these inhomogeneities was also noted. In the area of this study microcline does not occur with these features but free quartz, often in large pods or veins, is present. The mineralogy of the lenses consists of quartz and clinozoisite in the study area while in the greenschist facies in western Barrie township free calcite is also present.

Holdaway (1966), discussed by Turner (1968), has experimentally determined the stability fields in the reaction:

$$4CaAl_2Si_3O_{12}(OH) + SiO_2 = 5CaAl_2Si_2O_8 + Ca_3Al_2Si_3O_{12} + 2H_2O$$

Clinozoisite + Quartz = Anorthite + Grossularite

This is a common reaction in high grade regional metamorphism of impure marbles. The results of this work are shown in Figure 12. Turner points out that the elimination of epidote in favor of plagioclase in rocks of more complex composition such as amphibolites will occur at a lower temperature than in impure carbonates. If, as Miyashiro (1953) found, diffusion was limited Holdaway's data shows that the assemblage clinozoisite + quartz that occurs in the Plevna Lake area would be stable in the almandine-amphibolite facies.

The field study showed that a reaction was taking place between the calcium-rich lenses and the amphibolite resulting in the elimination of amphibole in a halo surrounding the lenses (Figure 13). In one sample studied, the textures indicated a replacement origin, at least in part, for these features. The original rock contained plagioclase phenocrysts. Both the amphibole and plagioclase have been replaced by the assemblage clinozoisite + quartz with the original rock textures recognizable because of pseudomorphous relicts after plagioclase lathes.

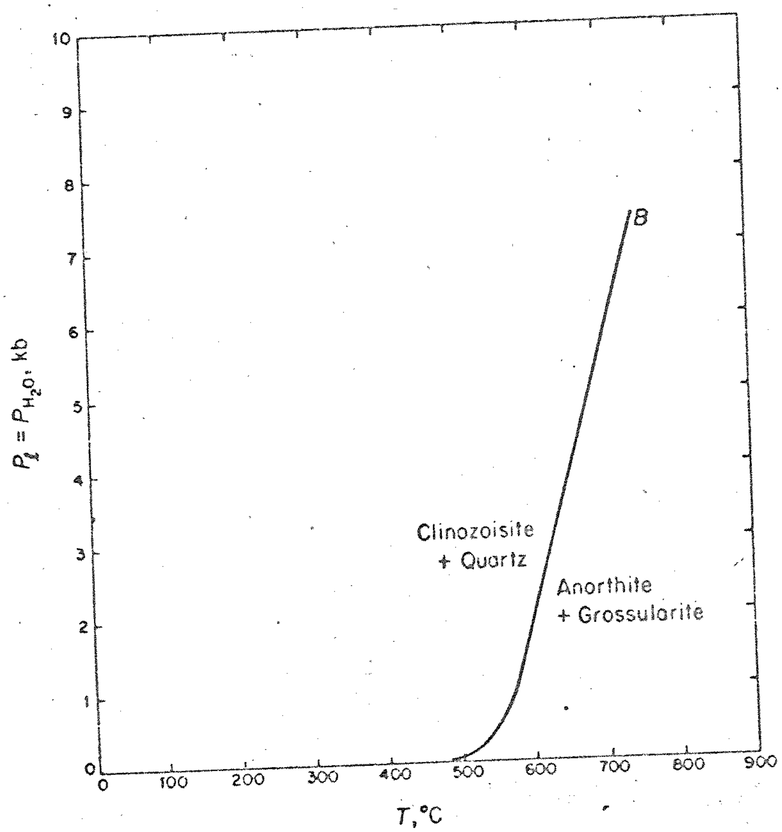

FIGURE 12. Equilibrium curve for 4 clinozoisite + Quartz = 5 Anorthite + Grossularite + 2 water. (Holdaway, 1966).

FIGURE 13. Calcium-rich lens in metavolcanic rock.

Any explanation for the origin of these features must account for their common occurrence in the metavolcanics of this region, the free quartz associated with them, and the high calcium content. An origin from "epidotized volcanic bombs" seems insufficient to explain the free quartz and the high calcium content. It is interesting to note that carbonate rocks occur in both the area that Miyashiro (1953) studied and the area of this study. A possible explanation for these features is that they are carbonate xenoliths incorporated in the magma from an underlying carbonate unit. A representative reaction between a volcanic plagioclase of assumed composition of An_{60} and free carbonate can be written as

$$7CaCO_3 + 15\ Na_{.4}Ca_{.6}Al_{1.6}Si_{2.4}O_8 + 8\ H^+ + O^= \rightleftharpoons$$

Calcite + Labradorite

$$8Ca_2Al_3Si_3O_{12}(OH) + 12SiO_2 + 7\ CO_2 + 6\ Na^+$$

Clinozoisite + Quartz

A similar reaction can be written for a reaction involving calcite and amphibole. An origin of this nature can explain the occurrence, high calcium content, associated free quartz and replacement phenomena. However, the postulated origin by this mechanism is hypothetical and these features remain an enigma.

Bulk chemical analyses were made for silicon, calcium and potassium for five selected metavolcanic samples (Table 1). For three samples duplicate pellets were prepared for the X-ray fluorescence study to check the accuracy of the sample preparation. Three of the samples were porphyritic flows, the remaining samples are so completely recrystallized that recognition of the original rock type is not possible. The rocks are basic to intermediate in composition and, excluding sample 7-10G, all are quite low in potassium. Sample 7-10G is a garnet amphibolite approximately 250 feet from the granite contact and shows retrogressive metamorphism from the effects of the intrusion. Mobilization of alkalis (e.g. potassium) in this zone cannot be discounted but insufficient chemical analyses are available to clarify whether this higher potassium content is an original feature or is secondary enrichment due to the intrusion. The remaining samples compare favorably with Nockolds (1954) "average" andesite.

TABLE 1

Sample	SiO_2	CaO	K_2O
7-3 B	52.5	8.74	0.61
	53.1	8.95	0.67
7-4 A	56.0	10.04	0.41
	55.7	9.91	0.41
11-8 N	58.4	8.50	0.54
	58.1	8.45	0.47
11-14 A	51.0	9.47	0.52
7-10G	48.4	5.19	2.74
"average" andesite	54.20	7.92	1.11

"Average" andesite after Nockolds (1954).

Metamorphism

Miyashiro (1961) was the first to point out that the succession of metamorphic zones developed in different areas will vary according to the regional distribution of temperature and pressure and therefore can be represented by a curve in a pressure-temperature diagram. A high geothermal gradient will cause a particular temperature to be attained at a relatively low pressure while a lower geothermal gradient will result in this same temperature being reached at a higher pressure. Metamorphic petrologists have long recognized that regional metamorphism is restricted to orogenic belts and is essentially a thermal event; that is, it occurs where a higher than normal geothermal gradient is operative. Thus in different orogenic belts and even within the same orogenic belt variable geothermal gradients give rise to the various metamorphic facies series. Since Miyashiro's work was published in 1961, new experimental work on the stability fields of various minerals, especially the Al_2SiO_5 polymorphs (kyanite, sillimanite and andalusite) has required a revision in the position of the facies series curves in a pressure-temperature diagram. The triple point of the Al_2SiO_5 polymorphs, that is the point where all three can coexist in equilibrium, is the principal reference point for the calibration of these curves. The exact position of this triple point is still uncertain and this uncertainty is reflected in the most recently published curves (Hietanen, 1967; Turner, 1968). The tentative pressure-temperature diagram of Hietanen (1967) is shown here as Figure 14. This figure also graphically illustrates

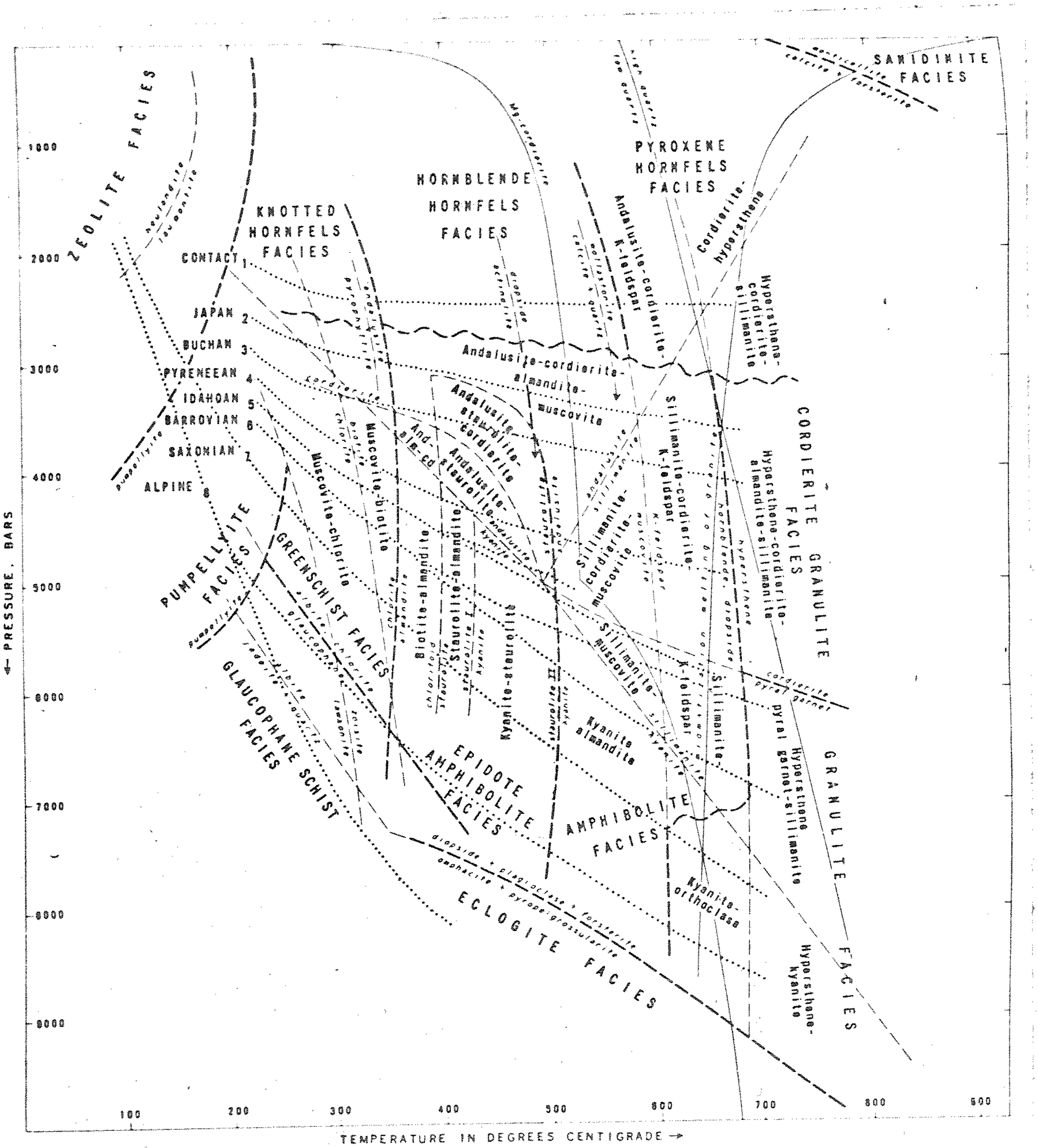

FIGURE 14. Tentative PT diagram showing possible stability fields of metamorphic facies and PT gradients in various types of metamorphism. (Hietanen, 1967).

that contact metamorphism is confined to relatively shallow depths, which has long been recognized by metamorphic petrologists.

Study of coexisting minerals has shown that the metasediments and metavolcanics were regionally metamorphosed to the almandine-amphibolite facies at the pressure-temperature conditions of the Barrovian-type (kyanite-sillimanite type) facies series. Work by Smith (1958), Hounslow and Moore (1967), and Moore (1967) on a belt of pelitic rocks in this area which can be traced for over twenty five miles from the greenschist facies to the upper almandine-amphibolite facies shows the following succession of index minerals:

biotite-garnet-staurolite-kyanite-sillimanite

This succession is typical of the Barrovian-type facies series. Figure 15, after Lumbers (1967a) and Wynne-Edwards (1967b), shows the regional metamorphic zonation.

The boundary between the greenschist facies and the amphibolite facies is defined (Eskola, 1939) as that point where albite disappears and plagioclase (usually greater than An_{20}) becomes stable. Plagioclase determinations in the metavolcanics show an An content ranging from An_{20} to An_{40}. These determinations were made by the Tsuboi method (Tsuboi, 1923; Vogel, 1967) and by electron microprobe analysis. No albite is present in these rocks.

Almandine garnet, determined by a computation of the cell edge from an X-ray diffraction pattern (d_{642} = 1.55, a = 11.53) and refractive index (1.798 ± .002), occurs sparsely in the metavolcanics and its occurrence is compositionally controlled. Thinly

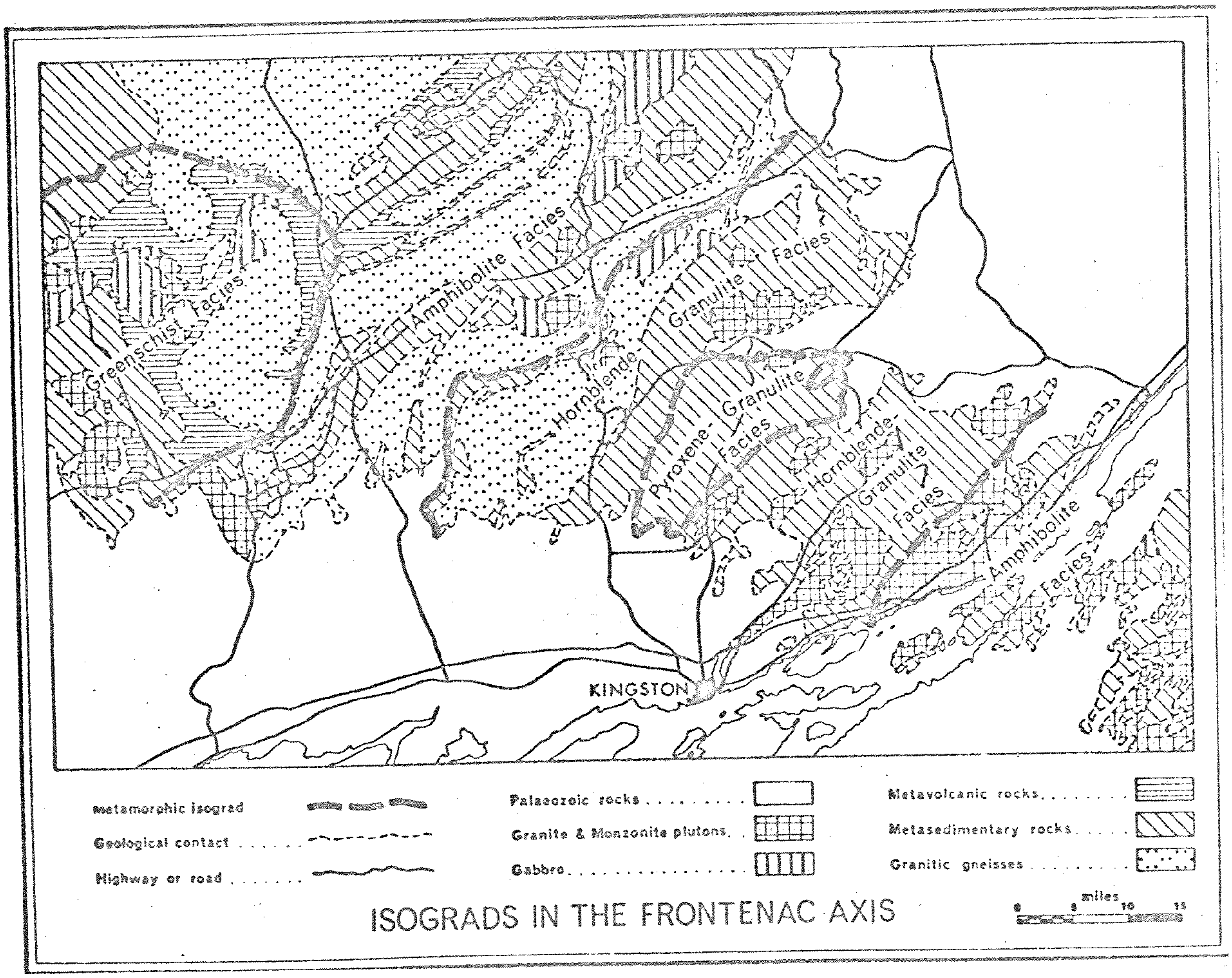

FIGURE 15. Metamorphic zonation after Lumbers (1967a) and Wynne-Edwards (1967b).

interbedded flows and pyroclastic material are present with large (1/2 inch) garnet crystals present in some layers and absent in others. Kyanite occurs locally in the metaconglomerate in Barrie township but staurolite has not been found. A study of the amphibole from the amphibolites indicates that its composition is close to that of pure tremolite in the tremolite-actinolite series. This is not a commonly reported amphibole from metamorphic rocks of this composition although Leake (1965) reports that tremolite can occur in metamorphosed ultrabasic rocks in the almandine-amphibolite facies. The X-ray diffraction pattern of the tremolite in the amphibolites was compared with the pattern from large, fibrous crystals of tremolite occurring in the marble and they are identical (Figure 16). The amphibole from the amphibolite is pleochroic from straw yellow to dark blue green while that from the marble is not pleochroic. Pure tremolite is usually non-pleochroic (Winchell and Winchell, 1951) and the pleochroism may indicate the presence of Fe or Ti in the structure although Binns (1965) has indicated that the depth of color in hornblendes from regionally metamorphosed rocks in New South Wales can be correlated with filling of the vacant site in the amphibole structure. The 110 d-spacing was determined by X-ray diffraction using synthetic fluor-phlogopite as an internal standard and compared to the curve of Hellner and Schurmann (1966) of synthetic amphiboles in the tremolite-ferroactinolite series. The value of d_{110} indicates a close approach to the tremolite end member composition but exact determination would require a complete chemical analysis as there are discrepencies in the

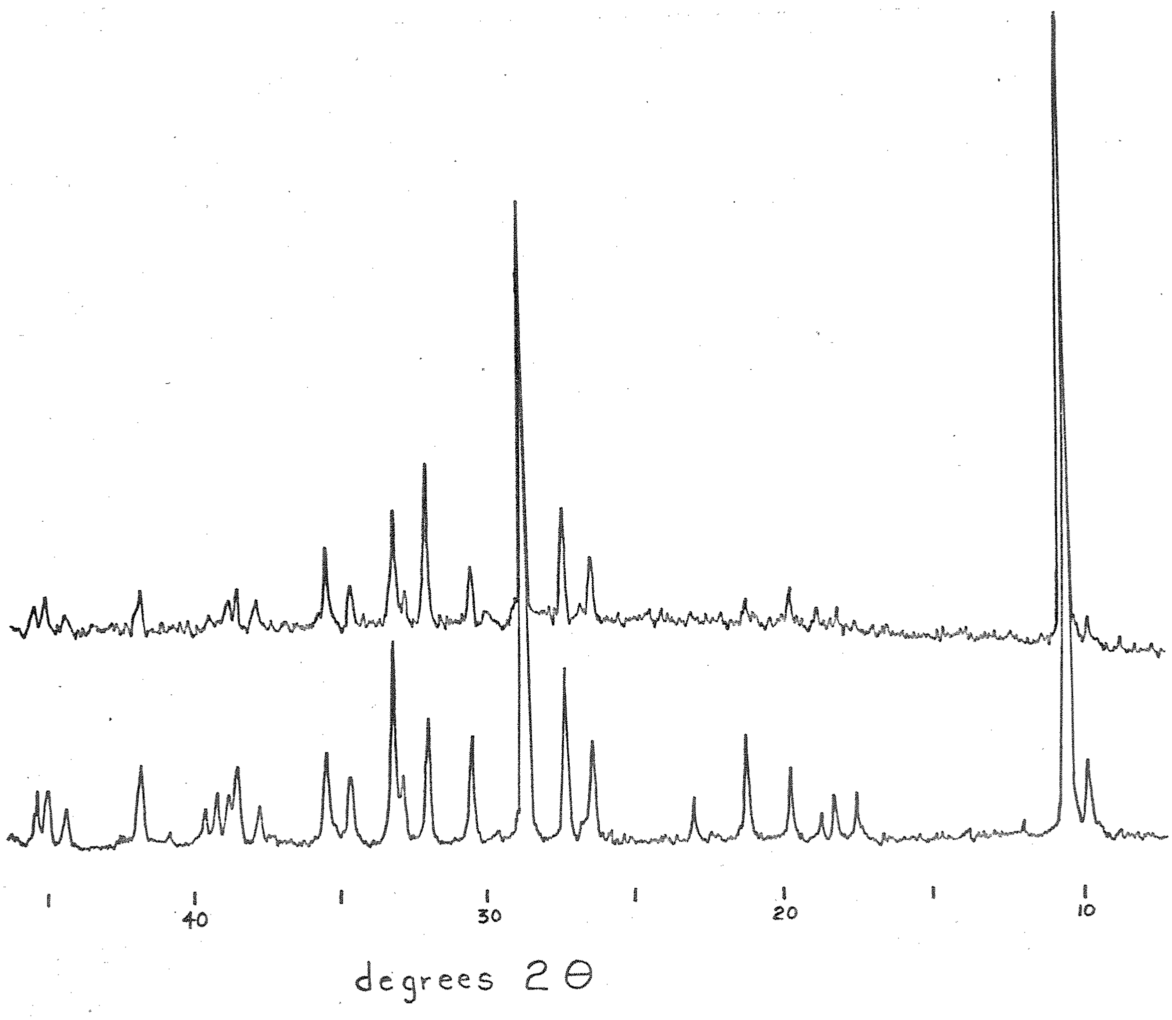

FIGURE 16. Comparison of X-ray diffraction patterns of Amphibole from Metavolcanics and Amphibole from Mable.

available X-ray data on the exact position of this peak.

The assemblages tremolite-calcite and tremolite-dolomite have been thought to be diagonistic of the greenschist facies. However, Trommsdorff (1966), discussed by Turner (1968), has found the assemblage dolomite-quartz in siliceous dolomitic marbles stable up to the kyanite isograd. At this point or just beyond it dolomite and quartz react to give talc, followed almost immediately by tremolite. The assemblages tremolite-calcite-quartz and tremolite-calcite-dolomite then remain stable well beyond the An_{70} isograd of Wenk (1962) in calcite-plagioclase assemblages before breaking down to fosterite-calcite or diopside-calcite below the sillimanite isograd. It is clear from this work that tremolite-calcite and tremolite-dolomite is stable well into the almandine-amphibolite facies and is not diagonistic of the greenschist facies. The example given was in carbonate rocks where the probability of a high P_{CO_2} is great and this will almost certainly influence the stability fields as CO_2 is a component in this system.

A study of the mineral assemblages present at Plevna Lake shows that they belong either to the staurolite-almandine subfacies or to the kyanite-almandine subfacies of the almandine-amphibolite facies. The presence of plagioclase and kyanite is sufficient for the placement of the rocks in one of these subfacies. Winkler (1965) has pointed out that the only possibility of distinguishing between these two subfacies is the disappearance of staurolite. Figures 17 and 18 show the ACF and A'KF diagrams for these subfacies after Winkler.

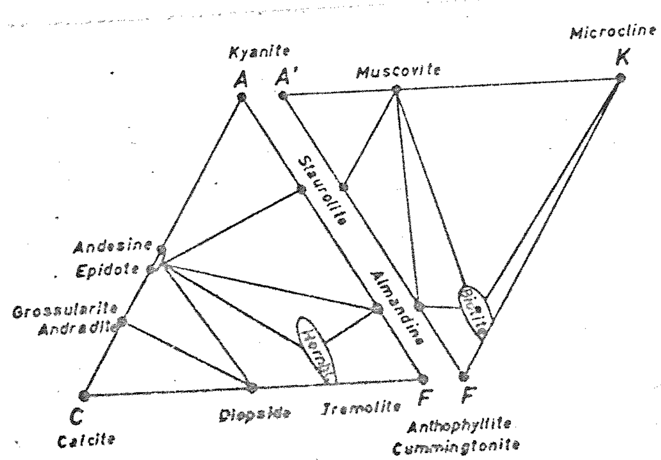

FIGURE 17. ACF-A'KF diagrams for the staurolite-almandine subfacies of the almandine-amphibolite facies. (Winkler, 1965).

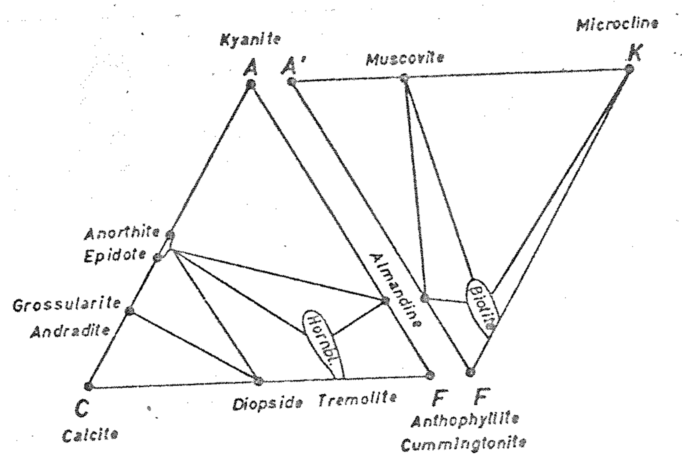

FIGURE 18. ACF-A'KF diagrams for the kyanite-almandine-muscovite subfacies of the almandine-amphibolite facies. (Winkler, 1965).

Only a very few of the rocks in the study area have compositions approaching that necessary for the formation of staurolite. Thus definitive criteria are lacking for placement into one or the other of the two subfacies.

Superimposed on the regionally metamorphosed rocks near the granite contact is the contact metamorphic aureole. This is most apparent in the field by a coarsening of grain size and the development of biotite in the metavolcanics. Local recrystallization around granite dikes and sills is also seen. In thin section it is clear that the amphibole was unstable and partially altered to both biotite and chlorite. Figure 19 is a photomicrograph showing garnet being retrogressively transformed to biotite and chlorite.

The degree of preservation of original textures and especially the occurrence of original phenocrysts is unexpected in this environment. The progressive metamorphism of basic igneous rocks requires the addition of water. Eskola (1939) and Tilley's (1926) analyses of metamorphic equivalents of basic igneous rocks showed that greenschists contain 3.15%, epidote amphibolites 0.69%, amphibolites 1.03% and granulites 0.35% water. Nockholds(1954) found less than one percent in all the average andesite and basalt types that he studied. A lack of volatiles in the main body of the metavolcanics may have played a large part in their preservation. An apparent rise in metamorphic grade in the metavolcanics from west to east was noted in the field. This was based on the progressive loss of primary features and the development of "turkey-track" amphibolites. It is probable

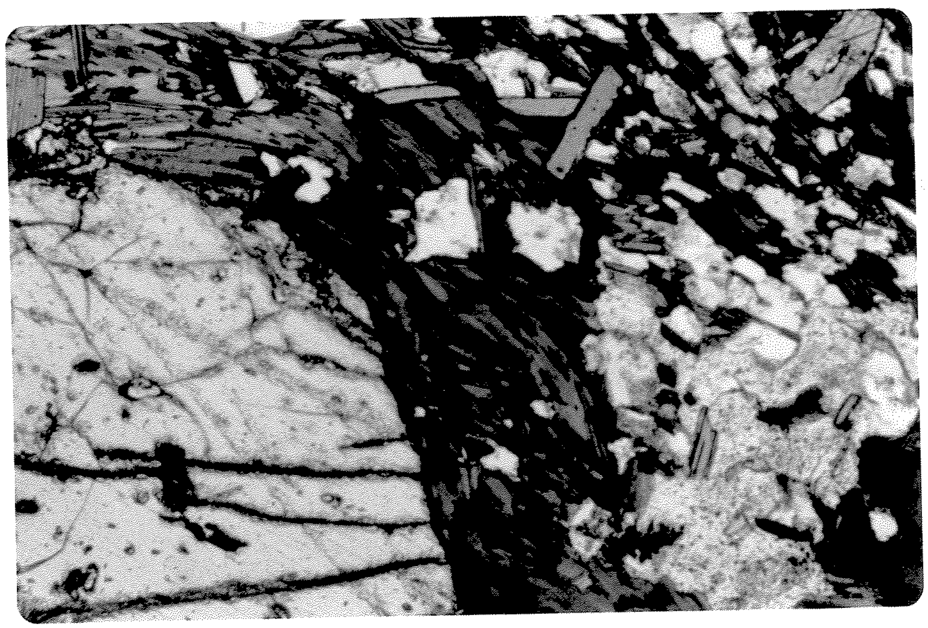

FIGURE 19. Photomicrograph of retrogressive metamorphic effects in the contact aureole surrounding the granite. Garnet is altered to biotite and chlorite.

that this is related to the thinning of the metavolcanics and access of volatiles from the metasediments rather than to differing pressure-temperature conditions. The samples showing primary plagioclase phenocrysts were all taken from the center of the metavolcanic mass where they were best shielded from volatiles.

The breakdown and recrystallization of plagioclase phenocrysts can be directly correlated with the amount of deformation that the rock has undergone and the preservation of delicate phenocrysts and other primary features in the metavolcanic rocks would seem to indicate that the regional metamorphic event was largely unaccompanied by deformation. However, the cushioning effect of the overlying marble and the underlying paragneiss-metaconglomerate unit may have taken up stresses which would have otherwise deformed the metavolcanics. Smith (1958), working in the Ompah syncline, found large-scale cross bedding perfectly preserved in quartzite while the clasts of a nearby conglomerate have been deformed into ellipsoidal shapes with a ratio of about six to one of greatest to least diameters. Thus, preservation of primary features in the metavolcanics at Plevna Lake indicates only that they were not deformed during the regional event but does not necessarily mean that deformation of other units was not taking place.

The main deformational event in the metavolcanics appear to have accompanied the emplacement of the granite and simultaneous doming of the metasedimentary-metavolcanic sequence. This is indicated by the development of foliation, which is poorly developed throughout the metavolcanic sequence, but is somewhat better developed as the granite contact is approached.

PLAGIOCLASE STUDY

Introduction

Naturally occurring plagioclase feldspars are found in a range of structural modifications from a disordered form through intermediate states to an ordered form. The degree of ordering is related to the partitioning of aluminum and silicon atoms among the tetrahedral sites in the feldspar structure and probably also on the distribution of calcium and sodium atoms which has not yet been fully evaluated. In the disordered structure silicon and aluminum atoms substitute randomly for one another in the tetrahedral sites and as the degree of order increases silicon and aluminum atoms are segregated more and more into preferred lattice positions. The disordered plagioclases are also known as "high-temperature" or "volcanic" plagioclases while the ordered plagioclases are often referred to as "low-temperature" or "plutonic" plagioclases. As implied by these names, the structural state is dependent to a large extent on the thermal history of the crystal. At high temperatures aluminum can substitute at random in the tetrahedral site and, if the crystal is cooled rapidly, this modification will remain indefinitely in this metastable state. Conversely, slow cooling leads to an ordering of the structure.

The plagioclase stable in the greenschist facies is an ordered albite and as the degree of metamorphism increases albite is converted to a more calcic plagioclase (usually greater than An_{20}). Compositional changes in the plagioclase series are complicated by the changing silicon to aluminum ratio in addition to the changing sodium to calcium ratio.

Metamorphism of Plagioclase in Volcanic Rocks

The plagioclase feldspars of basic volcanic rocks are calcium-rich and in either a disordered or intermediate structural state. The effects of metamorphism on these plagioclases has received relatively little attention with the exception of a study by Noble (1966).

In this study of regionally metamorphosed volcanic rocks Noble found relict, calcium-bearing plagioclases (An_{20}-An_{60}) which had survived low-grade metamorphism. The important conclusions from his study are summarized below.

(1) The delicate oscillatory compositional zoning typical of plagioclase phenocrysts from volcanic rocks is perfectly preserved.

(2) The phenocrysts that survived behaved effectively as closed systems - i.e. there was no reaction between the plagioclase and the remainder of the rock.

(3) There is no microscopic evidence of isochemical breakdown of the plagioclase into two or more phases.

(4) Nonhydrostatic stress appears markedly to encourage the chemical breakdown of the calcium-bearing plagioclase.

(5) Plagioclase phenocrysts can be found which have inverted to the low structural state while maintaining the oscillatory compositional zoning in a contact aureole around a granodiorite intrusion.

(6) At middle greenschist facies conditions the original

disordered structures of the calcium-bearing plagioclases inverted to the ordered state. Inversion seems to have taken place isochemically with neither reaction of the plagioclase with the rest of the rock nor with isochemical breakdown of the plagioclase into two or more phases.

(7) A minimum temperature of between 250° and 450° C at a partial pressure of water of from 1000 - 2000 bars appears to have been required for the inversion of the relict plagioclase to the low structural state.

Plagioclase Twinning

A twin is a rational, symmetrical intergrowth of two individual crystals of the same species, in which the orientation of one individual can be transformed into the orientation of the other by the operation of either a symmetry plane or of a two-fold axis. In a genetic classification of twinning all twins fall into one of the four following groups.

(1) growth (or primary) twins

(2) agglutination (or synneusis) twins

(3) deformation (or glide) twins

(4) transformation twins

The first three types listed occur commonly in plagioclase feldspars. It is not yet clear whether transformation twinning takes place in plagioclase (Vance, 1961); if it does occur no suitable criteria have been established for its recognition.

Burger (1945) has discussed the origin of growth twinning which he regards as developing as a result of accidents during the growth process. A twin boundary is a locus of higher energy in a crystal and to understand growth twinning it is necessary to explain how the atoms at the twin boundary were permitted to assume this higher energy configuration. An atom may be added to a growing crystal plane in a position so that the coordination requirements with the surrounding atoms are met and yet still not continue the original pattern of growth. Atoms in these positions - the twin positions - do not have the minimum energy configurations and thus tend to be dislodged and replaced by more favorably oriented atoms. The atoms are more likely to be maintained in the twinned position if other atoms arrive simultaneously at neighboring positions and coordinate with the first atom or if a coordinated group of atoms arrives at the growing crystal face and assumes the twinned position. As Burger points out, the development of twinned crystals in this manner will be favored by supersaturation of the liquid and rapid growth. Vance (1961) has also suggested that anhedral growth is less conducive to the development of growth twinning than euhedral growth. This is because atoms being added to the growing surface are less likely to take up the twinned position due to the difficulties of lateral coordination with adjacent atoms and also because groups of already coordinated atoms are less likely to become attached to irregular surfaces.

Vance (1961) has also developed criteria for the recognition of growth twins. There is a regular relation between the distribution of twin lamellae and the external form, and especially an occurrence of re-entrant angles at twin boundaries in growth twins. These re-entrant angles are readily understood if the lamellae are primary, while a diminution in volume of part of the crystal - an exceedingly unlikely occurrence - must be invoked if the lamellae are to be considered secondary. In addition, twinning is usually simple or, if multiple, lamellae are few. Lamellae in individual grains vary widely in thickness, are usually broad, and often change width or terminate abruptly and irregularly. They also thicken, thin and terminate independently of each other without relation to later bending or fracture. Primary zoning, if present, can also be valuable in determining the relationship between the twin lamellae and the crystal during growth.

Ross (1957) has called attention to the importance of agglutination twins. These twins are formed by the drifting together and bonding in a twinned position of two separate crystals in a magma. In the volcanic rocks Ross studied the plagioclases are largely tabular with the result that the (010) faces have the largest surface area. This probably accounts for the fact that most twins studied had a composition plane of (010). The most common twin laws found were Carlsbad, albite-Carlsbad and albite-Ala in order of decreasing frequency. These agglutination twins provide irrefutable evidence of igneous origin where they can be recognized.

The characteristics for recognition of deformation twinning have been discussed by several authors. Vance (1961) has shown that the distribution of these lamellae is often obviously linked to the deformation of the crystal as shown by their relation to evident bending of the crystal with the lamellae localized in the areas of greatest strain. The lamellae often terminate at cracks within the crystal and do not match in either number, width or relative distribution across the cracks. They commonly taper to long, fine points which may be bent so that they transect the composition plane at a slight angle. Vogel (1964) suggests that deformation twinning in plagioclase starts at crystal boundaries, imperfections or impurities and that the first twins to form are lenticular lamellae. These widen and straighten out as the lamellae reach the other side. Many of the lamellae coalesce and the result is a merging of nearly all the twins in the crystal with only a few thin continuous lamellae remaining. If this process is carried out repeatedly the end product may be a crystal which is untwinned. Both Vance (1961) and Vogel (1964) suggest that this may be the explanation for the frequently untwinned grains in metamorphic rocks known to have formed in a high stress environment. The common lack of twinning in metamorphic plagioclase has been commented on by numerous petrographers.

The occurrence of twin types according to a particular twin law for plagioclase of igneous and metamorphic rocks has been studied by Gorai (1951) and Turner (1951). Ross (1957) and

Sarbadhikari (1965) have studied twin types in volcanic rocks. All these studies show that Carlsbad and albite-Carlsbad are very rare in rocks of non-igneous origin, although it should be noted that Tobi (1962) has found these twin types, apparently as growth twins, in porphyroblasts in some greenschist facies rocks.

Optical-Crystallographic Scatter

Vogel (1964) discussed optical-crystallographic scatter in plagioclase. Plagioclase twinning was studied by the five-axis method of Emmons (1943). In this method one unit of a twinned crystal is oriented optically and the positions of X, Y, and Z are determined. The composition plane is then made vertical and north-south and the pole to this plane is plotted in relation to the optical orientation of the crystal on a stereographic projection. The same procedure is then carried out for the adjacent twin. If the units are in a perfect twinned relationship and have identical optical properties, the plots of adjacent lamellae will coincide. Vogel recognized and defined two types of scatter. Internal is the optical-crystallographic scatter between twin lamellae within a grain. Adjacent lamellae which show internal scatter are not in a true twinned relationship. Internal scatter is random relative to the migration curve. One unit may plot on or near a migration curve and the other unit may be completely irrational. Vogel found that frequently only a few grains in a sample will show internal scatter and that this scatter can occur in all twin types from all environments.

External scatter was defined as the optical-crystallographic scatter between different grains in the same sample. It was found to be nearly always confined to coarse-grained, igneous-appearing rocks and the pole plots are restricted to the area between the migration curves. Most volcanic and regional metamorphic rocks show no external scatter. The conclusion reached by Vogel is that external scatter is due to twinning throughout the ordering process. Therefore, most volcanic plagioclases do not have external scatter because they formed, twinned and remained in the disordered state. Regional metamorphic rocks have no external scatter because they twinned and remained in the ordered state.

Results of the Investigation

Reconnaissance study of the metavolcanic rocks at Plevna Lake showed that, in rare instances, relict igneous phenocrysts are preserved in some of these rocks. These phenocrysts are proven to be relict igneous grains by the type of twinning displayed and also by re-entrant angles (Figure 20) on some grains. Carlsbad and albite-Carlsbad twins are common and probable agglutination twins have been observed. A study of these phenocrysts was undertaken to determine their composition and structural state and how these may have been effected by metamorphism. These crystals are known to have formed and twinned in a disordered state and in this state the position of

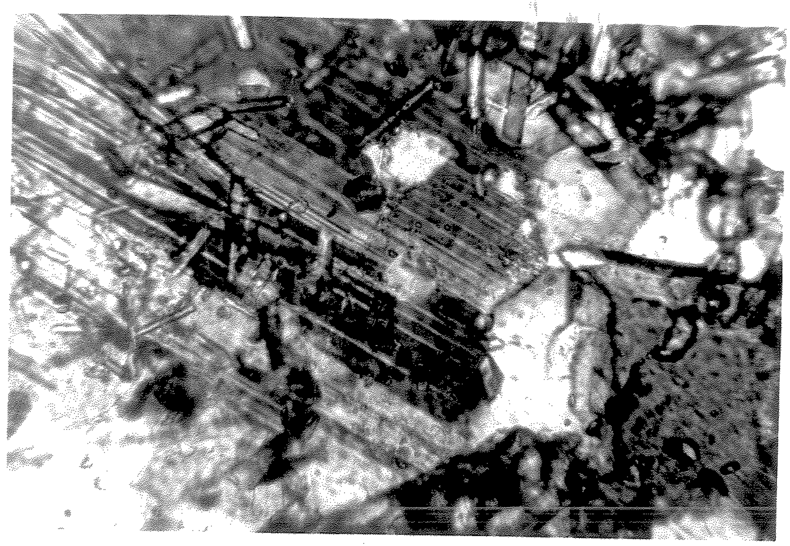

FIGURE 20. Photomicrograph of a relict plagioclase phenocryst showing re-entrant angles.

the (010) composition plane differs from that of the (010) composition plane of an ordered crystal. The optical properties and their relation to the twin plane were of special interest in this study.

During the detailed sampling for this study a special emphasis was placed on obtaining as many examples of relict phenocrysts as possible. The phenocrysts have been deformed and recrystallized in a great majority of the samples - this is usually identifiable in the field. In other instances, the original crystals are recrystallized to a fine-grained mosaic with the relict crystal outline preserved and little or no deformation is apparent in the specimen. Figure 21 shows an example of the fine mosaic of grains which results as the phenocrysts breakdown. With continued deformation these mosaics are stretched out further and further until the plagioclase is distributed throughout the groundmass and the original porphyritic texture is destroyed.

Three samples were found to contain a suitable number of relict phenocrysts for a detailed study. It is significant that these samples were taken from the central part of the metavolcanic sequence where they were afforded the most protection from deformation and also volatiles. The preservation of the phenocrysts was also a function of their physical size. Turner and Verhoogen (1960) have discussed the variation in chemical potential of any component of a phase as a function of the pressure inside the phase. This pressure is dependent on the radius of curvature, and therefore, the grain size, so that variation in chemical potentials is a function of grain size.

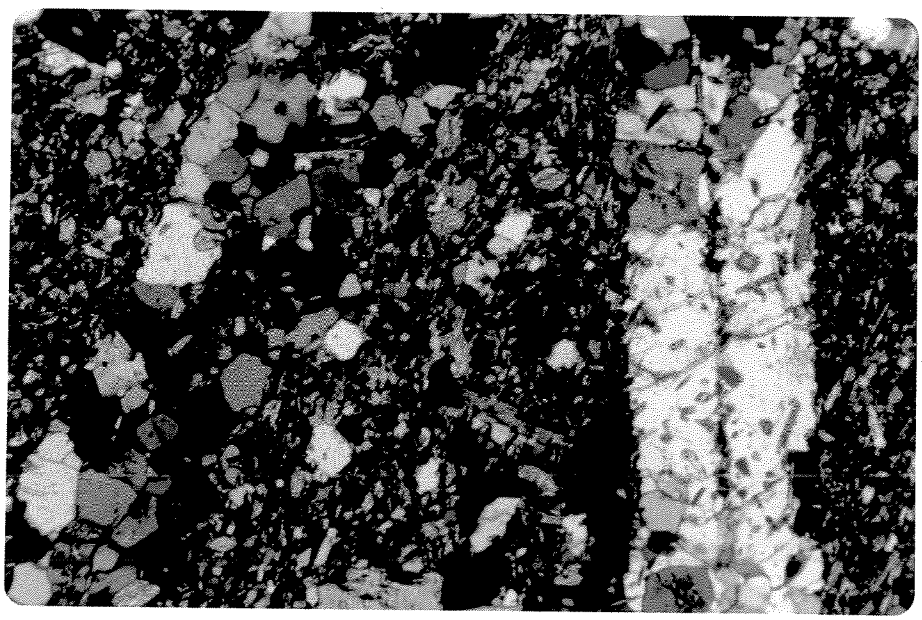

FIGURE 21. Photomicrograph illustrating both a completely recrystallized phenocryst and a phenocryst which is only partially recrystallized.

The result is that small grains are unstable with respect to larger grains. The fine-grained groundmass also contributed to the preservation of the phenocrysts by cushioning them from non-hydrostatic stresses.

The composition of relict phenocrysts and secondary groundmass plagioclase grains were studied by means of electron microprobe analyses, the Tsuboi method and five-axis universal stage techniques. The electron microprobe study was invaluable in studying the relationship between relict phenocrysts and secondary grains and also for testing compositional variation within single grains. All electron microprobe analyses were preformed by Dr. L. S. Walter at the Petrology Laboratory of the Goddard Spaceflight Center in Greenbelt, Maryland. In the three samples studied in detail by the microprobe, nine individual phenocrysts and the surrounding groundmass plagioclase grains were studied. Eighty three individual analyses were obtained. One of these phenocrysts is shown in Figure 22. The probed locations are shown as solid circles. The compositions of the relict phenocrysts and the secondary grains in the groundmass are very similar and fall within the same narrow range. No compositional variation across twin boundaries was observed.

Optical examination by the five-axis method (Emmons, 1943; Noble, 1965) shows that the phenocrysts are in an ordered structural state, and that all original compositional zoning has been obliterated. Pole to both the primary twin planes and secondary albite deformation

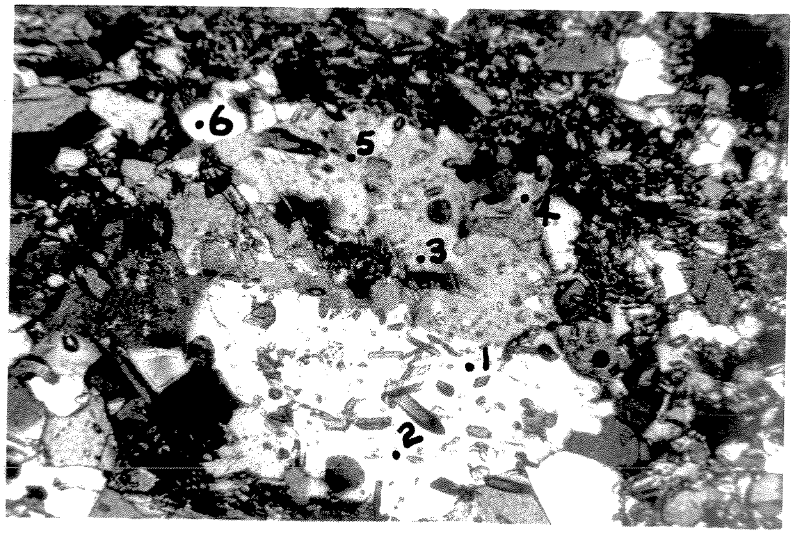

FIGURE 22. Photomicrograph of relict phenocryst showing location of electron microprobe analyses. Secondary groundmass plagioclase grains have a composition of An_{22} and the relict phenocryst analyses fall in the range An_{19}-An_{22}. These An-contents are probably slightly lower than the true An-contents as explained in the text.

twins fall on or near the ordered migration curve. These pole plots (Figures 23 - 25) indicate a slightly more calcic composition than the values obtained from the microprobe analyses. Vogel (personal communication) has studied these samples very carefully by the Tsuboi method and it appears that the standards used for calibration in the microprobe study differ slightly from their stated values. This resulted in the values obtained in the probe study being slightly more sodic than they actually are. Vogel's data obtained by the Tsuboi method as modified by Vogel (1967, unpublished research) and Morse (1968) is compared in Table 2 to the microprobe analyses.

TABLE 2

Sample	Tsuboi	Electron Microprobe
7-4A	An_{39-41}	An_{34-39}
7-3B	An_{24-28}	An_{19-23}
11-8N	An_{30-38}	An_{25-32}

The Tsuboi values are in good agreement with the five-axis study. All values are in mole percent and have been rounded to the nearest whole percent.

The compositions of the original plagioclase phenocrysts were probably quite calcic. The average composition of plagioclase in andesites is approximately An_{40}, that in basalts is approximately An_{55} and the porphyritic plagioclase in most andesites is more

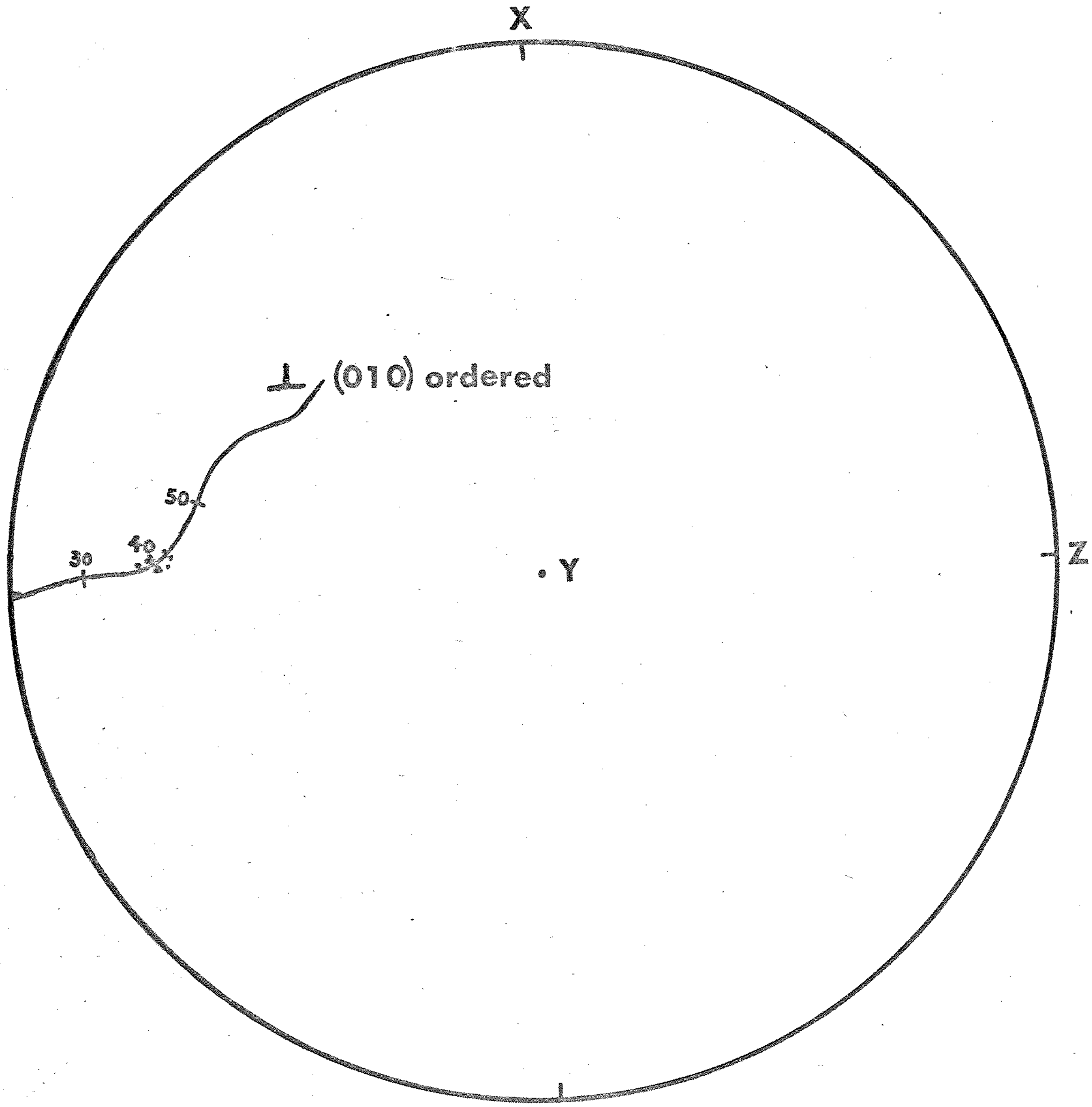

FIGURE 23. Stereographic projection of (010) poles of primary twins in relict phenocrysts in sample 7-4A.

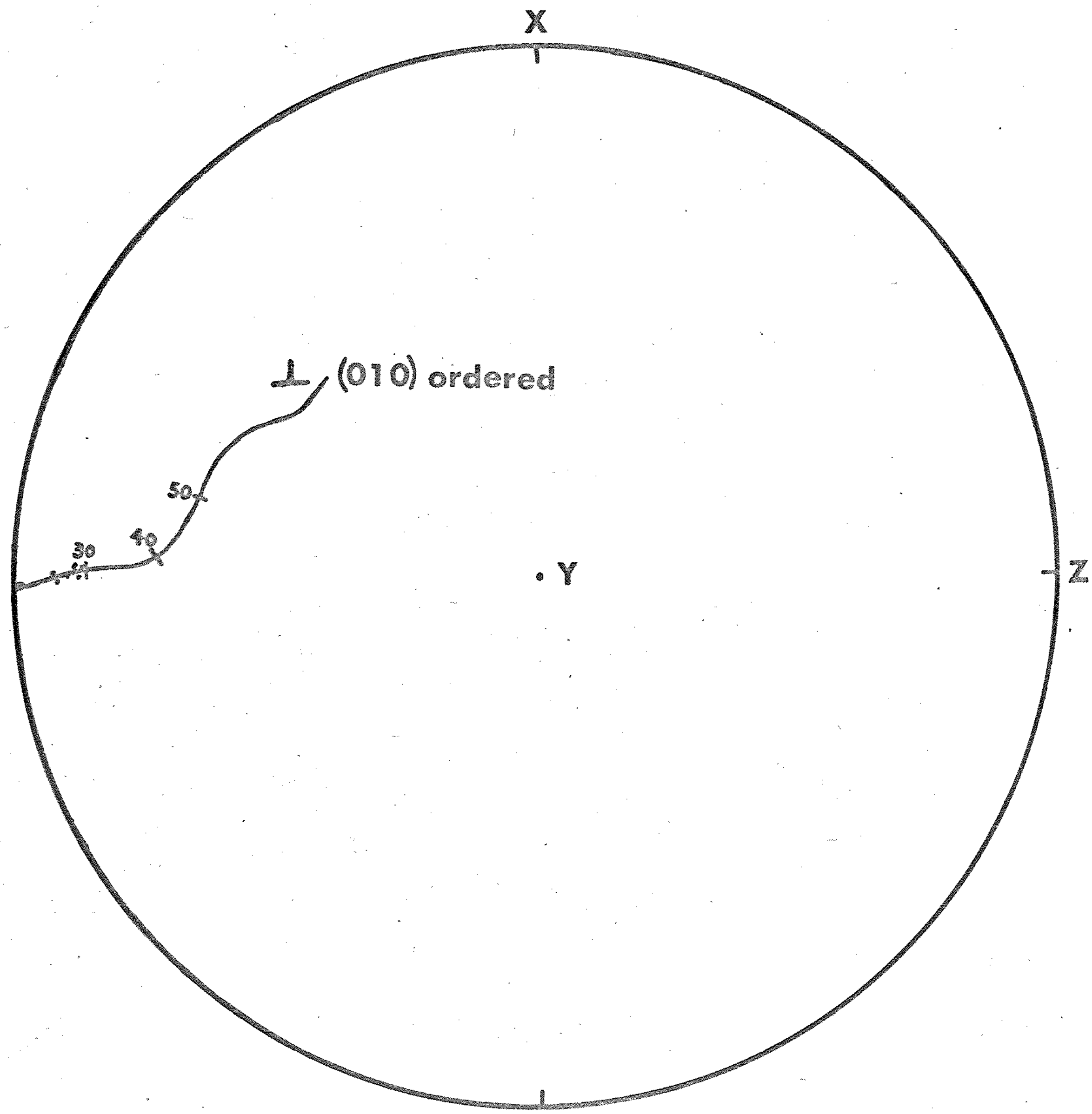

FIGURE 24. Stereographic projection of (010) poles of primary twins in relict phenocrysts in sample 7-3B.

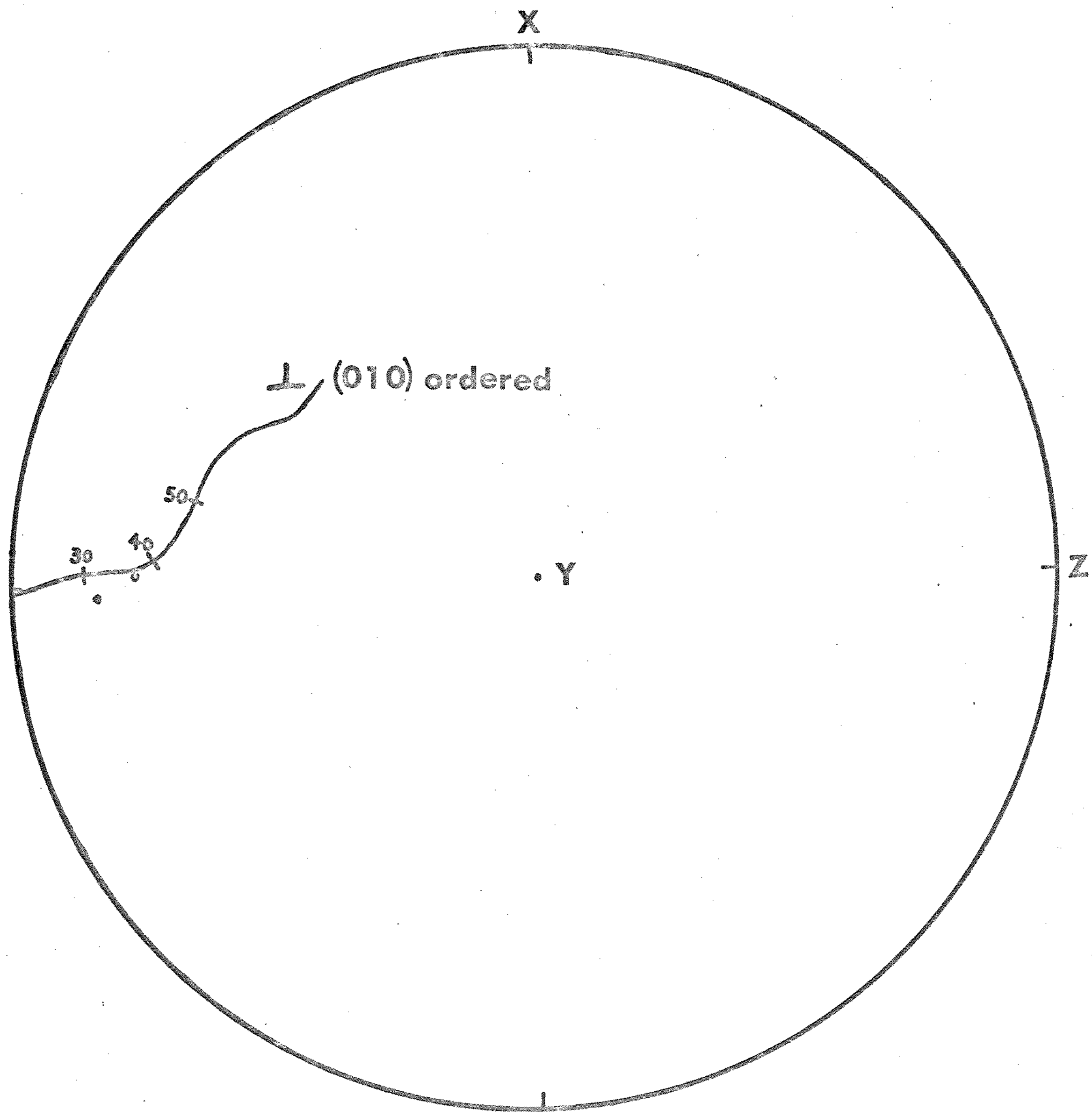

FIGURE 25. Stereographic projection of (010) poles of primary twins in sample 11-8N. The two poles plotted are from adjacent twin lamellae and display the small but consistent internal scatter found in this sample.

calcic than An_{55} (Williams, Turner and Gilbert, 1954). Completely recrystallized "turkey-track" amphibolites in this metavolcanic band have plagioclase compositions in the approximate range of An_{20-30} as determined by the Tsuboi method. The whole rock chemical analyses for silicon, calcium and potassium (previously discussed Table 1) indicate very similar bulk chemical analyses for these samples. The three individual samples now show different ranges of plagioclase compositions; An_{24-28} , An_{30-38} and An_{39-41}. All three samples represent disequilibrium assemblages. Each contains relict amphibole crystals which have been partially converted to a secondary amphibole. Sample 7-3B, which has the most sodic plagioclase (An_{24-28}), has more secondary amphibole developed than the other samples and therefore represents a closer approach to equilibrium. This evidence, in addition to the compositional similarity of the phenocrysts and the secondary grains, demonstrates that the relict phenocrysts have homogenized and changed composition by solid state diffusion without recrystallization. In this process original twin planes and re-entrant angles were preserved.

Pole plots for adjacent twin lamellae show no optical-crystallographic scatter in samples 7-4A and 7-3B. A small but consistant scatter was noted in sample 11-8N. In this sample, a thin area of zoning is present in the area adjacent to the composition planes of the simple twins and, in some cases, a very thin lamella of differing extinction was noted between the simple twins (Figure 26). The nature of both the zoning and the seemingly "extra" twin lamella is not known. The zoning next to the twin boundary may be compositional in nature or could conceivably be induced by strain near the twin boundary, perhaps as a result of an incomplete adjustment of the now-ordered sodium-rich structure to the compositional plane of the disordered calcium-rich structure. This also provides a possible explanation for the seemingly "extra" central twin lamella. Tobi (1962) has commented on wedge-shaped central lamella between simple albite-Carlsbad twins in albite porphyroblasts in low-grade metamorphic pelitic rocks. An explanation for this phenomena is also lacking and whether this entirely different occurrence is related to the features of this study is not known.

The fact that in some of the phenocrysts the poles plot on the ordered curve without any internal or external optical-crystallographic scatter would indicate that the twin plane has reoriented itself to its new composition and structural state, for the position of the twin plane is controlled by the composition of the crystal as well as its structural state (Vogel, 1964). The fact that there is a consistent internal scatter in sample 11-8N may indicate that the reorientation in this sample is not complete.

Noble (1966) found relict, calcium-rich, disordered phenocrysts preserved in low-grade metamorphic rocks up to middle greenschist facies. At this point, they inverted to an ordered structural state while still maintaining the delicate compositional zoning. This structural inversion without compositional change by diffusion is in agreement with the work of Goldsmith (1952) who pointed out that local rearrangement of aluminum and silicon atoms will occur much more readily than the long range diffusion of aluminum and silicon (as well as sodium and calcium) needed to change the composition and homogenize the crystal. Noble also showed that the relict phenocrysts apparently acted as closed systems and no evidence for an isochemical breakdown into two or more phases was noted.

At Plevna Lake, the relict phenocrysts have been subjected to a more intense metamorphism - either to the staurolite-almandine subfacies or to the kyanite-almandine subfacies of the almandine-amphibolite facies. Under these conditions the phenocrysts have not only inverted to the ordered form but, in addition, they have homogenized compositionally and even changed their bulk chemical composition by diffusion in the solid state and reaction with the remainder of the rock. But, as Noble found, there is no evidence for a breakdown of the plagioclase into two or more phases. In being metamorphosed to the almandine-amphibolite facies, the metavolcanics had to pass through the temperature-pressure conditions of the greenschist facies. The plagioclase phenocrysts did not reach equilibrium in the greenschist facies (which would have required their breakdown to form albite with the calcium entering another phase) but rather "overstepped" the greenschist facies. This was due to their physical size, a lack of deformation and almost certainly to a lack of volatiles as well. A rapid rise through the temperature-pressure conditions of the greenschist facies could also have aided in their preservation.

SUMMARY OF CONCLUSIONS

Detailed mapping has shown that the structure is an elongate granite dome overlain by metaconglomerate, paragneiss and metavolcanic rocks. Apparently anomalous field relationships between metaconglomerate with granitic clasts and the underlying granite are clarified by evidence that (i) while the clasts closely resemble the granite megascopically, modal analyses show that most of them are unrelated plutonic rocks and (ii) there is a border zone of the granite that is mineralogically and texturally distinct which is a chilled zone.

The metaconglomerate is not derived from the granite but rather the latter was intruded into the sequence of metaconglomerate, metavolcanics, paragneiss and marble. A temperature gradient between granite and country rock is indicated by the chilled zone and a contact metamorphic zone in the adjacent metamorphic rocks.

The metaconglomerate appears to be at or near the base of the known section in this area but the clasts represent an even earlier time of plutonic activity.

Differentiation trends in the chilled zone, which closely approximates the system $NaAlSi_3O_8 - KAlSi_3O_8 - SiO_2 - H_2O$, demonstrate that the granite was emplaced at a P_{H_2O} of less than 1000 bars.

Prior to the intrusion of the granite, the metasedimentary-metavolcanic sequence was regionally metamorphosed to either the staurolite-almandine subfacies or the kyanite-almandine subfacies of the almandine-amphibolite facies. Pressure conditions of the Barrovian-type metamorphic facies series prevailed.

The metavolcanic sequence includes both pyroclastic rocks and porphyritic andesite - basalt flows. Most of the plagioclase phenocrysts in these flows are completely recrystallized; other relict plagioclase phenocrystals are preserved near the center of the metavolcanic mass. These relict phenocrysts reacted with the remainder of the rock and changed composition by solid state diffusion without recrystallizing. Original twin planes and re-entrant angles are preserved. The phenocrysts are in an ordered structural state, all original compositional zoning has been destroyed and the secondary groundmass plagioclase grains have compositions in the same range as that of the relict phenocrysts. The preservation of these phenocrysts is a result of their size, a lack of deformation and to a low volatile content in the center of the metavolcanic mass during metamorphism.

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