A PETROGRAPHIC AND STRUCTURAL STUDY OF A PORTION OF THE PALMER GNEISS AREA, MARQUETTE DISTRICT, MICHIGAN

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A PETROGRAPHIC AND STRUCTURAL STUDY
OF A PORTION OF THE PALMER GNEISS AREA,
MARQUETTE DISTRICT, MICHIGAN

By

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ABSTRACT

Section 36, T47N, R26W, constitutes a portion of what is known as the Palmer gneiss. The Palmer gneiss and, to a larger extent, the Southern Complex south of the Marquette synclinorium in Michigan have been a point of controversy during the last one hundred years. A petrographic and structural examination, in addition to the mapping of the area, point to certain possible conclusions regarding the geologic interpretations of observed phenomena.

Three major rock types comprise the area: (1) hornblende gneiss, (2) granites and pegmatites, and (3) metabasalts. The gneiss appears to have developed through liquid injections or, less probably, through metamorphic differentiation. The original rock was basalt, later metamorphosed to amphibolite schist. The amphibolite was in turn intruded, it is suggested, by Algoman granite in the late pre-Huronian. The post-Algoman granitic and pegmatitic intrusions are related to the latest major orogenic period, the Killarney Revolution. The metabasalts might be Huronian in age.

The joint patterns present suggest an anticlinal belt trending E-W to NW-SE, with a general N-S stress field. The major stress direction is generally perpendicular to the direction of the foliation, the latter striking roughly N45W to N85W. Stress differentials appear to have played a

significant role in the preferential alignment of the mafic minerals prior to the intrusion of the Algoman granite.

All evidence of this study points to a Precambrian origin for the major lithologic units of the area.

ACKNOWLEDGMENTS

The writer is deeply indebted to Dr. J. Zinn for the original conception of this problem, as well as for his unselfish aid in directing the project. Sincere thanks also go to Dr. J. W. Trow and Dr. B. T. Sandefur and Dr. H. B. Stonehouse for their constructive criticism and helpful suggestions.

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INTRODUCTION

Location and Accessibility

Section 36, T47N, R26W, of the Palmer-Sands Quadrangles, is located in Marquette County of Michigan, roughly twelve miles southeast of Palmer (Figure 1). The area under study extends from the fire lane running approximately parallel to the southern border of Section 36 to the northernmost boundary of the major outcrops in the section.

The site of this study is readily accessible as major highways (connecting Palmer, Negaunee and Marquette) surround this area, and the interior is well traversed by numerous auto trails, permitting motoring throughout the area during the summer months.

Physical Features and Climate

The terrain is composed of rolling, terraced and pitted sand outwash, with rounded rock-cored hills and occasional outcrops protruding above the comparatively flat landscape. The immediate vicinity is thickly wooded with jack pine trees and a dense growth of underbrush. Glacial scouring and polishing is evident on the outcrops.

The summers are temperate to hot. There is a considerable amount of rainfall during the summer months and nights tend to be cool. Winters are commonly severe, with heavy snowfalls and recorded low temperatures of -30F.

The principal industry of the Marquette area is the mining and shipping of iron ores and concentrates. In the immediate map area occasional pulp wood cutting serves as the only economic activity.

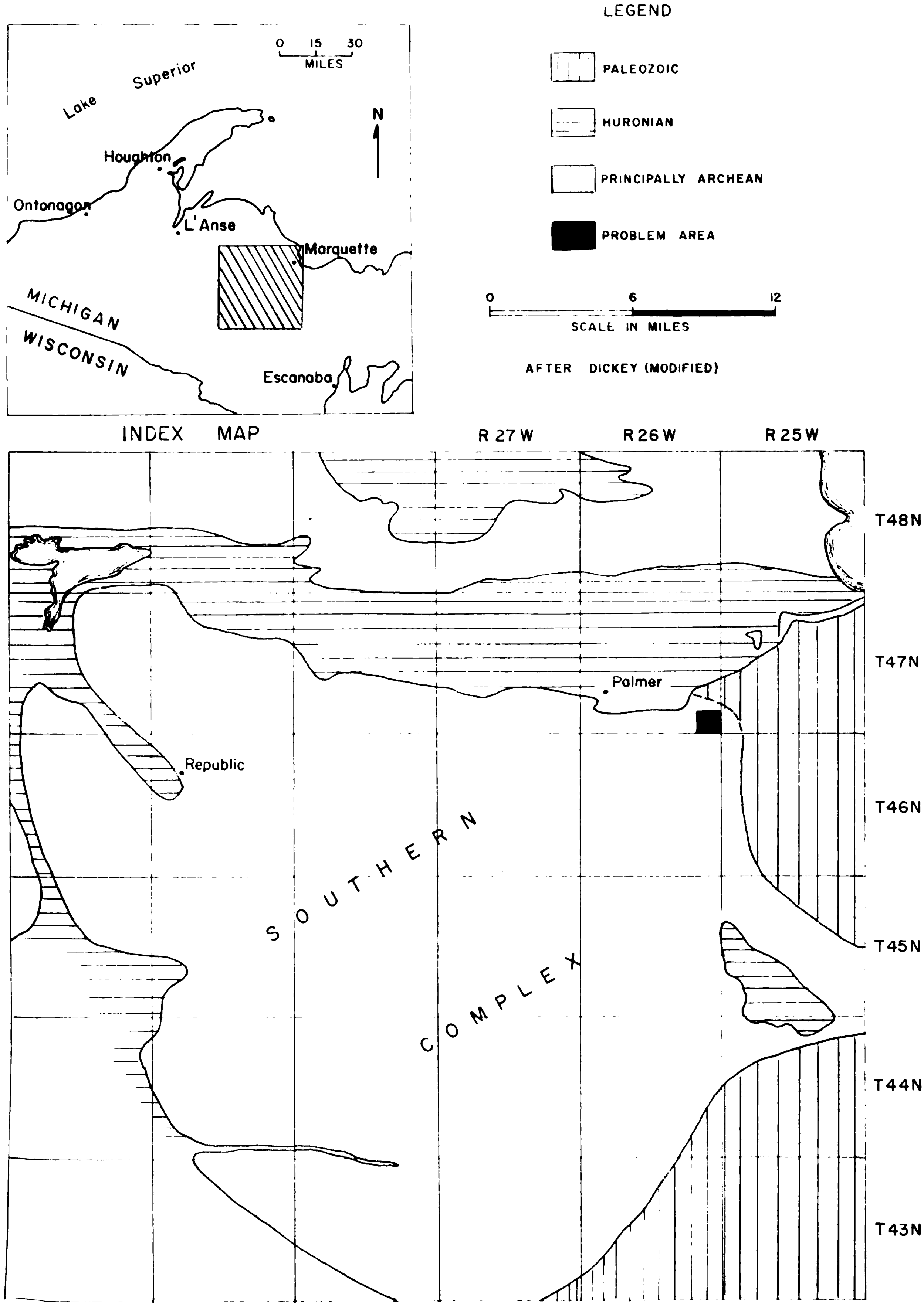

FIGURE I. LOCATION MAP OF PROBLEM AREA IN SOUTHERN COMPLEX.

Regional Geologic Background

Section 36 constitutes a small segment of what is known as the Southern Complex bordering the Marquette iron-bearing District. The geology of the igneous and metamorphic rocks of the Southern Complex, situated directly south of the Marquette synclinorium, has been a point of controversy since the middle of the 19th Century. Various postulations as to the age of the granitic rocks and gneisses in the Complex have been recorded, with a notable lack of agreement on the part of the researchers.

In 1851, Foster and Whitney (1851, Vol. III, No. 4) suggested that the granite south of the Marquette synclinorium was an intrusive into what were called Huronian rocks. There followed, in the ensuing years, references by different investigators to the age of the rocks. They were variously regarded as Archean, Archean and post-Huronian, post-Huronian and post-Cambrian. Van Hise, Bayley and Smyth (1897, p. 1-148), summarized the arguments from 1851 to 1897, and Van Hise and Leith in 1909 (1909, p. 104) arrived at the conclusion that the granites of the Marquette District, including the Southern Complex, belonged to two separate ages, the Archean and the post-Huronian.

This train of thought continued until challenged by Lamey, in a series of articles (1931, p. 288-295; 1933, p. 487-500; 1934, p. 248-263), who postulated that the entire Southern Complex was predominantly made up of post-Huronian granite. He recognized one major period of granitic intrusion. Referring to the Palmer gneiss, Lamey considers that "at least a part of the Palmer gneiss in this area near Palmer may represent Lower Huronian formations..."

Finally, in 1936, Dickey (1936, p.317-340) attempting to reconcile the divergent views on the subject, concluded that there were three distinct periods of Precambrian intrusions in the Complex. Two of these are Archean and one post-Huronian. Thus, he regards the Southern Complex as made up dominantly of Archean rocks, and not as Lamey and others have proposed, composed of predominantly post-Huronian granite. There stands the essential difference.

Purpose and Scope

The basic reason underlying the undertaking of this project was to map and examine, lithologically and structurally, a hitherto unmapped portion of the so called Southern Complex in the Palmer gneiss area. It was hoped at the outset that this project would shed additional light on the complexities of this region and perhaps indicate opportunities for further research in this direction. The thesis presents the results of a combined field and laboratory examination of Section 36 of the Palmer-Sands Quadrangles. The field work, consisting of mapping of outcrops, study of joints and foliation and collection of samples, was completed during the summer of 1958. A petrographic examination was made of 29 thin sections cut from 29 of the 55 samples collected (see location map in back pocket).

Furthermore, the information gained by Messrs. Long and Vehrs, in their investigations of adjacent areas, may be applied in collective correlation with the results of this paper to gain a broader and more complete perspective of the geologic history of the area. However, many deductions expressed here should be regarded as still tentative, rather than comprehensive and final.

PETROGRAPHY AND PETROLOGY

Rock Types

The dominant rock type in Section 36 is a hornblende gneiss (Figure 2), which is similar to what Dickey (1936, p. 323) refers to as the Archean injection gneiss. The original country rock, thought to be basalt flows, was apparently altered to gneiss during severe folding and intrusions by granitic magma.

Figure 2. Typical appearance of the gneiss.

Associated with the gneiss are several varieties of granitic intrusions. It is convenient to divide these into three groups. What appears to be the youngest granite is typically coarse to pegmatitic in texture and is bright pink. The pegmatites are a part of the youngest granitic intrusion, and as a rule, appear in an extremely irregular and erratic pattern and are of little value to the investigator except for possible metamorphic effects. Consequently, they will not be discussed in detail. A second type consists of a relatively equi-granular, medium-grained, grayish-pink granite. The remaining granites display a porphyritic texture and range from pink in the feldspars to the blacks of the ferromagnesians.

Intruding the above described rocks are metamorphosed dikes or sills which are predominantly basic in composition. Metadiabases and metabasalts are the common representatives.

The Gneiss

The hornblende gneiss, characterized by alternating dark bands of ferromagnesian minerals and light bands of granitic material, constitutes the most prevalent lithologic unit. Its banding strikes from E-W to NW-SE, with an average dip of 55° to the south, and is indiscriminately intruded by numerous quartzo-feldspathic dikes and veins. The contacts between these intrusions and the gneiss are often sharp and show little gradational phenomena.

Sample 5b. Megascopically, the rock is a dark green, medium grained amphibolite converted into a gneiss as a consequence of quartzo-feldspathic intrusions. The acidic bands vary in thickness (.05-.25 in.) and are parallel to cleavage planes.

Under the microscope the texture is hypautomorphic-granular to xenomorphic. The thin section shows two bands. The dark band of the gneiss is predominantly composed of hornblende, while the light band is quartzo-feldspathic in composition. The hornblende, some showing prismatic cleavage, commonly appears anhedral to subhedral. The crystals often display inclusions of quartz, zircon and magnetite. Sphene overgrowths on magnetite are relatively common. The sphene is frequently observed surrounding a core of magnetite, this phenomenon being quite representative of the gneissic rocks. It is especially abundant in the vicinity of veins and intrusives (Figure 3). Epidote, in the form of clinozoisite and pistacite, occurs in small quantities as formless aggregates or intrusive veinlets. The feldspar determination is complicated by the advanced stage of sericitization and profuse quantities of clinozoisite and piedmontite. The plagioclase appears more distinctly in the light intrusive band, although again exhibiting advanced paragonitization. The Ab.An content was determined to be Ab54An46 in the light band, and Ab46An54 in the dark band. Undulatory extinction is a characteristic of the quartz. It is frequently fractured.

Figure 3. Photomicrograph of sphene stringers between subhedral, prismatic sections of hornblende (sample 5b). Plain light, x54 diameters.

TABLE I

MODAL ANALYSES OF GNEISS

Analysis	Sample No. 5b	6b	12b
Hornblende	60	30	40
Chlorite	5	22	3
K-feldspar	15	5	15
Plagioclase (andesine)	10	15	25
Quartz	5	20	10
Biotite		2	3
Epidote*	3	5	3
Pyrite	tr.	tr.	tr.
Magnetite	tr.	tr.	tr.
Sericite and/or paragonite**	**	**	**
Sphene	tr.	tr.	tr.
Apatite	tr.	tr.	tr.
Zircon	tr.	tr.	tr.
Carbonate		tr.	
Leucoxene	tr.		tr.
Total	98	99	99

* clinozoisite, pistacite, zoisite (?)

** percentage of feldspar altered 25 25 15

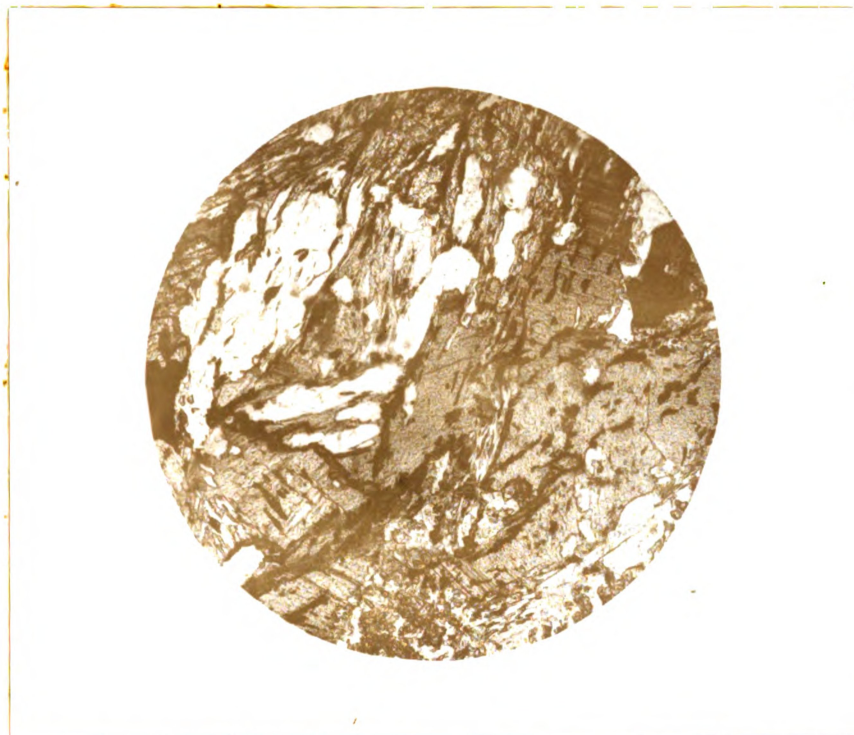

Figure 4. Illustrative photomicrograph showing profusion of sphene stringers in the vicinity of intrusives (sample 6b). Plain light. x54 diameters.

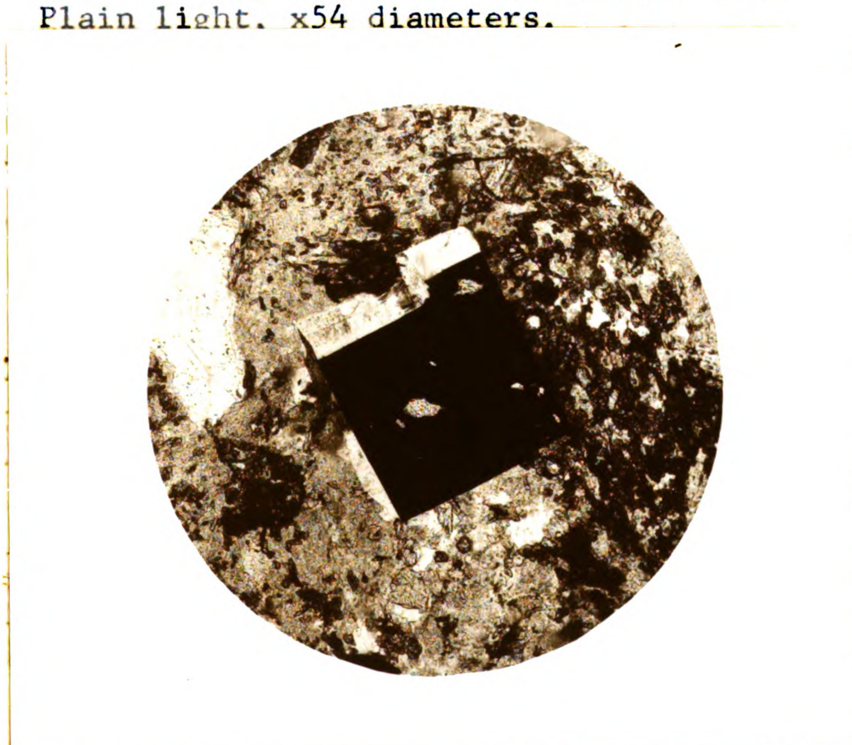

Figure 5. Photomicrograph showing euhedral pyrite in intrusive zone. Partial replacement by quartz. Epidote inclusions (sample 6b). Crossed nicols, x54 diameters.

<u>Sample 6b</u>. The rock consists of alternate hornblende (chloritic) and quartzo-feldspathic bands. The acidic bands range in width from .05 to .10 inches, while the dark bands average .40 inches.

Microscopically, the texture ranges from hypautomorphic-granular to xenomorphic. Hornblende and chlorite form the bulk of the ferromagnesian minerals in the mafic bands of the gneiss. Hornblende occurs in quantities up to 30 per cent, and chlorite, showing characteristic Berlin blue under crossed nicols, up to a maximum of 25 per cent. The chlorite appears to be an alteration product of and pseudomorphous after biotite. Unaltered flakes of biotite are still present but rare. Profuse quantities of sphene in the form of stringers, or anhedral to subhedral crystals, occur at contact zones with the granitic bands (Figure 4). Also associated are large formless aggregates of epidote (clinozoisite, pistacite). Pyrite appears in large subhedral to euhedral crystals, partially altering to hematite (Figure 5). The plagioclase (15 per cent) is extensively replaced by piedmontite and clinozoisite. Some secondary calcite is present. The quartz, constituting up to 20 per cent of the sample, is often severely shredded and fractured, with granulation at grain boundaries and liquid inclusions not uncommon. Mylonitization is suggested by the intensive dragging out of the constituent minerals into streaks, apparently during the intrusion of the youngest granitic intrusive, and is observed running roughly parallel to the contact of the gneiss and the intrusive (Figure 6). The light bands exhibit comparatively little alteration of major constituents. Quartz (35 per cent) and plagioclase ($Ab_{58}An_{42}$) are the major constituents of the acidic bands. The plagioclase runs up to 50 per cent. Accessory minerals

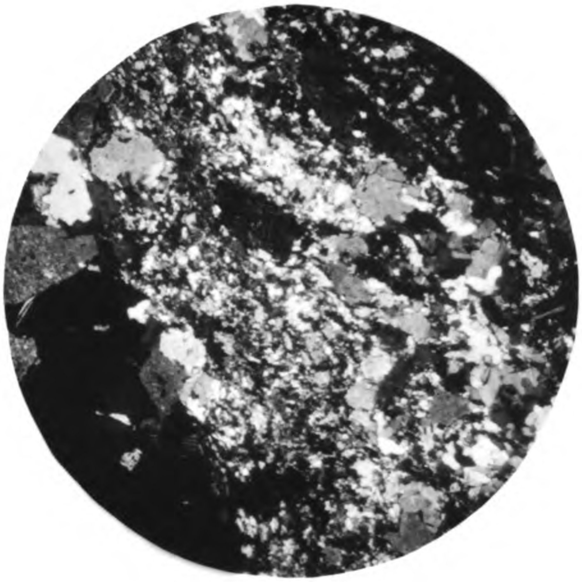

Figure 6. Photomicrograph exhibiting mylonitization of quartz at contact zone of acidic intrusive and gneiss (sample 6b). Crossed nicols, x21 diameters.

are at a minimum. Undulatory extinction is present in the quartz, and although fracturing and granulation of grain boundaries is observed, most of the quartz appears relatively fresh and undisturbed. Phenocrysts of micro-perthite are common as patch perthite, with microcline remnants in plagioclase host (Figure 7). Subhedral to euhedral apatite is present.

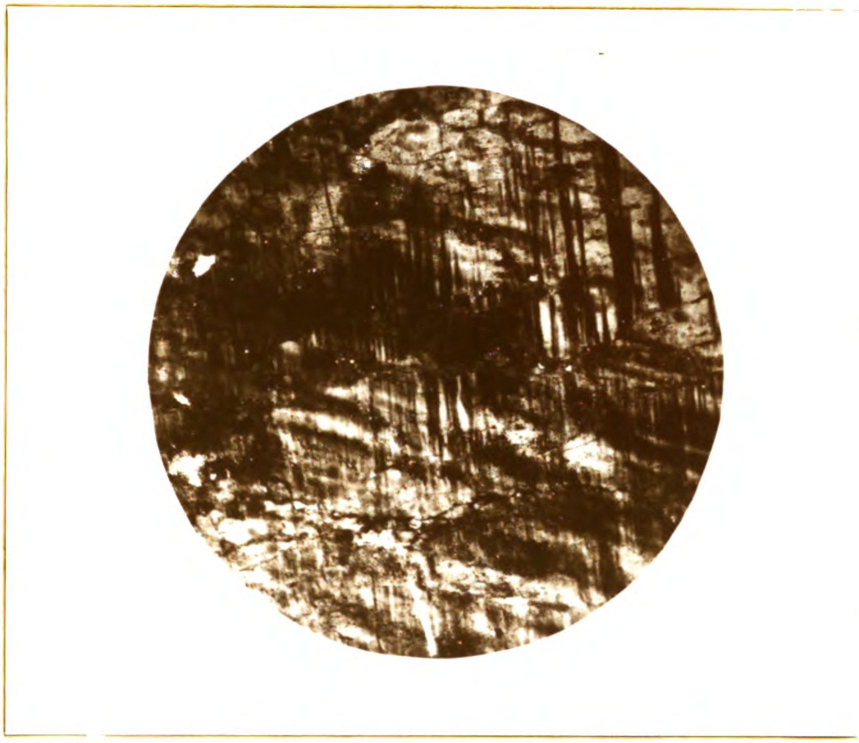

Figure 7. Photomicrograph of patch perthite from microcline (sample 6b). Crossed nicols, x54 diameters.

<u>Sample 12a</u>. The megascopic description of this rock is very similar to the preceding two samples mentioned above. It is medium-grained, granular, dark green and cut by two sets of acidic intrusions. One set is parallel to the gneissic pattern. The youngest intrusion, mainly quartzose in composition, cuts the rock at an angle of 50 degrees with sharp contact.

In the thin section, the texture is xenomorphic-granular to hypautomorphic. Hornblende is again the most important mafic constituent. Prismatic sections are common. Chlorite is observed, probably as an alteration product of biotite. The feldspars are sericitized to an advanced stage. There is a smattering of biotite, often in a partial alteration condition.

Sphene appears frequently, anhedral and commonly associated with magnetite. The malacon zircon is rounded to subhedral, clouded and colorless. Prismatic and hexagonal sections of apatite are observed, mainly subhedral. Reaction strips of epidote at the contacts of basic and acidic bands are noted (Figure 8). Pyrite is infrequent and sometimes altering to hematite. Cataclasis and mashing is widespread.

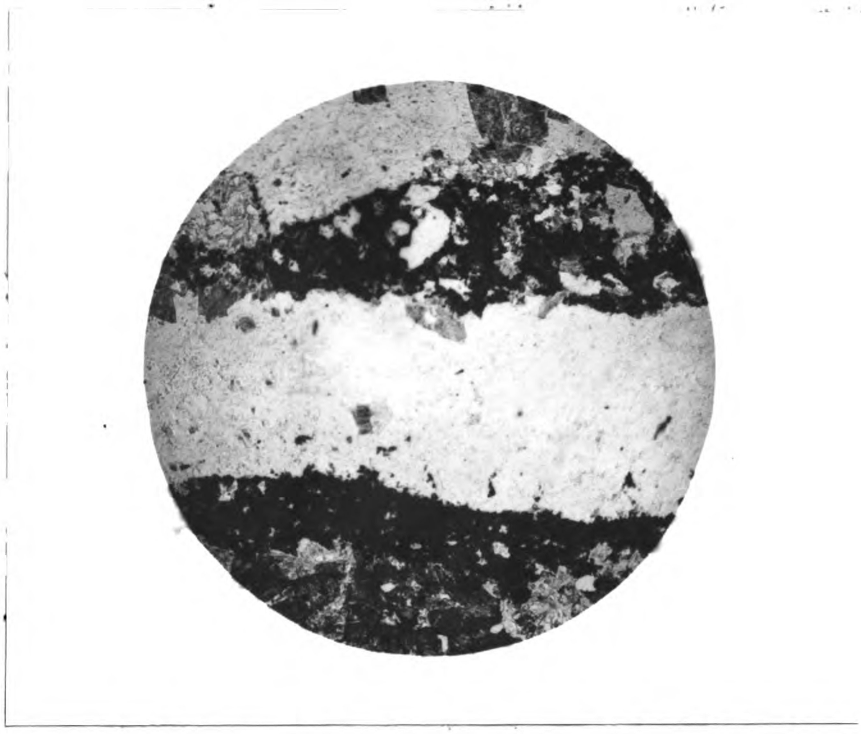

Figure 8. Photomicrograph showing epidote veins adjacent to quartzo-feldspathic intrusive (sample 12a). Crossed nicols, x21 diameters.

General Observations and Possible Interpretations. The dominance of hornblende in the gneisses studied, comprising 35 to 65 per cent of the rock, suggests an original rock of basalt or basic tuff in composition. The hornblende commonly appears in prismatic sections, mostly subhedral, light yellow to brownish yellow and is of the uralitic variety. It is often accompanied by chlorite which appears to be an alteration product of biotite (Figure 9), possibly as a result of

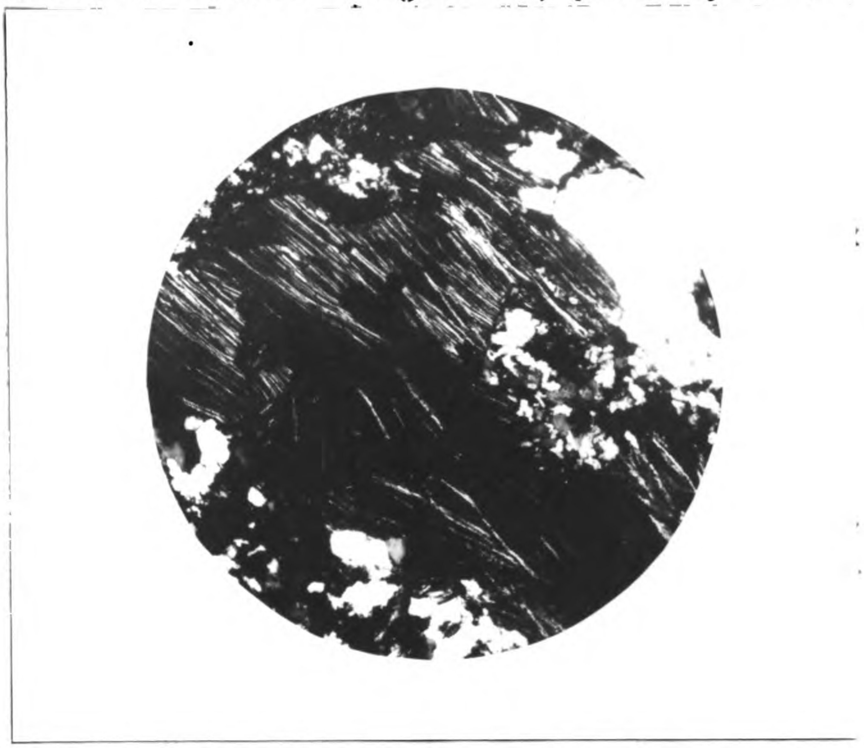

Figure 9. Photomicrograph exhibiting chlorite as alteration product of biotite and pseudomorphous after it. Sub-parallel arrangement evident (sample 3). Crossed nicols, x54 diameters.

retrograde metamorphism. The chlorite content varies from 5 to 25 per cent, and is sometimes associated with small quantities of relatively unaltered biotite. Another possible indicator of the basic origin of the country rock is the profusion of sphene at the contacts of light and dark bands.

Epidote is also locally abundant, as clinozoisite and pistacite, particularly where associated with mylonitization of quartz. The presence of epidote may be explained by the process of saussuritization, a retrograde effect, which involves the breakdown of the Ca content of the plagioclase with concurrent separation of the Na content. This phenomenon is prevalent in the dark amphibolite bands of the gneiss which show an Ab46An54 ratio in the plagioclase. This contrasts with the Ab54An46 ratio of the andesine in the light bands, in which the An content is subordinate. Given the extra Ca content of the dark bands, epidote may form through hydrothermal activity, often accompanied by uralitization of pyroxene into hornblende. Large euhedral crystals of pyrite are present at contact zones of acidic intrusions and are another evidence of hydrothermal activity. The feldspar in the light bands is dominantly plagioclase. Andesine comprises up to 30 per cent of the rock, while orthoclase runs to about 15 per cent. The feldspars, as a rule, are heavily sericitized and/or paragonitized and are difficult to identify in the dark bands, while in the light bands they appear relatively fresh. The albite, Carlsbad and occasional pericline twinning is more distinct in the light bands. Zircon is present in subhedral to rounded crystals of the malacon type. The presence of some secondary calcite (Figure 10) may be associated with the general process of saussuritization encountered in the gneisses, as a result of the breakdown of the plagioclase into Ca and Na. Quartz appears mylonitized at contact zones of the amphibolite and the youngest granitic intrusions. The mylonitization can be attributed to strong differential movement in the stress field. It is noteworthy that the

Figure 10. Photomicrograph of secondary carbonate vein with chlorite pseudomorphous after biotite (sample 20). Crossed nicols, x21 diameters.

pulverization of quartz is restricted to the vicinity of the youngest acidic intrusive contacts with the gneiss. There is comparatively little deformation displayed in the intrusive itself. Thus the mylonitization may represent the last major period of structural deformation. As the epidote occurrence is strongly associated with these youngest intrusives, it may also be regarded as a late event.

According to Turner and Verhoogen (1951), metamorphic differentiation may account for veins or laminae of simple compositon in initially homogeneous rocks. An example of this are the epidosite (epidote and quartz) veins in amphibolites, and quartz-calcite veins in various kinds of low grade schists. Epidosite and quartz-calcite veins, which are common in the gneiss studied, may be due to metamorphic differentiation and derived from the rock in which they occur. This is explained by the property of the particular mineral to be readily dissolved and redeposited under low-grade metamorphic conditions, which appear to be applicable to the metamorphic rank of the area under study. Turner and Verhoogen (1951) regard metamorphic differentiation as "a result of differential migration of the component ions of the metamorphic system through short distances, under the influence of local gradients in chemical potential."

The foliation observed in the gneiss can also be attributed to segregation resulting from metamorphic differentiation. The differentiation involves mechanical deformation synchronous with chemical activity, the former agent being subordinate. Mechanical activity results in shear surfaces from the induced rotation and gliding of crystals, thus facilitating passage of pore solution. Since minerals such as quartz and calcite deform with ease, they are conducive to the development of layers and bands due to segregation. The subparallel arrangment of the platy or prismatic crystals of the dominant constituents is achieved through flow movement accompanying deformation. Cataclasis, in the form of extreme shredding and mashing, is amply evidenced in the hornblende gneiss of the area, although relatively absent in the youngest granites. If the development of the layered structures were attributed to the interplay of mechanical deformation, solution and crystallization, i.e., metamorphic differentiation, one period of metamorphism would be sufficient. However, the writer questions the probability of metamorphic differentiation as the chief agent in the development of the gneiss. It is doubtful whether the original basaltic rock included the necessary amounts of quartz and calcite to provide for the essential property of comparatively high solubility, thus facilitating segregation of the minerals into bands and layers and accounting for the prevalence of the quartz, calcite, epidote and granite in veins, stringers and dikes.

An interesting sidelight on the issue of diffusion and differentiation is Barth's description (1952) of what he calls secretion pegmatities. These form, in his view, first, through the formation of fissures and open cracks by stress differentials, and second, through the action of the gradients in the chemical activities set up by mechanical pressure gradients. The haphazardness of the youngest quartzose and pegmatitic bodies cutting the gneiss, and their extreme irregularity in the area studied by this writer, could perhaps be explained by advocating the absence of ducts leading to magmatic sources. Rather, since stress differentials have existed in this area, the lack of any order to the youngest acidic bodies may be due to their dependence on the presence of fissures and cracks, and consequent filling of these cavities by secretion or excretion. This, in fact, appears to be a possibility since a definite zoning in the pegmatite is noticeable. The marginal zone displays crystals of quartz and plagioclase up to .6 inch in length embedded in a fine-to-medium grained matrix, often showing graphic intergrowths. The inner zone appears more coarse-grained; single crystals of microcline attain 1.6 inches in length.

If the injection of the acidic intrusives were regarded as the agent responsible for the genesis of the hornblende gneiss, then two major periods of metamorphism would have to be postulated, plus a minor one as a result of various periods of granitic "intrusions" on a smaller scale, giving rise to stringers and veins of epidote and calcite. These, when in any type of linear aggregates, appear closely associated with the contacts of the younger acidic bodies and the gneiss.

The writer would suggest the following sequence for the genesis of the hornblende gneiss in the area, which is, for all practical purposes, part of the Palmer gneiss nearby. The first major period of metamorphism could coincide with the Laurentian disturbance and result in the alteration of the original Keewatin basic flows to amphibolite. The formation of the gneiss could be attributed to late pre-Huronian granitic activity and the Algoman Revolution. This is in view of the predominance of the malacon-type zircons, and the conclusions of Tyler and Marsden (1940). The important point to bear in mind, however, is that the formation of the gneiss involved a second major period of metamorphism in the late pre-Huronian. A third period of metamorphism could be related to the Killarney Revolution which led to the haphazard pattern of the youngest quartzo-feldspathic and pegmatitic intruding bodies. The solutions in turn, it is suggested, were instrumental in the formation of epidote and calcite stringers and veins, through the hydrothermal alteration of Ca bearing minerals, particularly the plagioclase, and for the retrograde minerals such as chlorite.

Distortion of laminae, drag effects, crenulations and the like make some type of injection of the gneiss, or perhaps lateral secretion, as a likely process. The acidic bands in the gneiss, however, are not the uniform, lit par lit type, but tend to differ in their concentrations. The thin sections display a (subparallel) preferred orientation in the hornblende. Cataclasis, in the form of extreme shredding and mashing, evident in the dark bands, also appears to favor the intrusion of relatively solid strata by foreign bodies. This extreme form of cataclasis is absent in the younger granitic intrusions. The role of cataclasis in the development of the gneiss will be further explored in the succeeding section when its correlation with the granites is discussed.

The gneiss is similar to what Dickey (1936, p. 323) described as the Archean injection gneiss:

> " (developing) through the intimate intrusion of Keewatin-type schists, generally along cleavage planes, by granite."

Observed relationships he saw led him to regard the intrusive granite as belonging to the older or Laurentian granite.

The Granite

Late Granite

The characteristic properties of what is probably the youngest granitic intrusion make easy its recognition and differentiation from other varieties of granite in the map area. The orthoclase crystals are conspicuously red to pink and may appear as intergrowths with quartz. The texture ranges from coarse to pegmatitic. As a rule, the granite is distributed sporadically in irregular masses, crosscutting dikes and veinlets, and is observed intruding the earlier rocks in a haphazard manner. This rock is comparatively devoid of mashing and cataclasis and appears to have been introduced concurrently with the last major period of orogeny. The above description is not unlike the Killarney granite described by Dickey (1936, p. 333).

Porphyritic Granite

A porphyritic granite, very similar to what Dickey refers to as the Laurentian granite porphyry, is "characteristically pink to gray in color, and where not deformed subsequent to its emplacement, bears large phenocrysts of orthoclase, microcline, and microperthite, in a groundmass of quartz and biotite, with lesser amounts of oligoclase, apatite, zircon and muscovite (Dickey, 1936)". The porphyry appears deformed to a medium degree, and displays some realignment of the constituent minerals. It should be noted that Dickey considers the Laurentian granite porphyry as younger than the Laurentian granite responsible for the Archean gneiss.

Sample 2. In the hand specimen, a porphyritic granite similar to Dickey's Laurentian granite porphyry is seen to have a granophyric texture. The pink feldspar phenocrysts range from .10 inch to .30 inch in length, against a dark, phaneritic matrix of biotite and quartz and plagioclase.

Under the microscope, the granite exhibits a hypautomorphic-granular texture with large phenocrysts of microcline and microperthite. Quartz, andesine, orthoclase, microcline and perthites are the major constituents. Accessory minerals include pyrite, apatite, zircon, magnetite and leucoxene. The quartz is fractured and shows undulatory extinction. Andesine constitutes upward of 25 per cent of the thin section, frequently exhibiting incomplete twinning and some deformation. It is extensively paragonitized. Microcline is common, often grading to microperthite (Figure 11). Graphic intergrowths of feldspar and quartz (Figure 12) and complex varieties of perthites in veins and braids are significantly present (Figure 13). Blebs of quartz are common throughout

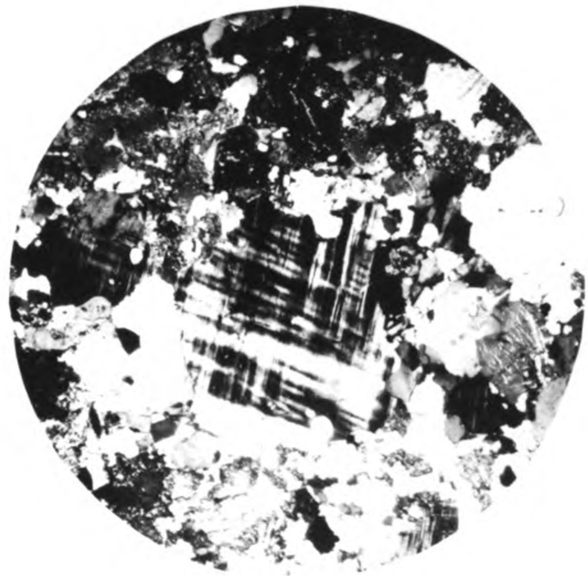

Figure 11. Photomicrograph of microcline surrounded by perthites, quartz and various types of intergrowths (sample 2). Crossed nicols, x54 diameters.

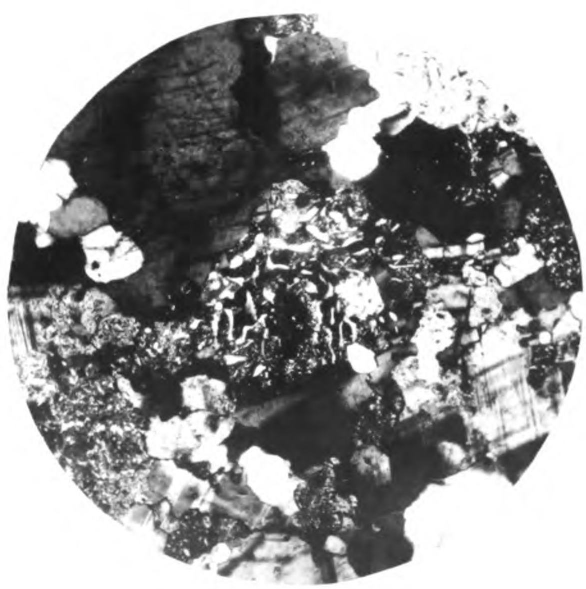

Figure 12. Photomicrograph of example of graphic intergrowth (sample 2). Crossed nicols, x54 diameters.

the section. Biotite occurs in random, sparse flakes, occasionally showing alteration to chlorite. Muscovite is rare. Crystals of apatite are unusually large and prismatic to rounded and irregular in form. Hematite staining is not very prevalent but evident locally. Predominantly anhedral to subhedral crystals of magnetite, sometimes as euhedral octahedrons, exhibit alteration to martite. The rock displays cataclasis. Occasional appearance of clino-zoisite and pistacite is noted.

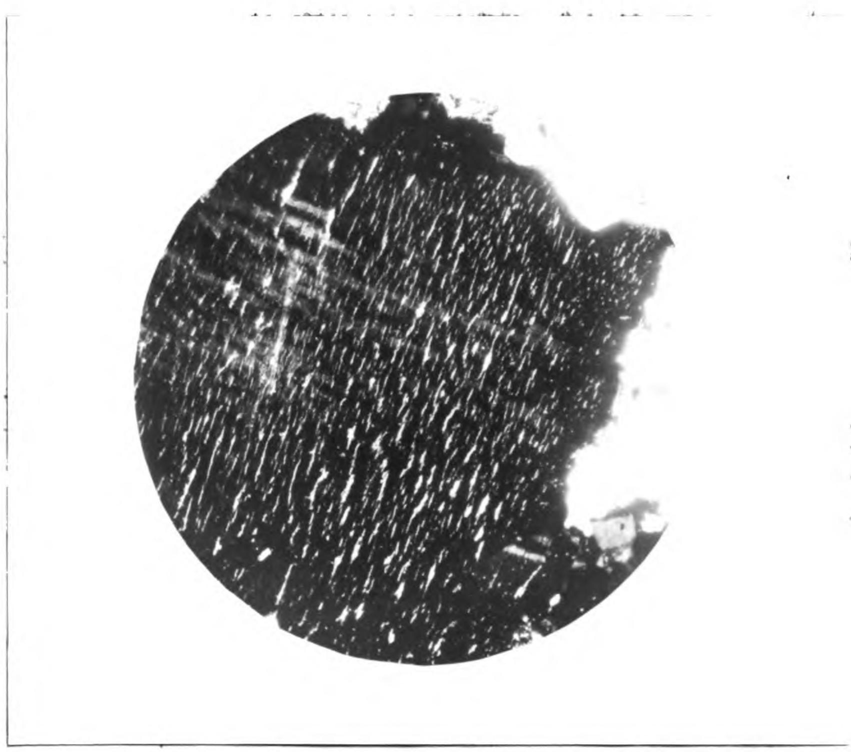

Figure 13. Photomicrograph of vein and string perthite. Orthoclase is at extinction (sample 2). Crossed nicols, x54 diameters.

TABLE II

MODAL ANALYSES OF GRANITE

Analysis	Sample No. 2	6a	15
Quartz	20	40	40
K-feldspar	33	28	23
Plagioclase (andesine)	25	30	18
Microcline	6		9
Perthite	4		7
Biotite	10		tr.
Muscovite	tr.		tr.
Chlorite	1	tr.	2
Zircon	tr.	tr.	tr.
Apatite	tr.	tr.	tr.
Magnetite	tr.	tr.	tr.
Epidote*	tr.		tr.
Carbonate		tr.	
Leucoxene	tr.		
Sericite and/or paragonite**	**	**	**
Total	99	98	99

* Clinozoisite, pistacite

** Percentage of feldspar altered . . 15 20 25

Non-porphyritic Granite

A third type of granite in the map area is relatively equigranular, medium-grained, gray, pink to red in appearance. This rock exhibits few effects of intense deformation although some cataclasis is locally present. It is characterized by a lack of porphyritic texture. The writer feels that this granite can also be referred to the youngest granitic intrusion, i.e., the Killarney, as described by Dickey (1936). He defined the granite as:

> "...marked by the presence of red to pink granite with a broad textural range, varying from fine-grained to pegmatitic. The characteristic color, lack of porphyritic texture, and absence of cataclasis or mashing produced by deformation subsequent to intrusion makes it readily distinguishable from the Laurentian granite porphyry."

Sample 6a. In the hand specimen, the rock is a light-pink granite, predominantly feldspar and quartz. It is medium-grained in texture.

Microscopic examination reveals the pronounced lack of any ferromagnesian minerals. The major constituents are orthoclase, andesine and quartz. Little fracturing is shown by the quartz crystals, which exhibit undulatory extinction and commonly contain liquid inclusions. Paragonitization and sericitization of the feldspars, as is usually the case, occurs extensively. Carlsbad, albite and pericline twinning is present. Secondary calcite occurs sparsely, commonly associated with quartz veinlets or fracture zones. The presence of iron-staining is evident as a result of what appears to be the breakdown of magnetite into martite. In contrast to former samples, there is a positive lack of any epidote. Also, the rock shows little effects of cataclasis, which is a dominant feature of the gneisses of the area. Apatite appears in euhedral hexagonal cross-sections and subhedral grains, although comparatively scarce.

<u>Sample 15</u>. Although very similar to the last specimen megascopically, the thin section exhibits distinguishing properties. Megascopically, the rock is light grayish-pink in color and shows traces of ferromagnesian minerals, and also, more significantly, it does not appear as fresh and undeformed as sample 6a.

Under the microscope, the major portion of the mineral constituents is comprised of the feldspars, andesine and orthoclase, and quartz. The plagioclase shows paragonitization to a marked degree. Albite twinning is extremely prevalent, although not always distinct because of paragonite. Microcline is very common and microperthite is seen occasionally. Perthite appears in various forms -- patch, vein or braid -- and occurs frequently. Chlorite and epidote (clinozoisite and pistacite) are observed in a few, intermittent patches and stringers. As a rule, the biotite content is very low and it has largely altered to chlorite. There are traces of small, rounded grains of zircon. Muscovite is extremely rare. Evidence of cataclasis can be seen only locally, in the form of mashing and fracturing of quartz crystals, but is significantly absent in adjacent feldspars. The texture exhibited by the thin section is hypautomorphic-granular.

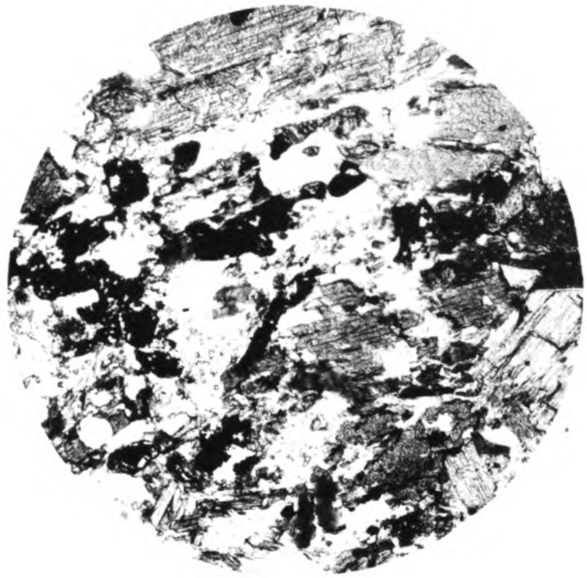

Figure 14. Photomicrograph of thin section showing breakdown of magnetite and pyrite into martite and hematite in granite (sample 1c). Crossed nicols, x54 diameters.

General Observations and Possible Interpretations. A noteworthy characteristic of what are considered to be the younger granites, i.e., those seen cutting the gneiss and non-porphyritic in texture, is the apparent restriction of the more prominent fracturing and mashing to the quartz. This could coincide with the mylonitization observed along the contacts of the latest granitic intrusion and the gneiss. However, the quartz in the latest granitic intrusions shows little advanced deformation, so that the above-mentioned fractured quartz may be the product of an earlier period of deformation. A separate major period of deformation is exhibited by the cataclastic nature of both the quartz and the feldspars in the porphyritic granite. There appears to be no selectivity in the cataclasis noticed in the thin section. Another major period of orogeny is evident in the extreme shredding and mashing often present in the gneiss, which is in turn cut by the younger granites.

To account for the deformation observed, three major orogenic periods appear to be necessary.

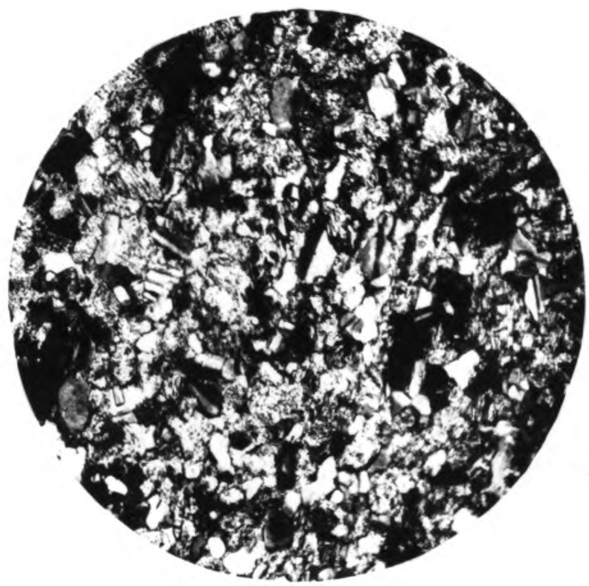

Figure 15. Photomicrograph illustrating diabasic texture (sample 12c). Crossed nicols, x54 diameters.

Metadiabases and Associated Basic Rocks

By far the least abundant of the rock types encountered, the basic intrusives are found in localized masses, usually as dikes, and appear to have been intruded prior to the last major period of folding, i.e., the Killarney Revolution. It is suggested that the basic rocks are a part of the Huronian volcanic activity, e.g., the Clarksburg, which underwent later metamorphism, notably during the pre-Keweenawan Killarney orogeny (Zinn, 1959). Although the writer has differentiated between the metadiabases (Figure 15) and the basaltic-type rocks (Figure 16), it should be pointed out that gradations exist between the two, and that it is often difficult to ascertain the differences.

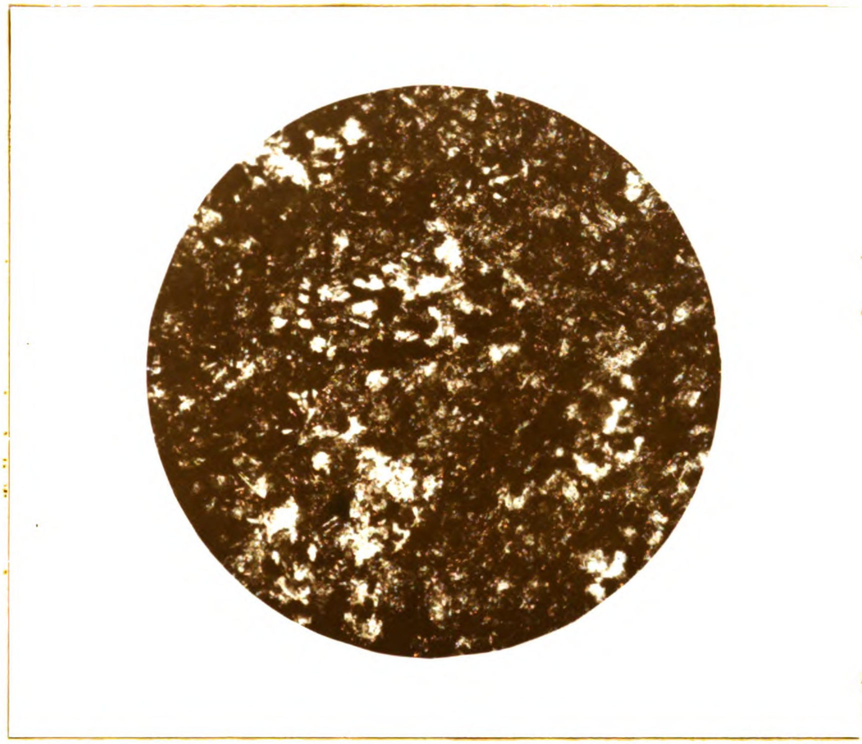

Figure 16. Photomicrograph illustrating felsitic texture in metabasalt (sample 22). Crossed nicols, x54 diameters.

Sample 19b. On its weathered face, the rock shows the characteristic intergrowth pattern of plagioclase laths and ferromagnesian minerals, which identify the diabasic texture. The rock is grayish-green in color and appears microphaneritic in texture.

Microscopically, an ophitic texture is observed. Hornblende is the most abundant mineral, frequently exhibiting various stages of alteration to chlorite. Large, formless aggregates of sphene are common in occurence, often associated with magnetite. Pyrite is present in anhedral crystals. The identification of the plagioclase is complicated by the heavy replacement by piedmontite and clinozoisite. Some zoning is present in the plagioclase laths, as well as some albite and Carlsbad twinning. The plagioclase has a composition close to labradorite. The feldspathic laths are intimately associated with anhedral to subhedral hornblende. Some quartz can be seen and, if primary, indicates the diabase to be of the tholeiitic type (Heinrich, 1956). Apatite appears only sporadically in individual, small, rounded crystals.

Sample 22. This dike-like rock is basaltic in appearance, dirty green in color and the matrix has an aphanitic texture. Disseminated pyrite is noticeable.

In the thin section, the texture is holocrystalline, with aggregates of epidote and calcite (secondary). Epidote is present in a variety of forms -- clinozoisite, pistacite and possibly zoisite. The epidote may be an alteration product of the augite. The original pyroxene may have also altered to carbonate or chlorite. Chlorite is the dominant constituent of the matrix. The determination of the feldspars is extremely difficult by usual petrographic means. Quartz is present as an accessory mineral in insignificant amounts. Accessory minerals include sphene and pyrite in anhedral crystals, the former appearing abundantly, especially in irregular stringers and patches.

PETROGENIC AND PETROLOGIC INTERPRETATIONS

Sericitization and Paragonitization. In the writer's opinion, more attention should be focused, than has usually been the case, on the various patterns and environmental frameworks in in the confines of which sericitization and paragonitization are seen to develop. As Eskola summarized (1939), the development of sericite, through the action of hydrothermal metasomatism, is dependent on the alkali concentration and the temperature of the active solutions.

The question of the actual composition and the nomenclature of the sericitization of different feldspars has not been resolved. It has been suggested (Johannsen) that paragonite, and not sericite, is the plagioclase alteration product and is similar to sodic mica in composition. The thesis has been advanced that the term sericite should be employed only when occuring with orthoclase, and that paragonite should be associated with plagioclase. Emmons (1953), on the other hand, mentions that T.C. Patrick is to report on the thesis that "paragonite characterizes orthoclase and sericite characterizes plagioclase. These micas need not be 'alteration products'."

Emmons and his co-researchers (1953) came to the following conclusions regarding the sericitization of feldspars:

> "We regard sericitic alteration in zones of an oscillatorily zoned plagioclase as consequent to the unmixing of potash on cooling. Our analyses suggest this by the low potash content and the excess silica. This sericitization takes place at about the time of twinning. In progressively zoned plagioclase sericitization is much more general throughout the crystal. On these premises we further

> conclude that some zones of oscillatorily zoned crystals contained more potash than others and hence carry more sericite. Or the high potash of some zones may have been transferred to alternate twin lamellae, and hence alternate lamellae may carry more sericite -- a frequent observation."

Emmons (1953) bases his concept of sericitization of the plagioclases on the premise that, within limits, twinning and zoning are mutually exclusive in that an increase in the former results in a roughly proportionate decrease in the latter.

In discussing the alteration products of feldspars, the writer shall restrict the term sericitization to the K-feldspars and paragonitization to the Na-feldspars, regardless of their respective compositions. Four main patterns of paragonitization were evident in their relationships to plagioclase in the samples studied by the writer. First, paragonitization was sometimes observed to develop in alternate lamellae, almost obscuring the twinning lamellae. Second, paragonitization was observed restricted to rims of crystals. Third, paragonitization was observed confined to what appears as former zone outlines. Finally, a fourth pattern consisted of various combinations of the above, such as paragonitization regardless of twinning.

In the first case (Figure 17), it is quite probable that there are compositional variations between the adjacent lamellae, which makes possible the selective paragonitization of alternate lamellae. This difference in composition may be inherited from the preceding zone structures. Emmons and Mann (1953) state that "the difference in composition of contiguous twin lamellae, in part at least, substitutes for the difference in composition between zones."

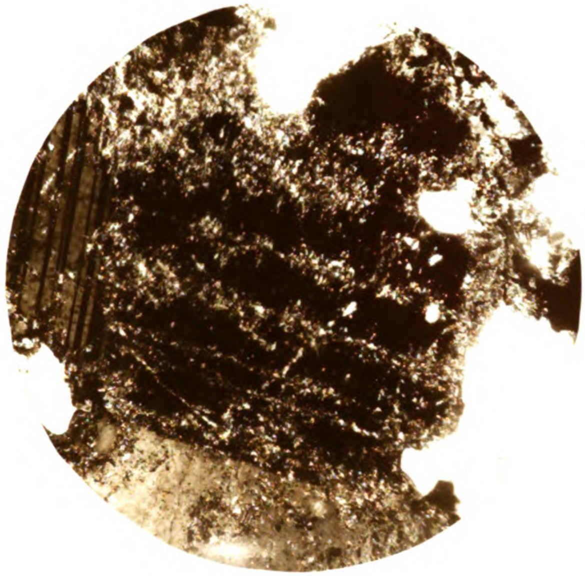

Figure 17. Photomicrograph exhibiting sericitization along twinning lamellae (sample 4). Crossed nicols, x54 diameters

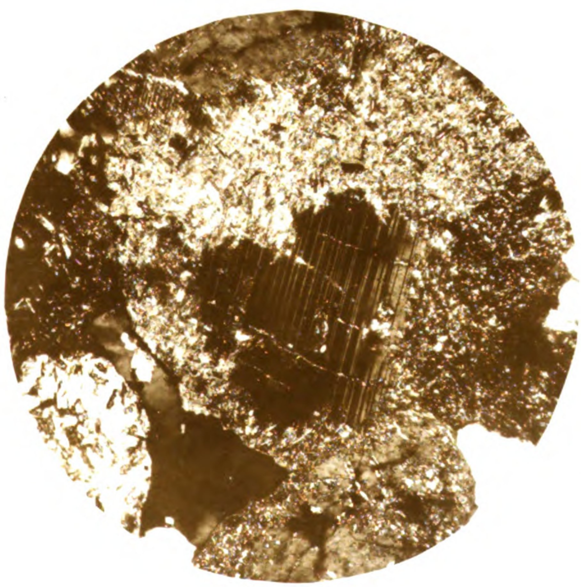

Figure 18. Photomicrograph showing partial development of twinning lamellae in plagioclase crystal (sample 1c). Crossed nicols, x54 diameters.

The second case (Figure 18) might be explained by the concentration or segregation of potash at the borders of the crystals, thus establishing a conducive area for the paragonitization of the plagioclase. As a case in point, the non-permanence of a difference in composition, whether between the lamellae or zones, should not be overlooked. This difference may be removed with the advancing age of the crystal (Emmons and Mann, 1953). An agent for the concentration and segregation of the potash content could be the presence of hydrothermal solutions. The relative abundance of paragonite in the borders of a crystal may also be explained through the migration of the potash as a consequence of periods of viscous fluidity; however, without the effects of cataclasis (Bradley and Lyons, 1953).

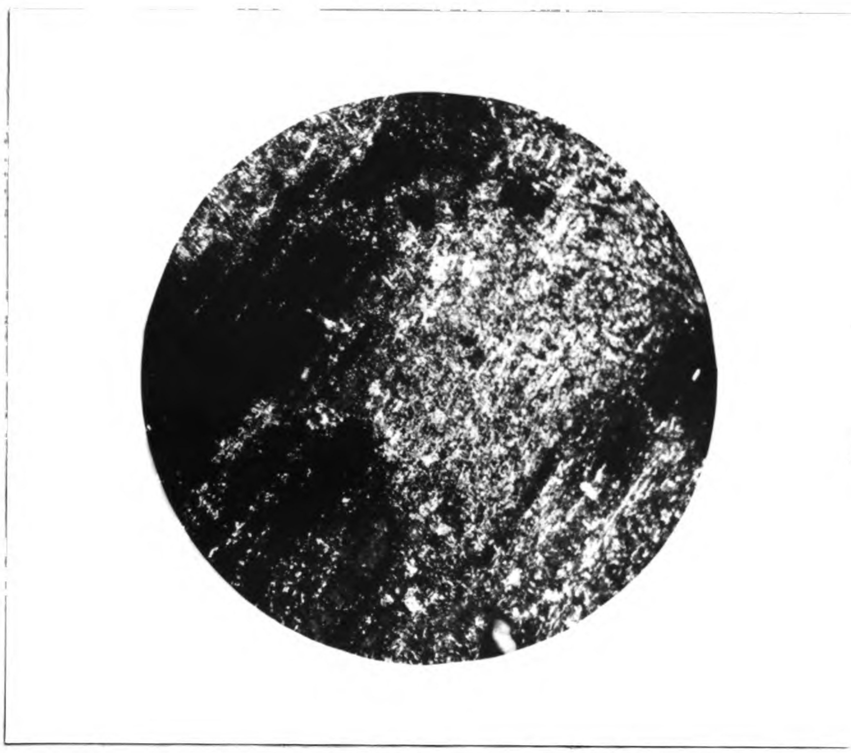

Figure 19. Photomicrograph exhibiting different zones and intensities of sericitization in plagioclase crystal (sample 12b). Crossed nicols, x54 diameters.

The reasoning applied to the first example may be employed in attempting to explain paragonitization with certain former zone outlines. This must again be due to differences in composition, resulting in selective paragonitization of particular zones (Figure 19).

In the absence of sufficient compositional differences or other pertinent controlling factors, such as, perhaps, the absence of twins or zones, or the interruption of paragonitization by potash transfer, paragonitization may be expected to assume a random habit with no particular selectivity.

The general tendency in Section 36 of paragonitization to be characteristically not confined to one or two patterns, involves the consideration of various possible affecting factors. It must be emphasized that unlike the orthoclase-based sericite which appears to attack the crystal in a more random and non-preferential manner, the paragonitized plagioclase often displays differing patterns of concentration, as discussed above, which may perhaps be of additional use as an aid in the identification of what might be untwinned plagioclases. Emmons' and Mann's statement (1953), that the difference in composition between lamellae is not constant throughout the crystal is significant in that it permits an explanation of the eccentricities of paragonitization that have been observed.

Sericitization and paragonitization may help in the relative dating of rocks in a regionally metamorphosed area. However, until more exact information is available regarding the proportional relationships of the composition of the alteration product and the chemical composition of the original rock, the usefulness of age determination on the basis of paragonitization and sericitization is of a doubtful nature. Of interest here is Emmons' and Gates' view that paragonitization along twinning lamellae would imply a late date in the development of the crystal.

Plagioclases. Turner (1951), in his studies of twinning patterns, arrived at the tentative conclusion that complex twin patterns could be attributed to a magmatic ancestry and, conversely, that relatively simple twinning or no twinning could be related to a metamorphic origin. This seems to agree, to a certain degree, with the manifestations of twinning in what the writer considers as metamorphosed rocks, as opposed to twin patterns found in granitic rocks of magmatic origin which were introduced into the gneisses during various periods of deformation. Albite, Carlsbad, and pericline twinning and combinations thereof are evident in the rocks studied, their relative abundances in the order given. Albite twinning, the most abundant, often displays thin, straight lamellae, not infrequently incomplete and covering only part of the crystal. Typically, the sodic plagioclases studied do not exhibit sharply defined twins because of the advanced stage of paragonitization. Ideally, according to Emmons and Mann (1953), "the twin lamellae of sodic plagioclase are typically straight, sharply defined, uniform, or nearly so, and narrow." There also appears to be a relationship between the degree of cataclasis evident in the rocks studied and the fineness of lamellae. The greater the degree of deformation suffered by the granite, within limits, the more intimate the twinning appears to be. Emmons and Mann (1953) point out that it is quite possible that "rapidly applied stress, below the shattering point, will create the most intimate twinning, i.e., narrow lamellae."

It is interesting to note the remarkable frequency of sodic feldspar crystals exhibiting incomplete twinning, e.g., twinning only in the center of the crystal. This may be due to differential stress and cataclasis. Gorai (1950) describes untwinned plagioclase as resulting predominantly from conditions prevalent in roof and wall rock areas, and, further, that untwinned plagioclase belongs to a metamorphic environment. It would be expected then that all degrees of gradations between twinned and untwinned plagioclases could possibly be explained in terms of their distance from roof and wall zones of major igneous bodies. As Emmons stated (1953), "in roof-rock occurences the lamellae of the core may not continue into the outer later portions of the crystal." This seems likely, in the writer's view, since the samples collected for study are thought to be for the most part from roof-rock regions. This tendency of twinning to be confined to the crystal nucleus, and its inability or failure to grow into the newer portions of the crystal, is regarded by Emmons and Mann (1953) as an "outstanding characteristic......which contrasts strongly with those crystals formed from igneous liquids...." Furthermore, they hypothesize that this is also probably due to the frequent occurence of unzoned plagioclases in these reconstituted rocks. The reader's attention is drawn to the point that Emmons and Mann (1953) are of the opinion that "...twinning which forms late in the history of the crystal and postdates zoning, is one of the factors and often a dominant one in the elimination of zoning." In other words, the possibility of twinning and zoning being mutually exclusive is thought to be highly probable.

If nothing else, the variations in the patterns of twinning encountered in the different granites point to periods of deformation as one of the geologic agents at work. The above discussion is more difficult to apply to the gneiss proper since the sodic feldspars in the gneiss are often obscured by the effects of repeated deformation. Incomplete twinning in some of the granites may be taken as an argument against the crystallization of sodic feldspars from igneous liquids.

Perthites. In a paper on the petrogenic significance of perthite, Gates (1953) states that the "textural variations are thought to originate through two chemical processes -- unmixing and replacement -- operating almost simultaneously." Gates attempts to explain perthitic features by attributing it to greater mobility of the plagioclase factor than formerly believed, and concludes that unmixing (Figure 20) as the sole

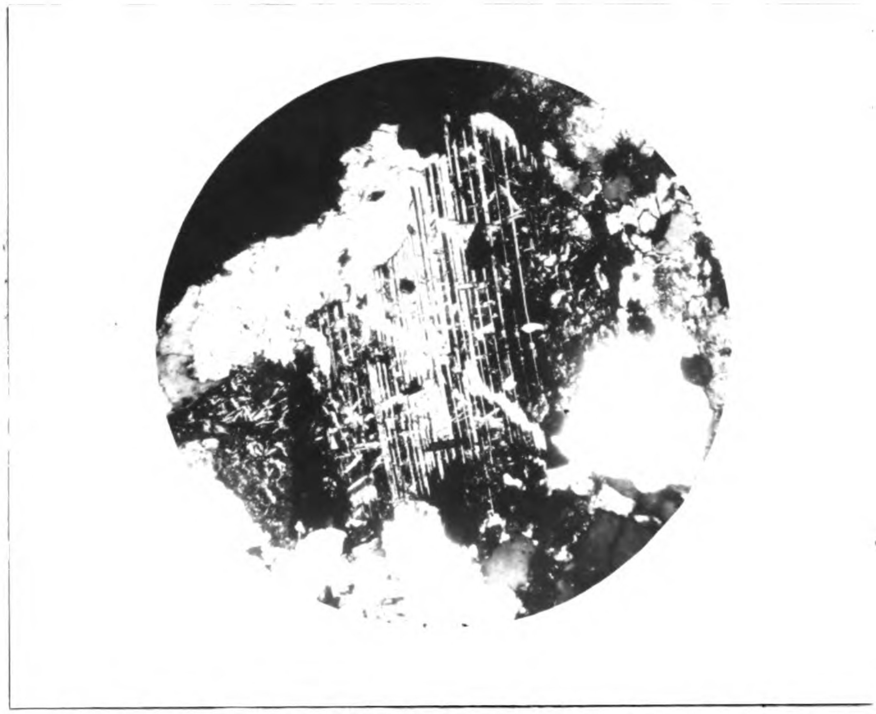

Figure 20. Photomicrograph of perthitic intergrowth, probably due to exsolution (sample 1a). Crossed nicols, x54 diameters.

instrument of perthitization is hardly sufficient to account for the textural variations encountered. In sum, three theories as to the formation of perthitic textures are generally recognized. They are: 1) unmixing, 2) simultaneous crystallization, and 3) replacement.

Although the occurence of perthitic textures in the area is limited, specifically, to those rock units which are believed by the writer to be of magmatic origin, i.e., the acidic intrusives, a wide variation is observed between the divergent types. There is an apparent absence of braid perthites; however, examples of vein, string (Figure 13) and patch perthites can be seen. Especially striking are the large phenocrysts showing patch perthite, which appear to support Goldich and Kinser's view (1939) that "by further replacement of microcline by albite, braid and vein perthites grade into typical patch perthites." The patch perthites observed frequently include remnants of the original microcline in one form or another. According to Gates (1953), "patch perthites and especially extreme examples suggest local accumulation of sodic materials from a greater distance." In contrast, he concludes that the origin of the sodic material necessary for the development of string and film perthite is of a local nature. In the former case, an underlying batholith, which the writer is proposing as a possible explanation of the structural and magmatic phenomena studied, could presumably fulfill the role of a distant magmatic source. It becomes apparent that differential pressures would be a major factor, e.g., the attraction of a low pressure fracture area -- in a feldspar -- for unmixing plagioclase in a mobile state (Emmons, 1953). It is not improbable then that stress considerations in the area under study are of considerable importance in the interpretations offered concerning perthites. In the latter case, given the prevalence of a variety of forms of intrusive feldspathic bodies, the development of film and shadow perthites "may be the result of a hydrostatic pressure change during the last stages of crystallization...." (Gates, 1953).

Tuttle rules out as improbable the possibility of granitization at low temperatures of rocks containing perthites of equal albite and microcline composition. Concurrently, the writer wishes to emphasize that the perthitic occurence is by no means a major constituent in the thin sections studied, neither is it found in all the granite types. Notwithstanding, there appears to be a tendency in the examples observed for the dependence of perthitic development on the degree of stress deformation present.

Since the main lithologic units in the area developed under relatively low temperature conditions, Tuttle's conclusions would imply the genesis of the granite through processes other than granitization. This is in general agreement with the writer's hypothesis that the granitic intrusions were introduced either in a liquid state from an outside source, or formed through metamorphic differentiation.

Plagioclase and epidote. A persistent characteristic of the gneisses in the mapped area is the frequent plagioclase-epidote associations observed. This phenomenon may be viewed as "saussuritization" which took place in plagioclases that were retrogressively metamorphosed (Ramberg, 1950), since epidote represents a low-temperature association relative to the feldspars. According to Ramberg, the most common reactions involving plagioclase and epidote are indicated in the following equations:

$$\underset{\text{epidote}}{2Ca_3Al_3Si_3O_{12}OH} + \underset{\text{kyanite}}{3Al_2SiO_5} + 3SiO_2 \rightleftharpoons \underset{\text{anorthite}}{6CaAl_2Si_2O_8} + H_2O$$

$$\underset{\text{epidote}}{2Ca_2Al_3Si_3O_{12}OH} + \underset{\text{muscovite}}{KAl_3Si_3O_{10}(OH)_2} + 2SiO_2 \overset{T_u}{\rightleftharpoons}$$

$$\underset{\text{anorthite}}{4CaAl_2Si_3O_8} + \underset{\text{orthoclase}}{KAlSi_3O_8} + H_2O$$

It is clear that the above equations presuppose an adequate supply of Ca in the form of the anorthite content of plagioclase. The need may be filled by the greater anorthite content (Ab46An54) in the dark bands of the gneiss. Hence, epidote may form as a result of the loss of Ca in dark bands upon metamorphism. Below a certain temperature, T_u, the anorthite content of the plagioclase will react with potash feldspar and water, because of the fact that they are then unstable. The products of this reaction will be epidote, muscovite and some type of an acid plagioclase. Pertinent to the above are the water-vapor pressure and the Fe^{3+}/Al^{3+} ratio. According to Ramberg, the increase of the water-vapor pressure will favor the formation of epidote and muscovite and will as a result raise the temperature level, T_u, of the reaction points in the above equations. In like manner, an increase in the Fe^{3+}/Al^{3+} ratio of a rock will result in an environment favorable to an increase in the growth of epidote so as to again displace the equilibrium curves to higher temperatures. The latter phenomenon is due to the ability of epidote, in contrast to that of plagioclase, to replace large amounts of Al with Fe^{3+}.

The epidote in the gneisses of the mapped area represents the latest period of metamorphism, coinciding with the youngest acidic intrusions. It probably represents a separate period of metamorphism, coming after the first two major orogenies resulting in the genesis of the gneiss. However, if metamorphic differentiation were postulated for the development of the gneiss, the epidote veins could be explained as products of retrograde metamorphism associated with one major period of metamorphism.

DIFFERENTIATION OF ZIRCONS FOR CORRELATION PURPOSES

In their investigation of zircons of various types occuring in the granites of the Lake Superior Region, Tyler and Marsden (1940) suggest that "the hyacinth occurs in the older granites, to the almost entire exclusion of malacon, whereas the malacon is found in the younger granites..."

The malacon zircons, according to Tyler and Marsden, are characteristically dull in luster, with a cloudy appearance and extremely weak birefrigence. The grains commonly exhibit striated and etched surfaces, and as a rule are rounded prismatic in form. Elongate dipyramidal prisms are rare. They are colorless to pale dirty yellow, sometimes with dustlike inclusions reminiscent of alteration. Apparently, there exists a relationship between the malacon and the igneous and compositional history of an intrusive.

The hyacinth zircon, on the other hand, is characterized by a "very faint pinkish tint to a deep brownish purple, purple, and pink" color (Tyler and Marsden, 1940). Unlike the malacon, the hyacinth is slightly pleochroic ranging from dark to light purple. The grains are usually observed as rounded, and prismatic examples with several pyramidal faces are common.

Tyler and Marsden (1940) arrive at the conclusion that the hyacinth and malacon zircons characterize granites of two ages in the pre-Huronian. The older pre-Huronian granite is represented by the hyacinth variety, whereas the younger is represented by the malacon. However, it is not possible to distinguish some of the pre-Huronian granite from Huronian igneous rocks, as the malacon is also observed to occur in igneous intrusives into the Huronian. Therefore, the only

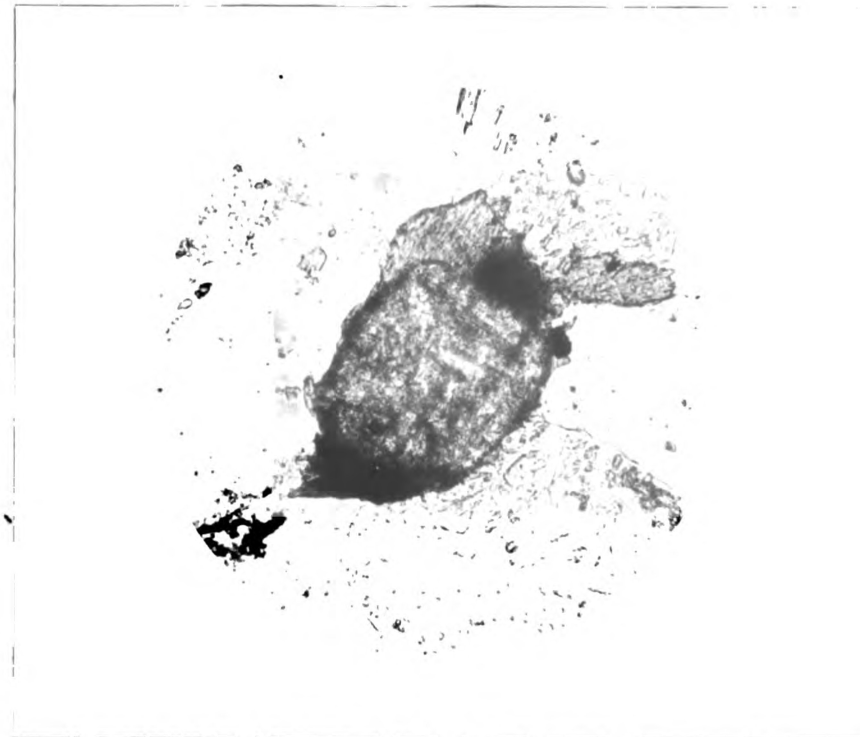

Figure 21. Photomicrograph of malacon-type zircon, typically cloudy in appearance, occuring in granite. Alteration zone along borders (sample 19a). Plain light. x225 diameters.

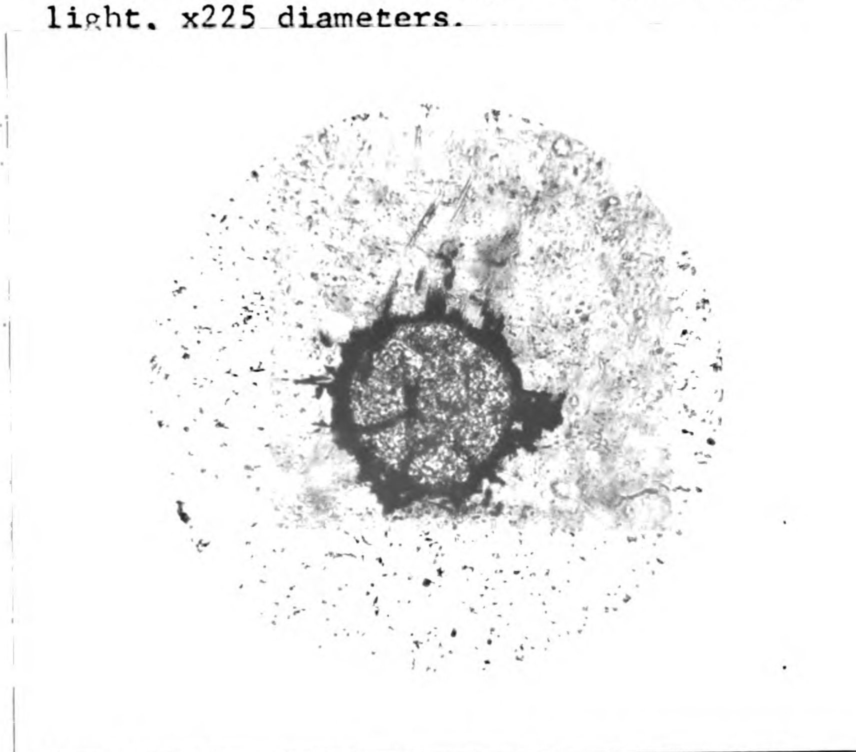

Figure 22. Photomicrograph of rounded zircon with breakdown along periphery in granite (sample 14). Plain light, x225 diameters.

valid conclusion to be drawn is that hyacinth-bearing granites are pre-Huronian in age and older than the granites carrying malacon zircons.

In the thin sections studied, the malacon variety is the dominant zircon present (Figures 21 and 22). The zircons are frequently rounded to rounded prismatic. Dull, cloudy color, abnormally low birefrigence, dust-like inclusions and reaction rims are characteristic of the malacon. Complete, elongate, prismatic sections are seldom seen. In applying Tyler and Marsden's results, the writer feels that it would be reasonable to assume that the granites studied are either late pre-Huronian or Huronian in age.

STRUCTURAL GEOLOGY

The outcrops in Section 36 appear to be part of an elongate belt exhibiting a series of anticlinal folds, the fold axes of which trend in an E-W to NW-SE direction. A cross-sectional view of an anticline is evident west of outcrop XXXIV, directly adjacent to the road (see location map in back pocket). Additional evidence of the anticlinal structure is indirect, but an analysis of the structure can be made through the examination of structural deformation phenomena observed. Because of the small area that this study encompasses, however, a structural picture of the entire Southern Complex, or that part known as the Palmer gneiss, will not be possible.

Structural Setting

The outcrops have a predominantly NW-SE trend, and the foliation of the gneisses in them varies from E-W to NW-SE in strike and dips to the south at angles of 45° to 85° (see structure map in back pocket). The most prevalent value for the dip of the s-surface is 55° to the south. The gneiss often appears quite distorted, with numerous small drag folds (Figure 23) and crenulations. These are local phenomena but may reflect upon the general structure. The axes of these microfolds frequently trend parallel to the general strike of the gneissosity. Elliptical quartzo-feldspathic concentrations (Figure 24) are common in the gneiss, and they also trend in the direction of the foliation. Assigning the A-axis to the major axis of the ellipsoid, the AB plane then parallels the plane of foliation, with the C-axis perpendicular to the s-surface (striking E-W).

The entire area is criss-crossed by a maze of quartzo-feldspathic intrusions. However, due to their lack of any continuity or extent, and their extreme haphazard pattern, these appear to be of little value in deducing any sequence involving them.

Figure 23. Minor drag phenomena. Fold axis roughly parallel to gneissosity.

Figure 24. Quartzose elliptical concentrations along gneissosity.

Figure 25. Photomicrograph showing quartzose ellipsoids in biotite displaying flow structure (sample 20). Crossed nicols, x54 diameters.

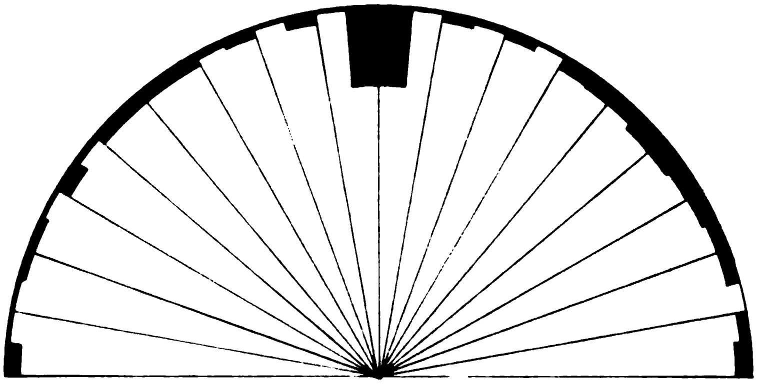

Figure 26. Strike frequency diagram of 168 joints

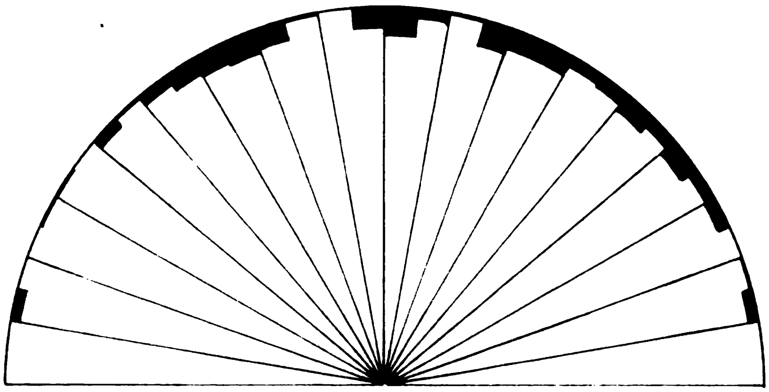

Figure 27. Strike frequency diagram of acute bisectrices

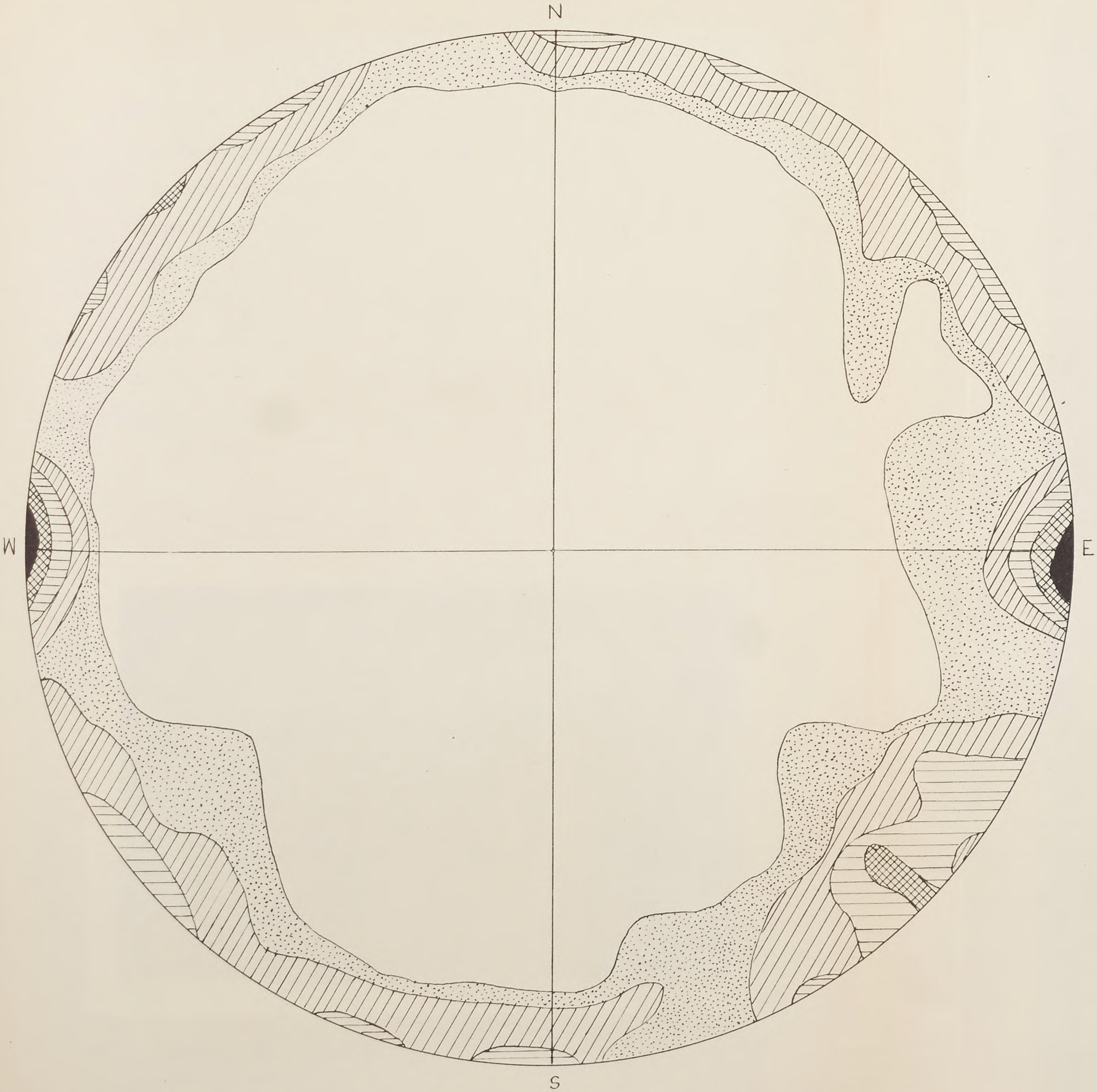

FIGURE 28. CONTOUR DIAGRAM OF POLES TO 168 JOINTS. CONTOURS 22-11-6-4-2-1 PERCENT

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Joints and Acute Bisectrices

A study of 168 joints (see structure map in back pocket) was made of what are thought to be shear joints belonging to conjugate joint systems. Joints belonging to definite conjugate systems could not be ascertained in spite of the fact that the overwhelming percentage of joint planes intersect one or more other joint planes. The most prominent set of joints with 22 per cent maxima (Figures 26 and 28) strike N 5° W to N 5° E and dip steeply. The two next prominent sets, with maxima of 11 per cent and 6 per cent strike roughly from N 30° E to N 75° E and N 10° W to N 60° W respectively and are also steeply dipping.

Figure 29. Fissures ascribed to tension. Note quartz vein intruding along fissure, parallel to major stress direction.

Fissures, which appear to be tension joints (Figure 29), occur more or less at right angles to the proposed major fold axis, and hence also to the trend of the gneissosity. These can be ascribed to the AC plane and may be regarded as resulting from the partial release of stress in a general E-W direction, i.e., parallel to the s-surface.

Assigning the B-axis to the strike of the foliation and the AC plane perpendicular to the foliation, we find a degree of agreement with the predominant direction of the strike of the shear joints. Examining the contour diagram of the acute bisectrices (Figures 27 and 30), i.e., the direction of the major stress, the writer comes to the tentative conclusion that the structural unit underwent a stress field which caused release of stress in a general E-W to NW-SE direction as well as in a vertical sense. Two sets of acute bisectrices are prominent: trending from N 15° W to N 35° W and from N to N 30° E. Both plunge very gently.

A contour map of the angles of the conjugate joint systems (Figure 31) proved to be of little value, although it did significantly show the greater occurence of higher values of 51 to 89 degrees at the two extremities of the NW-SE structural belt. This might lead to the assumption that the beds behaved in a more ductile manner towards the ends of the structural unit than elsewhere. To explain the latter, the writer suggests the possibility of an underlying batholith, elongate in the general NW-SE direction, which while providing the intrusive magma for some of the later emanations, also acted as a device for the buckling up of the regional structure

In an article on the mechanical interpretations of joints, Bucher (1921) stated the important generalization

FIGURE 30. CONTOUR DIAGRAM OF ACUTE BISECTRICES. CONTOURS 12-8-4-2-1 PERCENT

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"that the angle of shearing of a material is the more acute the more brittle the substance is and vice versa." Thus the initial problem is that of deciding whether the material under consideration has the properties of a brittle substance or those of a ductile substance. Of course, if the direction of the greatest principal stress is known, the relative degree of ductility at the time of deformation may be arrived at by an examination of the resulting joint planes.

The writer is inclined to believe, because of the diversity of angles between joint planes in a relatively homogeneous unit, that the beds behaved in a neither completely ductile nor completely brittle manner. Rather, the differences in the angles appear to be due to local limiting conditions of intimately intruded strata. Hartman observed that the angle of shearing is independent of the nature and intensity of the stresses involved. More recently, Seigel (1950) shows that fracture in an isotropic medium takes place "across a pair of conjugate surface elements, equally inclined to the direction of the maximum pressure at an angle which is a function of the limiting stresses as well as constants of the medium." The greater stress, then, would be in the center.

Quartzo-feldspathic Ellipsoids

The origin of the quartzo-feldspathic elliptical inclusions (Figures 24 and 25) is clearly due to the tendency of the inclusions (formed during metamorphism) with growth anisotropy to orient their major axes parallel to the direction of least growth resistance, i.e., in conformity with the trend of foliation. It would appear probable that the elliptical structures resulted from drag effects exercised by the intrusion of igneous liquids along the s-surface.

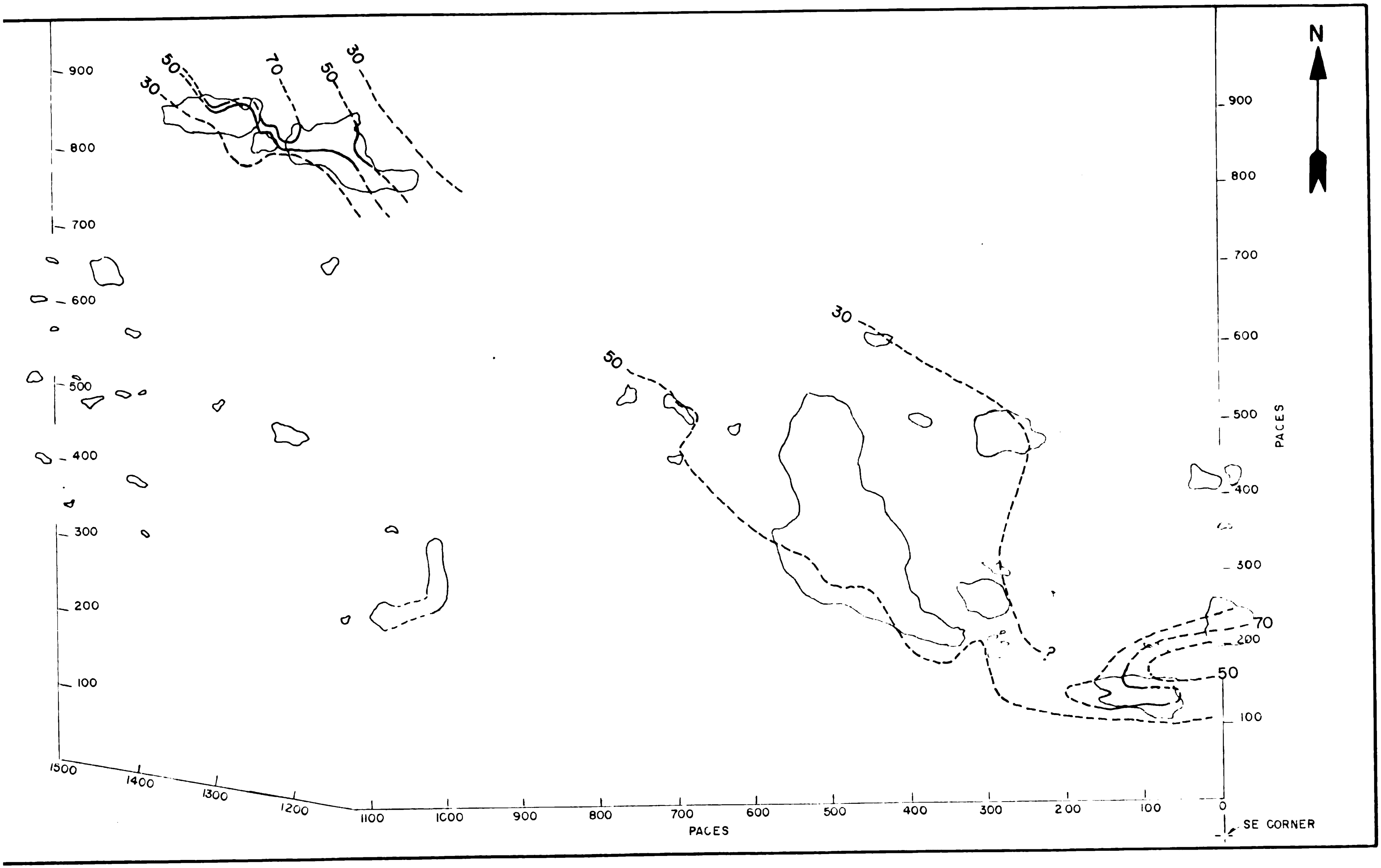

FIGURE 31. CONTOUR MAP OF ANGLES OF CONJUGATE JOINT SYSTEMS

However, Ramberg (1952) is of the opinion that deformation under mechanical stress accounts for the greater part of anisotropic structures in metamorphic rocks, and apparently discounts the importance of the role of fluid mechanics resulting from introduced igneous liquids. It is pointed out by Ramberg that:

> "The crystalloblastic structure in most metamorphic rocks shows that recrystallization flow is the most important type of yield in silicate rocks, provided that they do not contain mainly ductile minerals like chlorites, talc and some micas. It appears then, that the ionic, atomic or molecular mobility in quartzo-feldspathic rocks during regional metamorphism is, as a common rule, considerably greater than this type of mobility in basic rocks."

In other words, despite the observation that in dry melts basic bodies are less viscous than acidic bodies, Ramberg asserts that the crucial factor during regional metamorphism appears to be the ability or ease with which a rock can undergo chemical rearrangement or recrystallization. These, in turn, it is suggested, may be the controlling factors in the formation of quartzo-feldspathic ellipsoids during regional metamorphism. If metamorphic differentiation were postulated, the elliptical structures could have formed as a result of lateral secretion into planes of weakness.

Banding and Foliation

Gneissosity, except in local areas, is clearly exhibited and trends in a general NW-SE to E-W direction. The prominent foliation of the gneisses is due to subparallel alignment of hornblende and biotite. Alternate layers of mafic minerals and quartzo-feldspathic "intrusives" accentuate the banding. The gneisses frequently display local minor drag structures (Figure 23). The extreme irregularity of these microfolds, with included acidic lenses, favors the formation of the gneisses through the action of introduced acid solutions. Additional discussion of the gneiss development is included in the section on rock types.

The plane of the gneissosity (foliation) is roughly parallel to the B-axis of the major structure, i.e., the fold axis and generally perpendicular to the major stress directions. An interpretation of the gneissosity in terms of the structural deformation phenomena (Figure 32), could account for the general agreement of the s-surface and the major fold axis. Successive periods of metamorphism could result in the development of gneisses in the solid state, without the necessity of having to undergo the invasion of fluid magmas of high enough temperature (Ramberg, 1952). It is the writer's modest opinion, however, that the field phenomena observed appear to favor an invasion by fluid magmas of sufficiently high temperatures to account for the irregularity of drag structures, crenulations and cross-cutting veins.

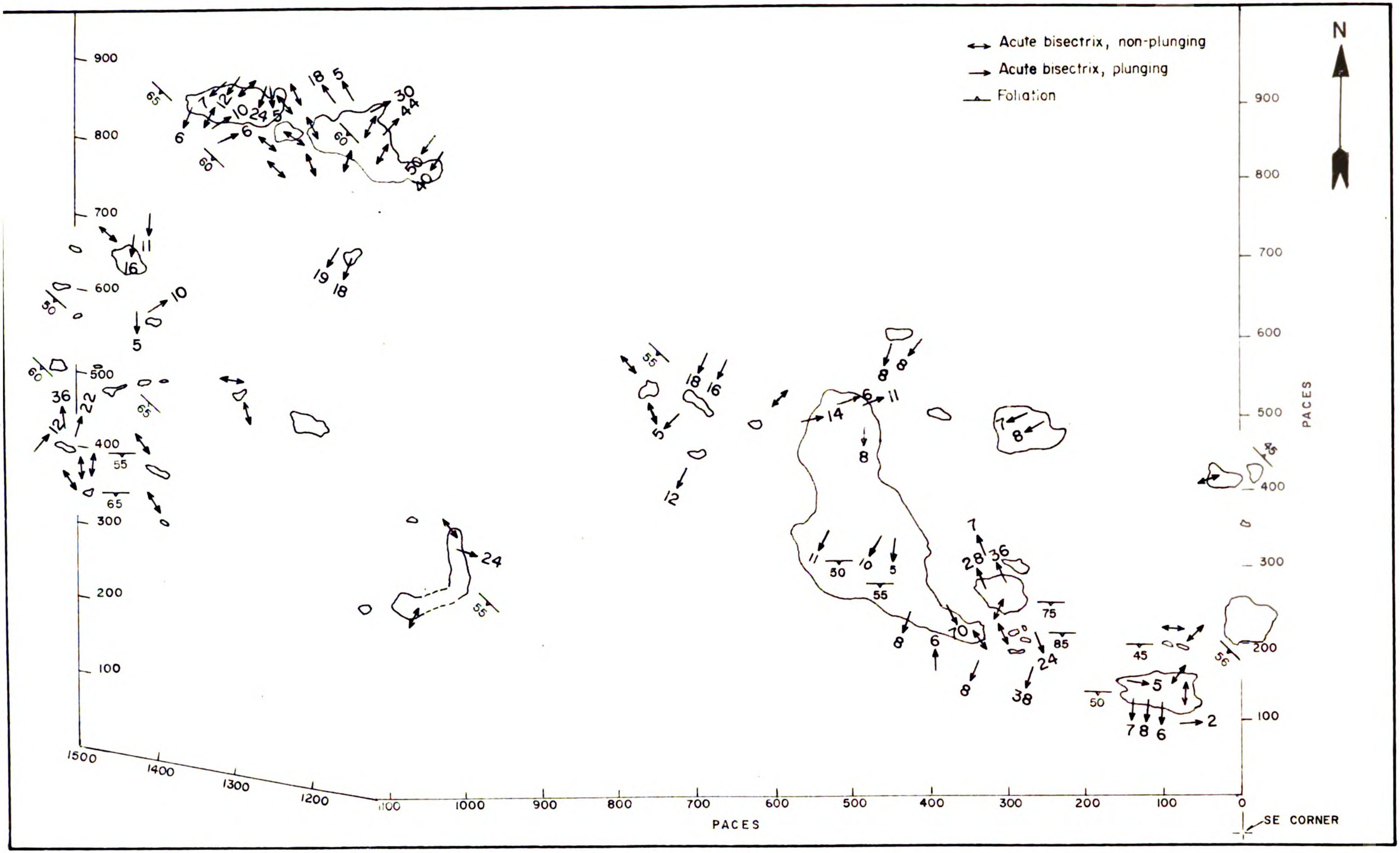

FIGURE 32. ACUTE BISECTRICES OF ASSUMED CONJUGATE JOINT SYSTEMS

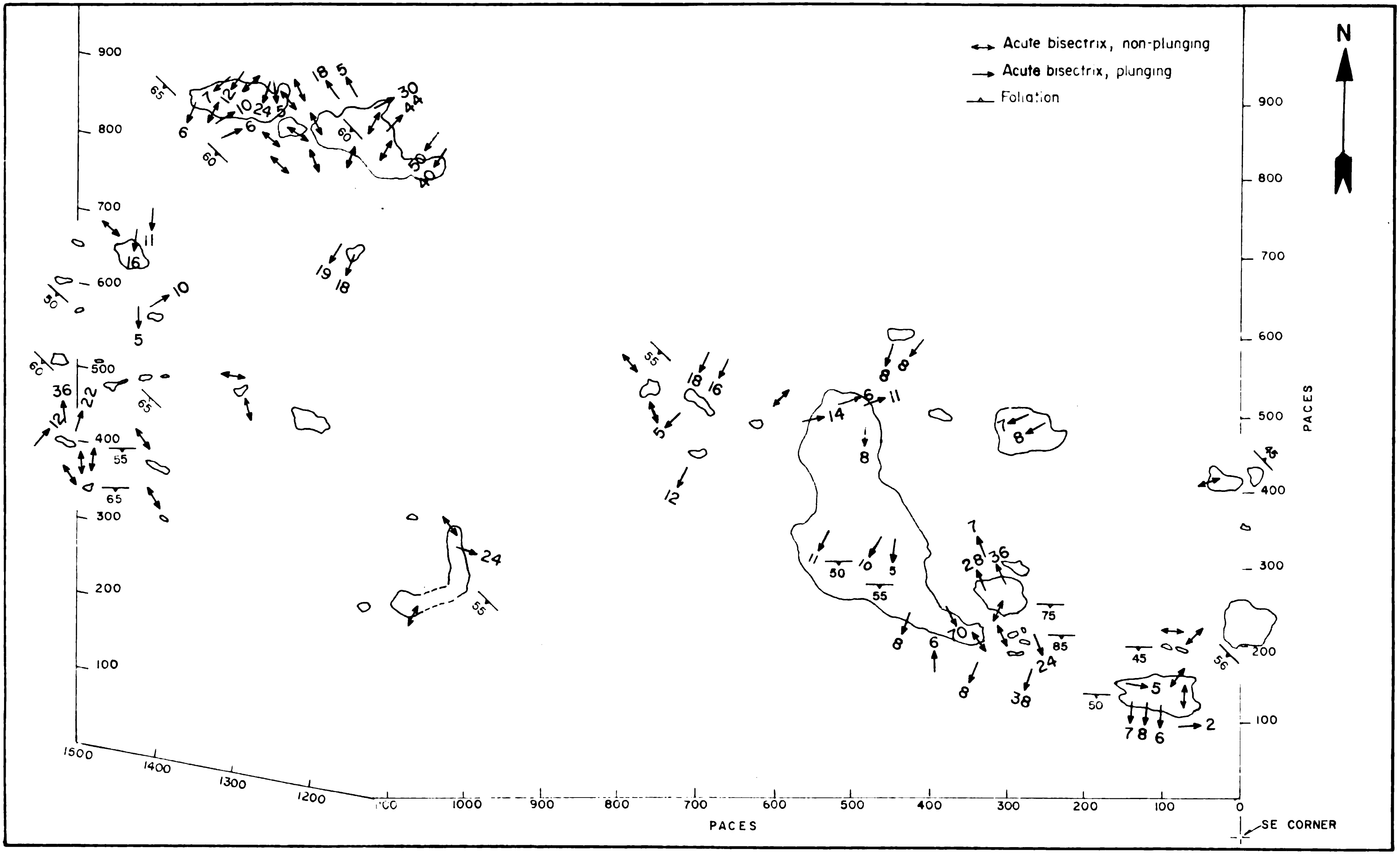

FIGURE 32. ACUTE BISECTRICES OF ASSUMED CONJUGATE JOINT SYSTEMS

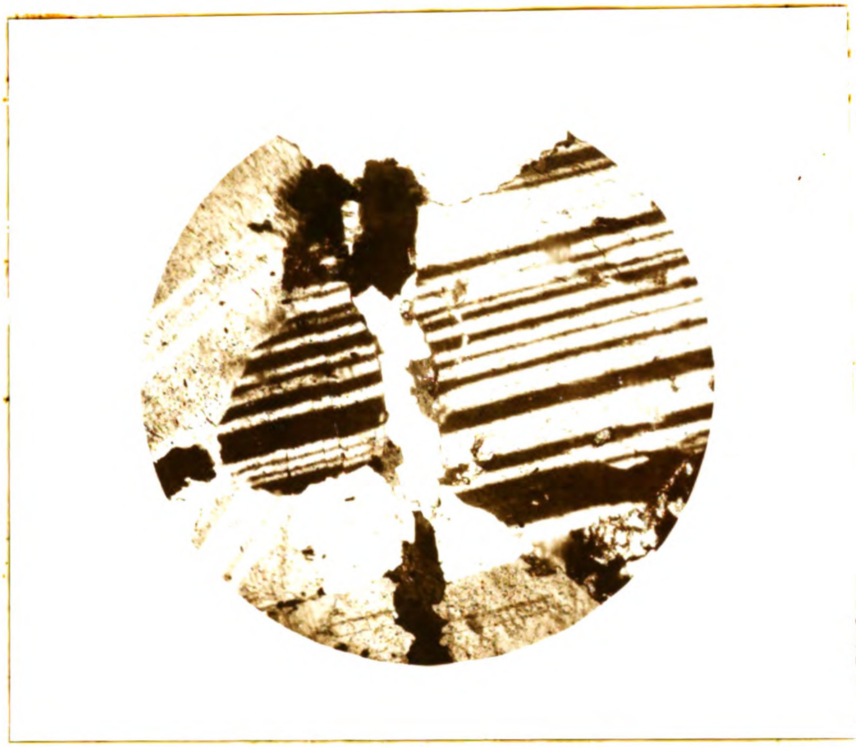

Figure 33. Photomicrograph showing fracture and displacement of twinning lamellae. Quartz crystallization in fracture zone (sample 14). Crossed nicols, x54 diameters.

Figure 34. Photomicrograph showing displacement of twinning lamellae through stress differentials (sample 14). Crossed nicols, x54 diameters.

CONCLUSIONS

A resume of the field and laboratory data pertinent to a broader understanding of the geologic agents at work in Section 36, led the writer to a number of assumptions which are tentative at best. Limitations in time and space have not allowed for as complete and exhaustive a study as would be desired. However, within the limitations set, the writer feels free to offer a number of points which may contribute to a more complete picture of the Southern Complex.

Three major lithologic units constitute the bulk of the outcrops observed: 1) gneiss, 2) granite and 3) pegmatitic and basic intrusives, the above listed in their respective order of abundance in the field. The writer is inclined to favor the granitic sequence in the Southern Complex of Upper Michigan, as proposed by Dickey (1936), with certain reservations.

The presence of hornblende as the major constituent of the gneisses studied implies a basaltic composition for the original rock. The original basalt underwent two major and one minor periods of metamorphism. These coincided, it is suggested, with 1) early Laurentian disturbance, 2) the Algoman Revolution and 3) the Killarney Revolution. The gneiss was formed through the intrusion of the metamorphosed basalt by Algoman granite. Observed phenomena could lend themselves to an explanation of the genesis of the gneiss on the basis of metamorphic differentiation.

What is referred to as the Algoman granite is the oldest type granite present and represents the intrusive material of what has been called the Archean gneiss. The porphyritic granite is seen to intrude the gneiss and may be classed as younger. A final period of intrusion was the Killarney granite, characterized by a wide textural range, from fine-grained to pegmatitic, lack of appreciable cataclasis and absence of porphyritic texture. The distribution of the granite, displayed in cross-cutting veins, dikes and irregular masses, is extremely sporadic and random.

The third major group of rock types, composed of basic rock types, and quartz and pegmatite veins, merits only a cursory reference as it appears to be of little significance in its relationship to the granitic sequence. Suffice it to mention that those showing evidence of deformation were probably intruded prior to the Killarney Revolution.

The interpretation of the structural data points to the presence of a possible anticlinal belt, with the major fold axis trending in a general E-W to NW-SE direction, i.e., perpendicular to the greatest stress direction. However, the probability of more than one period of deformation complicates the picture and limits the assumptions that may be drawn. On the other hand, the writer is of the opinion that the role played by the stress field in the preferential alignment of the mafic minerals in the gneisses, at right angles to the proposed major stress direction, is significant.

The mineral assemblages observed can be classed in the epidote-amphibolite facies, with an approximate temperature range of from 300 to 500 degrees Centigrade. Manifestations of retrograde metamorphism may be implied from the occurences of biotite to chlorite alteration.

Observed relationships led the writer to assume the presence of hydrothermal alteration as an active participant in the geologic history of the area. A source area for the acidic emanations could be realized if the presence of a subsurface batholith were inferred. However, the occurence of intruding acidic veinlets, stringers and dikes could also be attributed to the refusion of existing lithologic units in periods of deformation, the latter possibly conducive to the necessary pressure-temperature differentials.

Of primary interest is the fact that the gneiss is the dominant lithologic unit in the area. Thus, the map of the Southern Complex and associated rocks by Dickey (1936) appears to err in ascribing the portion studied by the writer to the Paleozoic.

The predominance of the malacon-type zircons encountered in what is commonly referred to as the Archean gneiss points to a late pre-Huronian or Huronian age for the formation of the gneisses. This conclusion is based on the results of Tyler and Marsden's examination of the zircons in the Lake Superior Region.

SUGGESTIONS FOR FURTHER RESEARCH

As a result of the preliminary study undertaken by the writer, a number of problems become apparent as necessitating further investigation. The following are suggestions, thought worthy of consideration:

1. Extremely detailed mapping of a small area would be instrumental in the exact definitions of the sequence of different granitic intrusions.

2. A re-examination of the plagioclases present in light of the significance that varying twin patterns may hold in relationship to structural phenomena present.

3. The possible interpretation of sericitization and/or paragonitization patterns as due to limiting environmental conditions.

4. Examination of the prevalence of untwinned plagioclases, and their possible relationship to roof-rock regions.

5. A petrofabric study of preferred orientations of quartz axes may contribute to a more complete understanding of structural phenomena observed.

6. An intensive investigation of joint patterns, taking into consideration different periods of deformation that the area is thought to have undergone, and their effects on the joints, may be pertinent to the unraveling of conjugate joint systems.

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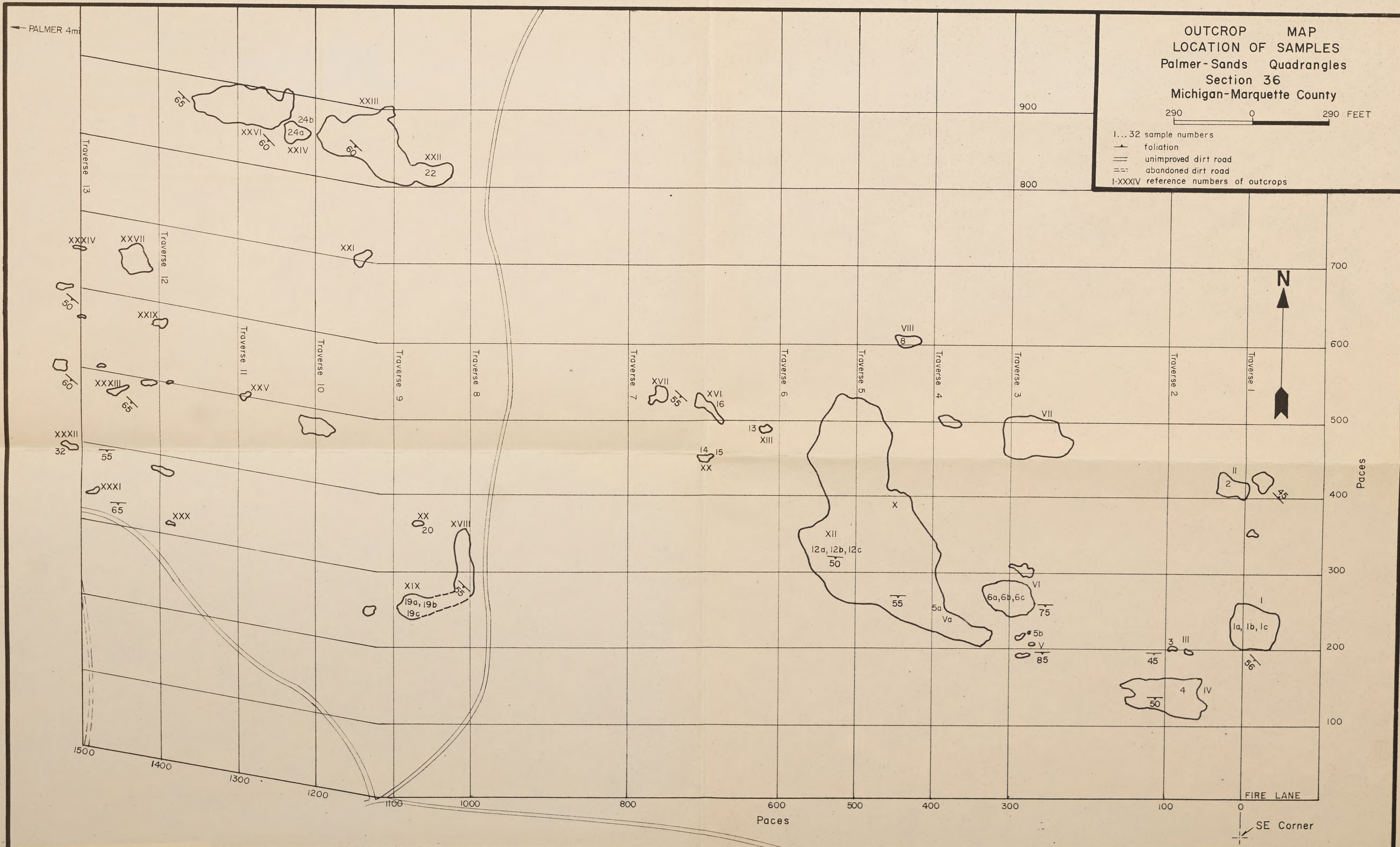
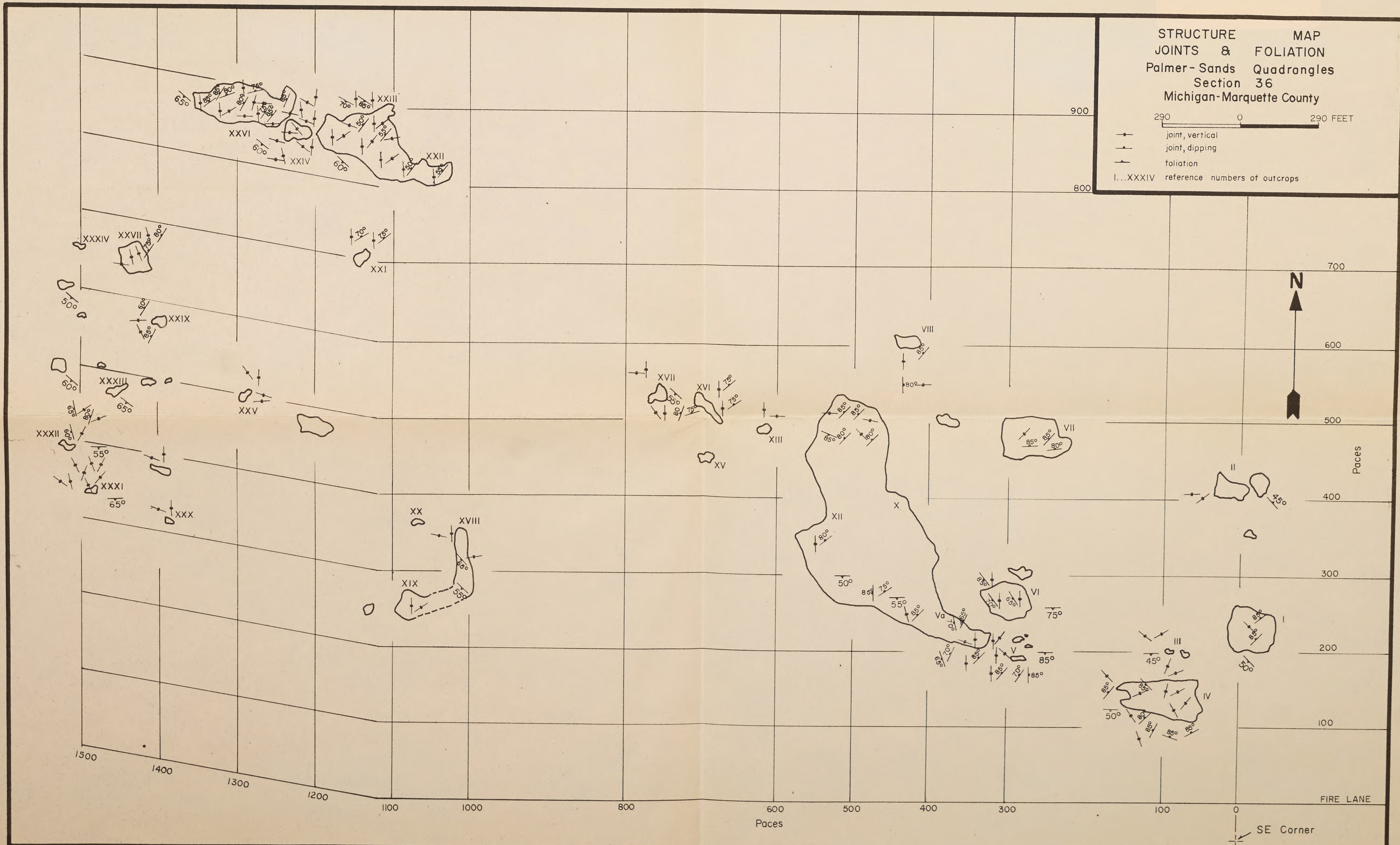


OUTCROP MAP
LOCATION OF SAMPLES
Palmer-Sands Quadrangles
Section 36
Michigan-Marquette County
290 0 290 FEET
1...32 sample numbers
foliation
unimproved dirt road
abandoned dirt road
I-XXXIV reference numbers of outcrops
PALMER 4mi
N
Paces
FIRE LANE
SE Corner


STRUCTURE MAP
JOINTS & FOLIATION
Palmer-Sands Quadrangles
Section 36
Michigan-Marquette County
290 0 290 FEET
joint, vertical
joint, dipping
foliation
I...XXXIV reference numbers of outcrops
N
Paces
FIRE LANE
SE Corner
Paces
1500
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