A PETROFABRIC STUDY OF THE
FALCON LAKE STOCK,
EASTERN MANITOBA

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ABSTRACT OF THESIS

An investigation has been carried out to determine the degree of preferred orientation shown by both plagioclase and quartz crystals in rocks from the eastern half of the Falcon Lake Stock. For the plagioclase crystals, the orientation of the (010) composition planes of albite twinning was determined. These (010) planes, parallel to the largest faces of the lath-shaped crystals, were found to show a strongly preferred orientation. This planar parallelism has been related to alignment of the crystals in primary flow layers within the stock. The flow layers in the quartz monzonite core were found to be steeply inclined, possibly as a result of re-orientation of a pre-existing plagioclase "mesh" by upward streaming of an acidic differentiate; the mechanism suggested by Brownell (1941) to explain the formation of the core. In the outer parts of the stock, there appears to be an arch of flow layers.

A close relationship has been found to exist between the orientation of the quartz c-axes and the inferred attitudes of the flow layers. In general the majority of the quartz axes are consistently contained within the plane of the flow layers and most of the axes are also horizontal. It is suggested that the quartz grains assumed their preferred orientation as they crystallized, in response to a prolongation of the forces which originally propelled the magma upwards. It would appear that their orientation was also influenced by the pre-existing framework of plagioclase crystals which had already been aligned within parallel flow layers.

ACKNOWLEDGEMENTS

The research on which this thesis is based was carried out in the Geology Department of the University of Manitoba during the 1959 - 60 semester.

Following a memorable year in the company of both staff and students of the Geology Department, I am especially indebted to Dr. G.M. Brownell for providing the opportunity for me to undertake this research, and to the University of Manitoba for a generous grant.

To Professor W.C. Brisbin, I wish to express my sincere gratitude, not only for suggesting the problem, but for his excellent supervision and advice throughout the work.

I am also under obligation to the Manitoba Mines Branch and particularly to Mr. J.F. Davies, for the use of the geological map and accompanying report on the Falcon Lake - West Hawk Lake area of eastern Manitoba.

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I. INTRODUCTION

The Falcon Lake Stock is a relatively small intrusion lying between Star Lake and Falcon Lake, about three miles west of the Manitoba - Ontario border. It outcrops over an area of approximately 2.6 square miles.

Topographically, the area is one of fairly gentle relief, and typical of much of the Pre-Cambrian Shield of Canada. Areas of glacial drift and muskeg are interspersed with rounded hills and ridges. The latter are for the most part clear of overburden, and consequently very well exposed. The central part of the stock is least exposed, but small hummocks of bare rock protruding through the overburden are adequate for an uninterrupted impression of the geology of the area. In fact, an overall picture of the terrain is one of extensive rock outcrop and this greatly facilitates a geological study of the intrusion.

The regional setting of the stock is shown in Plate 1 (p. 3). The stock is accessible by road, and the majority of it lies within a mile of the Trans-Canada Highway which runs in a northeasterly direction across the southern part of the stock. A good road linking Falcon Lake with No. 4 Highway near West Hawk Lake, follows the eastern margin of the stock, and from this road a gravel road extends as far as the old mine shafts on the Sunbeam and Kirkland claims.

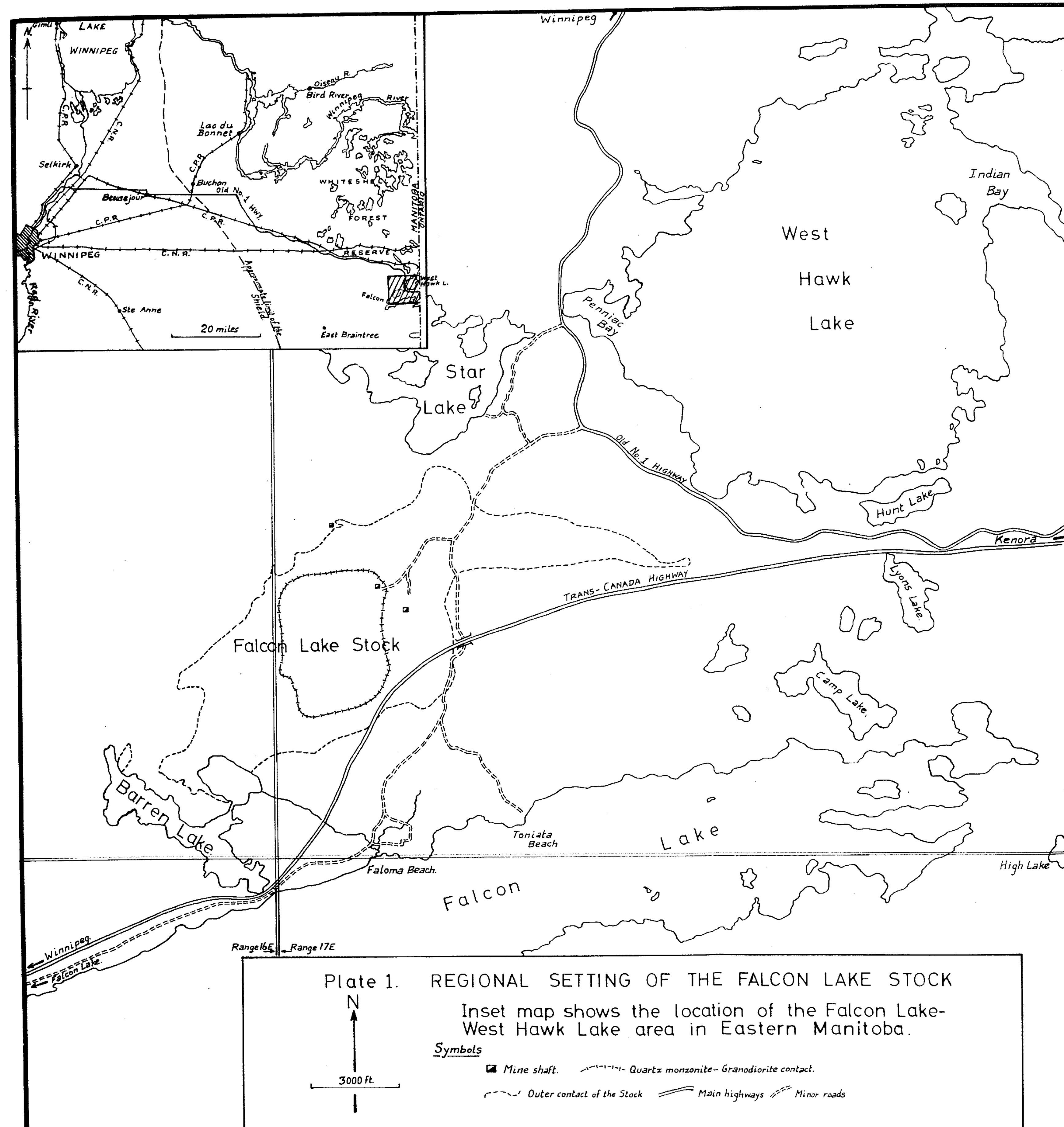


Plate 1. REGIONAL SETTING OF THE FALCON LAKE STOCK

Inset map shows the location of the Falcon Lake-West Hawk Lake area in Eastern Manitoba.

Symbols

Mine shaft. Quartz monzonite-Granodiorite contact.

Outer contact of the Stock. Main highways. Minor roads.

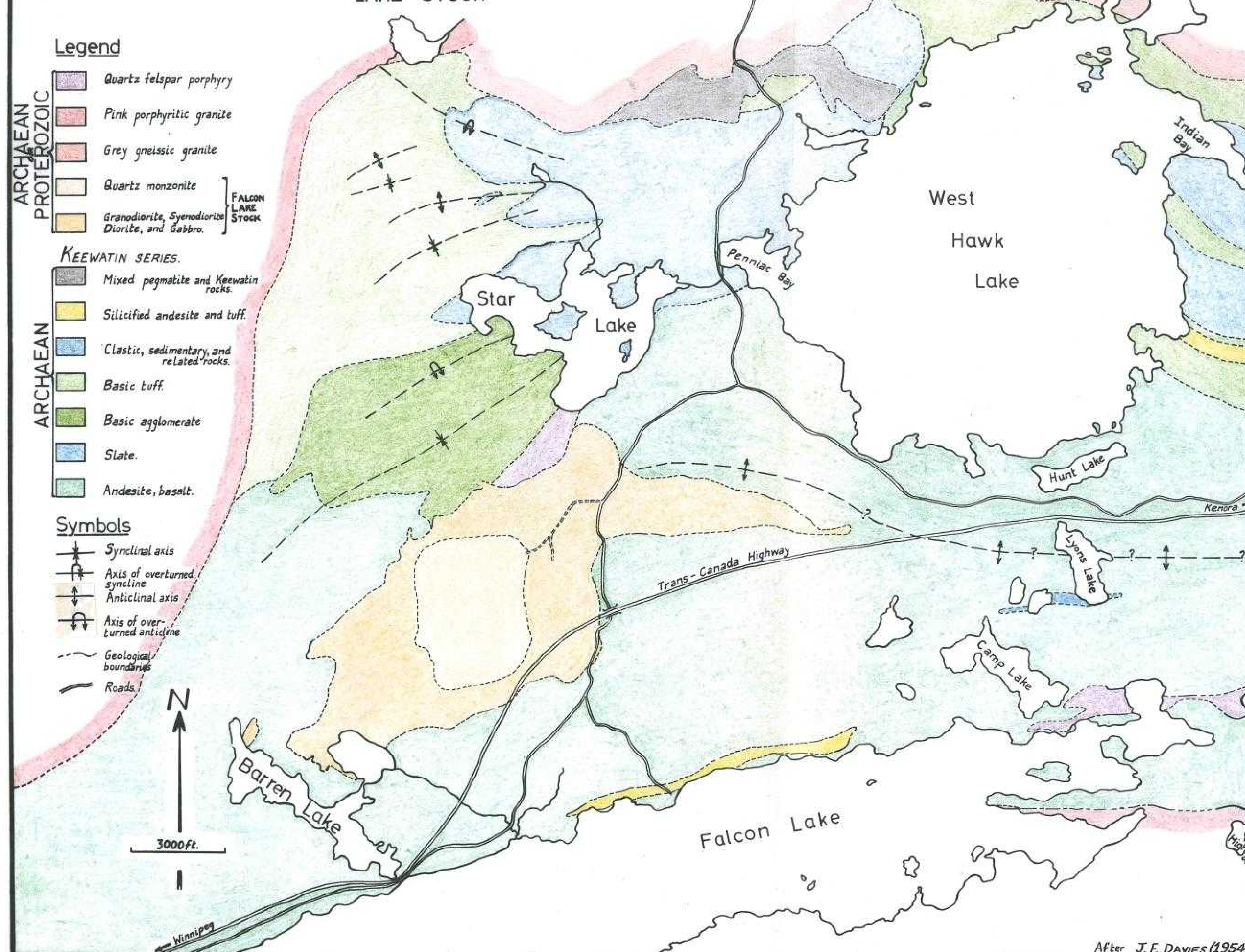
II. GEOLOGICAL SETTING OF THE STOCK

A study of the country rocks surrounding the stock was beyond the scope of this thesis, but in order to consider the regional geological setting of the intrusion, reference will be made to previous work on the area as a whole.

The stock occupies a position near the middle of a band of predominantly volcanic rocks and associated meta-sedimentary rocks, which extends eastwards into the Lake of the Woods area (Plate 2, p. 5). Where this band crosses the interprovincial boundary, it has a width of four and a half miles, but in the vicinity of the stock it narrows to a width of about two miles. Towards the southwest end of the stock, the band pinches out rather sharply between masses of granite and granite gneiss to the north and south.

Accompanying this attenuation, the general trend of folding swings from a westerly to a southwesterly direction. This is well demonstrated in a series of anticlines and synclines mapped by Davies (1954) in the group of tuffs, agglomerates and overlying meta-sediments to the north and west of Star

Plate 2. REGIONAL GEOLOGICAL SETTING OF THE FALCON LAKE STOCK



Lake. Between the Falcon Lake Stock and the large granitic mass to the north, the fold axes trend towards the southwest, but in the vicinity of Star Lake they change to a westerly direction, usually within a distance of one-half mile. At the present level of erosion, the main part of the stock outcrops over an area which is elongated in a northeast - southwest direction, parallel to the major structural trend in the adjacent country rocks.

According to Davies (1954), one of the more prominent structural elements of the area is an approximately westward trending anticline which affects the andesitic rocks outcropping between West Hawk Lake and Falcon Lake. Davies' map (1954) indicates that near the southwestern corner of West Hawk Lake, the axis of this fold adopts a westerly direction, and in doing so, trends towards the Falcon Lake Stock.

In addition to the Falcon Lake Stock, the volcanic and meta-sedimentary rocks of the area are intruded by extensive masses of grey gneissic granite to the north and pink porphyritic granite to the south and west. Two small intrusions of quartz-felspar porphyry, one at the northeast end of Falcon Lake and the other to the south of Star Lake, are also injected into the volcanic rocks. Any petrogenetic or age relationship between the Falcon Lake Stock and the other intrusions of the area remains, as yet, a matter for speculation.

The work of Davies (1954) presents the most recent and comprehensive survey of the geology and mineral deposits of the area to date, and as a result of this work a detailed geological map on a scale of 1,000 feet to the inch was published by the Manitoba Mines Branch. This map has proved to be very useful in the compilation of this thesis.

Working in association with Davies, samples were collected from the Falcon Lake Stock by R.D. House (1955). In his subsequent laboratory study, House investigated the distribution of radioactivity in the stock.

Apart from the work of Davies and House, a detailed petrological study of the Falcon Lake Stock was done by Brownell (1941). Brownell's work will be referred to in the following section.

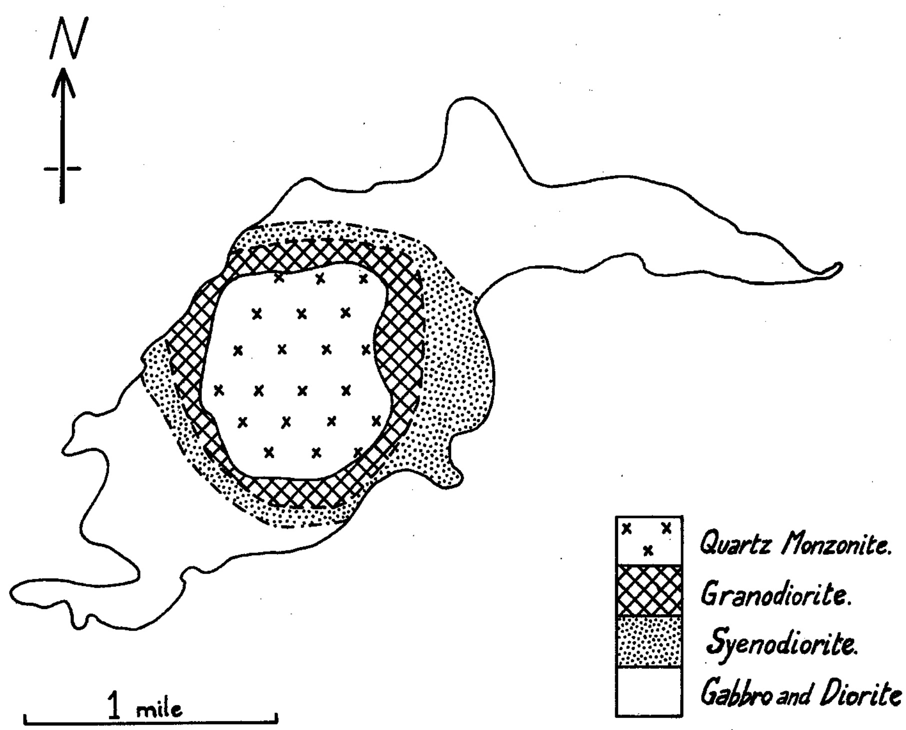
IV. GEOLOGY OF THE FALCON LAKE STOCK

The Falcon Lake Stock is a composite intrusion made up of three fairly distinct units ranging in composition from gabbro to quartz monzonite. The stock was first shown to have a composite nature by Brownell (1941), whose petrological study led to the present sub-division of an outer rim of gabbro and diorite, an intermediate zone of granodiorite and syenodiorite, and a central core of quartz monzonite (Plate 3, p. 11).

According to Brownell (1941), gabbroic rocks are not abundant in the outer rim, but are restricted to parts of the extreme outer edge of the intrusion and to the northern half of the eastward extending arm of the stock. A small amount of gabbro completely enclosed by diorite was also noted by Brownell. Samples of gabbro collected by Brownell contained up to 80% labradorite, varying amounts of hornblende and a little biotite.

In many places, diorite and not gabbro extends to the edge of the intrusion. In fact most of this outer zone is dioritic in composition. The diorite is also a dark rock comprising about 70%

Plate 3.



Map showing the distribution of the principal rock types in the Falcon Lake Stock

(After BROWNELL 1941)

andesine and approximately equal amounts of hornblende and biotite. In some of the diorite samples collected by Brownell, particularly on the northwestern side of the stock, quartz was present in sufficient quantities for the rock to be classified as a quartz diorite.

The intermediate zone of granodiorite and syenodiorite forms a continuous band which completely encircles the central monzonite core of the stock (Plate 3). To the north and south of the core, the granodiorite-syenodiorite grades outward into diorite, but to the east and west this zone extends as far as the outer contact of the stock.

The syenodiorite lies in a transitional zone between granodiorite and diorite, and according to Brownell (1941), differs from the former in that it contains less than 5% quartz. Both the syenodiorite and the granodiorite have similar felspar composition. Microcline (or microperthite) constitutes up to one-third of the total felspar, and plagioclase, mostly in the andesine range, makes up the remainder. In both rock types the plagioclase is frequently enclosed by the later microline, with quartz grains arranged along the intergranular boundaries. The earlier plagioclase may also be considerably corroded. In addition to the felspar and quartz, both the syenodiorite and the granodiorite may contain up to 10% hornblende and a similar amount of biotite.

Many petrologists consider the term "syenodiorite" to be synonymous with monzonite, and use it accordingly. Under this system, only the syenodiorites recorded by Brownell (1941) from the eastern part of the stock would then have the requisite mineral composition of a true monzonite. It would be necessary to re-name the other syenodiorites as quartz diorites. However, opinion is divided on this issue, as with many others concerning rock classification and terminology. To other schools of thought, the term syenodiorite refers to a rock with a felspar composition like that of granodiorite, but containing less than 5% quartz, and in this sense, the term is applied to the Falcon Lake Stock.

The granodiorite-quartz monzonite contact is not always sharply defined, but may be gradational from one rock type to the other. In places however, particularly a few hundred feet southeast of the northernmost of the two abandoned gold mines, the contact is very distinct, and numerous xenoliths of granodioritic material are enclosed in the quartz monzonite.

The central core of the stock outcrops over an area which is approximately rectangular in shape, measuring three quarters of a mile in an easterly direction, and a mile from north to south. It is composed throughout of quartz monzonite which tends to be finer grained and lighter in colour than the rocks of the outer part of the stock. A faint buff tinge is also characteristic.

The rock was first termed a quartz monzonite by Brownell (1941), who estimated the mode of this rock in several thin sections. The plagioclase consistently lies within the oligoclase range (Ab70 to Ab80) and the alkali felspar is microcline; both felspars usually amount to less than 50% of the rock. For the majority of the sections studied by Brownell, the oligoclase and microcline occur in equal abundance, but in several cases oligoclase is the dominant constituent. The quartz content appears to be high, varying from 10% to 20% of the rock, and the remaining constituents are hornblende and/or biotite.

The microcline encloses and replaces the oligoclase and must therefore have crystallized later than the oligoclase. Locally the microcline forms crystals which are sufficiently large to give the rock a somewhat porphyritic texture.

The type monzonite, first described by Brögger from the Monzoni Complex in the Tyrol, contains approximately equal amounts of orthoclase and oligoclase-andesine, with 2.5% free quartz. Both types of felspar amount to at least one-third of the total felspar content of the rock, and from Brownell's work, this is also the case with the monzonite of the Falcon Lake Stock. However, for rocks of this composition, but containing more than 10% free quartz, (that is, with quartz an essential constituent rather than an accessory mineral) the term "adamellite" is favoured by the present writer.

The fact that the intermediate zone of the stock completely surrounds the inner core, was interpreted by Brownell (1941) as convincing evidence that this zone was formed as a result of interaction between acidic material from the central core and the earlier formed diorite-gabbro. A further important point observed by Brownell is the definite increase in the soda content of the plagioclase passing from the outer diorite to the quartz monzonite of the core. The plagioclase in the gabbro has the composition of labradorite (Ab_{46} An_{54}). Towards the core, the Ab content of the plagioclase molecule gradually increases until in the core itself, the plagioclase lies in the oligoclase range. Greater acidity of the rocks towards the centre of the stock is also marked by a progressive increase in the proportion of microcline and quartz present in the rocks.

The concentric zoning observed in the stock must obviously be related in some way to the formation of the intrusion. The mineral composition of the rock types also suggests that they have a close genetic relationship. Brownell (1941) suggested that a magma of basic to intermediate composition was injected first; from this magma, a basic fraction separated giving rise to the gabbro around parts of the outer margin of the stock. With the removal of the gabbroic fraction, the magma became less basic in composition, and it is thought that a large part solidified. Davies (1954) does not expand his theory further, but in order to account for the present day distribution of the different rock types in the Falcon Lake Stock, the crystallization differentiation would have to be accompanied by lateral movement of material while crystallization of the magma was taking place. It would seem that either convection currents or some form of filter press action, coupled perhaps with auto-intrusion of the acidic end product of the magma, are the only possible mechanisms available to account for this lateral movement. In either case, the process of differentiation would be quite complex. The corrosion of the plagioclase and the partial replacement by microcline are difficult to explain by this theory.

Shear Zones and Faulting

Numerous shear zones and faults have been recorded both in the area around the stock and also within the stock itself. Most of the shear zones extend for a short distance and are quite narrow. Even where they are mineralized the deposits are of little economic importance.

According to Davies (1954), the gold

deposits within the stock do not appear to be controlled by any well-defined structural element. They occur in irregular zones of silicified rock which do not follow any definite vein pattern. It is interesting to note, however, that practically all of these deposits occur in very close proximity to the quartz monzonite - granodiorite contact and on both sides of it.

Shafts were sunk on two deposits in the stock, one on the Sunbeam claim and the other a quarter of a mile to the southeast on the Waverley claim. Little information has been published on the exact form and size of the latter deposit. The deposit on the Sunbeam claim is described by Brownell (1941) as a pipe-like body, the axis of which plunges at 55 - 65 degrees in a direction N. 30 degrees W. The ore body follows the quartz monzonite - granodiorite contact. It is cut by several faults, all of which strike in a northeasterly direction. Apparent displacements along the fault planes vary from a few inches to ten feet except in the case of a fairly large fault between the third and fourth levels of the mine on which the total displacement amounts to sixty-five feet.

Gold deposits also occur in a series of shear zones a few hundred feet northwest of the stock. The strike of these shear zones is parallel to the outer contact of the stock. It seems reasonable to assume that these deposits belong to the same period of mineralization as those within the stock itself in which case, they must also post-date the intrusion.

It is interesting to note that practically all the shear zones and faults in the region have either an easterly or a northeasterly strike, and in that respect lie parallel to the axes of the folds described in an earlier section.

V. SCOPE OF PRESENT WORK

Apart from observations on the structures related to the gold deposits within the Falcon Lake Stock, no detailed study has yet been undertaken of the internal structure of the intrusion. Foliation, either of a primary nature, or as a result of later deformation, has not been recorded in any part of the stock outside the mineralized zones. Consequently, it was thought that a microscopic study of the rock fabric, with the use of petrofabric analyses, might reveal orientation of component minerals which could be related to the mode of emplacement of the stock.

The study was carried out on the eastern half of the stock, and the results and conclusions drawn from this work are presented in later sections.

VI. FIELD WORK

The Falcon Lake Stock was visited on two occasions by the writer, in October and in November of 1959. The express purpose of the visits was to collect sufficient rock samples for the ensuing laboratory study. In collecting the samples, Davies' map (1954) of the area proved to be of invaluable assistance in delimiting the extent of the main rock types of the stock. The exact location of the specimens collected, based on Davies' map (1954) is shown in Plate 4, (p. 24).

Samples were collected at discreet intervals along selected traverse lines. A large proportion of the samples was collected near the margin of the core and from locations alongside the outer contact of the stock, specifically to study mineral orientations at both these contacts. An attempt was also made to gather representative rock types from the different parts of the stock. No samples were collected in the vicinity of any recognizable mineralized zones. The effects of shearing in and around such zones would tend to obscure or obliterate the

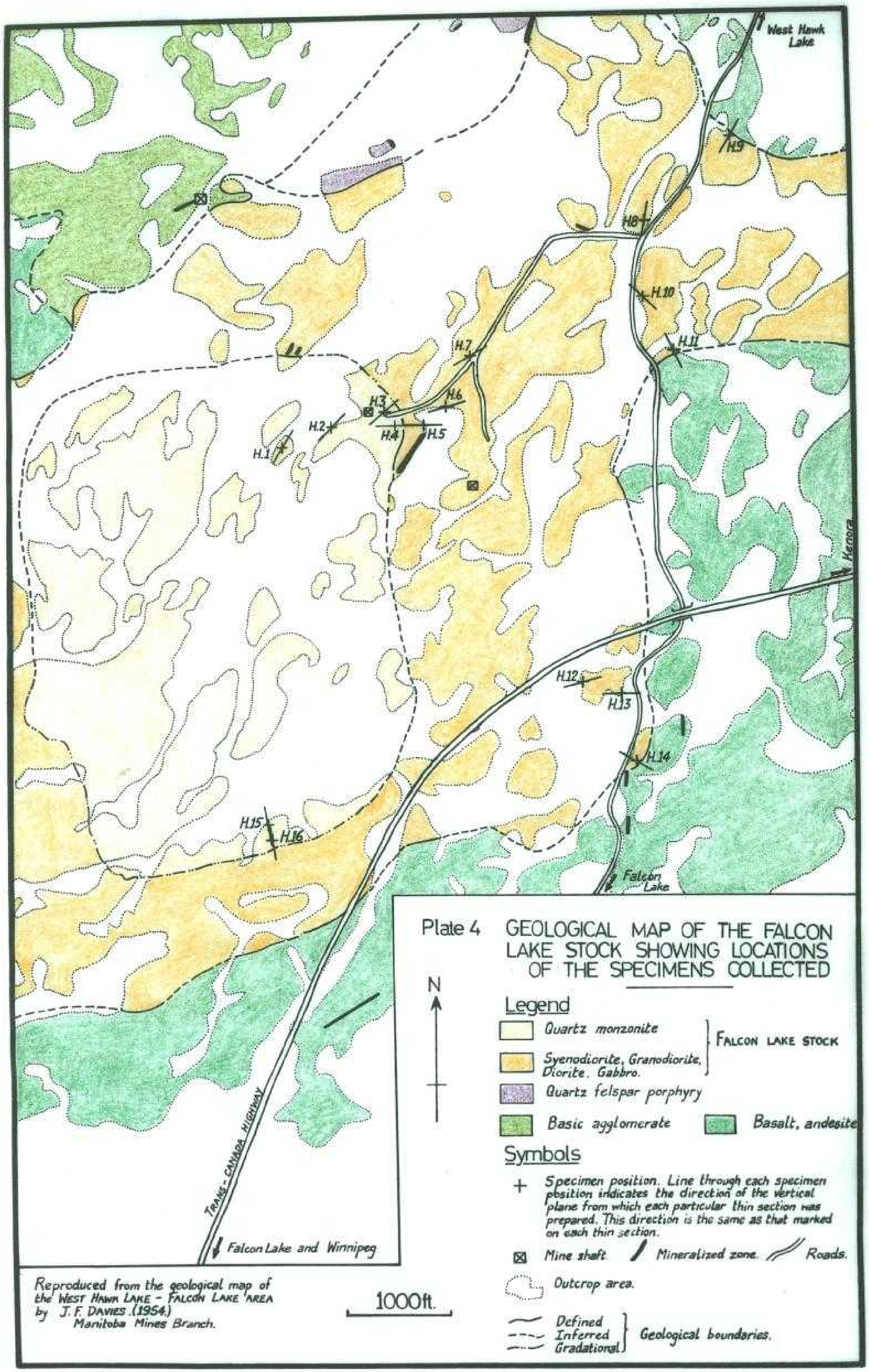


Plate 4 GEOLOGICAL MAP OF THE FALCON LAKE STOCK SHOWING LOCATIONS OF THE SPECIMENS COLLECTED

original internal constitution of the rock.

Accurate orientation of the specimens in the field was essential in order to maintain the necessary degree of accuracy, and a Brunton compass, corrected for magnetic declination, was used. The orientation of all but two of the specimens was recorded by marking two horizontal lines, approximately at right angles to each other on each specimen. The azimuth of one of these lines, shown by an arrowhead, was recorded. To complete the orientation, the upper surface of the specimen was indicated. For the other two specimens, where this method of orientation was impossible, two arrows representing dip and strike, were marked on each of them.

VII. PREPARATION OF THIN SECTIONS

A preliminary macroscopic examination of all rock specimens collected from the stock revealed no apparent anisotropy of the rock fabric. For example, none of the rocks showed any form of banding, and there was no obvious preferred orientation of the component mineral grains. In less homogeneous igneous bodies, primary flow layers are probably the most commonly developed structures present. Ideally, such flow layers strike parallel to the outer margin of the particular intrusion; the traces of adjacent flow layers on the outcrop surface are mutually parallel. (A full description of these structures and their relation to the present work is given in Section IX. See also Plate 6).

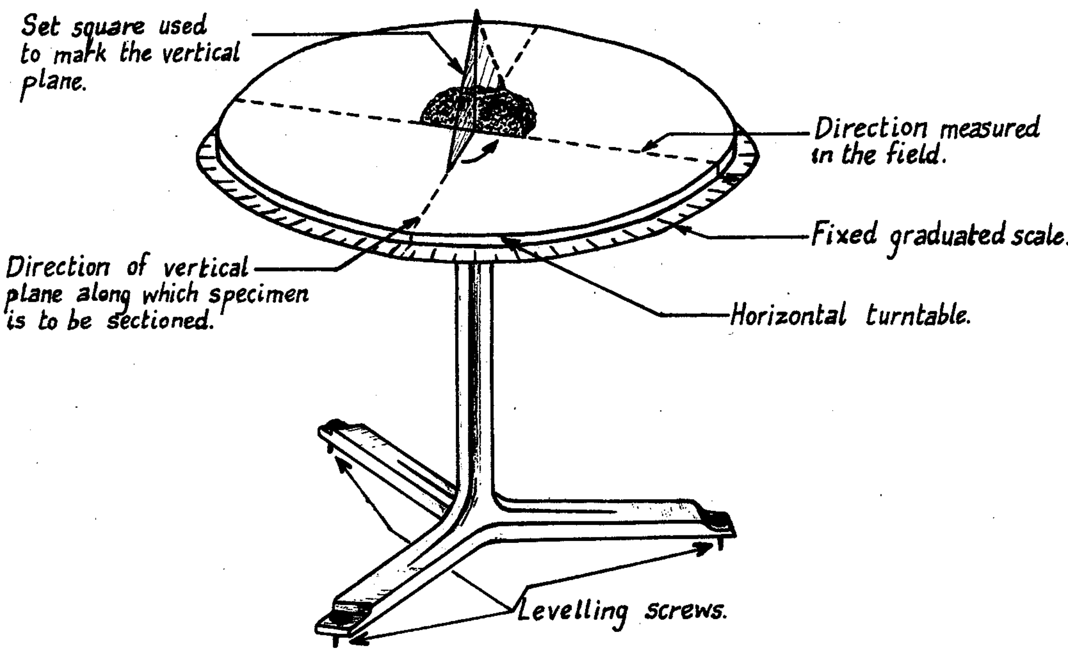
Most of the thin sections used in this study were cut in a vertical plane at right angles to either the quartz monzonite - granodiorite contact, or the outer margin of the stock depending on which of the two contacts was nearer to the particular specimen location. It was reasoned that if a flow foliation were in fact present, the sections would then be cut perpendicular to this foliation, and the orientation of the fabric would be easily determined. Accordingly the azimuth of the appropriate vertical plane at each specimen location was determined from Davies' map (1954) of the area.

In order to prepare the oriented thin sections, the specimens were first cut along a horizontal plane by following the horizontal lines marked in the field (p. 25). (Those specimens marked with dip and strike lines were initially re-oriented in space with the aid of various non-magnetic clamps and a Brunton compass, and the necessary horizontal lines then inscribed on them). The upper half of each specimen was then placed with the horizontal plane on a horizontal circular turntable graduated in degrees around the circumference (Fig. (i), Plate 5). The side of the specimen containing the direction measured in the field was correctly oriented relative to the graduated circle. With the specimen in this position, the proposed vertical plane of the thin section was then outlined on the specimen with the aid of a set square and a straight edge, again making use of the graduated scale for the correct orientation of the plane. Finally, a slice of rock was cut from the specimen parallel to the outlined plane, and the thin section prepared from it.

In order to record the orientation of each thin section, an arrow was scratched on the glass mount exactly parallel to the edge of the mount to give the accurate azimuth direction. The upper side of the thin section was also recorded directly on the section. A fully marked thin section with its orientation fixed completely and accurately is depicted in Plate 5, Fig. (ii). Care was maintained throughout these operations to ensure correct orientation of the thin section relative to the parent specimen, and to prevent any inversion of the rock slice.

For specimens H.15 and H.16, thin sections were made from horizontal rock slices cut parallel to the horizontal plane through the specimen. The turntable with the graduated scale was used to mark the correct azimuth for each specimen. In both sections the cover-slip side of the section was the upper side.

Plate 5.



Fig(i). Apparatus used for marking specimens in readiness for sectioning

Fig.(ii). A fully oriented thin section.

VIII. MICROSCOPE TECHNIQUE AND PREPARATION OF PETRO-FABRIC DIAGRAMS

The rock specimens collected for this study included representatives of all the rock types identified by Brownell (1941) within the stock. (Compare Plates 3 and 4). The thin sections from all the specimens contained a high proportion of plagioclase felspar, and quartz grains were found to be abundant in all except three of the sections. Consequently it was possible to conduct a reliable statistical analysis of the degree of preferred orientation shown by both the quartz and plagioclase felspar grains in most of the sections.

Quartz

There are countless recorded instances of the apparent susceptibility of quartz crystals to assume a preferred orientation when subjected to an imposed stress field. If the quartz grains within the Falcon Lake Stock crystallized under conditions of stress it is possible therefore that they might also show some degree of preferred orientation. Furthermore, there might be some link between this preferred orientation, if present, and the mechanism of intrusion of the stock.

A four-axis Leitz Universal Stage, mounted on a Leitz research microscope, was used in the study of all thin sections. For those sections containing at least one hundred quartz grains, the orientation of the crystallographic c-axes of all the quartz grains present was determined. Only 66 quartz grains were present in the thin section for specimen H.10, but a petrofabric analysis of this specimen is also included. The respective position in space of each optical direction was plotted on an equal-area projection with the aid of a Schmidt net. By then "counting out" the projection of the quartz axes and drawing density contours through points of equal density distribution, a non-selective quartz fabric diagram for each thin section was produced.

It may be noted here that the field of view seen through a petrological microscope, is transposed relative to the thin section under observation. Consequently, each diagram had to be rotated through 180 degrees about its centre to orient it correctly, relative to the azimuth marked on the thin section.

When first plotted, the orientation

diagrams for those thin sections cut in a vertical plane, (i.e. all except H.15 and H.16) represented the projection of the quartz axes on a vertical plane. In other words, the plane of the projection corresponded to the plane of the thin section. However, in order to facilitate subsequent descriptions and comparisons of the diagrams, it was decided to consider a projection of the quartz axes from all the thin sections on a horizontal plane. This was achieved by rotating the diagrams of the vertical projections through 90 degrees about a horizontal axis. In all diagrams, the axis of rotation corresponded to the north-south equator. It was essential to exercise care when rotating the diagrams to avoid any inversion of the diagrams relative to the thin section. When the operation was completed, each of the new diagrams represented the projection of the lower hemisphere of the sphere of reference.

Plagioclase Felspar

In many igneous bodies, lath-shaped felspar crystals have been found to exhibit a parallel arrangement of both their longest axes and their largest crystal faces, producing either primary flow lines or flow layers within the particular intrusion. Once these primary flow structures have been detected, they can then be directly related to the movement pattern of the magma during the emplacement process of the intrusion. (A full discussion of the relationship between felspar orientation and primary flow structures is given in Section IX, p. 36).

A statistical analysis of the degree of preferred orientation shown by the plagioclase crystals was therefore carried out in thin sections taken from a representative selection of the specimens collected. Almost without exception, the plagioclase crystals exhibited multiple lamellar twinning and the orientation of the composition plane of this twinning in each crystal was determined using the Universal Stage. The pole to the composition plane was then plotted on an equal area projection, using a Schmidt net, and the diagram "counted out" and contoured in the usual manner. The number of plagioclase crystals present in each thin section varied between forty and seventy grains, with fifty-five an average number.

The orientation of composition planes parallel to the plane of the thin section or inclined to it at angles of up to 30 degrees cannot be determined with a Universal Stage. In all the thin sections used in this study however, the composition plane orientation in no more than one or two plagioclase crystals in each section, was indeterminable. The poles to such composition planes, sub-parallel to the plane of the thin section, would be plotted near the centre of the projection; from an examination of the composition plane orientation diagrams (Plates 7, 8 and 9) it will be seen that even if such planes could be measured and their poles plotted, the effect of so few points on the basic overall orientation pattern would be negligible.

All projections of the poles to composition planes were made on a vertical plane corresponding to the plane of the respective thin sections, again using the lower hemisphere of the sphere of reference. No subsequent rotation of the resulting diagrams was necessary.

Complex twins were observed in some of the plagioclase crystals, the majority involving a combination of albite and Carlsbad twinning. Twinning on the Pericline Law was also combined with albite twinning in some crystals. When such complex twins were observed, the orientation of the multiple twin lamellae parallel to the longest visible crystal dimension was the sole direction measured. Lath-shaped plagioclase crystals of the type observed in these thin sections are usually elongated parallel to the crystallographic c-axis and the (010) crystal face is usually strongly developed. Practically all the plagioclase crystals observed were also elongated parallel to the multiple twin lamellae. It seems probable therefore, that the composition planes consistently measured in this investigation were all (010) planes, that is, composition planes of twinning on the albite Law.

With only two dimensions of each plagioclase crystal dominantly visible in the thin sections, the linear trace of each twin lamellae cannot be directly equated to the longest axis of the crystal. However, if a particular type of twin lamellae in a large number of crystals shows some degree of preferred orientation (or parallelism) in a planar sense, then this orientation can be directly related to a platy parallelism of the crystals as a whole.

IX. DISCUSSION OF THE PLAGIOCLASE ORIENTATION IN THE FALCON LAKE STOCK

(i) General outline of plagioclase felspar orientation in igneous intrusions

Crystallization of an intrusive mass of magma may take place while the magma is moving into the overlying crustal regions, and expanding to occupy its final position. Plagioclase is one of the first minerals to crystallize, and at an early stage in the crystallization of the magma, the crystals may be expected to have a euhedral and tabular form. The crystals may also be elongated, usually parallel to the crystallographic c-axis.

In the moving magma body, the differential movement of flow layers produces shear couples which act on the suspended tabular plagioclase crystals. The shear couples tend to rotate the crystals until the largest flat surfaces of the crystals commonly the (010) faces, are lying within the parallel flow layers. When the crystals are in this parallel position, the shear couples have their minimum effect on the crystals and the crystals are therefore in their most stable position.

If on the other hand, crystals in the moving magma body are highly elongated and even needle-shaped, differential movement in the magma along flow lines will produce a linear parallelism of the longest axes of the crystals. Such linear flow structure has been described for example in the Snowbank Stock, Minnesota, (Balk and Grout, 1934) where long prismatic hornblende crystals show a high degree of preferred orientation.

Plagioclase crystals may be only slightly elongated with the result that they seldom show a good linear parallelism. A platy parallelism however is commonly shown by tabular plagioclase crystals, oriented so that they lie within primary flow layers. If the crystals are concentrated together, they will produce a foliation or schlieren structure in the consolidated rock.

Up to the present day, practically all examples of such a platy parallelism have been described from intrusions in which the felspar forms well-developed phenocrysts. Particular instances of this are seen in the Duluth gabbro (Grout, 1918), the Adirondack anorthosite (Balk, 1931) and the

Kekequabic granite, Minnesota (Stark, 1927). In these intrusions only the megascopic character of the rocks was examined.

It seems reasonable that studies of the flow structures of intrusions can be safely extended to include a microscopic investigation of the rock fabrics when megascopic flow structures are not visible. It may be argued that such an investigation is limited to the small fraction of rock represented by one thin section, and any slight variation in the rock fabric from place to place will immediately nullify the conclusions derived from the thin section examination. However, if the sampling methods employed in statistical studies are valid in such an investigation, there seems to be no reason why a highly representative sample should not be obtained. Also, if the overall pattern established by this work agrees with previous concepts of flow structures in igneous bodies, there can be no grounds for objection to these methods being successfully employed.

For many intrusions it has been found that the flow layers and flow lines are arranged in either the form of a dome, or in the form of an arch, depending on the distribution of the flow structures throughout the whole igneous mass. If the structures extend over the complete area of the intrusion, culminating in a particular central area, then the term "dome" is applied, but if the interior of the mass is quite massive and the structures are confined to the marginal zones, then the term "arch" is used. (See Plate 6, Figs. (i) and (ii).

To explain the broad overall pattern of flow structures in an intrusion, a uniform and constant mechanism which affected the intrusion as a whole has been invoked. H. Cloos (1925) and R. Balk (1937) suggest that dome and arch structures are undoubtedly formed as a result of the upward movement of the intruding magma, directed by pressure from below. It is this upward-directed pressure which produces the differential flow in adjacent layers or lines within the magma. It has already been described (pp. 36 and 37) how the differential flow in turn brings about the parallel orientation of tabular crystals in flow layers or elongated crystals in flow lines, through the action of shear couples.

As suggested by E. Sherbon Hills (1943), it is perhaps better to regard flow layers and flow lines in large intrusions as an indication of the direction of "stretching", rather than the direction of widespread movement of the suspended crystals in stream lines, (Plate 6, Fig. (iii). Obviously a complete dome of flow lines or layers will be produced by this mechanism. In the instance where only an arch of flow structures is apparent from a megascopic study of a particular intrusion, it is probable that the upper-most part of the original dome has been removed by erosion.

Plate 6.

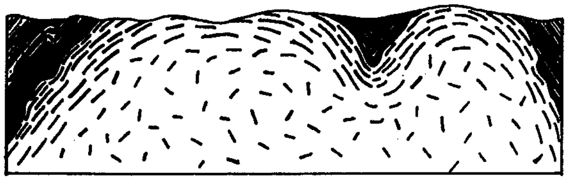
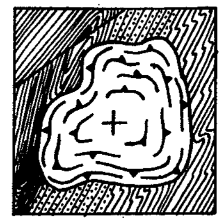


Fig.(i) Dome of flow layers.



Plan view showing strike and dip of flow layers, denoted by the lines with black triangles. The cross represents horizontal layers.

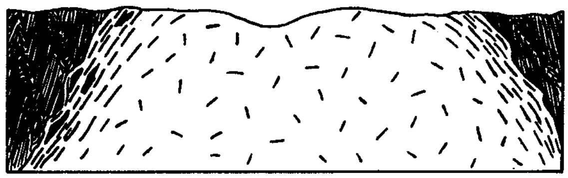
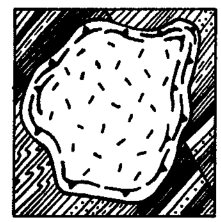


Fig.(ii) Arch of flow layers.



Plan view. Flow layers absent in the central part of the intrusion.

(Figs. (i) and (ii) are modified after BALK 1937)

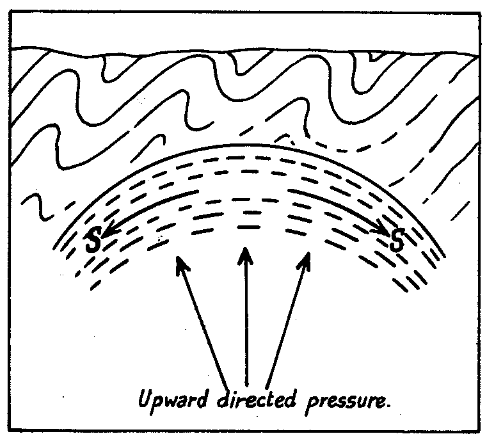


Fig.(iii) Diagrammatic section across an intruding mass of magma showing the formation of a dome of flow structures.

Suspended crystals are aligned with their longest axes parallel to the direction of stretching (S) and at right angles to the applied pressure. (After SHERBON HILLS 1943).

(ii) Description of the plagioclase orientation diagrams from the Falcon Lake Stock

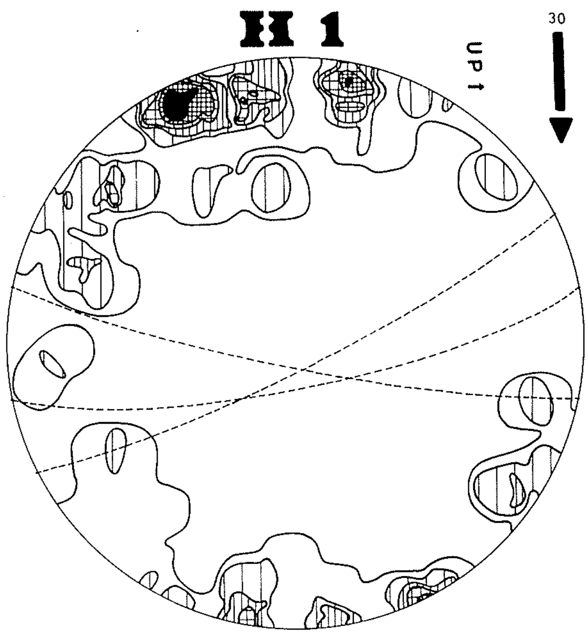
Without exception, the plagioclase crystals in all the thin sections examined, show a high degree of preferred orientation when statistically analyzed. The orientation diagrams for the plagioclase consistently show strongly developed maxima lying close to or on the periphery of the plot. There is some tendency for the development of a peripheral girdle but the point maxima nevertheless constitute the dominant element in the orientation pattern. (See Plates 7, 8 and 9, pp. 45 - 47). In only one of the diagrams, (that for specimen H.13) can any ambiguity arise in the interpretation of the orientation pattern. The remaining eight diagrams show either a single point maximum (as in H.10), or a cluster of maxima confined to a localized area of the diagram.

On each of the plagioclase orientation diagrams, one or more great circles have been drawn at an angular distance of 90 degrees from the central point of each strongly developed maximum. (Plates 7, 8 and 9). The great circles then represent the most prevalent attitude (or attitudes) in space of the albite twin lamellae in the plagioclase crystals at each specimen location. Bearing in mind that each diagram is projected on a particular vertical plane, the majority of the twin lamellae are seen to be oriented almost at right angles to the plane of the thin section and with varying inclinations to the horizontal. This implies that the largest faces of the tabular plagioclase crystals, usually parallel to the (010) composition plane of the albite twinning, are also oriented in this same manner. Planar parallelism of the crystals is therefore indicated by the microscopic study and this strongly suggests the presence of platy flow structures in the Falcon Lake Stock.

The parallel alignment of crystals of a particular mineral in flow lines or flow layers is never perfect, and all degrees of preferred orientation have been recorded. A statistical analysis does however bring to light any parallelism which may exist, and also indicates the predominant direction of crystal orientation. The cluster of maxima (rather than a single maximum) present in most of the plagioclase orientation diagrams, and the tendency towards the development of a peripheral girdle, are factors expected in work of this nature.

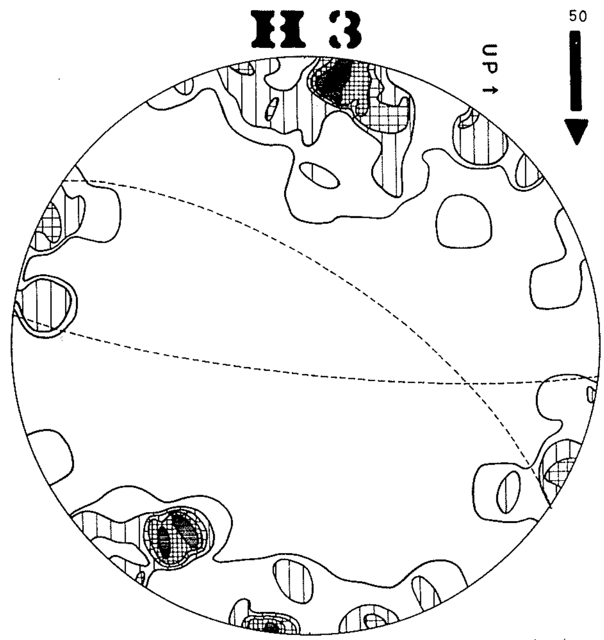
Table I (pp. 48 and 49) gives the most prevalent attitudes of the plagioclase crystals at each specimen location, which have been established from each of the orientation diagrams. The attitudes are represented by strike and dip readings on the crystal faces parallel to the (010) composition plane of the albite twinning.

Plate 7



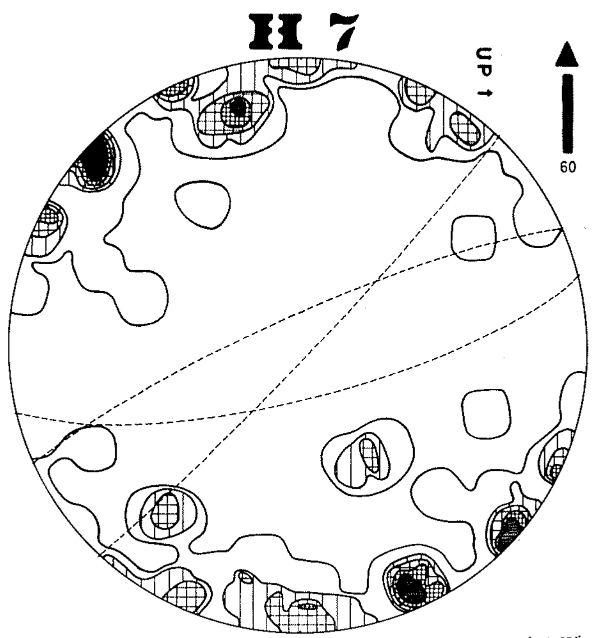
60 poles to (010) composition planes. Contours: 1.67%, 3.33%, 5%, 6.67%, 8.33%, 10% Max. 11.67%

Fig.(i)



50 poles to plagioclase (010) composition planes. Contours: 2%, 4%, 6%, 8%, 10%, 12% Max. 12%

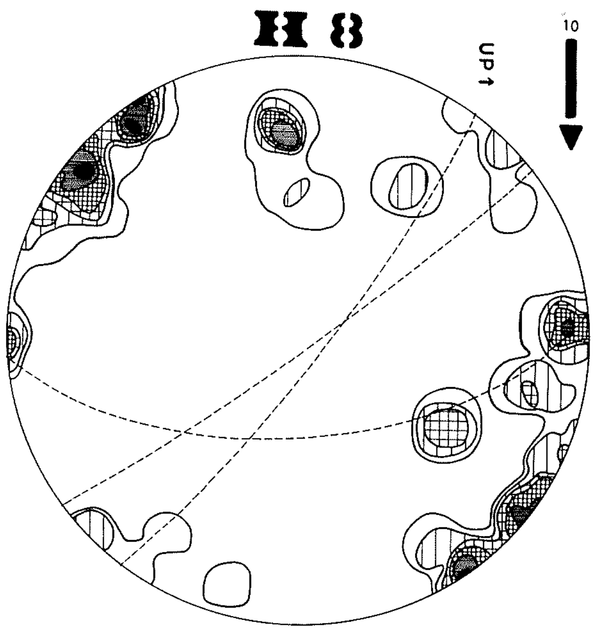
Fig.(ii)



60 poles to plagioclase (010) composition planes. Contours: 1.67%, 3.33% 5%, 6.67%, 8.33%, 10% Max. 10%

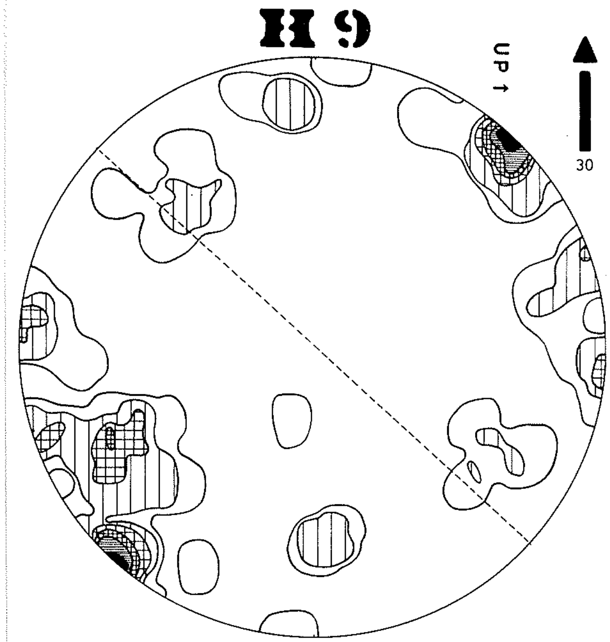
Fig.(iii)

Plate 8



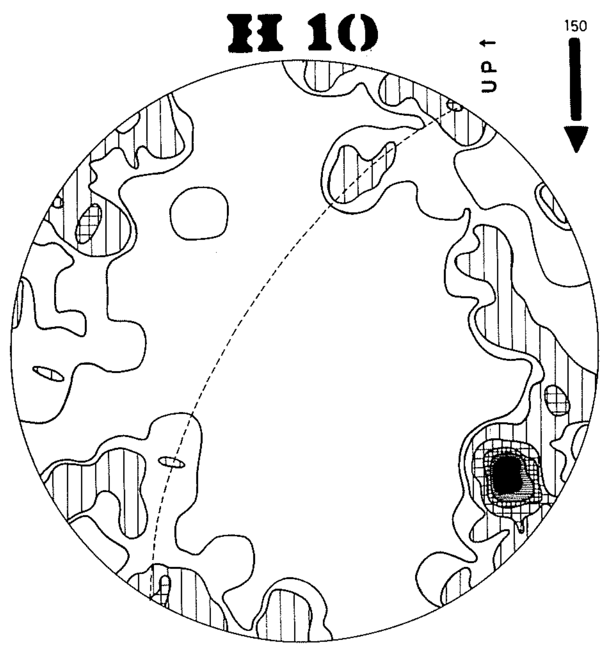
50 poles to plagioclase (010) composition planes. Contours: 2%, 4%, 6%, 8%, 10%, 12%
Max. 12%

Fig. (i)



60 poles to plagioclase (010) composition planes. Contours: 1.67%
3.33%, 6.67%, 10%, 13.33%, 16.67%
Max. 18.33%

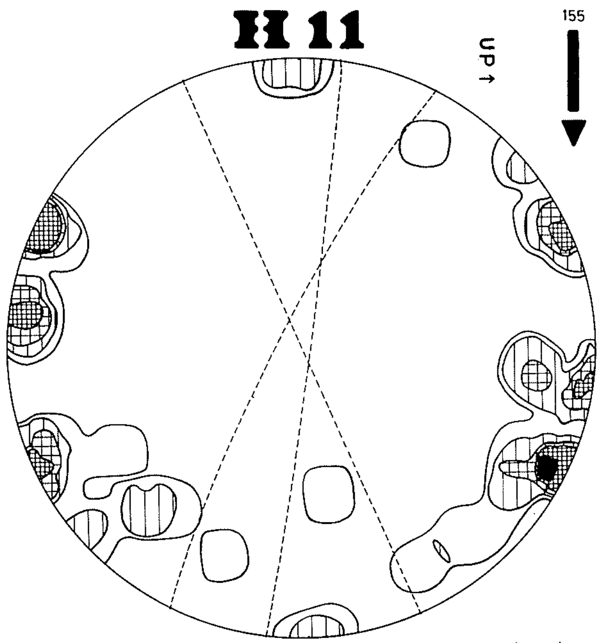
Fig(ii)



72 poles to plagioclase (010) composition planes. Contours: 4%, 8%,
5.6%, 8.4%, 11.2%, 14%
Max. 16.8%

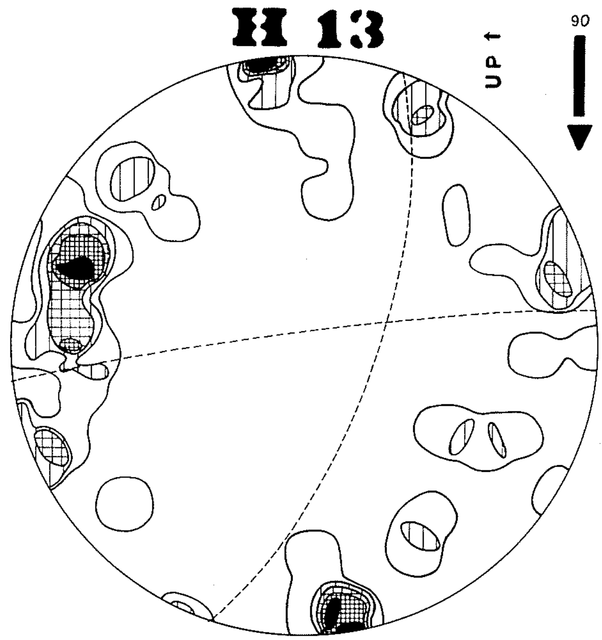
Fig. (iii)

Plate 9



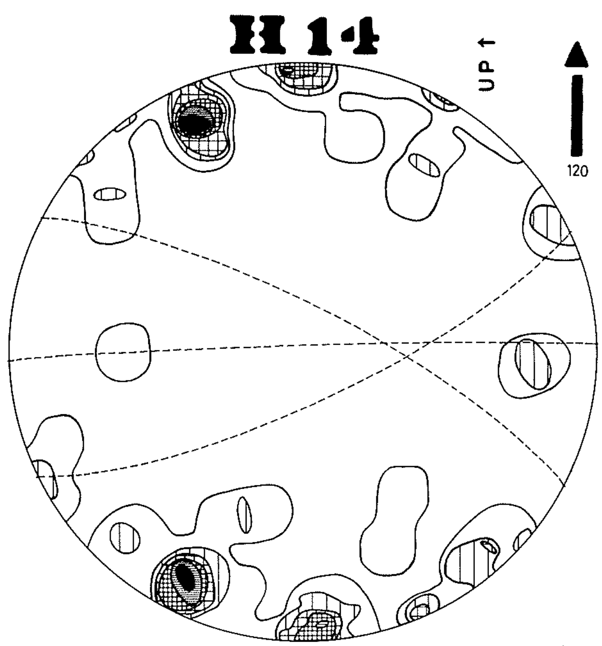
45 poles to plagioclase (010) composition planes. Contours: 2.2%, 4.4%, 8.8%, 13.2%, 17.6% Max. 17.6%

Fig. (i)



45 poles to plagioclase (010) composition planes. Contours: 2.2%, 4.4%, 6.6%, 8.8%, 11% Max. 15.5%

Fig. (ii)



40 poles to plagioclase (010) composition planes. Contours: 2.5%, 5%, 7.5%, 10%, 12.5%, 15% Max. 15%

Fig. (iii)

Table I

Specimen number	Attitudes of (010) faces of plagioclase crystals	
	Strike	Dip
H. 1	310	65 NE.
	309	78 SW.
	315	80 NE.
H. 3	328	84 SW.
	393	58 SW.
H. 7	336	44 SW.
	347	76 SW.
	322	66 SW.
H. 8	290	37 NE.
	286	53 NE.
	310	86 NE.
H. 9	301	47 NE.

Table I (continued)

Specimen number	Attitudes of (010) faces of plagioclase crystals	
	Strike	Dip
H. 10	279	38 N.
H. 11	49	28 SE.
	96	9 S.
	66	23 NW.
H. 13	5	84 W.
	311	26 SW.
H. 14	46	63 NW.
	15	65 SE.
	32	89 SE.

All strike readings are in degrees east of north.

(iii) Interpretation of the plagioclase orientation diagrams from the Falcon Lake Stock

The foregoing exposition of part (i) of this section served to establish certain principles governing some of the internal structures of igneous bodies. In the interpretation of the plagioclase orientation diagrams for rocks from the Falcon Lake Stock, the conclusions drawn have been related to these principles.

The overall picture of the plagioclase orientation suggested by this work is presented in three dimensional form in Plate 10, (p. 51). At each specimen locality, the most prevalent attitude (or attitudes) of the tabular felspar crystals, listed in Table I (pp. 48 and 49), is shown. The inferred positions of individual flow layers suggested by the orientation of the plagioclase crystals at each specimen locality, are depicted by the broken surfaces in Plate 10. Where more than a single predominant attitude of the crystals exists, the flow layers are related to that crystal orientation corresponding to the most strongly developed maximum on the orientation diagram.

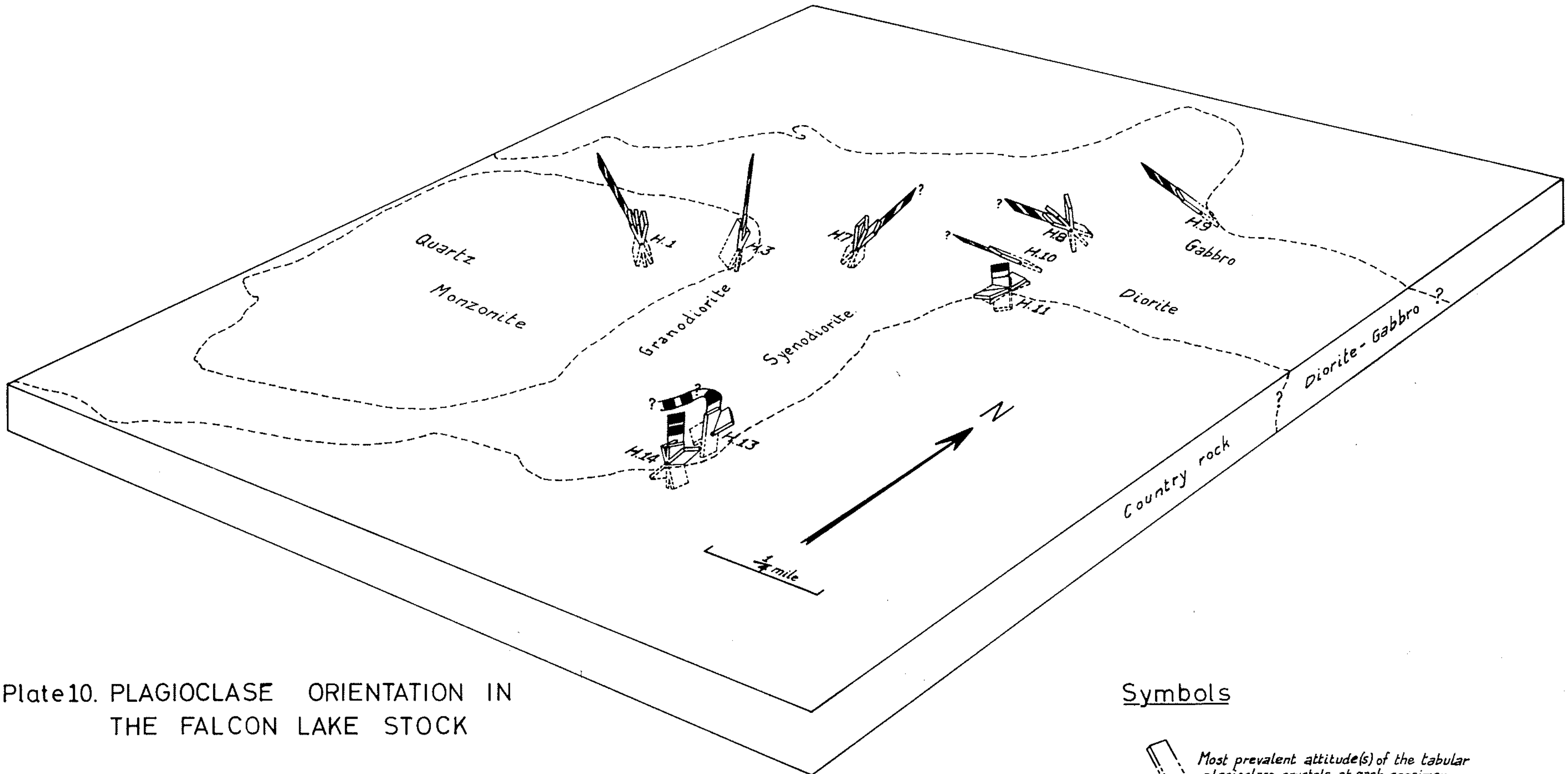


Plate 10. PLAGIOCLASE ORIENTATION IN THE FALCON LAKE STOCK

Symbols

Most prevalent attitude(s) of the tabular plagioclase crystals at each specimen locality.

Inferred positions of individual flow layers.

Geological boundaries.

Consider the traverse H.1 - H.3 - H.7 first. It can be seen from the block diagram (Plate 10) that the majority of the recorded twin lamellae along this line, are inclined at high angles to the horizontal and are, in places, vertical. The apparent flow pattern which then emerges from these results, is obviously dissimilar from the usual dome or arch of flow structures in which the flow layers near the center of the intrusion are either gently inclined to the horizontal, or are absent altogether. However, it must be stressed that information is afforded by only three specimens, and any conclusions based on these results must be tentative.

In order to account for this particular arrangement of the flow structures, the following explanations are suggested.

1. If the quartz monzonite core does in fact represent completely new acidic material which was forcibly intruded into the original solidified diorite, then a new dome of flow structures would have been produced by this second intrusion, and steeply inclined flow layers would have resulted near the margin of the core at the locations of specimens

H.1 and H.3. Such a relationship between a broad, older dome of flow structures, and a younger core also with a well-defined but smaller dome structure, has been recorded in the Sierra Nevada intrusion by Ernst Cloos (1937).

This hypothesis must be rejected for the Falcon Lake Stock however, on the grounds stated by Brownell (1941). (See Section IV., p. 17). There is no evidence to suggest that a later forcible injection of the quartz monzonite core into solidified diorite ever took place.

A new dome of flow structures would also have been produced in the core of the stock if new acidic material had been injected into the still unconsolidated central portion of the mass of cooling diorite, and completely replaced the dioritic material. This hypothesis is also not acceptable, for as Brownell (1941) points out, the quartz monzonite of the core shows a very close mineralogical relationship to the rocks in the surrounding parts of the stock and does not represent completely new acidic material.

2. If Brownell's theory (1941) is accepted for the origin of the quartz monzonite core of the

stock, then the proposed arrangement of flow layers at H.1 and H.3 localities can be more feasibly explained. Upward streaming of the acid differentiate through the mesh of interlocking plagioclase in the central core region, would have tended to re-orient the plagioclase crystals into their present day attitude, especially if this part of the stock were in a "mushy" semi-crystalline state as Brownell suggests. This hypothesis cannot be regarded as additional support for Brownell's theory, but it would seem that such a mechanism could easily have accounted for the steeply inclined attitude of the plagioclase crystals in this part of the core.

3. The steeply inclined flow layers suggested by the orientation diagram for specimen H.7 must be explained by a different hypothesis. The present day erosion level may be only a short distance below the original roof of the intrusion. If the north-eastern area of the stock in the vicinity of specimen H.7 is then regarded as the basal zone of a formerly upward extending protuberance, a steep, up-arching of the flow layers into this protuberance would account for the steeply inclined flow layers at this locality.

This hypothesis could easily be tested by analyzing more specimens from the area.

The flow structure pattern along the line of specimens H.9, H.8, H.10 and H.11 (Plate 10), consists of an assymetrical arch. The steeply dipping flow layers at H.9 are to be expected alongside the outer contact of the intrusion, but as far south as H.10, a steep northerly dip is maintained. Close to the southern contact, the flow layers begin to arch over, and at the southern contact, they have a gentle southerly dip. This particular arrangement of flow layers can possibly be explained by considering that beyond the southern edge of this part of the stock, more diorite or gabbro of the intrusion may be concealed below a fairly thin cover of roof rock. Some distance south of H.11, the flow layers should assume a steep southerly dip as the steeper contact wall of the stock is approached.

On the eastern side of the stock at the locality of specimen H.14, the flow layers appear to have an approximately vertical attitude (Plate 10). Specimen H.14 was actually collected only a few yards from the contact between the syenodiorite and the country rocks. It can be inferred that to the east of H.14, there is probably no great extension of the intrusive rocks below the country rocks. In other words, the outer contact wall of this part of the stock can be interpreted to be practically vertical.

The orientation diagram for the plagioclase twin lamellae in specimen H.13 (Plate 9, Fig. (ii) contains two widely separated and equally developed maxima. One of the maxima corresponds to an almost vertical attitude of the plagioclase crystals which suggests a tendency towards the development of very steeply dipping flow layers at the locality of this specimen. The outer contact of the stock is only a short distance to the east of this locality and it has already been observed from the orientation diagram for specimen H.14 that steeply dipping flow structures occur in this part of the stock. The other maximum in the diagram for specimen H.13 corresponds to an almost horizontal attitude for most of the remaining plagioclase crystals, and such an attitude is less easily explained. These crystals may be arranged parallel to the eroded roof of the intrusion. If this is so, then specimen H.13 may have been collected from a transition zone where the flow layers are in the process of changing from an almost horizontal to a vertical attitude (Plate 10).

As a final point, it may be noted that examination with a hand lens of the thin sections used in this study, reveals in most cases, a well defined parallelism of the elongated lath-shaped plagioclase crystals. The apparent direction of their preferred orientation agrees in all cases with that derived from the twin lamellae orientation diagrams. Clots of mafic minerals (hornblende and biotite) in some of the thin sections, were also observed to be drawn out in the direction of parallelism of the plagioclase laths.

X. DISCUSSION OF THE QUARTZ ORIENTATION IN THE FALCON LAKE STOCK

(i) Introduction

An explanation of the preferred orientation shown by the plagioclase crystals, became a relatively straightforward procedure when the orientation was considered in relation to flow structures within the stock. In view of the amount of work which has been done on the subject of flow structures in igneous bodies, there can be no doubt that the orientation of inequidimensional mineral grains in flow lines or flow layers is a very common phenomenon. On the other hand, preferred orientation of quartz grains in igneous intrusions presents a more complex problem, particularly because the quartz grains rarely show any recognizable form. Linear parallelism of slightly ellipsoidal quartz crystals has been recorded from a few granitic intrusions, for example the granite of Barre, Vermont, (Balk 1937) and the granite of Saganaga Lake, Minnesota (Grout 1929). The quartz grains in the Falcon Lake Stock however, have irregular shapes and no obvious parallelism.

(ii) Quartz orientation in other igneous intrusions

Previous petrofabric work on quartz orientation in several igneous bodies, has revealed girdles of quartz c-axes at right angles to the observed lineation direction in each particular intrusion. The lineation is usually present as a parallel alignment of mineral grains or of elongated inclusions. A comparison has been drawn between this type of girdle and the a - c girdle of the typical B-tectonite, considered by Sander (1930) to be the result of rotational movement about the b fabric axis in association with forward movement parallel to a. Even if a lineation in a particular intrusion can be shown to be a product of deformation, the lineation need not necessarily represent the b direction. Many examples of lineations produced by deformation have been described where the lineations are found to be parallel to the a direction. Where rotation about the lineation can be demonstrated however, the lineation probably does represent the b direction, and a quartz girdle at right angles to it is an a - c girdle. If, on the other hand, the lineation is a primary flow structure and not a product of deformation, then as Fairbairn (1949, p. 233) suggests, it is necessary to find a different mechanism to explain the formation of the quartz girdles.

In his study of the Val Verde tonalite in southern California, Osborn (1939) concludes that the lineation present in the tonalite, "probably represents the original direction of elongation of the magma". He does however, entertain the possibility that deformation of the solidified magma may have re-oriented the component mineral grains and impressed the present linear structure on the rock. He believes that orientation of the quartz grains to produce girdles at right angles to the lineation is "not the result of fluidal movement in the magma", for the irregular grains show no constant dimensional relationship to the optic axes. Alternatively, if the quartz orientation resulted from post-magmatic deformation, the alignment of plagioclase and biotite parallel to the lineation could also be the result of deformation.

Other petrofabric studies of igneous rocks have shown that post-magmatic deformation has definitely caused the particular orientation of the quartz grains. In a granite studied by Maroschek

(1933) for example, no lineation was observed megascopically, but quartz girdles were nevertheless found in the rock fabric. These girdles were parallel to a prominent set of tension fractures.

A quartz girdle, normal to the lineation, was also found to represent the orientation pattern in a quartz porphyry intrusion, described by Johs (1933). In this case, the lineation direction in the quartz porphyry coincided with that in the mica schist country rock, and was not the direction to be expected if the linear structure had resulted from magmatic flow. Johs concluded therefore, that orientation of the quartz grains had probably been caused by deformation during the last stage of crystallization of the quartz porphyry.

Not all investigations in this field have called upon post-magmatic deformation as the most probable mechanism for producing the observed quartz orientation. E. Cloos (1946, 1947), suggested that all grain orientation in the Ellicot City granite of Maryland, resulted from the upward movement of the granite during intrusion. Orientation of the early formed felspar and mica crystals, parallel to the flow direction in the magma, produced an "oriented mesh" of interstices, in which the quartz grains subsequently crystallized. Cloos suggested that if the mesh were also linear, then the crystallographic orientation of the quartz crystals during growth, may have been influenced by the space available, and the observed girdle orientation would possibly have resulted.

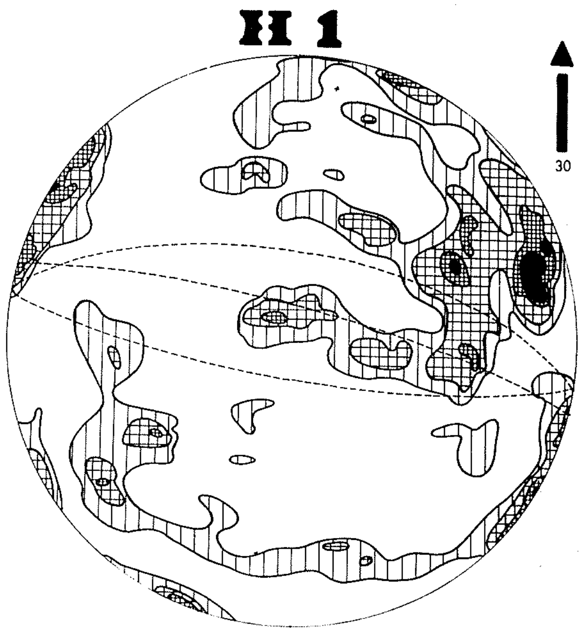
(iii) Description of the quartz orientation diagrams from the Falcon Lake Stock

A statistical analysis of the orientation of the quartz c-axes was carried out in thin sections taken from thirteen of the specimens collected, and the resulting orientation diagrams are described below. All rock types present in the stock were represented in this analysis, except the gabbro (eg. specimen H.9), which contained considerably fewer quartz grains than were necessary for such an analysis. In addition to specimen H.9, specimens H.11 and H.14 also contained an insufficient number of grains for a reliable analysis.

The quartz orientation diagrams are presented in Plates 11, 12, 13 and 14. Each diagram represents the projection of the lower hemisphere of the sphere of reference on to a horizontal plane. The direction of the azimuth alongside each diagram is approximately at right angles to either the margin of the core, or the outer contact of the stock, depending on whichever was nearer to the particular specimen locality. The location of each specimen from the stock is shown on the map on page 24, (Plate 4).

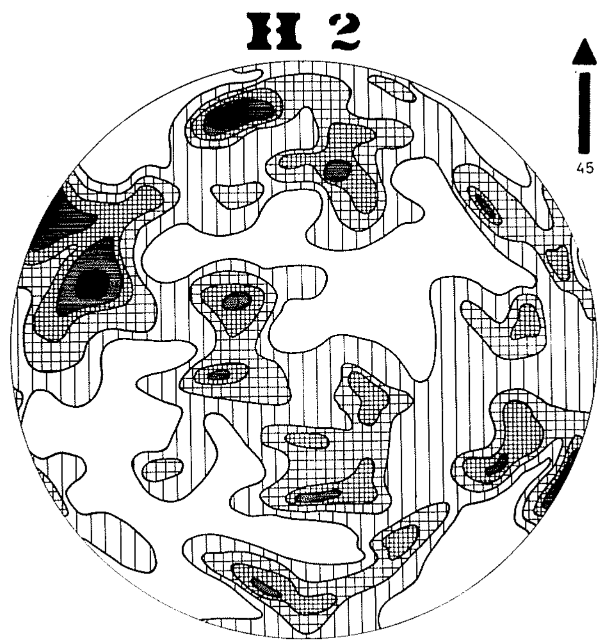
In several of the diagrams, the orientation pattern may appear at first sight to be rather vague and ill-defined, but when these diagrams are compared with those which show good preferred orientation, the pattern is considerably clarified. The diagram for specimen H.4 for example, (Fig. (iv), Plate 11, p. 64) indicates a strong development of preferred orientation of the quartz grains in this specimen. The majority of the grains lie with their c-axes approximately horizontal and almost parallel to the margin of the core, which is just to the east of this specimen locality. There is also a faint development of a girdle, linking the peripheral maximum areas. Diagram H.3 (Plate 11, Fig. (iii) on the other hand

Plate 11



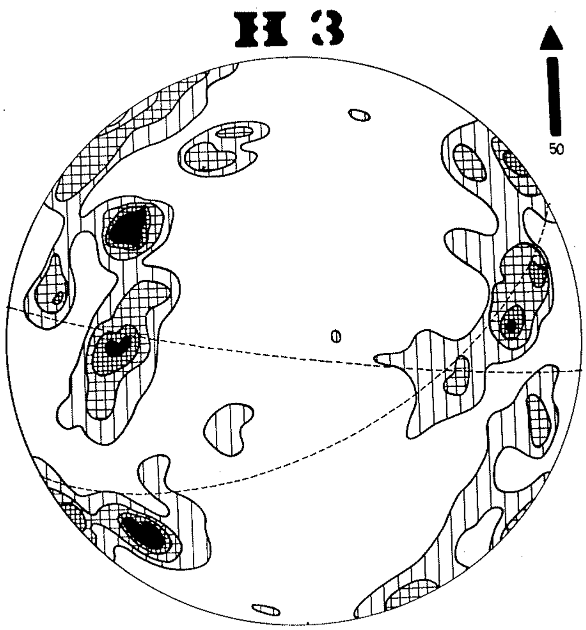
250 quartz c-axes. Contours: 1.2%, 2%, 2.8%, 3.6%
Max. 4%

Fig.(i)



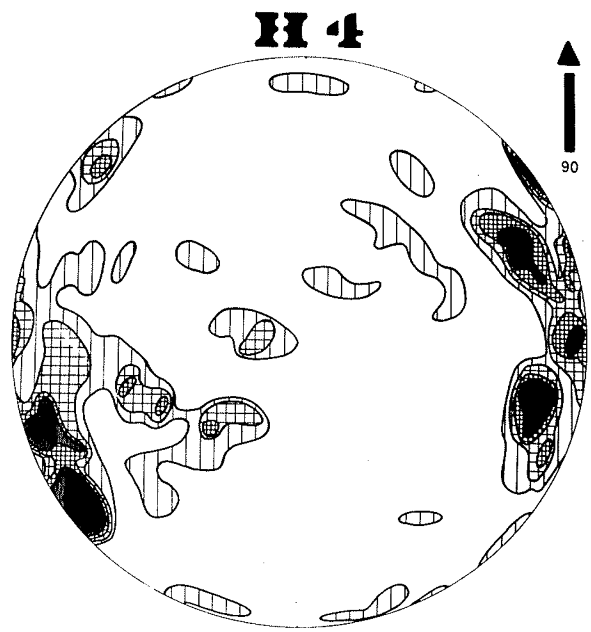
390 quartz c-axes. Contours: 0.8%, 1.3%, 1.8%, 2.3%, 2.8%
Max. 3.6%

Fig.(ii)



300 quartz c-axes. Contours: 1.33%, 2%, 2.67%, 3.33%
Max. 4%

Fig.(iii)



115 quartz c-axes. Contours: 1.75%, 2.60%, 3.50%, 4.35%, 5.2%
Max. 7%

Fig(iv)

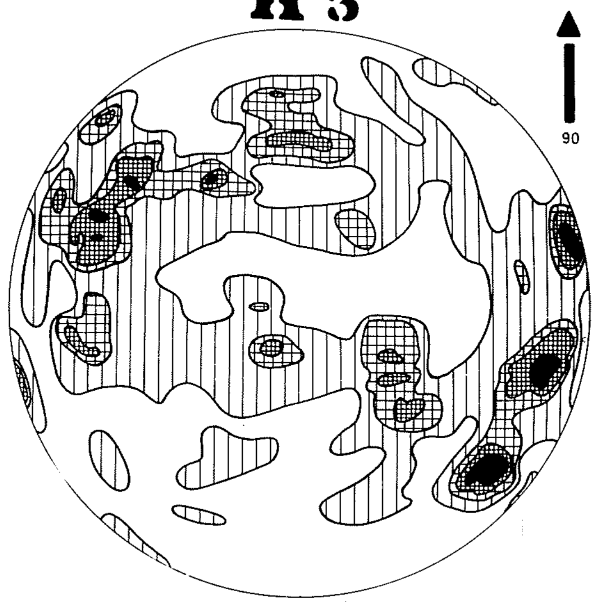
lacks this girdle development, but shows the same cluster of maxima close to the periphery.

Farther into the core at H.1 and H.2 (Plate 11, Figs. (i) and (ii), the orientation pattern is perhaps less distinct, but the diagram for specimen H.1 can undoubtedly be interpreted in the same way as H.2. It reveals an incomplete and rather dispersed girdle linking the peripheral maximum areas. A preliminary examination of the diagram for specimen H.2 might suggest that the fabric of this specimen is isotropic. However, by considering the minimum rather than the maximum areas, it becomes apparent that there is a similar pattern to that seen in foregoing diagrams, but with a more strongly developed and continuous girdle linking the maxima. The maxima show a considerable spread around the periphery of the diagram.

There is a close resemblance between the diagrams for specimens H.5 and H.6 (Plate 12, Figs. (i) and (ii), p. 66). Both show peripheral maxima linked by an equatorial girdle in the same manner as diagram H.4. The girdle is complete in diagram H.5 and almost so in H.6. In both cases, the development

Plate 12

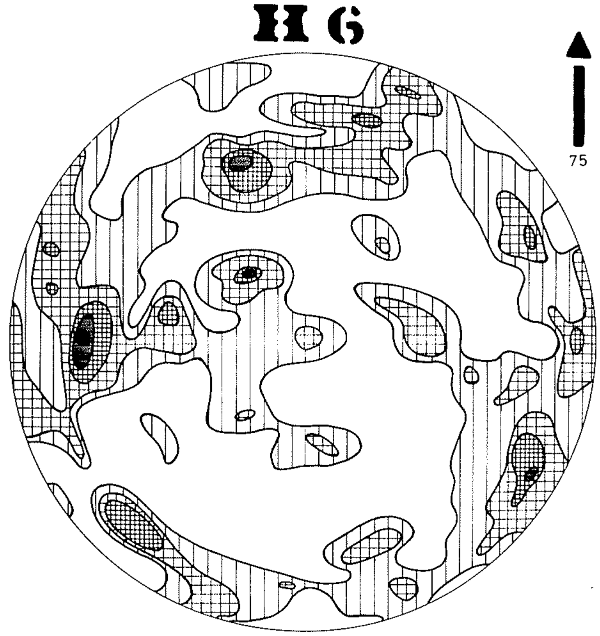
H 5



200 quartz c-axes. Contours: 1%, 2%, 3%, 4%
Max. 5%

Fig. (i)

H 6



185 quartz c-axes. Contours: 1.0[illegible], 1.[illegible], 2.70, [illegible], 4.[illegible]
Max. 4.[illegible]

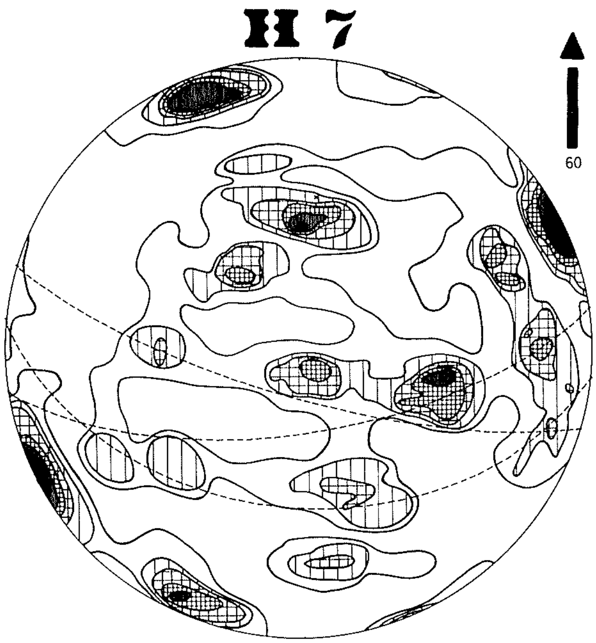
Fig. (ii)

of a second girdle containing a significant maximum near the periphery, may be interpreted as a tendency for some of the axes to lie at right angles to the core margin and within a plane approaching the horizontal.

Although Davies' map (1954) of the area shows the quartz monzonite - granodiorite contact running between the location of specimen H.4 and that of specimen H.5, both specimens H.5 and H.6 appear to be identical in composition and texture to the quartz monzonite specimens collected within the boundary set by Davies. For this reason, the diagrams from specimens H.1 to H.6 are discussed collectively.

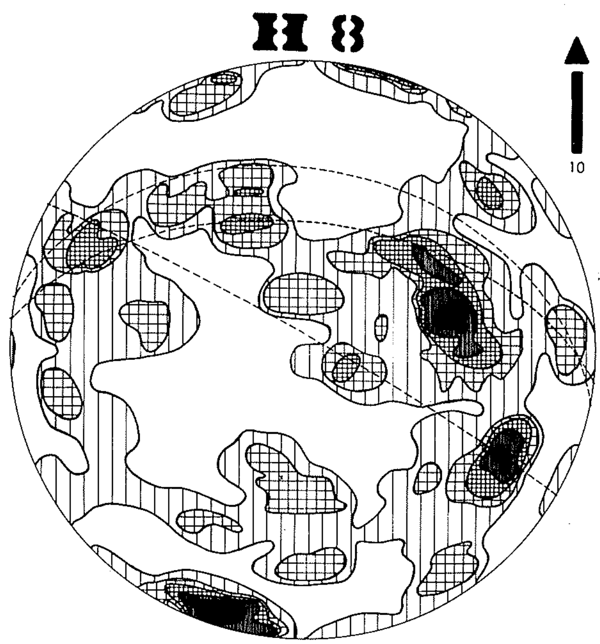
Diagram H.7 (Plate 13, Fig. (i), p. 68) shows a close similarity to the diagram for specimen H.5 and, to a certain extent, H.6, in the development of a "split girdle" arrangement. Both girdles again contain significant maxima and bifurcate from a peripheral maximum, although in the diagrams H.5 and H.6, the girdles lie more symmetrically about the centre of the diagram. In addition there is a further isolated peripheral maximum lying exactly 90 degrees from the maxima linked by the girdles.

Plate 13



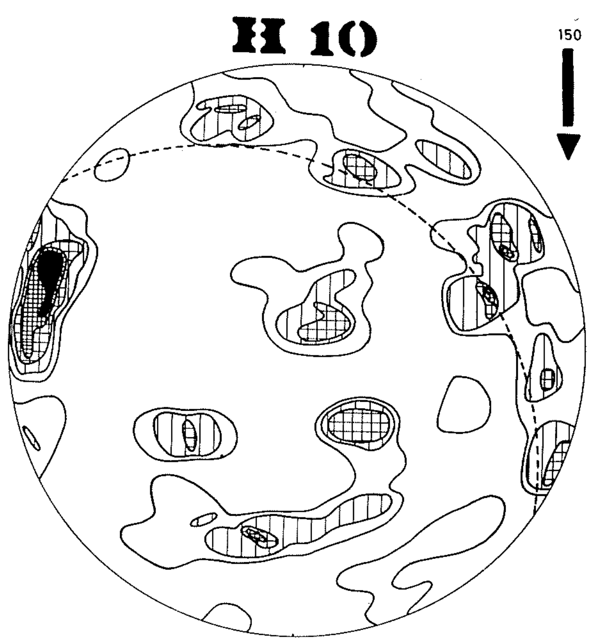
100 quartz c-axes. Contours: 1%, 2%, 3%, 4%, 5%, 7%
Max. 11%

Fig. (i)



100 quartz c-axes. Contours: 1%, 2%, 3%, 4%, 6%
Max. 8%

Fig (ii)



62 quartz c-axes. Contours: 1.5%, 3%, 4.5%, 6%, 7.5%
Max. 10.5%

Fig. (iii)

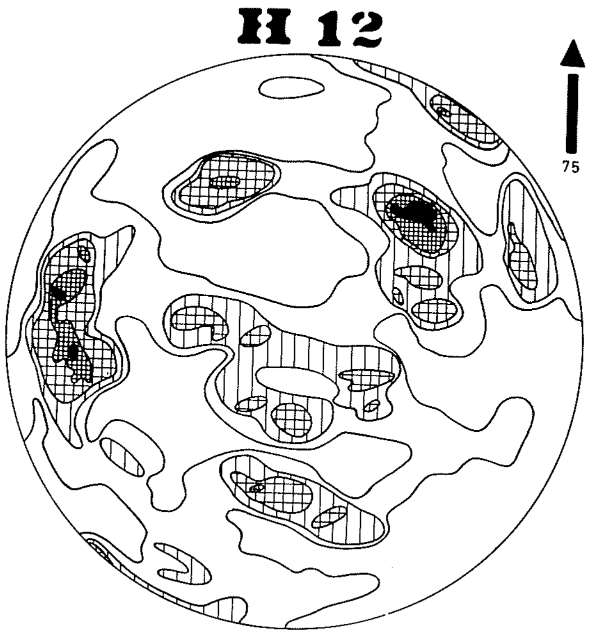
Diagram H.8 (Plate 13, Fig. (ii) shows a very similar pattern to that of H.7, but with a few minor differences. The two girdles are more clearly and widely separated from each other, and rather than bifurcating from a single peripheral maximum, they each contain a very prominent maximum where they are in juxtaposition. Both these maxima are a short distance away from the periphery, but several factors, including a possible slight error in the preparation of the thin section, could account for this discrepancy. An additional maximum lying right on the periphery and about 90 degrees from the other maxima, is again present.

No similar girdle development is seen in the diagram for specimen H.10, (Plate 13, Fig. (iii) and in fact, the pattern in the central part of the diagram is rather vague and dispersed. However, the most important and conspicuous maximum indicates in yet another instance that the c-axes of the quartz grains in this part of the stock lie predominantly within a horizontal plane and also approximately parallel to the outer contact of the stock.

Further to the south, the orientation of the quartz grains near the eastern edge of the stock, is represented in two diagrams, i.e. those for specimens H.12 and H.13. The diagram for H.12 (Plate 14, Fig. (i), p. 71) shows a very ragged and irregular girdle, and the girdle again encloses significant maximum areas lying near the periphery. On the other hand, diagram H.13 (Plate 14, Fig. (ii) is more complex. There is again a rather incomplete girdle crossing the centre of this diagram and enclosing a maximum near the periphery. The most prominent element of the orientation pattern however, is a more pronounced maximum, also near the periphery but lying almost 90 degrees from the maximum contained in the girdle. A similar development of such an additional maximum has already been noted in the diagrams for specimens H.7 and H.8.

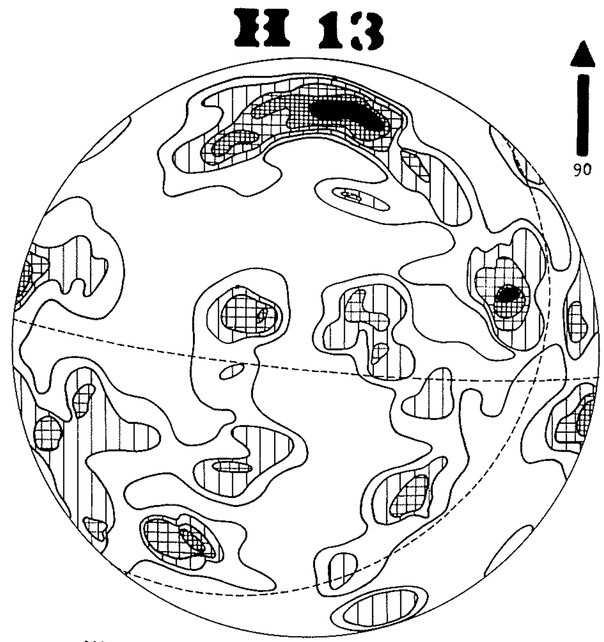
Near the southern edge of the stock, two specimens were collected on either side of the core margin, and quartz orientation diagrams were prepared for both of them. It is evident that neither diagram bears any resemblance to the other diagrams which have been considered. In fact, it would appear that there is a complete lack of orientation in the fabric of specimen H.15 (Plate 14, Fig. (iii), and although

Plate 14



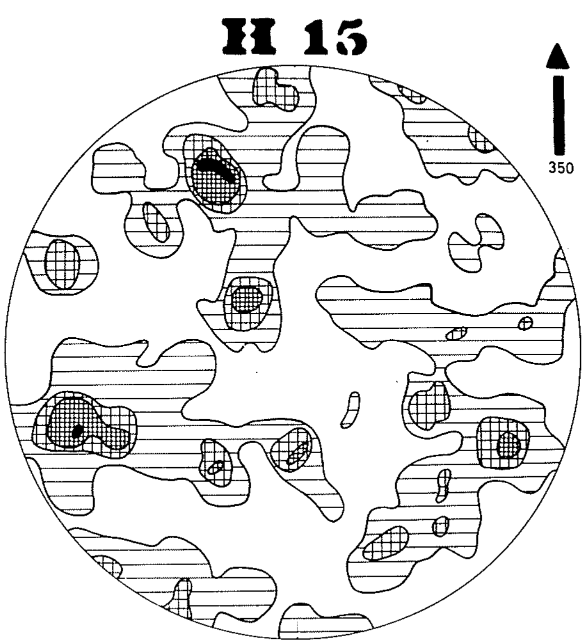
100 quartz c-axes. Contours: 1%, 2%, 3%, 5%, 7% Max. 8%

Fig.(i)



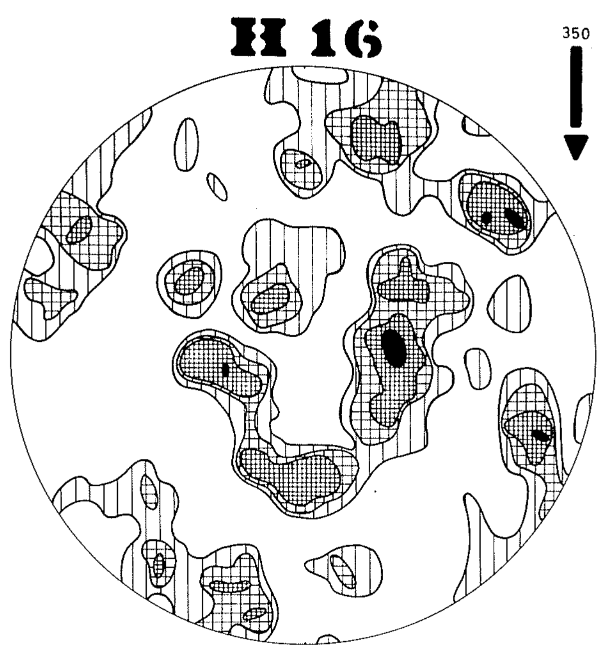
100 quartz c-axes. Contours: 1%, 2%, 3%, 4%, 6% Max. 8%

Fig. (ii)



175 quartz c-axes. Contours: 1.15%, 2.30%, 3.45%, 4.60% Max. 5.7%

Fig.(iii)



150 quartz c-axes. Contours: 1.33%, 2%, 2.67%, 4% Max. 5.33%

Fig.(iv)

one might interpret diagram H.16 (Plate 14, Fig. (iv) as showing two incomplete girdles intersecting at right angles, this diagram also shows no other recognizable or familiar pattern. It may be that the appreciable degree of randomness in both these diagrams reflects a lack of orientation of the quartz grains in the parent rock fabric in this southern part of the stock.

(iv) Interpretation of the quartz orientation patterns in the Falcon Lake Stock

(a) Relationship between the quartz orientation patterns and primary flow layers

Assuming the presence of platy flow structures within the stock, a definite and fairly constant relationship is seen to exist between the quartz orientation patterns and the attitude of the corresponding flow layers. It is possible to demonstrate this relationship for the six specimens from which both quartz and plagioclase orientation diagrams were prepared (H.1, H.3, H.7, H.8, H.10 and H.13). On each of the quartz diagrams for these specimens, great circles have been drawn to represent the most prevalent attitude (or attitudes) of the tabular plagioclase crystals at each specimen locality. The orientation of the great circles was determined from the corresponding plagioclase orientation diagram. It has already been suggested (p. 43) that these great circles also define the attitude of the inferred flow layers at each specimen position. On the basis of this premise therefore, the relationship between the quartz orientation and the attitude of the corresponding flow layers can be deduced. In all diagrams except that for specimen H.13, the great circles either pass through the principal maxima of the diagrams, or lie very close to them. This means that the majority of the quartz c-axes lie within the plane of the flow layers. The principal maxima also lie very close to or actually on the periphery so that as well as being contained in the planar flow layers, the axes are also mostly horizontal.

The diagrams for specimen H.13 represent a special case. Two possible attitudes of the flow layers at this specimen locality have already been inferred (p. 56). When great circles are drawn on the quartz diagram to represent both attitudes, the great circles intersect in a point which is very close to one of the two maxima present. In other words, a relatively large proportion of the quartz axes are again contained within the plane of the flow layers. It appears however, that the quartz orientation pattern for this specimen can be more easily related to the almost vertical attitude of the flow layers. In this respect, the great circle representing this attitude is almost coincident with the incomplete girdle which crosses the quartz diagram; the pole to the plane of the flow layers lies very close to the other maximum present in the diagram. No similar relationships to the quartz orientation can be established for the great circle representing the almost horizontal attitude of the flow layers.

Well-defined isolated maxima have also been described in the quartz diagrams for specimens H.7 and H.8 (pp. 67 and 69). Here too, these maxima are almost coincident with the pole to the plane of the flow layers. It can be deduced that quartz grains in specimens H.7, H.8 and H.13 have grown with their axes lying in two distinct directions - at right angles to the plane of the flow layers, and contained within this plane.

The principal maxima in the quartz diagrams for specimens H.2, H.4, H.5 and H.6 consistently define an approximately horizontal attitude for the majority of the quartz axes in these specimens. The quartz axes also show a strong tendency to lie almost parallel to the quartz monzonite - granodiorite contact. The general attitude of the flow layers in the vicinity of these specimens can be inferred from the information supplied by the plagioclase orientation diagrams for specimens H.1, H.3 and H.7. In general, the strike of the flow layers is also parallel to the quartz monzonite - granodiorite contact. It may be tentatively proposed therefore that the majority of the quartz axes in specimens H.2, H.4, H.5 and H.6 also lie within the plane of the flow layers. A similar relationship probably exists for the quartz axes in specimen H.12 (Plate 14, Fig. (i).

(b) <u>Discussion of a possible mechanism responsible for the quartz orientation</u>

Whether or not one accepts Brownell's hypothesis for the mode of emplacement of the stock, the quartz was still probably the last mineral to crystallize. As such, it infilled the remaining interstices within the felspar - hornblende - biotite framework. Such an interstitial arrangement is particularly well demonstrated in the more basic rocks of the outer rim.

It has been shown that the plagioclase crystals at least, were oriented during intrusion of the magma, and together with the mafic minerals, they may have been arranged as an oriented mesh in the manner suggested by Cloos (1947) for the early formed minerals in a Maryland granite. Even so, the quartz grains would still be expected to crystallize within the available interstices with a totally haphazard arrangement of their respective optic axes, unless oriented by an internal or external stress field.

The texture of the rocks from all parts of the stock, is unquestionably igneous in character with no suggestion of a crystalloblastic nature, and the stock itself shows no obvious effects of deformation by external forces. These facts make it improbable that stresses originating outside the stock caused the orientation of quartz optic axes in the manner described above.

In order to explain the observed quartz orientation it is suggested by the writer that the force of intrusion which propelled the magma upwards, caused the quartz grains to assume their preferred orientation. It is possible to envisage a lapse in the application of this force, allowing the quartz to crystallize freely, followed by a renewal of the upward pressure which oriented the quartz grains. However, it is easier and more logical to consider that the quartz actually crystallized within the stress field produced by a continuing upward-directed force. Evidence that the quartz was subject to some form of stress is seen in the undulatory extinction observed in a few of the quartz crystals.

The felspar - hornblende framework, within which the quartz was oriented, would have to be sufficiently rigid to transmit the orienting stresses, and yet also be able to withstand cataclasis, re-orientation, or any other effects of deformation. Bending or actual rupture of the plagioclase twin lamellae was noticed in a few of the thin sections, but it is impossible to say whether this was in fact caused by the deforming forces transmitted through the crystals.

Further work, particularly on the megascopic structures of the stock, is essential in order to learn more of the magnitude and scope of the forces which were active during the emplacement and crystallization of the stock. In this respect, the flat-lying faults which cut the ore body of the old Sunbeam - Kirkland gold mine, described by Brownell (1941), probably formed as the result of outward expansion of the intrusion in response to continuing pressure from below. The steeply dipping and mineralized shear zones which occur both close to the outer contact of the stock and within the intrusion itself (Davies (1954) and Brownell (1941), may have also been caused by the same upward-directed forces.

No attempt will be made here to review the various hypotheses which have been proposed to explain the development of quartz orientation. Excellent appraisals of these hypotheses appear elsewhere (eg. Fairbairn 1949, Harris and Rast 1960). Whether based on the fracturing of individual grains, on translation-gliding within the crystal lattice, or on a lattice orientation in response to stress, the hypotheses have been concerned solely with the orientation of quartz in tectonites. In such deformed rocks, the quartz is already in a crystalline state, prior to the deformation.

In considering the Falcon Lake Stock, the writer has suggested that the quartz grains actually crystallized in their present oriented position as a result of stresses acting on the crystallizing magma. No subsequent deformation is believed to have caused rotation or re-crystallization of the grains at a later time. The orienting mechanism is therefore fundamentally different from that which would produce orientation of the quartz in a tectonite.

If it is assumed that the preferred orientation was impressed on the quartz grains as they crystallized, then the majority of the grains appear to have grown with their c-axes approximately horizontal, and normal to an upward-directed pressure. Where a girdle is developed, it would seem that orientation of quartz c-axes perpendicular to the applied pressure, was incomplete. The attitude of the quartz axes also appears to have been controlled by the primary flow layers which were already in existence in the framework of plagioclase crystals when the quartz began to crystallize. As well as having a horizontal attitude, the majority of the quartz axes invariably lie within the plane of the flow layers. It has also been shown (p. 73) that even where a girdle of quartz axes is developed, the plane of the girdle coincides with the plane of the flow layers. The extraneous maxima or "split" girdle development in some of the quartz orientation diagrams are more difficult to explain. The quartz orientation was possibly influenced to a certain extent by differential movement of the material in adjacent flow layers, but so little is known of the exact way in which the quartz became oriented, that suggestions of this type must remain highly speculative.

XI. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The present study of the Falcon Lake Stock has shown that both the quartz and plagioclase crystals in several selected areas of the stock exhibit an appreciable degree of preferred orientation. The plagioclase orientation has been related to alignment of the lath-shaped crystals in primary flow layers within the stock. It has also been shown that a close relationship exists between the attitude of the quartz grains and the planes of these primary flow layers, as determined from the plagioclase orientation diagrams. It is clear that in general, the majority of the quartz c-axes are contained in the plane of the flow layers, and the most prominent maxima in each diagram (usually on the periphery), indicates that most of the axes are also horizontal. Where a girdle is present, the girdle coincides with the projection of the plane of the flow layers at the particular specimen locality. Because of this close relationship, it is recommended that the quartz orientation diagrams should be used in close co-ordination with the results provided by the diagrams of plagioclase orientation.

In those parts of the stock considered in this work, it has been possible therefore to determine the general attitude of the internal flow structures mostly through the evidence furnished by the plagioclase orientation diagrams. Further work on the orientation of the plagioclase crystals might well produce a more detailed and complete structural pattern of the intrusion, particularly with reference to the origin of the core.

The orienting mechanism that rotated the quartz grains into their present position is not fully understood, and although there is some consistency in the orientation patterns for different specimens, many of the patterns are in fact quite complex and difficult to interpret. The quartz grains do appear to show a stronger orientation in those specimens taken from the core, and it might be argued that a more powerful or prolonged stress field existed in this part of the stock. If this is so, then there is a strong possibility that the core was in fact formed under a different set of conditions from those which prevailed during crystallization of the rest of the stock, and perhaps therefore at a later time.

The petrofabric techniques have established that primary flow structures exist within the Falcon Lake Stock, and future application of the Cloos method of study may make it possible to determine the overall structural pattern of the stock. A careful investigation of megascopic features in the field may bring to light both primary flow structures and fracture systems which can then be used to clarify the mechanism of intrusion of the stock.

Further investigations might also be profitably extended beyond the outer margin of the stock, especially to determine evidence of stoping, or crowding aside of the wall rocks during emplacement of the stock. It may also be possible to determine the exact relationship of the stock to the general structural pattern of the surrounding area and to decide during which stage in the deformational history of the region, the stock was intruded.

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