

GEOLOGY OF THE LOOMIS-BLUE LAKE AREA,
OKANOGAN COUNTY, WASHINGTON

by

HAROLD A. PELTON

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Department Geology
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ABSTRACT

This thesis describes the geology of an area ten miles east of the Okanogan River and thirteen miles south of the Canadian border in north-central Okanogan County, Washington. Special attention is given to the petrology. The rocks of the area are a variously metamorphosed, eugeosynclinal sequence of sediments and volcanics, which have been locally granitized and, also, invaded by igneous granodiorite. The poorly sorted, very fine to very coarse grained clastic sediments have been recrystallized or metamorphosed to phyllite or fine grained schist under epizonal and mesozonal regional metamorphic conditions. The andesitic volcanics have been somewhat recrystallized and locally changed to fine grained amphibolite or schist. The granitic rock that outcrops in the north part of the area has uniform granodioritic composition, even texture, sharp borders, a contact metamorphic zone and other indications of an igneous origin. The granitic rock that outcrops in the south part of the area has a variety of compositions and fabrics, local crystalloblastic texture, gradational contacts, indications of metasomatism, some continuation of the regional structure into the granitic

rock, and other features indicative of a replacement origin. All of the rocks of the area were subjected to low grade retrogressive metamorphism which caused replacement of some of the earlier minerals, and obscured or destroyed many details of texture, structure and mineralogy. The present topography is largely a product of glacial erosion.

ACKNOWLEDGEMENTS

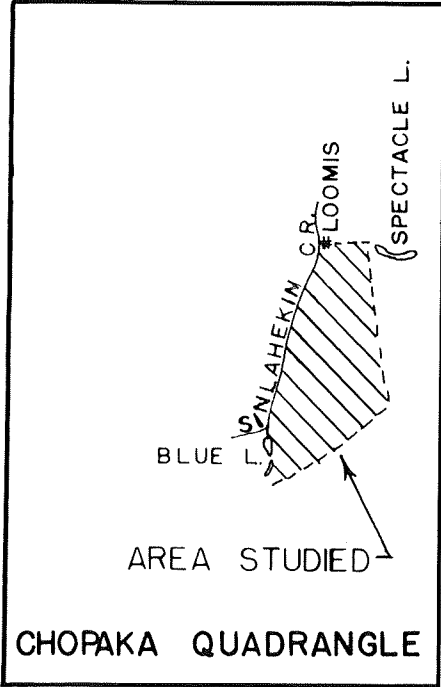
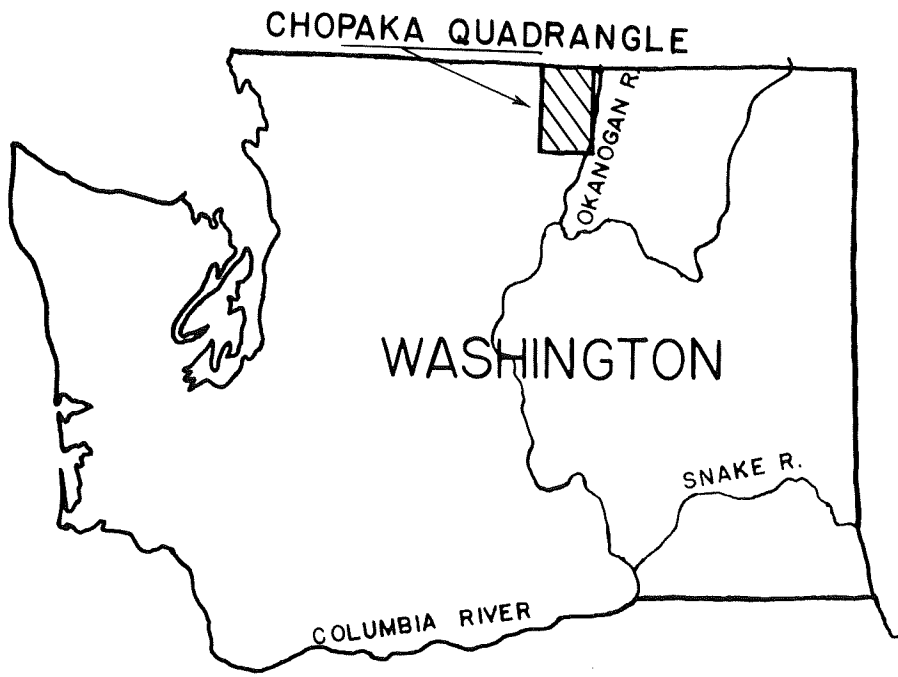
I want to express my sincere gratitude to Professor Peter Misch who suggested the area of this thesis, gave advice on field investigations, guided the laboratory work and critically read the thesis during its preparation. I am indebted to the Department of Geology of the University of Washington for providing me a fellowship during my graduate work there and to Mr. and Mrs. L. C. Dubigk whose hospitality I enjoyed during part of the field season.

INTRODUCTION

LOCATION AND GENERAL DESCRIPTION OF THE AREA

The area studied is about ten miles east of the Okanogan River valley and extends to within thirteen miles of the Canadian border. It is bounded on the west by Toats Coulee, which is now the valley of Sinlahekin Creek, and on the east by Horse Springs Coulee. These coulees converge to the north. The town of Loomis is at the apex of the angle they form. The southern limit is a line extending roughly northeast from Blue Lake in Toats Coulee. These boundaries include an area which measures approximately ten miles north and south by four miles east and west. Refer to the index and geologic maps (Figure 1 and Plate I).

With the exception of the steep coulee walls, the surface is gently rolling to slightly mountainous (Figure 2 and Figure 3). The coulees--products of Pleistocene glaciation--are, however, deeply incised and provide a maximum relief of nearly 3900 feet. The coulee sides are 2000 to over 2500 feet high. They are locally precipitous and are the site of the best and, in fact, most of the outcrops. Exposures are very good, although sometimes inaccessible, along Toats Coulee. They are progressively poorer along Horse Springs Coulee, on the hill tops, on the remainder of the uplands and on the coulee floors.



INDEX MAPS



Figure 2



Figure 3

Bed rock is locally exposed in Horse Springs Coulee but is completely covered by alluvium and glacial drift in Toats Coulee. Much of the upland is covered by open pine forest. The coulee floors are grassland with scattered brush and with deciduous trees along the streams. A small part of the area is farmed and much of it is used for grazing.

PREVIOUS WORK

For most of this area no earlier work appears in the literature. However, there have been some investigations of nearby and, in part, directly adjacent areas. In 1904 Smith and Calkins published a report on their reconnaissance survey of the northernmost Washington Cascades from the Okanogan River to the coast (1904). Their mapping ends just north of this area, as does that of Daly's Forty-ninth Parallel Survey report (1912). The area described in a paper by Waters and Krauskopf extends, in one place, slightly west of Horse Springs Coulee (1941). Work done by Misch overlaps mine at the south as does the doctoral thesis of Goldsmith (Misch 1949c, 1949d, 1951, and unpublished material, Goldsmith 1952). These papers refer to some of the rocks present in the area but, chiefly, to their occurrences outside the actual area. They have all been helpful and are cited in this report but, for the most part, they are lacking in applicable detail and

are not specifically concerned with the area here under consideration. Other authors, as indicated by the references and bibliography, have also contributed useful information.

PURPOSE AND METHOD OF THE INVESTIGATION

This area was suggested as a thesis problem by Doctor Peter Misch in the spring of 1952. The field work was done during parts of July, August and September of that year, and the laboratory work the following winter. My objects in the field were to make a geologic map, determine the structure and stratigraphy, and collect specimens for petrographic study. I was able only to determine the gross stratigraphy and general structural trends, so the petrography of the region will be my chief subject. About two hundred fifty specimens were obtained and more than one hundred sixty of these were studied in thin section. Field mapping was done on aerial photographs of 1:20,000 scale which were purchased from the Soil Conservation Service of the United States Department of Agriculture. The final map was made from these, using methods described in Aerial Photographs: Their Use and Interpretation by A. J. Eardly.

OUTLINE OF THE AREAL GEOLOGY

The area is underlain by a variously metamorphosed sequence of sediments and volcanics and by granitic rocks. The original sediments ranged from argillaceous through silty and sandy to conglomeratic, and were poorly sorted. The volcanics are of intermediate, usually andesitic, composition. The sequence is typical of eugeosynclinal deposition. It resembles the comprehensive "Anarchist formation" which Daly (1912) mapped near the Canadian border and which Waters and Krauskopf (1941) extended southward to near the present area. However, no actual correlation by detailed mapping or paleontologic evidence has been made. Similar rocks, such as the Cache Creek series, the Chilliwak series, the Hazelton group and others, have been described in Washington, British Columbia and as far north as Alaska for which ages ranging from upper Paleozoic through Jurassic have been suggested. The almost complete absence of fossils and the lack of distinctive, identifiable lithologic units in the "Anarchist formation" and in the present area, combined with the, as yet, very incomplete mapping, make any correlations or datings somewhat suspect. Therefore, it seems advisable to refrain from assigning the rocks of this area to a definite age and from correlating them with any named series or group. They will

be referred to only by the descriptive term "conglomerate bearing metasediments and metavolcanics". Their only definite relationship to other layered rocks was established through detailed mapping by Misch and his students south of the present area. Their work demonstrated that the carbonates of the Alkali Lake formation, though once considered the youngest pre-Tertiary rocks of the general region (Waters and Krauskopf, 1941), are actually stratigraphically lower and, therefore, older than the rocks of the subject area and the intervening Scotch Creek and Evans Lake formations. Waters and Krauskopf tentatively assigned the carbonates to the Triassic. Subsequently, Misch (1949c), on the basis of preliminary fossil determinations by H. E. Wheeler, tentatively assigned them to the Devonian. Further study, though, seems to indicate that the originally suggested Triassic age is probably correct (Misch, oral communication). However, the other pre-Tertiary rocks of the region, which are essentially metamorphosed clastic sediments and volcanics, are younger and not older than the carbonates of the Alkali Lake formation. The rocks of the present area appear to overly the Scotch Creek formation and thus continue the sequence established by Misch (Figure 4). Some of the rocks in the south of the mapped area probably belong to the Scotch Creek formation. The limits of this formation cannot be accurately determined, but it is apparently succeeded by the conglomerate

GEOLOGIC COLUMN FOR RIVERSIDE- FISH LAKE AREA

P MISCH 1948 (REVISED 1950)

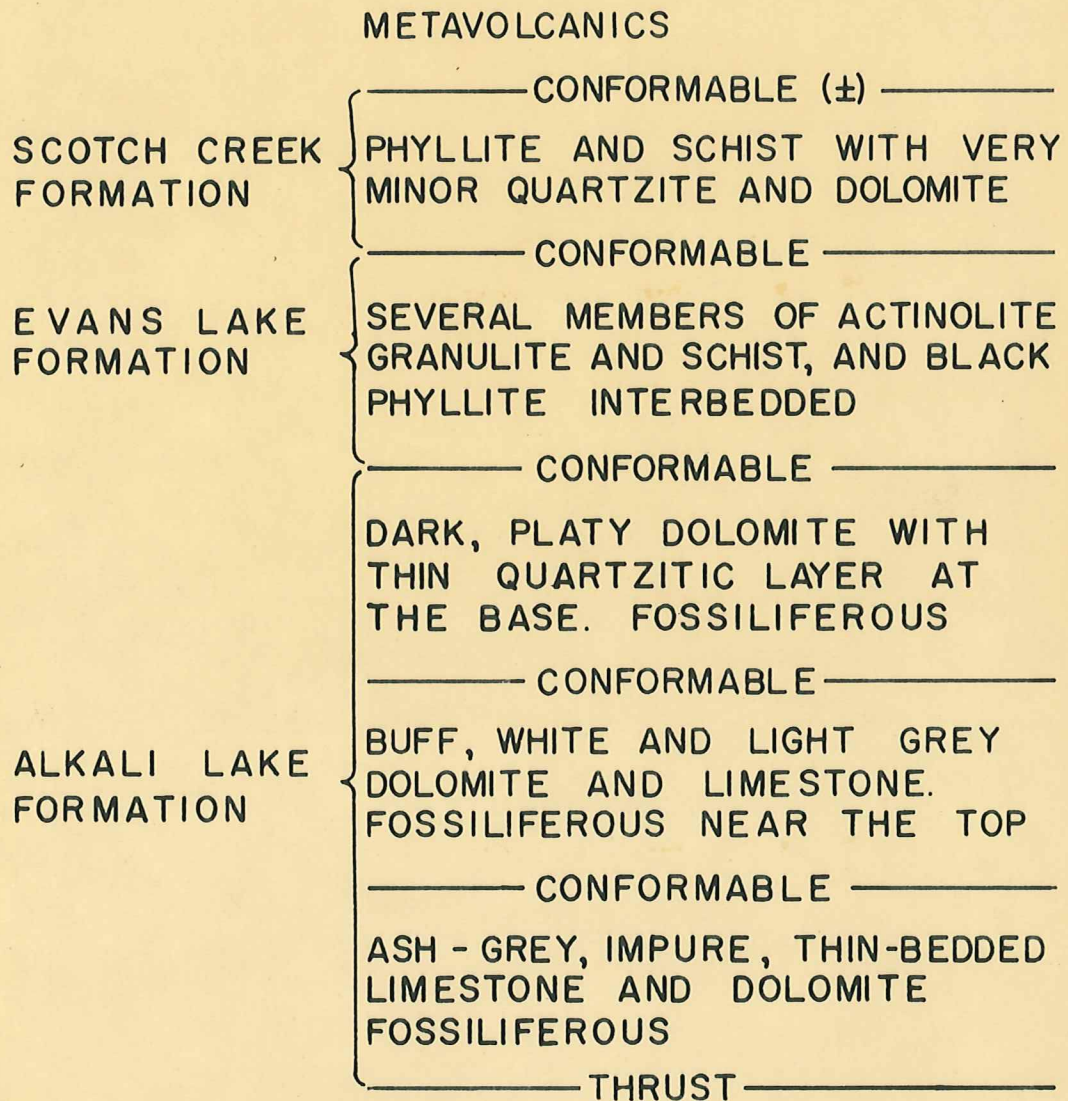


Figure 4

bearing metasediments and metavolcanics. Even though their exact relationship cannot be determined, there is little question about the relative stratigraphic position of the Scotch Creek formation and the other rocks of the area. The stratigraphic sequence, up to and including the Scotch Creek has been established to the south, while, to the north, the Scotch Creek is followed by the conglomerate bearing metasediments and metavolcanics. In addition, Scotch Creek rocks, associated with conglomerate and other rocks similar to those of the subject area are exposed in tectonic windows in thrust sheets of Alkali Lake carbonate rocks.

The several bodies of granitic rock are of two distinct origins. Those in the north of the area are thought to be igneous intrusions, while those in the south are interpreted as products of granitization. These latter are part of the Fish Lake complex of Goldsmith (1952).

The area was subject to fairly strong deformation. The deformation was sufficiently intense throughout the area to control crystal orientation and produce foliated rocks from the more argillaceous sediments. Locally, it was strong enough to thoroughly shear and make foliated rocks of the coarse grained clastics and of the volcanics. It also caused rather tight folding. Steep dips, usually in excess of sixty degrees, were found to predominate, and some reversals were noted, although enough information to establish the details

of structure is lacking. The strike and the structural trends average roughly north-south. The time of the deformation is obscure, just as is the age of the rocks affected by it. In the traditional view it is upper Jurassic or Nevadian. However, it is apparent from more recent work that this general portion of the Cordilleran geosyncline experienced repeated orogenic activity from at least late Triassic or early Jurassic to early Tertiary time. When the maximum deformation occurred in this particular area, is open to question. Certainly it cannot be dated from evidence in the immediate vicinity. The regional metamorphism, being contemporaneous with and, in part, a product of the deformation, has the same age, whatever that may be. The granitization overlapped the orogenic activity, but was mainly subsequent to it or essentially static. The igneous granitic rock may have been implaced soon after the decline of orogenic activity.

The present topography is largely a product of glacial erosion which was influenced by, but which greatly modified the pre-existing landscape. Though ice at some time completely covered the area, its greatest movement was along the present coulees, which were probably established in the first place by marginal drainage since they cut, nearly at right angles, across the earlier eastward drainage. Ice movement and ice-marginal drainage are chiefly responsible for the form and dimensions of the coulees (Figure 5) and, of course, for most

of the relief. Preservation of glacial striae (Figure 7), drift and eskers (Figure 6) indicates that only minor erosion has taken place since the retreat of the ice.



Figure 5. Looking south across Blue Lake in Toats Coulee. Notice the characteristic U-shaped valley and the glacial drift or morainal material on the coulee floor.

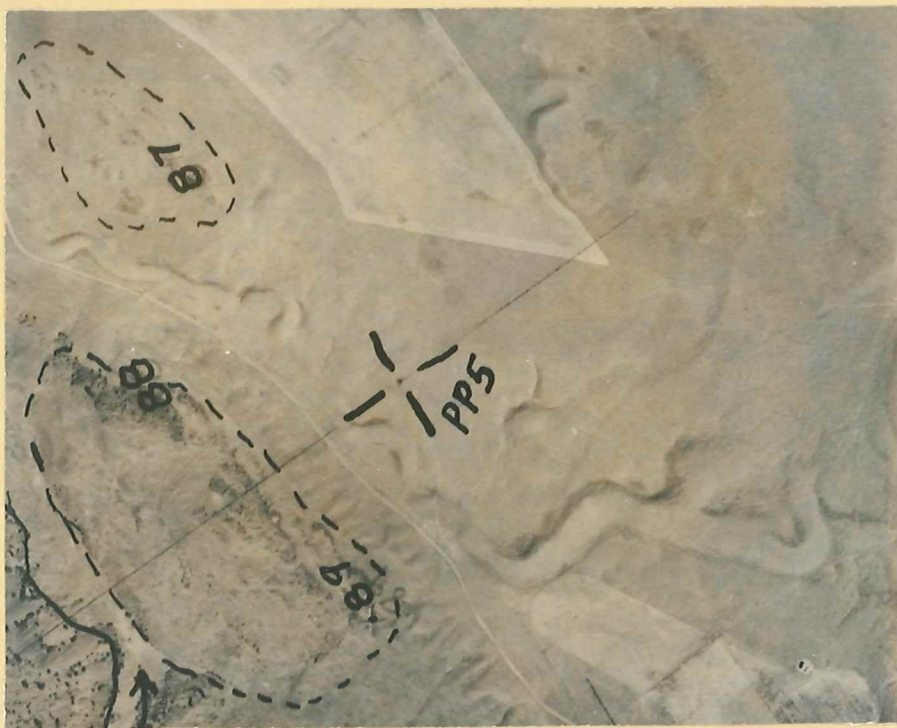


Figure 6. An enlarged portion of an aerial photograph showing the remains of an esker in Horse Springs Coulee. The scale is approximately 1:12,000 or five inches to one mile.

PETROLOGY, PETROGRAPHY AND PETROGENESIS

GENERAL STATEMENT

Aside from superficial glacial deposits and alluvium, the rocks of this area are those considered typical of eugeo-synclines. They are granitics set in a metamorphosed sequence of volcanics and poorly sorted sediments. Metamorphism under various combinations and degrees of heating, deformation and metasomatism has altered or recrystallized the sediments and volcanics or changed them to, for example, hornfels, phyllite, schist or amphibolite. The product of the most profound of the metamorphic transformations is directionless granitic rock. Not all of the granitic bodies, however, are the result of replacement. Some are true igneous intrusions.

In addition to the primary metamorphism, the entire area has undergone a period of static retrogressive metamorphism which has produced chlorite, sericite and other low grade minerals at the expense of the original or earlier formed constituents. These fine grained, often unidentifiable, minerals tend to obscure much of the prior mineralogy, texture and structure. Their presence makes precise identification of the feldspars particularly difficult and limits the accuracy of composition estimates. Their veiling effect frequently makes illustration of various features by photo-

micrographs virtually impossible.

In spite of the retrogressive metamorphism nearly all of the rocks are relatively resistant. This is borne out by their notably minor response to differential erosion. Rock types as diverse as granodiorite, metaconglomerate, and meta-argillite have been eroded at nearly the same rate. A further indication of their strength is the fact that only a few especially well foliated specimens required special treatment during preparation of thin sections. None of the others had any tendency to part or crumble.

In the following chapters, to facilitate petrographic synthesis, the metamorphic rocks will, with few exceptions, be described and associated with their parent sediments or volcanics. The exceptions to this scheme will include the granitized rocks which will be treated separately, and certain metasediments and metavolcanics that are closely associated with or related to the granitic bodies and will therefore be described with them.

METACONGLOMERATE

Metaconglomerate is the most conspicuous sediment and perhaps the most distinctive rock of the area. In contrast to the dark and drab aspect of the other sediments and the volcanics it is frequently light colored. It sometimes stands

a little above the other rocks because of its superior resistance to erosion. It is relatively abundant, constituting roughly an eighth or more of the volume of sediments. Beds vary in thickness from a few inches (Figure 7) to several tens of feet generally, although one exceptional unit exceeds a hundred feet. It is, however, broken by thin interbeds of sandstone and consists mainly of granule-size fragments.

In outcrop and hand specimen the conglomerate is, with a few exceptions, light colored. Some examples, particularly those of finer grain size, are medium grey to nearly black. The identifiable fragments are quartz, quartzite, chert and, rarely, metamorphic and volcanic rock. These are set in a dark fine grained matrix. The fragments are angular to subrounded, but most commonly subangular. They range in size from fine granules to cobbles several inches in diameter. Larger cobbles and boulders were not observed though there may be some. The bulk are of granule and pebble size. Determination of fragment size and shape is hampered in many specimens by recrystallization which has obscured or even obliterated the outlines or boundaries. A few granule-size conglomerates were identified only with the help of the microscope. Bedding is absent except for rude traces in some of the granule conglomerates. Effects of dynamic metamorphism are very minor in most specimens. Even where in

morphic fragments. A third has a few pieces of foliated metamorphic rock. The fourth has several small pebbles with a diabasic texture. Only a single specimen is really a polymict conglomerate. In addition to the ubiquitous quartzite and chert, this specimen is composed of fragments of foliated metamorphic rock and of hornblende rich rock which may have been a statically metamorphosed dolomitic shale. Thus, by far the greater number contain no more than a single rock type.

The matrix, in contrast, has very little tendency to be quartzose or siliceous. In only a few specimens are the interstices filled with quartz in the form of silt, sand or cement. In most samples the interstices contain material much like the matrix of greywackes. It is presently composed of various amounts and combinations of chlorite, sericite, biotite, hornblende, muscovite. There may also be minor quantities of actinolite, tremolite, epidote minerals, carbonate and diopside. Chlorite and biotite are the most abundant. The minerals and their combinations indicate that the interstices were filled variously with quartz, with carbonate, with clay, with mixed clay and carbonate or, most commonly, a material approaching the chemical composition of chlorite. Besides depending on this original composition, the present mineralogy is also a function of the metamorphic grade and history. Diopside, indicative of at least the temperature

of the warmer mesozone, is the highest temperature mineral identified. Some rocks show no indication of having attained a higher grade than the epizone and contain only chlorite and sericite as new minerals. Most commonly, metamorphism has reached the warmest portion of the epizone or the cooler mesozone and produced fine grained biotite and some muscovite and hornblende. Besides the primary metamorphic assemblage which, where the relationship can be established, appears to be essentially synkinematic, there is a postkinematic retrogressive growth of chlorite and sericite, often at the expense of earlier biotite and muscovite.

Determination of the derivation and depositional environment of these conglomerates is complicated by the apparent inconsistency between the composition of the fragments and of the matrix, as well as between the uniformly quartzose composition and the poor rounding and sorting of the fragments. Since their fragments are, with rare exceptions, of essentially a single rock type, the conglomerates are in a sense oligomict. Yet they conform to none of the other implications of this term. They tend to be angular rather than rounded. They are often very poorly rather than well sorted. The interstices are filled not with sand and cement of quartz, but with chloritic material. Finally, they are associated with shale and dirty sandstone rather than orthoquartzite. Therefore, they are not beach gravels of a transgressive sea or products of

any other of those environments usually indicated by normal oligomict conglomerate. Instead, they have characteristics suggestive of vigorous erosion and rapid deposition and, by virtue of these same characteristics, they rather represent the kind of environment characterized by greywacke. The fragments are angular and poorly sorted. The matrix, being commonly composed of chlorite, some sericite, lesser amounts of carbonate and other accessories, approaches an ideal greywacke matrix composition. Then too, the conglomerates are associated with shale and poorly sorted, dirty sandstone. The only thing they lack to be equivalent to greywacke is variety of rock fragments. Indeed, since the other features so strongly indicate rapid erosion and deposition and fail to suggest any way in which sorting or selection of rock types could have occurred, the conclusion that no other types were available seems justified. If the erosional terrane could have supplied an appreciable quantity of rocks, other than quartz, quartzite and chert, they should be more in evidence than they are.

META-ARENITES

More sand was deposited in this area than any other class of sediments. It probably makes up a little more than half of the total volume of sediments. Sandstone or rocks derived from

it are to be found in contact with virtually every other type of rock present in the area. It exists in all gradations and mixtures with finer and coarser elastics. It occurs in beds varying from literally one sand grain thickness to units several tens of feet thick. Thicker accumulations are broken by interbeds of shale or, less often, conglomerate. The sandstone is medium gray to black, with the darker shades of grey predominating. Individual beds are usually massive. Bedding or other sedimentary structures are seldom visible. Because the sandstone usually lacks both sedimentary and metamorphic structures and is thoroughly cemented or recrystallized, it rivals the conglomerate and surpasses most other rocks in resistance to erosion. Its fracture is irregular to conchoidal and is sometimes related to metamorphic but not to sedimentary structure.

In hand specimen individual grains are seldom distinct, but enough grains can be seen to establish the fact that they vary widely in size. This is noticeable within individual specimens and between separate specimens. There is a complete gradation and sometimes a mixture of sizes from silt to granules. The rock frequently looks like quartzite and was so named in the field. It breaks across the grains, sometimes forming a conchoidal surface. It has a somewhat sugary appearance and, even when dark colored, is translucent on thin edges. Microscopic identification of constituents

other than quartz usually, however, modifies or even invalidates the field classification as quartzite. On the other hand, many specimens are obviously impure and may be described in the field as dirty, argillaceous or arkosic. There is all too often a troublesome similarity to the volcanics. The more uniform, dark, recrystallized units look very much like aphanitic or finely crystalline andesite, while those which contain fragments of quartz, chert or feldspar resemble porphyritic andesite. The likeness is enhanced by recrystallization and the blurring effect of retrogressive metamorphism. Distinctions can, of course, be made, but they require careful observation. This similarity is a decided hindrance to determination of stratigraphy and structure in the field. As implied by the foregoing descriptions, very few of these rocks have developed significant metamorphic structures. Though some of the limited quantities of schist and mylonite in the area are developed from arenaceous sediments, this fact is evident only under the microscope. As a rule, the only visible effects of deformation are moderate fracturing or shearing. The megascopically identifiable minerals are quartz in the form of grains or of fragments of chert, fine grained micas and, occasionally, feldspar.

The grain size variation noted in hand specimen is even more apparent under the microscope since the clastic texture is still visible in many of the rocks. Average grain sizes

of the different specimens vary through the entire sand range. Furthermore, most individual samples exhibit a wide variety of grain sizes. Some in fact contain appreciable quantities of very fine grained material and of granules in addition to sand. With few exceptions the sorting is poor. When their original shape is not obscured or destroyed by recrystallization or shearing, it can be seen that the grains are largely angular or subangular. A large portion of the clastic particles are quartz, quartzite and chert - more than ninety percent in some specimens. Clastic feldspar is sometimes present though usually in minor quantities. Rock fragments, of other than pure silica rock such as quartzite, are a little less plentiful than feldspar, and both are absent from the majority of samples. Small amounts of clastic biotite, muscovite and hornblende are occasionally included. With the exception of the quartz, quartzite and chert, all of the clastic constituents are at times difficult to distinguish from the matrix or from metamorphically formed minerals. It is believed, however, that this has not introduced any serious error into the estimates of relative quantities. In nearly all of these rocks the clastic grains are surrounded by a matrix which constitutes five to about thirty-five percent of the volume. The matrix now consists of chlorite, sericite, muscovite, biotite, very fine grained quartz and feldspar and, occasionally, epidote, calcite, actinolite, actinolitic horn-

blende, leucokene, hematite, limonite and more or less unidentifiable submicroscopic material. Chlorite and biotite are the most common and the most abundant minerals.

Several of the arenites are greywacke with roughly fifteen percent feldspar, fifteen percent non-quartzose rock fragments, fifty percent quartz and chert fragments and twenty percent clay-derived and finely detrital matrix. There are a very few arkoses, one of which for example is somewhat more than half feldspar with the remainder approximately equal parts of quartz and matrix material. The greywackes and arkoses, however, account for only a small share of the arenites. The great bulk of them resist exact classification under the usual systems, just as do the conglomerates. This is especially true if consideration is given to the textural, structural, environmental and genetic implications of most sandstone names. Many of the rocks contain sixty to ninety-five percent clastic quartz. On the basis of a purely mineralogical classification many of them could be called orthoquartzite. Yet, their angular grains, poor sorting and non-quartzose detrital matrix are certainly not typical of orthoquartzite. Again, some of those with less than ninety percent quartz might be subgreywacke but they do not satisfy Pettijohn's most recent definition or that of Krumbein, Sloss and Dapples (Pettijohn, 1957, page 316).

Most of them do not contain appreciable amounts of feldspar or rock fragments, and the non-quartzose detrital matrix is decidedly not minor. With the exception of quartz, the matrix is frequently the only significant component and may account for ten to thirty percent of the volume. Nor are the implications of moderate sorting and rounding in subgreywacke satisfied. Kryzine's term protoquartzite, or cleaned-up greywacke and subgreywacke seems inapplicable to these rocks because of their poor sorting and relatively high matrix content (Op. Cit., page 321). On the other hand their poor sorting, lack of rounding and high content of non-quartzose detrital matrix are characteristic of greywacke. The feldspar and rock fragments characteristic of normal greywacke, however, are missing. Thus, it seems reasonable to suggest that the conditions of erosion and deposition were suited to the accumulation of greywacke but that all of the necessary components simply were not available. Perhaps if the source terrane could have supplied sufficient feldspar and rock fragments, these rocks would be greywacke or subgreywacke. The source rocks were, incidentally, at least partly marine sediments as is indicated by the abundance of chert.

Metamorphic effects in the sandstone are intermediate between those observed in the conglomerate and those in the shale. Changes in the sandstone are similar to, but greater than those in the conglomerate and consider-

ably less than those in the shale. In portions of the area subject only to epizonal metamorphism (Plate I), mineralogical changes are limited to the development of chlorite, sericite, epidote and clinozoisite in the matrix and minor recrystallization of quartz and of calcite if it is present. With increasing metamorphic grade the chlorite and sericite are gradually replaced by biotite and muscovite. Infrequently, actinolite or actinolitic hornblende have formed. Feldspar is not distributed widely enough to permit determination of systematic changes, but a little oligoclase does form in the matrix under mesozonal conditions. In addition to this newly formed oligoclase and the recrystallization of clastic feldspar grains, both of which are isochemical changes, some plagioclase and potassium feldspar are the result of metasomatism in the vicinity of the granitic bodies near Blue Lake. This development will be discussed in more detail elsewhere. Near the stock south of Loomis there is some hornfelsing. It is usually incomplete, but there are local areas of almost complete recrystallization. Here again, the matrix is first and most noticeably affected.

The effects produced by penetrative deformation during the regional metamorphism vary considerably and have a distribution not unlike that of the metamorphic grades indicated by the newly formed minerals. That is, the most pronounced effects are to be found in the southwest part of the area

which is also the site of the highest grade metamorphism, while there is only minor shearing and crushing in the regions of epizonal metamorphism. Throughout most of the area, deformation and development of metamorphic structures were essentially confined to the more fine grained sediments. This is indicated in the field by the common interlayering of massive sandstone with slate or phyllite derived from shale. The same thing is evident on a microscopic scale, too. Layers high in fine grained material show alignment of micaceous minerals and shearing and lensing of included fragments, while adjacent silty or sandy layers contain unoriented micas and unbroken clastic grains. Only in the southwest corner of the area was deformation intense enough to produce foliated rocks from the sandstone. Here some rather poorly crystallized schist and blastomylonite were formed (Figure 8). Part of the crystallization in the schist and most of that in the mylonite is postkinematic.

SHALE-DERIVED ROCKS

Rocks derived from shale are only a little less abundant than those derived from sandstone. They probably constitute somewhat more than one-third of the total volume of sediments. Individual beds range from mere partings in sandstone to units exceeding several hundred feet in thickness.



Figure 8. Blastomylonite from near contact of southernmost granitic rock near Blue Lake.

These fine grained metasediments show much more pronounced effects of the penetrative deformation during regional metamorphism than do the more coarse grained sediments. They frequently have well developed foliation while adjacent or interbedded sandstones reveal no trace of metamorphic structure. In most instances where the relationship could be determined, the foliation is more or less parallel to the bedding. Cleavage or schistosity is not, however, universal in the fine grained sediments. Many units, particularly the thicker ones, are partly to completely massive. The resistance to erosion of these rocks is inversely related

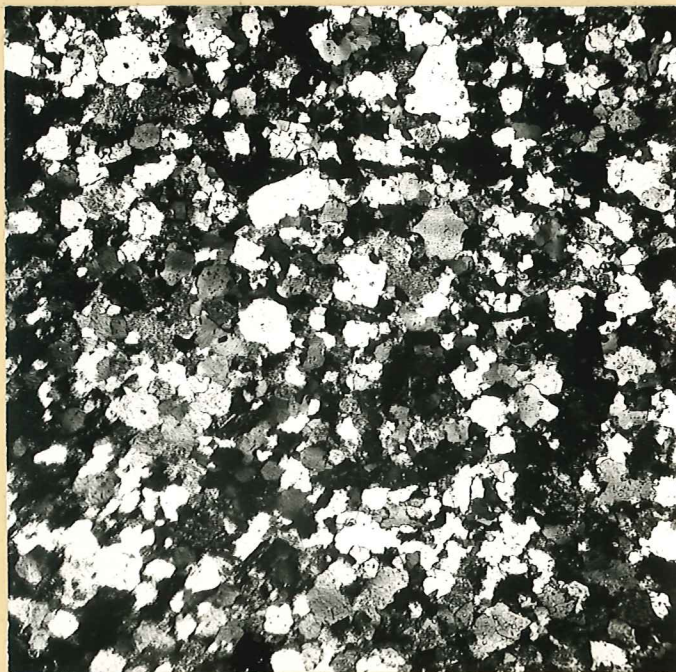
to the degree of development of foliation. The phyllite is very susceptible to erosion while the blocky argillite or hornfels is nearly as strong as the more coarse grained sediments or the volcanics.

On fresh surfaces the metamorphosed shales are medium to dark grey or black and occasionally greenish or brownish grey. There are no light or bright colors. Bedding may sometimes be seen as faint color or compositional banding. Metamorphic structures are more obvious. Phyllites are common. Their parting varies from well developed and closely spaced to rude and widely spaced. Some specimens may be broken into paper-thin fragments while others may be split easily only at intervals of an inch or more. The foliation planes of some of the phyllites are deformed into parallel wrinkles. A few thin sections show this wrinkling to represent the development of a new s plane (s_2). This may indicate a second phase of deformation, implying a shift in the direction from which force was being applied, but it may also merely represent a shift in the direction of yielding of the rock during the same phase of deformation. Since this s_2 is only locally apparent, it may well represent the second of the two alternatives stated.

Microscopic examination is somewhat hampered by the fine grain size, as well as the masking effect of the low grade retrogressive metamorphism. Most specimens display clastic

relict texture, with at least some silt and sand sized grains recognizable. It is thus indicated that the poor sorting which characterizes the more coarse grained sediments, extends to the fine grained sediments also. Moreover, just as the other sediments, the fine grained sediments are relatively high in quartz. Some samples contain forty percent or more of identifiable quartz, with more probably present in the very fine grained matrix. High quartz content is also suggested by the massiveness and resistance to erosion of many occurrences of these rocks.

In some specimens metamorphic changes are limited to unoriented crystallization. These are from the blocky or structurless units. Though it is not always evident, recrystallization is probably complete throughout the area. It is best developed in hornfelsized rocks near the Loomis granitic stock where it represents contact metamorphism (Figure 9). In numerous specimens it is sufficiently advanced to permit identification of some or all of the constituents. Percentage composition estimates are seldom possible, however. The minerals include quartz, feldspar in amounts varying from zero to thirty percent, abundant biotite, chlorite, muscovite and sericite, occasional hornblende which is a major constituent in a few rocks, and minor amounts of carbonate, epidote, actinolite, sphene, pyrite, limonite, hematite and graphite. Proportions vary



1 mm

Figure 9. Photomicrograph of hornfels from near the Loomis stock. This is an exceptionally well recrystallized specimen.

widely, but quartz is nearly always present in considerable quantities. It is usually accompanied by micaceous minerals - chlorite and sericite or biotite and muscovite, depending on metamorphic grade - and less often by feldspar or amphibole. Although the feldspar can seldom be accurately identified, it is apparent that both orthoclase and plagioclase may be present. The little plagioclase that permits determination is calcic oligoclase or sodic andesine.

A number of outcrops of rock with fine grained texture and poor to fair cleavage was described in the field as slate.

Almost without exception they proved, when seen in thin sections, to be more coarsely crystalline than was apparent from megascopic examination. Sericite, chlorite and the micas are particularly well represented. Biotite and muscovite crystals up to a half millimeter in length are common. Many of the crystals are aligned, indicating synkinematic growth, while others, which are usually more fine grained or have developed at the expense of earlier aligned grains, are postkinematic. It is probably this postkinematic crystallization combined with the presence of large portions of non-elongate minerals - mostly quartz - which accounts for the poor cleavage in spite of the good development and orientation of much of the mica. The randomly oriented tabular crystals tend to bind the rock together, while the quartz does not contribute much to the foliation in any of these rocks. Since these rocks are, at least to a limited degree, cleavable and contain an appreciable quantity of identifiable, aligned minerals, they appear to qualify, perhaps with reservation, as phyllites. Only a few examples of cleavable rock with no more than the extremely fine grained to submicroscopic minerals proper to slate were found. They occur only as thin beds in more coarse grained sediments.

In addition to the atypical phyllite described, there are numerous outcrops of more normal phyllite. It is iden-

tifiable in the field by its characteristic cleavage and sheen. In addition to some submicroscopic, unidentifiable minerals, specimens contain various proportions of chlorite, sericite, biotite, muscovite, quartz in usually somewhat smaller amounts than in the poorly foliated rocks, as well as minor amounts of feldspar, amphibole and several accessory minerals. The quality of the foliation or cleavage appears to be directly related to the quantity of micaceous minerals present and thus to the amount of clay, clastic mica and related minerals in the original sediments.

Some of the phyllites and hornfelses are spotted. The spots are oval in cross section and oriented with their long axes parallel to the foliation. They are lighter colored than the remainder of the rock and appear to be concentrations of sericite in a more chloritic matrix. The reason for the concentrations is not definitely known. The sericite may be due to retrogressive replacement of andalusite, which was formed during contact heating.

In the southern part of the area, in the region of relatively higher grade metamorphism, there are minor quantities of schist and para-amphibolite. Part of these may have been derived from shale and dolomitic shale. However, since their origin is not clear, they will be described elsewhere.

These pelitic rocks are of less help than the more coarse grained sediments in determining the environments

of erosion and deposition. Nevertheless, they do support the conclusions based on evidence supplied by the other sediments. The salient feature of the environment already postulated was rapidity of erosion and deposition. This is again suggested by poor sorting, and a large amount of quartz in proportion to mica-forming constituents. Active mechanical erosion with little chemical weathering and rapid accumulation without sorting or reworking are indicated; these conditions are appropriate to a eugeosyncline.

CHERT

In striking contrast to the usual heterogenous, poorly sorted, frequently coarse sediments of the area there is, on a hillside about two miles northeast of Blue Lake, an outcrop of massive chert. Isolated exposures are scattered for a third of a mile across the slope. Individual outcrops expose little more than ten feet of section though the total may be many times this amount. The attitude is obscure and the thickness and relation to adjacent beds are masked by soil cover. Although the chert is essentially massive, it shows a faint indication of northeast to east-northeast strike and steep south dip. The attitude is similar to that of the nearest foliated beds which, however, are separated from the chert by massive rocks and soil mantle. Aerial photographs show a vague lineation in a direction just east of north

and hint at the possibility of an open syncline plunging to the south. The chert would be in the trough of the syncline. The sum of available information leaves the stratigraphic and structural setting of the unit in doubt.

The chert in outcrop and hand specimen is massive and irregularly fractured. It is translucent on thin edges and ranges in color from nearly white to medium dark grey or to rusty brown where it is iron stained. In thin section it consists of a microcrystalline aggregate with incipient recrystallization of quartz. It contains scattered, minute calcite crystals, a percent or two of fine grained muscovite and a little magnetite which is being altered to hematite along fractures. Some of the fractures have been healed with quartz. There are no textures, structures or inclusions to give a clue to the mode of origin. The rocks found nearest, but unfortunately not in contact with the chert, are mineralogically and, perhaps, genetically similar. One is whitish, very rudely foliated, fine grained, quartzose rock. Under the microscope it appears to have been an argillaceous silt containing about eighty percent quartz. Although there was a significant admixture of argillaceous material, it was unusually pure as compared to the dirty matrix material of most of the sediments of the area. The rock was epizonally metamorphosed under weak dynamic conditions, with some recrystallization of quartz and formation of oriented sericite.

There is a trace of sericitiform biotite or possible stilpnomelane. Crystallization continued after movement ceased.

The other nearby rock type more closely resembles the chert. It is a hard, grey, very fine grained rock not greatly unlike the chert in appearance, yet, to some degree, lacking its density, luster and characteristic fracture. As determined microscopically, it consists of about one third sericite and two thirds extremely fine grained quartz. There is some indication of deformation, but most of the crystallization was not dynamically controlled. Mineralogically this is much like the previously described rock, though the quartz may not be of clastic origin. It is conceivable that this was an impure phase of the chert which was more easily deformed and more readily recrystallized.

The chert and, to a lesser extent, the other two rocks mentioned, mark a period during which conditions of deposition were considerable, though perhaps locally, different from those under which the bulk of the sedimentation took place in the area. Instead of a rapid piling up of poorly sorted detritus, there was an accumulation of relatively pure silica by chemical precipitation, organic processes or highly selective deposition. This was a time of greater stability with less vigorous erosion and less active transportation of eroded material.

MARBLE

Just south of the area mapped in relative detail, but, presumably, in the same general stratigraphic sequence, limited exposures of a marble unit were found. The nearest outcrops of other rocks which are several hundred yards away, consist of conglomerate and dark, pebbly greywacke. Soil cover and lack of visible bedding in any of the rocks prevent even approximate determination of relationships. No other marble or limestone members were found in the area.

In hand specimen this marble is a medium grey, even textured, fine grained rock. The microscope shows it to be composed almost entirely of irregular, interlocking carbonate crystals which average slightly less than one half millimeter in diameter. The composition of the carbonate was not determined but, judging from its reaction with weak hydrochloric acid and from the minerals formed from the small amounts of carbonate present in other rocks, it is probably somewhat dolomitic. Also in the thin section are a few sub-rounded quartz grains in a thin stringer and scattered sparsely through the matrix. There are no sedimentary or metamorphic structures or alignment.

As does the chert, this rock represents a period of deposition during which conditions were considerably more stable than during the formation of most of the sediments in the area.

VOLCANICS AND METAVOLCANICS

Volcanic rocks constitute roughly one third of the volcanic and sedimentary sequence of the area. They are concordantly interlayered with the sediments. It is assumed that they represent flows though no positive evidence to this effect was obtained. Again, while it is possible or even probable that most of the flows were submarine, no conclusive evidence of this was noted. Metamorphism may have destroyed many of the critical features. Individual units range in thickness from an observed minimum of about ten feet to well over one hundred feet. Some may actually be much thicker. The lateral extent was not determined, although some units could be traced for more than a mile.

The volcanics are generally massive. The only structures they exhibit have been induced by metamorphism. Fairly extensive fracturing and moderate shearing grade locally into schistosity (Figure 10). Most of the volcanics, however, have resisted deformation and remain structureless, even though adjacent shale beds commonly have been transformed into phyllite. The metavolcanics vary in color from light grey to black and often have a greenish cast. Most of them are medium or dark greenish grey. Weathered surfaces are stained brown by iron oxides. The predominant texture is aphanitic, although only a few specimens appear completely dense. Most contain some feldspar, hornblende or biotite phenocrysts. The phenocrysts



Figure 10. Typical fracturing and shearing in meta-andesite.

constitute several to perhaps seventy-five percent of the volume. They range up to ten millimeters, but are most often one or two millimeters in length. They occasionally show rude flow alignment.

Although they vary from light to dark and from dense aphanitic to coarsely porphyritic, most of the volcanics are mineralogically similar. Before metamorphism they were virtually all andesitic. The feldspar which constitutes about forty-five to seventy percent of the rocks is sodic andesine ranging from An_{30} to An_{40} in composition. Much of it occurs

as euhedral to subhedral phenocrysts or as fine laths in rocks with diabasic texture, and the remainder forms anhedral grains in the groundmass (Figure 11). Many of the



1 mm

Figure 11. Photomicrograph of a relatively well preserved specimen of volcanic rock with diabasic texture. It originally consisted of approximately sixty-five percent plagioclase and thirty-five percent hornblende. Note the ragged crystal borders and the overall speckled and fogged appearance due to incipient replacement of the igneous minerals and formation of very fine low grade minerals.

phenocrysts have normal and a few have oscillatory zoning.

Though the range of composition of the zoning can seldom be determined with any precision, it appears to lie within the limits mentioned. Hornblende accounts for most of the remainder of the majority of specimens, varying from about twenty to fifty percent, and commonly amounting to about thirty percent. It too is often in the form of stubby phenocrysts or, occasionally, in slender prisms. They are, however, seldom as large as the plagioclase crystals. Few exceed four millimeters and most are one millimeter or less in maximum dimension. A small portion of the hornblende is brown, but most of it is green. Biotite is the only other quantitatively important primary mineral. Percentage determination is made difficult by the abundance of secondary or metamorphic biotite derived from hornblende. Igneous biotite appears to constitute a maximum of about twenty percent of the volume, but it is frequently absent. Particularly when it is present in relatively large amounts, it tends to form phenocrysts of about the same size as the hornblende. Other minerals are rare in occurrence and minor in amount. A few samples contain a little orthoclase or quartz, while augite appears in only one. However, pyroxene would be unstable under low and medium grade metamorphic conditions and may therefore have been eliminated. All other minerals identified in thin section are interpreted as products of metamorphism or alteration.

Changes wrought by metamorphism in the volcanics are, in general, rather minor. As mentioned above, most units resisted the deformation which made foliated rock of closely associated fine grained sediments. Although fracturing and moderate shearing are widespread, development of schistosity is local and limited to the southwest part of the area where the grade of metamorphism was higher and the deformation apparently more intense. The product of this stronger metamorphism is orthoamphibolite or, more commonly, for lack of sufficient amphibole, a hornblende-plagioclase schist. Biotite is often present, though usually in minor amounts.

In the bulk of the volcanics only the mineralogy, and not the structure, has been changed by metamorphism. Since, over much of the area, the grade of the regional metamorphism approached, but did not exceed, the range of stability of andesine, hornblende, and biotite, it had little effect on these minerals except for limited alteration of andesine to oligoclase and epidote. Most of the mineralogical changes, therefore, took place during the retrogressive phase. The main exceptions to this tendency to form lower grade minerals were simple recrystallization of the igneous minerals and biotitization of hornblende. The latter reaction is apparently a response to potassium metasomatism which is also suggested by the local formation of orthoclase and microcline porphyroblasts. Recrystallization of the original minerals is extensive and noteworthy in some rock types such as the amphi-

bolites and hornblende-plagioclase schists, while in those rocks which have essentially retained their volcanic textures, recrystallization has occasionally given rise to incipient porphyroblasts and even to crystalloblastic textures in the original aphanitic fabric. The most common and obvious changes are, however, alteration of plagioclase to sericite and alteration of hornblende and biotite to chlorite. These reactions range from incipient attacks on crystal edges and partings to complete replacement of the original minerals. Alteration of either plagioclase or hornblende releases calcium to form epidote minerals or calcite which are commonly seen in close association with sericite and chlorite.

THE LOOMIS INTRUSIVE STOCK AND ASSOCIATED ROCKS

Rising sharply above the town of Loomis and extending to the south is an outcrop of granitic rock which shall be called here the Loomis stock (Plate I). The exposed portion of this stock is four miles long by about one and one fourth miles wide. Its western face rises more than 2500 feet above the floor of Toats Coulee. To the south, and separated from it by only a few hundred yards, is a smaller granitic body about one half mile wide and three miles long. The similarity and proximity of the two outcrops indicate that they are parts of the same unit.

The Loomis stock is slightly more resistant to erosion than the surrounding metasediments and volcanics. Both of its outcrops form moderate elevations. The contact, however, is only very locally marked by a pronounced change in slope or by obvious differential erosion. Wherever it was seen in the field, the contact is fairly sharp. The transition from granitic to country rock generally occurs over a few inches or less. Where foliation is present in the surrounding rocks, it is usually parallel or subparallel to the contact. The sole observed exception is at the southwest corner of the main, northern outcrop. There the surface trace of the foliation is approximately at right angles to the contact. No continuation of this trend could be found in the granitic rock. In fact, no structure of any kind was found in either outcrop of the stock. There is some fracturing and faulting of the stock but no obvious or well developed joint pattern. The present shape of the exposed portion of the stock does not appear to be determined by internal structure or by any other systematic controlling factor.

Specimens from various parts of the stock vary only slightly in appearance. They are medium or light grey to green-grey, structureless, medium-grained and occasionally, slightly porphyritic. The largest phenocrysts are about ten millimeters in maximum dimension, but only a few are big enough to be conspicuous in the medium grained

ground mass. Megascopically identifiable minerals, including those which form phenocrysts, are quartz, feldspar, and, less often, biotite. Quartz tends to be the most obvious mineral, because alteration has made the outlines of the feldspars indistinct and given the mafics an ill-defined appearance.

The microscope shows a typical sample of the Loomis stock to be hypautomorphic granular and medium grained with, at times, a few euhedral or subhedral phenocrysts of plagioclase, orthoclase or biotite and subhedral or anhedral phenocrysts of quartz. The bulk of the plagioclase and biotite has relatively good crystal form, while the quartz and orthoclase are largely interstitial. The rock, disregarding products of alteration, is composed of approximately twenty-five percent quartz, fifty percent plagioclase, fifteen percent orthoclase, and ten percent biotite or hornblende. The plagioclase varies from An₃₀ to An₃₇ and is most often about An₃₃. In addition to these dominant igneous minerals, many specimens contain sericite, chlorite, epidote minerals, calcite, leucoxene, hematite, pyrrhotite and pyrite.

The accuracy of composition estimates is limited by the ever present and sometimes extreme alteration. The alteration, for example, makes it difficult to distinguish between the various feldspars unless the plagioclase has good albite twinning or the potassium feldspar has the microcline grid. Unfortunately only a small share of the feldspar carries

some such distinguishing characteristic. As though in partial atonement for their usual role as hindrance to its determination, the products of alteration sometimes gives a clue to the original composition. For instance, calcite or epidote, which are sometimes associated with sericite, suggest that the latter mineral replaces plagioclase rather than orthoclase. The mafics are affected to, perhaps, an even greater extent than are the feldspars. In some slides chlorite has completely replaced the original dark minerals. In the others, practically none of the biotite or hornblende is completely fresh. All of the crystals have suffered at least incipient alteration. Incidentally, it is the retrogressive chlorite, along with a lesser amount of epidote, that imparts the greenish cast to many of the specimens. At present, biotite is by far the most abundant igneous mafic mineral. It is possible, however, that hornblende was originally much more plentiful than it is now. Epidote is frequently associated with the chlorite, indicating formation of these minerals from hornblende rather than biotite. It appears that most specimens at one time contained at least a little hornblende, and that some had considerable amounts.

Though the products of alteration unquestionably make composition determinations less precise than they might be if the rocks were fresh, most estimates are sufficiently accurate for purposes of rock classification. They indi-

cate that the Loomis stock is essentially granodiorite, varying locally to quartz-diorite.

Aplite dikes, related to the stock were found in the nearby country rock and in the stock itself. Although they occur in and about the stock, none were seen cutting the contact. They vary from a fraction of an inch to several feet in thickness and are either of reasonable uniform thickness or evenly tapered. Soil cover or pinchouts prevented tracing any of them for more than about thirty feet. The dike borders all appear to be sharp. In outcrop and hand specimen the rock of the dikes is white, cream or light grey and medium to fine grained. Feldspar, quartz and fine grained metallic minerals may be identified megascopically.

In thin section the aplitic dike-rocks show a strongly sutured micropegmatitic or aplitic texture with seriate grains of medium-fine average size. They are composed of quartz, feldspar and a little muscovite with minor amounts of biotite, pyrite and alteration products such as sericite, epidote, chlorite, hematite and limonite. Although each of the specimens examined contains both orthoclase and plagioclase, the relative proportions of the two feldspars vary widely. At one extreme a sample contains andesine with only a trace of orthoclase, while its opposite number is made up of orthoclase, microcline and perthite but only a minor amount of andesine. It appears that the latter or potassium feldspar

rich type is more nearly representative, although, admittedly, this statement is based on limited data.

There seems to be no reason to doubt that the usual explanation of pegmatites and aplites applies to these rocks. They are probably formed from the residuum of magmatic crystallization ejected from some internal site of concentration after the stock was essentially cooled. No reason is presently apparent for the rather unusual preponderance of plagioclase in part of the specimens.

The stock, at one place or another, is in contact with most of the local types of metasediments and metavolcanics, but it most commonly abuts fine or medium grained sediments. With the exception of locally numerous apophyses, the contact is fairly regular and sharp. The boundary zone between intrusive and country rock seldom occupies more than a few inches and often appears as the trace of a plane. Specimens from some of the sharper portions of the border were examined microscopically. The grain size of the granitic rock decreases as the contact is approached, but, in the thin sections studied, this change occurs only within about one centimeter of the contact. There is little apparent invasion of the country rock. In at least one case the sharpness of the boundary is limited only by the necessity of fitting the crystals of the two rocks together. There is some recrystallization in the country rock, particularly in the finer

grained sediments and the matrix of more coarse grained ones. In a few specimens the recrystallized sediments contain incipient feldspar porphyroblasts. They are best developed very near the contact, but even there they have an amoeboid shape and are filled with inclusions. Metasomatic addition of material from the intrusion may have contributed to the growth of the porphyroblasts but cannot be demonstrated. The fine grain size of the sediments precludes quantitative determination of the original composition and thus prevents detection of any chemical change.

As mentioned above, fine grained sediments show the greatest change due to contact metamorphism. Very locally, recrystallization was extensive enough to produce fine grained hornfels (Figure 9). The specimens of coarser sediments which were examined all retained much of their clastic texture. While fine grained micas were formed and quartz and feldspar were recrystallized in the matrix, the larger grains were unchanged or received only a thin overgrowth. The volcanics which were exposed to heat from the stock show few if any changes that can be distinguished from those caused by the regional main or retrogressive metamorphism; thus it is probable that the heating at the contact caused nothing more than minor recrystallization.

Since, in the foregoing paragraphs, the Loomis stock is referred to as igneous, while elsewhere in the paper, somewhat

similar granitic rocks are described as the products of granitization, it seems advisable to support these opposed interpretations as completely as possible. Therefore, evidence indicative of the igneous origin of the Loomis stock will be presented here and the signs of granitization will be described later in their appropriate place. Internal evidence will be considered first. An igneous origin is suggested by the uniform mineralogical composition of the Loomis stock. The samples examined were collected from scattered localities, but their composition varies only within narrow limits. Most of them are granodiorite, while a few are quartz diorite. The difference is chiefly due to a moderate variation in the amount of orthoclase present. In view of the considerable diversity in composition of the sediments and volcanics that would necessarily have been the parent material if the stock were a product of replacement, such uniformity would be most unexpected. The minerals, moreover, include none which are peculiar to metamorphic rocks except those that evidently have their origin in the late retrogressive metamorphism and replace earlier igneous minerals. Uniformity is also a characteristic of the grain size and of the texture. No particularly fine or coarse grained varieties were found. Virtually all of the specimens are medium grained, hypautomorphic granular. No metamorphic features such as crystalloblastic texture, schistosity or gneissose banding

were observed.

Other indications of igneous origin are to be found in the surrounding rocks and in their relationship to the stock. With minor exceptions the metamorphic structural elements in the country rock are approximately parallel to the contact. This parallelism probably indicates that the intrusion of igneous material was controlled by the regional structural fabric. Also, contrary to what might be expected if the stock were a product of replacement, the granodiorite is completely directionless and no metamorphic structural elements can be traced into it. In addition, there is little or no gradation between granitic and country rock. Some of the contacts are virtually knife sharp. The country rock contains no trace of the feldspathization that would have been a necessary part of granitization.

The granitized rocks near Blue Lake are, roughly speaking, centers of relatively high grade metamorphism surrounded by zones of successively lower grade. The metamorphic zones in the vicinity of the Loomis stock form no such pattern. None of the surrounding metamorphic rocks is of a grade higher than the cool mesozone. The stock is in a setting of incomplete and selective epizonal and cooler mesozonal metamorphism - a very improbable location for replacement granite. The metamorphic production of directionless granitic rock requires thorough recrystallization, metasomatism and transformation.

If the conditions necessary to bring about such changes had ever existed at the site of the Loomis stock, they would surely have had some visible effect on the surrounding rocks. Certainly something more than the known limited hornfelsing would be related to the stock or associated with it.

Most of the evidence - mineralogical, textural and structural - strongly supports an igneous interpretation and none of the evidence contradicts such an interpretation.

REPLACEMENT GRANITIC ROCKS

On the east side of Toats Coulee, near Blue Lake, in the southwest part of the mapped area there are two outcrops of granitic rock (Plate I). The northern outcrop is roughly equidimensional and about one half mile in diameter. The other is about one half mile wide at its north end and widens gradually to the south, in which direction it continues for about three miles to the vicinity of Fish Lake. It is believed that the two units are genetically related and perhaps connected at depth, but, to avoid confusion, they will be described separately. They probably belong to Goldsmith's Fish Lake complex (Goldsmith, 1952).

Northern Blue Lake Granitic Body

The northern body forms a knob directly east of the dam

at the north end of Blue Lake. The granitic rock is a little more resistant to erosion than are the surrounding metasediments and metavolcanics. In outcrop and hand specimen it is very light to medium grey, fine to medium grained and directionless. Feldspar and biotite are megascopically visible in most specimens and quartz in some. There is considerable variation in color, texture and composition in specimens from different locations within the unit.

In thin sections the variations among specimens are even more apparent than in hand specimens. Some of the samples have a very nearly igneous appearance, while others show definite indications of metamorphic origin. Though they have minor differences in detail, the igneous appearing rocks can, in general, be described as medium fine grained, xenomorphic to hypautomorphic granular granodiorite. An example contains approximately fifteen percent quartz, forty percent plagioclase, twenty percent alkali feldspar and fifteen percent mafic minerals. Some have a few percent of muscovite or sericite. The mafic minerals are hornblende, biotite and epidote. In most specimens nearly all of the hornblende has been replaced by biotite and epidote. The plagioclase, which ranges in composition from about An_{20} to An_{45} , commonly has normal or oscillatory zoning. It is occasionally in the form of glomeroblasts and porphyroblasts with crenulated borders and numerous inclusions, but the bulk of the plagioclase crystals are reasonably well formed. The

alkali feldspar includes orthoclase and microcline and is in part microperthitic.

There is considerably more variation among the less igneous appearing specimens. Their texture, grain size and composition are less similar and uniform. Individual crystals tend to be poorly formed. A single thin section may contain tiny, amoeboid porphyroblasts of quartz and feldspar and large, nearly euhedral plagioclase porphyroblasts as well as many of intermediate development. The feldspar porphyroblasts commonly surround and include grains of quartz, hornblende, biotite and epidote (Figures 12 and 14). The plagioclase is less often zoned in these rocks than in the more igneous appearing ones, but has a similar range of composition. Only small amounts of potassium feldspar are present, usually in the form of microcline. Biotitization of hornblendes is far advanced. In spite of the considerable compositional variety most of these rocks can be classified as quartz diorite.

The nearby country rocks include most of the types described in the chapters on metasediments and metavolcanics, such as altered andesite, greenstone, amphibolite, metaconglomerate, phyllite, schist and blastomylonite. On the whole, they differ from similar rocks to the north and east in being of a higher metamorphic grade and having undergone somewhat more deformation. Whereas most of the rocks which are farther from the Blue Lake granitic bodies belong to the epizone and

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1 mm

(A)



(B)

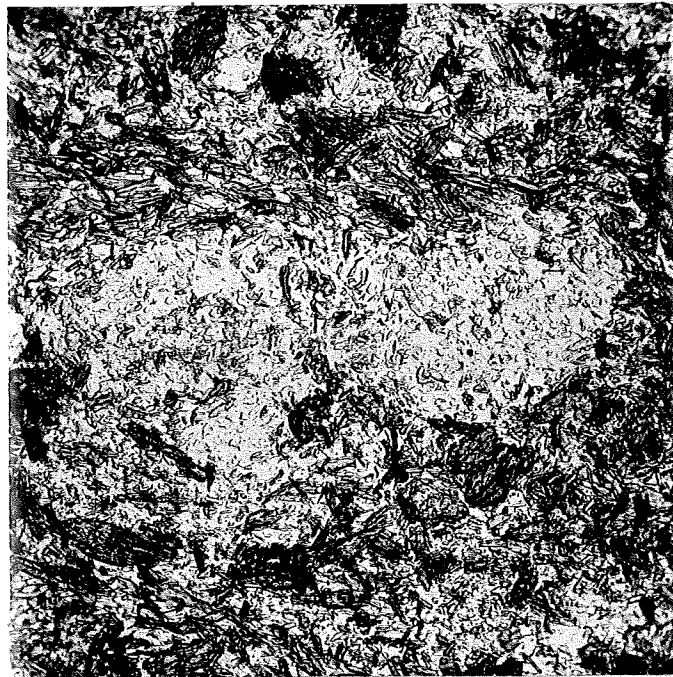
Figure 12

cool mesozone, those that are nearby contain minerals characteristic of the warm mesozone or even of the katazone. These higher temperature minerals include diopside, traces of vesuvianite, and such less definitive minerals as hornblende, biotite and andesine. Though the metamorphic grades of most of the rocks are not precisely defined, the minerals and their combinations are indicative generally of mesozonal and, locally, of warmest mesozonal temperatures. Even in the rocks with relatively well developed foliation, some of the well formed crystals of the higher grade minerals are unoriented and, therefore, postkinematic. The static metamorphism appears to have reached as high a grade as the synkinematic phase and was probably locally a little higher. That this part of the area was more strongly deformed is indicated by the presence of well sheared conglomerate, schistose amphibolite and blastomylonite - none of which were found to the north and east. There is, furthermore, a higher proportion of schistose, as opposed to structureless, metasediments. Still, however, some of the sediments and most of the volcanics failed to develop noticeable foliation.

Most of the amphibolites and amphibolitic schists in this southwest part of the area appear to be derived from sediments rather than volcanics. Most of them contain appreciable quartz - ten to twenty-five percent - which

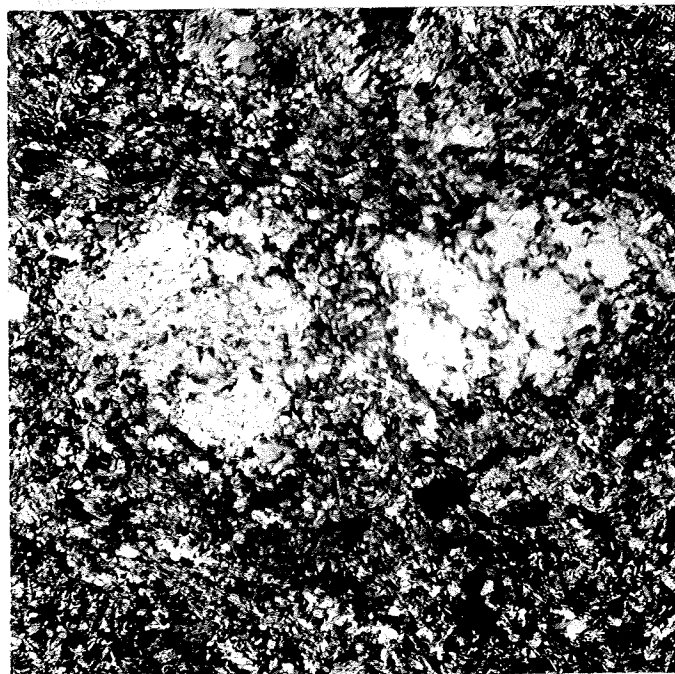
would not be available from andesite or basalt, and some contain seventy to eighty percent amphibole or roughly two to three times the amount in most of the volcanics. Some, moreover, have faint to strong compositional banding which is probably mimetic after bedding.

The granitic body and the rocks in its immediate vicinity and to the south are, to a greater or lesser extent, feldspathized. Porphyroblasts vary from minute, ill-defined growths (Figure 13) to large, inclusion-filled insets with crenulated growth-borders (Figure 14) and, finally, to nearly euhedral, clear crystals. Some of these last could easily be taken for igneous phenocrysts, were it not for their association with other porphyroblasts in all stages of development, their retention of a few inclusions of metamorphic minerals, or, at times, their presence in rocks of evident sedimentary origin. Most of the porphyroblasts are plagioclase which sometimes has normal or oscillatory zoning. In the volcanics, where a valid comparison can be made, the plagioclase is more sodic than the original igneous plagioclase. For example, an altered andesite with igneous plagioclase of the composition An_{35} , contains porphyroblasts with a composition of An_{27} . Some porphyroblasts in the granitic rocks and a few in the country rocks near the contact are microcline or orthoclase.



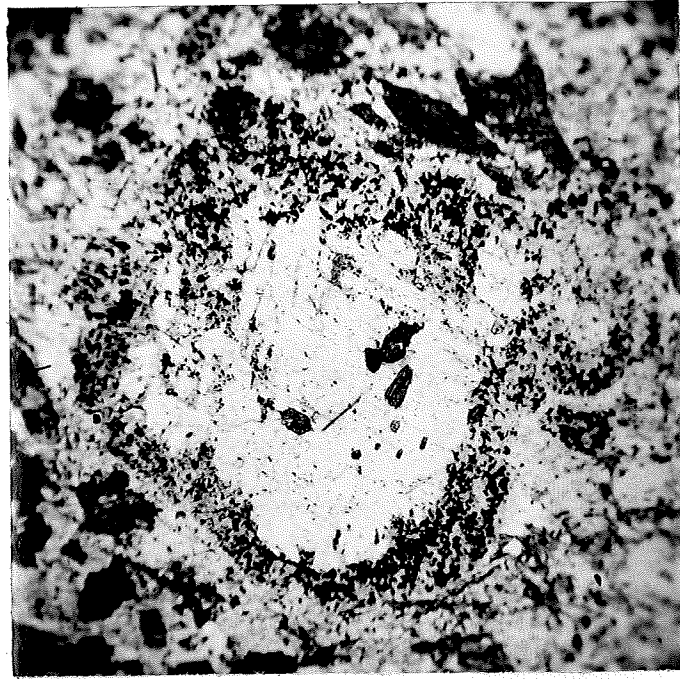
(A)

1 mm



(B)

Figure 13



(A)
1 mm



(B)

Figure 14.

The contacts of the northern Blue Lake granitic body are fairly well defined but not sharp. The narrowest transition zone observed occupies about one foot. In this distance fine grained schist gives way to what, in hand specimen, looks like a fine grained granitic porphyry. Under the microscope it may be seen to consist largely of rather uniform sized plagioclase porphyroblasts about two to three millimeters long. Some are nearly euhedral and clear while others contain inclusions and are poorly formed. They are set in a matrix of fine grained quartz and biotite and small, mostly incipient, plagioclase porphyroblasts. The contact at another place is a zone of transition about ten feet wide. Here the country rock is para-amphibolite and the granitic rock is fine grained hypautomorphic granular quartz diorite. The two differ only slightly in composition. The mafic assemblage of the quartz diorite includes epidote, part of which is enclosed in feldspar porphyroblasts. At another locality the four rocks shown in Figure 15 were collected from isolated outcrops distributed along a line one hundred feet long, roughly at right angles to the contact. The first is an altered andesite containing a small amount of quartz that may have been metasomatically added. The second is also an altered andesite, but it contains megascopically obvious feldspar patches. In thin section under plane light these patches are faintly discernable, very irregu-

lar, inclusion filled plagioclase porphyroblasts. The third is a fine grained, uneven textured quartz diorite. It apparently differs in composition from the altered andesite only in that it contains a significant amount of quartz and a trace of microcline and microperthite. The last is a medium fine grained hypautomorphic granular granodiorite. Some of the plagioclase is nearly euhedral. The rock contains about twenty percent orthoclase and microcline. It seems possible that the granitic rocks developed from the volcanics through recrystallization, feldspathization and addition of silica. However, the evidence supplied by the four specimens is neither complete nor continuous enough to conclusively demonstrate this. It does, nevertheless, suggest a progressive growth and development of the plagioclase, and a possible increase in its amount, as well as a definite increase in the amount of alkali feldspar.

Both field and petrographic evidence indicate that this body of granitic rock was formed in place by processes of granitization. It lacks many of the characteristics of an igneous intrusion. It has no sharp contacts, no concentric contact metamorphic zone, no chilled borders, and does not have widespread uniform textures or mineralogy. On the other hand, there are numerous affirmative indications of granitization. The contacts are more or less gradational. Specimens taken from various parts of the transition zone

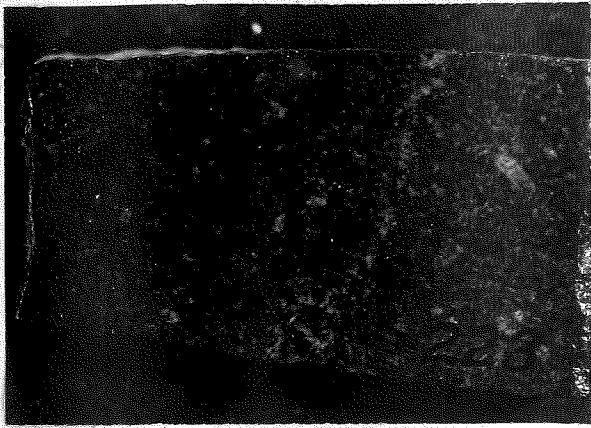
Figure 15. Macrophotographs of rock slices from specimens taken at intervals along a line roughly at right angles to the contact of the northern Blue Lake granitic body. The scale is indicated on each picture.

(A) An altered andesite. Changes include replacement of part of the original hornblende by biotite, chlorite and epidote. The rock contains a few percent of quartz which may have been metasomatically introduced.

(B) A somewhat more strongly altered andesite that contains very vague and poorly formed feldspar porphyroblasts which are full of inclusions.

(C) A xenomorphic quartz diorite with uneven texture and mineral distribution. It contains small amounts of microcline, orthoclase and microperthite.

(D) Hypautomorphic fairly even textured granodiorite.

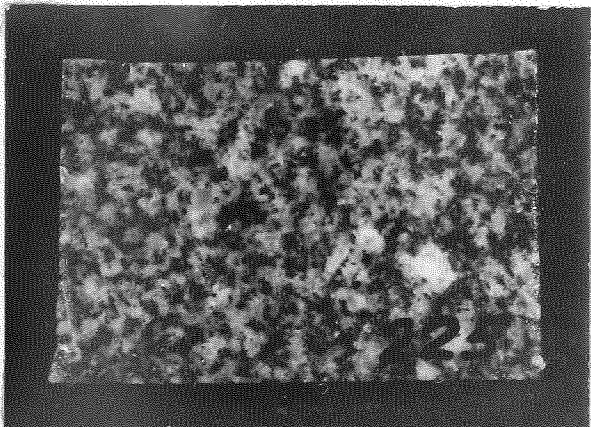


(A)

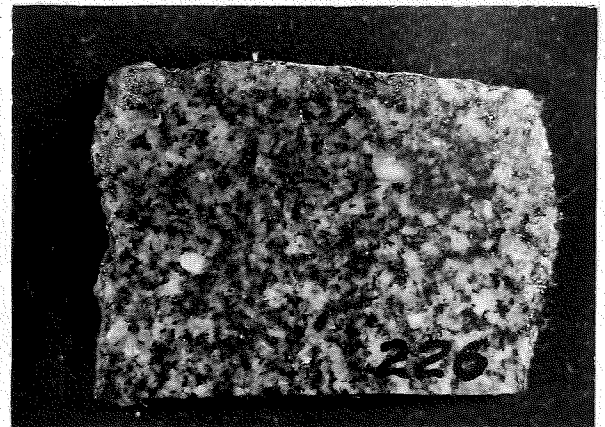


(B)

1 cm



(C)



(D)

Figure 15

appear to represent different stages in the development of the granitic rock. The first sign of this development is the appearance of incipient plagioclase porphyroblasts in the metasediments and metavolcanics. Particularly to the south, some of the porphyroblasts occur at a considerable distance from the granitic outcrop. At least a part of them are apparently due to sodium metasomatism. Metasomatism also supplied potassium to biotitize hornblende and probably to cause the formation of orthoclase and microcline in locally appreciable quantities in the granitic rocks and in very limited quantities in the country rock. Unfortunately, most of the potassium feldspar is in relatively well crystallized granitic rocks, where evidence of growth in place has been largely destroyed. However, the near-contact occurrences that were studied could, most reasonably, be interpreted as products of replacement. There may have been addition of silica from an outside source, but this would not be necessary. Some of the sediments contain an abundance of quartz, which, by local redistribution, could have made up any silica deficiency in the other sediments and the volcanics. Thus, through the recrystallization and metasomatism, which are seen in their primary and intermediate stages in the country rock and the contact zones, directionless granitic rock is finally formed. This transformation of a heterogeneous group of sediments and

volcanics does not, of course, produce a very uniform body of rock. Textures of the granitized rock range from obviously crystalloblastic through uneven xenomorphic granular to igneous appearing hypautomorphic granular. Potassium feldspar or quartz may be present in fairly large or in small quantities, or they may be absent from the mineral assemblage. Similarly, the plagioclase and mafics vary markedly in abundance. Finally, significant support of a granitization interpretation is found in the areal distribution of metamorphic grades. Although the granitic body is roughly at the center of the area of highest grade metamorphism, the metamorphic zones are not arranged closely and concentrically about it as if in response to contact heating. On the contrary, the isograds are widely spaced and somewhat irregular. Their configuration bears no direct relationship to the granitic body. The granitic rock is situated where the most heating occurred and where the greatest mobility of ions, atoms and molecules would be expected. Its location is a result rather than a cause of the distribution of metamorphic grades.

Southern Blue Lake Granitic Body

The second granitic body in the southwest part of the mapped area is about a mile south of the one just described.

Its boundaries, as shown on the accompanying geologic map, are somewhat arbitrary. The map indicates the limits of both directionless and gneissose granitoid rock. The boundary line, thus located, unavoidably includes some metasediments that are only slightly or very incompletely granitized. The east boundary in particular is loosely defined.

These granitic rocks, as do the others in the area, stand a little above the surrounding metasediments and metavolcanics. This topographic expression of superior resistance to erosion is very slight, however. In outcrop and hand specimen the granitic rocks are light grey, fine to medium grained, and range from gneissose to directionless (Figure 16). Feldspar, quartz and biotite are megascopically identifiable in most of them. The banding of the gneissose rocks is continuous or parallel with the structure of nearby foliated metamorphic rocks wherever the relationship could be determined. Some of the banding may be traced into the granitic body and is finally lost in directionless crystalline rock.

The granitoid rocks that exhibit metamorphic structure include gneissose granulite (Figure 16A) and recrystallized paragneiss (Figure 16D). The granulite is of quartz dioritic composition. It contains sodic andesine and quartz, and lesser amounts of biotite, chlorite, epidote, muscovite

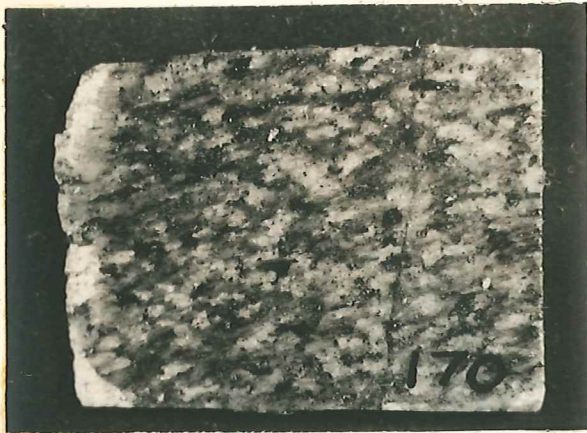
1. The first part of the report is devoted to a general survey of the situation in the country.

2. The second part of the report deals with the economic situation and the measures taken to improve it.

3. The third part of the report is devoted to the social situation and the measures taken to improve it.

4. The fourth part of the report deals with the cultural situation and the measures taken to improve it.

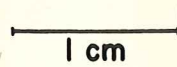
5. The fifth part of the report is devoted to the political situation and the measures taken to improve it.



(A)



(B)



(C)



(D)

Figure 16

and sphene. Some of the plagioclase is relatively well formed but much of it is in porphyroblasts. Part of these porphyroblasts are no more than incipient. Similarly, a large part of the quartz is in irregular segregations and amoeboid porphyroblasts. The biotite and epidote are closely associated, suggesting the formation of both from hornblende. The banding has the same attitude as the foliation of schists which occur on strike to the north. The paragneiss has a somewhat similar composition, but contains no muscovite and only a few percent of mafics. In the field the gneiss is interlayered with fine grained hornblende schist. The layers and the metamorphic structures within them are all essentially parallel. Actually the banding of both the granulite and paragneiss is now largely mimetic; for postkinematic recrystallization has destroyed much of the mineral alignment.

The directionless granitic rocks which were studied vary from quartz monzonite (Figure 16B) to quartz diorite (Figure 16C). The quartz monzonite contains about forty percent plagioclase of the composition An_{30} , thirty-five percent microcline, ten percent quartz and fifteen percent mafic minerals. The mafics are biotite, epidote, and remnants of hornblende that have escaped biotitization. The quartz diorite is approximately sixty percent oligoclase, thirty-five percent quartz, and five percent biotite with very minor calcite and sericite. The textures are very

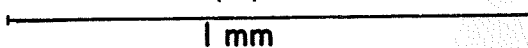
nearly igneous appearing and would probably be described as such in the absence of other evidence of metamorphic origin. Most specimens contain only such minor indications of replacement as inclusion of earlier calcite and epidote grains in plagioclase and occasional small patches which show a fabric suggestive of crystalloblastic growth.

The nearby and associated metamorphic rocks are similar to those near the granitic body just to the north. They include fine grained schist, greenstone, greenschist, hornblende schist, massive and schistose amphibolite and altered volcanics. A large portion of them are foliated and, in general, the foliation is better developed than it is elsewhere in the area. Postkinematic recrystallization has, however, destroyed much of the crystal alignment. This static phase may have been of slightly higher grade than the synkinematic crystallization, but generally appears to have been about the same. There are numerous indications of feldspathization in the rocks within and near this granitic area (Figures 18 and 19), and between this and the granitic body just to the north (Figure 13). Most of the feldspathization has produced plagioclase porphyroblasts and reflects sodium metasomatism. Near the contact some irregular patches and incipient porphyroblasts of orthoclase and microcline were found in recrystallized schists (Figure 17). The potassium metasomatism which they suggest is probably also

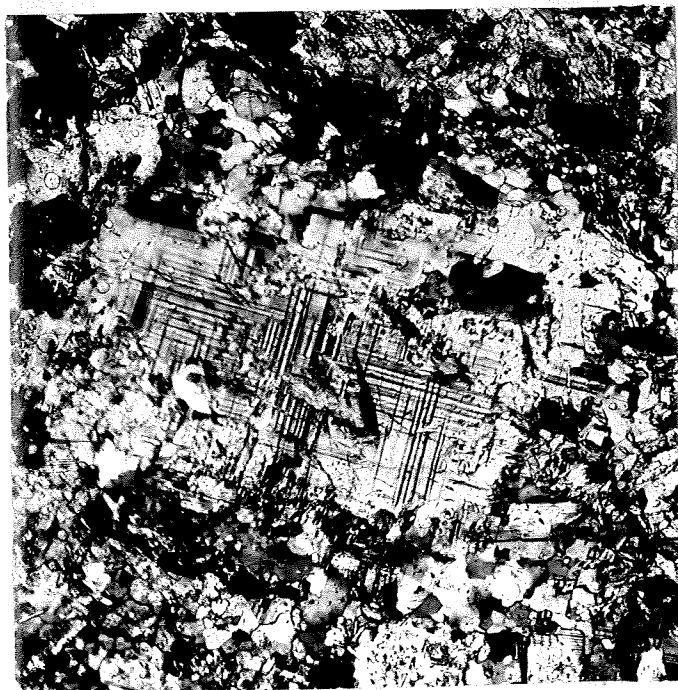
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(A)



1 mm



(B)

Figure 17

Faint, illegible text, possibly bleed-through from the reverse side of the page.

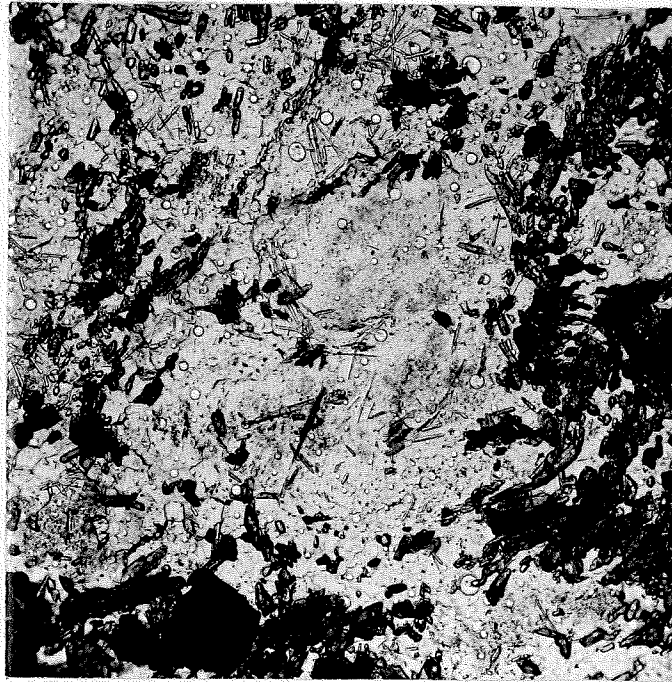


(A)
1mm



(B)

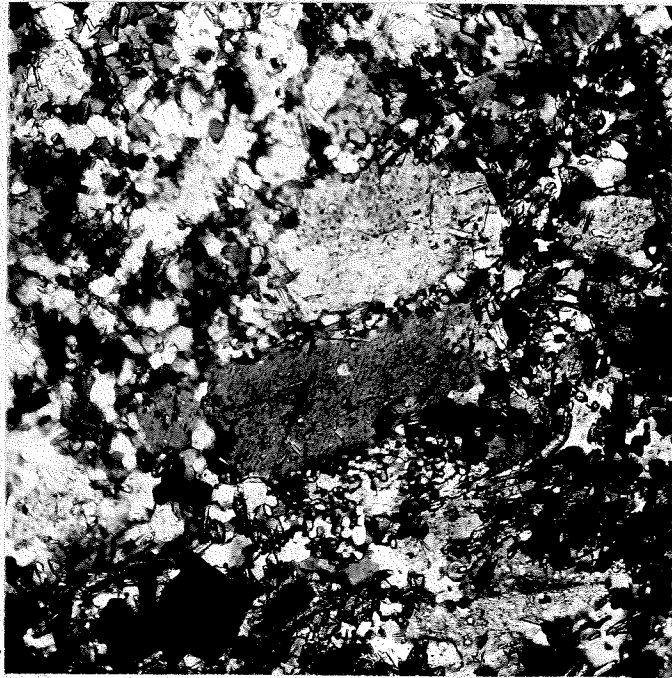
Figure 18



(A)



1mm



(B)

Figure 19

responsible for the rather extensive biotitization of hornblende in this vicinity.

Most of the evidence offered in support of a granitization interpretation of the northern Blue Lake granitic body may be used equally well to support the same interpretation for this southernmost granitic rock. Although it is very poorly exposed, the contact appears to be gradational. Feldspathization and recrystallization are evident in some of the metamorphic and granitic rocks. Crystalloblastic features are locally apparent in the granitic rock which also exhibits a significant lack of mineralogical and textural uniformity. The location of this granitic body relative to the metamorphic isograds is similar to that occupied by the granite just to the north. Finally, in addition to the indications of granitization which are common to both units, external metamorphic structures continue undisturbed and can be traced into the southern granitic body until they are lost in directionless rock. By itself, this feature virtually rules out the possibility of forceful intrusion and, combined with the other evidence, it permits no alternative to interpreting the granitic rock as a product of replacement.

METAMORPHIC ZONES

One of the results of the petrographic study was the deduction of the metamorphic history of the various rock types of the area through the study of many individual specimens. An important part of this historical reconstruction was determination of the metamorphic grade to which each specimen was subjected. By plotting this information on a map and using it as a basis for contouring, it has been possible to draw isograds or lines of equal metamorphic grade (Plate I). These lines thus indicate the distribution and limits of the various metamorphic zones. They are not, of course, to be considered exact limits, but it is felt that they are a reasonable representation of the known facts, and that no gross errors will be found in their placement.

Zonation is based on the presence of certain index minerals and mineral combinations. The most useful were chlorite, sericite, biotite, muscovite, hornblende, plagioclase subdivided according to its composition, diopside or vesuvianite in a few rocks and, to a limited extent, potassium feldspar and the epidote minerals. Since all of these have a more or less broad range of stability, combinations were used whenever possible to obtain the best definition

of metamorphic grade. Most rocks can, with reasonable certainty, be placed either in the epizone or in the mesozone, while only a very few specimens carry minerals suggestive of the katazone. These last, moreover, are, according to their associated minerals, products of the coolest katazone or perhaps only the warmest mesozone. Mineral combinations permitted similar relatively exact assignment of other specimens, for example, to the middle mesozone or to the vicinity of the epizonal-mesozonal boundary. However, for the majority of samples only a range could be determined. This necessitated a somewhat statistical approach to the drawing of isograds.

In addition to the main phase of metamorphism which varied in grade more or less systematically over the area, a subsequent stage of low grade retrogressive metamorphism was uniformly super-imposed. It resulted in the partial to almost complete reduction of higher grade or previously crystallized minerals to chlorite, sericite and other low grade minerals, often in very fine grained and sometimes unidentifiable form. This alteration has the effect of obscuring textures and structures and making mineral identification and composition estimation difficult or uncertain. As far as possible, the effects of this retrogression were separated from the main metamorphism and were not considered in the delineation of metamorphic zones.

In the vicinity of the Loomis intrusive stock, there was also some contact metamorphism superimposed on the regional metamorphism. An attempt was made to eliminate the contact effects by relying chiefly on synkinematic minerals for the determination of metamorphic grade. There is, nevertheless, a rough similarity between the shape of the stock and the configuration of one of the isograds. It is not believed, however, that the isograd reflects contact effects, but, rather, that the distribution of regional metamorphic grades was determined by structural trends which controlled the movement of heat and which subsequently also controlled the emplacement of the stock. The stock and the isograd are, therefore, related only in that the shape of each was, to some extent, determined by the same controlling factor - namely, structural fabric.

The isograds are based, essentially, on the highest grade minerals that can be related to the regional metamorphism. It is not suggested, however, that all of the minerals in all of the rocks were at one time of the grade indicated by the isograds, for the metamorphism was both selective and incomplete in most of the area. Particularly in those rocks which did not suffer penetrative deformation such as the coarse grained clastics and the still massive volcanics, many of the constituents failed, at least in part, to respond to the metamorphic conditions. Shearing

was evidently needed to trigger some of the reactions and, since deformation was not intense, many potential transformations did not take place.

SUMMARY OF GEOLOGIC HISTORY

The geologic history of the mapped area, as it has affected the rocks that may be seen there now, began with the deposition of sediments and the outpouring of volcanics in a eugeosynclinal trough. The age of the geosyncline and of the sediments and volcanics it contains is uncertain. Misch and his students have established the fact that the Alkali Lake carbonates to the south are stratigraphically lower than these rocks. It appears that the carbonates may be upper Triassic. The eugeosyncline, which surely became active in this area after the carbonate deposition, is, therefore, probably post-Triassic. The sediments and volcanics, separated as they are from the carbonates by the Evans Lake and Scotch Creek formations, must also be post-Triassic and may be Jurassic.

Deposition was followed by orogenic deformation during which penetrative movement and heating regionally metamorphosed the bulk of the rocks essentially to their present state. The time of this deformation, is also in doubt. The Cascades experienced major pulses of orogeny at least from earlier Mesozoic until early Tertiary time. The deformation of this particular locality, of course, followed the deposition of the clastic sediments, which, in turn, came after

the questionable Triassic deposition of the Alkali Lake formation. It is probably, therefore, post-Triassic, but there is no evidence to refine the dating further.

Granitization, though related, as a part of a continuing process, to the deformation and associated regional metamorphism, was essentially postkinematic. Its age is only slightly less than that of the deformation. The igneous granite of the Loomis stock was probably implaced at about the same time as, or perhaps slightly later than the granitization was taking place, for its contact metamorphic effects appear to be superimposed on those caused by the synkinematic regional metamorphism. In turn, the granitic rock was subjected to the late retrogressive metamorphism. Replacement granite formed at depth during regional granitization may have been mobilized and injected to produce the Loomis stock.

After the rocks and their structures were formed, the area participated in the epirogenic movements of the Cascades, during which uplift and erosion alternated with local deposition of such formations as the Eocene Swauk and Roslyn and the Mio-Pliocene Ellensburg. The area was brought to its present elevation during Pliocene time. Pleistocene ice movement and glacial runoff shaped the coulees and modified the remainder of the landscape, thus bringing the topography very nearly to the form it has to-

day. Subsequent erosion has made only local and minor changes.

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