GEOLOGY
OF
PART OF THE SOUTHEASTERN WALLOWA MOUNTAINS, NORTHEASTERN OREGON

by

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ABSTRACT

Within 40 square miles of the southeastern Wallowa Mountains, Oregon, eugeosynclinal Permian and Triassic formations comprising a section about 25,000 feet thick have been exposed by uplift and erosion of overlying Miocene Columbia River basalt. Deposition appears to have been continuous from Permian into Upper Triassic, but an apparent angular unconformity exists between Triassic formations. Neritic clastics of the Permian Trinity Creek formation are overlain by mixed volcanics and clastics of the Triassic Imnaha formation, which is terrestrial and littoral in its lower Russel member and neritic in its upper Norway member. Sandstone and conglomerate of the Upper Triassic Lower Sedimentary Series apparently rest unconformably on deformed pillow lavas and breccias of the Norway member.

A varied suite of small stocks intrudes the area. Gabbroic units of the Fish Lake complex are most widespread; other stocks are composed of metadiorite, keratophyre, bostonite, and trondjemite. Varied dikes are extremely abundant in older formations.

Marble and skarn of uncertain age, but believed unrelated to the Imnaha or Trinity Creek formations, are intimately associated with gabbroic stocks.

Deformation increases from east to west, and culminates with an overturned anticline in the Upper Triassic Lower Sedimentary Series at the western margin of the area. Faulting is minor except for the Pine Creek reverse fault which has a minimum vertical displacement of 2500 feet.

Alpine topography resulted from Pleistocene stream erosion and glaciation; post-Pleistocene erosion has not been extensive.

GEOLOGY

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The purpose of this thesis is to set forth the nature of a varied suite of rocks in a small area of the southeastern Wallowa Mountains; to show the relation of this suite of rocks to the regional development of the geologic environment in which they are found; and to map accurately the limits of the various units within the area so that later workers may continue with more detailed study of various problems.

The area consists of approximately forty square miles in northeastern Oregon between 117°04' and 117°16' W. longitude and between 45°01' and 45°06' N. latitude. Portions of Baker and Wallowa counties are included. (Figure 1) Entry into the eastern edge is provided by a gravel surface road from the town of Halfway, Oregon; other parts of the area may be reached only on foot or by horseback.

A mountainous region of late youthful topography, the area has a maximum relief of 4215 feet, and maximum elevation of 9555 feet. An integrated drainage system has not developed. Drainage is accomplished by numerous small streams, many of which are raging torrents in early spring

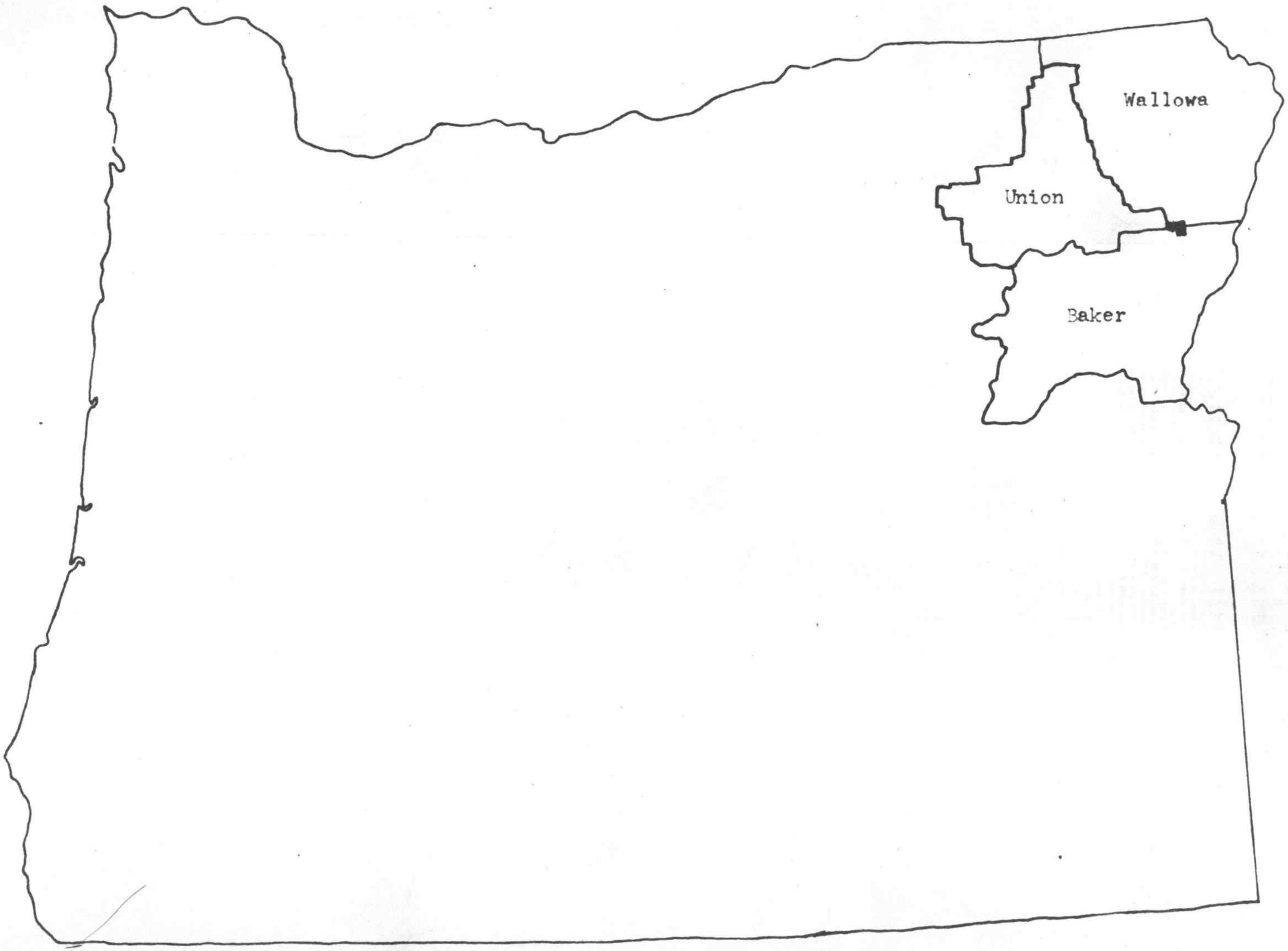


Fig. 1 Outline map of Oregon showing thesis area as black insert.

but completely dry by August. Short summers and heavy winter snowfall limit the field season from mid-June to late September. Areas below timberline, particularly in the canyons, are thickly covered with a heavy growth of evergreen timber and underbrush.

Field work was done during the summer of 1958, from June 12 to September 15. U. S. Geological Survey advanced topographic sheets of the Cornucopia and Eagle Cap Quadrangles were used as base maps, and the geology was plotted at a scale of 1/48,000. Finished maps were enlarged to 1/24,000 to provide room for legible structural symbols.

Previous geologic work in the area is limited. C. P. Ross (22) made a reconnaissance map of a large area in the southern Wallowas, including the thesis area, in 1918; his report was published in 1938. Roland K. Reid (21) studied approximately eight square miles around Fish Lake in 1953. Other work in the Wallowa Mountains outside of the thesis area is included in the bibliography.

During field work, the writer experienced difficulty in differentiating between glacial moraine and other unconsolidated material. Errors were called to his attention after the field season was so far advanced that remapping of such deposits was impossible. Areas covered by glacial veneer had been included as morainal deposits. Where justified by known exposures of rock, such alluvial contacts were redrawn from aerial photographs. Therefore, contacts of Quaternary alluvium except in Cliff River, East Pine, and Clear Creek canyons, can be only approximate.

Laboratory work was limited to the examination of 252 thin sections and to determinations of pyroxene composition for the Fish Lake complex by oil immersions. Composition of plagioclase was determined by symmetrical extinction of albite twins.

Modal analyses of igneous rocks were made with a point counter after the method of Chayes (4, p. 1-11). Traverses were made over the entire slide, and the total number of points per slide varied from 1500 to 2200. Percentage composition of sedimentary rocks was computed from a series of traverses with a Wentworth integrating stage.

Fossil identifications were made by S. W. Muller of Stanford University.

TABLE I

SUMMARY OF STRATIGRAPHIC UNITS

Age	Formation	Lithology	Thickness
Quaternary		alluvial valley fill	variable 1-200' (?)
	Unconformity		
Quaternary		glacial moraine	
	Unconformity		
Miocene	Columbia River basalt	basalt flows	appx. 1500'
	Unconformity		
Upper Triassic	Lower Sedimentary Series	thin-bedded marine sandstone, siltstone with minor conglomerate	3000-5000'
	Unconformity (?)		
Triassic	Imnaha formation		
	Norway member	predominantly spilitic pillow lavas and coarse jumbled breccias with bedded units near base	6000-8000'
	Blue Creek lentil	crystal tuffs, fine conglomerate, sandstone, and siltstone	max. 1400'

Age	Formation	Lithology	Thickness
	Russel member	lava flows, coarse conglomerate, angular breccias of meta-andesite and metabasalt	10-15000'
	Sugar-loaf lentil	volcanic sandstones, and conglomerate cemented by extensive matrix of calcite	600-800'
Permian	Trinity Creek formation	feldspathic wacke conglomerate, and siltstone	6500-7000'
(?)	Marble	small lenses around intrusive borders	300' (?)

STRATIGRAPHY

The Wallowa Mountains contain a thick section of Permian and Triassic rocks, but only the lower part of the section is exposed in the area covered in this thesis. In contrast to the previously known Permian Clover Creek greenstone, Permian rocks in the thesis area comprise a thick marine sedimentary sequence, herein called the Trinity Creek formation. The Trinity Creek formation is succeeded by the Imnaha formation, including the Russel and Norway members, and the Lower Sedimentary series.

No apparent break is recorded between the Permian sedimentary sequence and the overlying Triassic Imnaha formation which is composed of mixed volcanics and coarse conglomerate, and believed to be, in part, terrestrial.

The Permo-Triassic boundary, a profound unconformity throughout much of the world, here lies within several thousand feet of apparently continuously deposited rocks, separating fossil horizons for which Permian and Triassic ages have been determined. The environment of deposition is believed to have changed from neritic to littoral or terrestrial after the onset of extensive vulcanism, but no break in deposition is recognizable. Interfingering of the Imnaha and Trinity Creek formations south of Fish Lake and the presence of glomeroporphyritic andesite boulders in the upper Trinity Creek formation which are characteristic of the overlying Russel member of the Imnaha formation indicate that deposition was continuous. Small lost intervals may be overlooked in a terrestrial formation, such as the Russel member of the Imnaha formation, but certainly no major unconformity is present.

Triassic units, the Imnaha formation and Lower Sedimentary Series, are separated by an angular unconformity within the thesis area. Extent of this unconformity is not known because of juxtaposition with a major fault. Possibly the unconformable relation exposed in the area is the result of deformation in conjunction with faulting.

The following correlation chart is a compilation taken from published correlation tables for the Triassic of the United States and Canada. (15,20) It is presented to show the relation of the thesis area to the development of the Permo-Triassic eugeosyncline in the Frazer belt, and is not meant to imply absolute equivalency in either time or lithology. However, lithologic similarities for certain parts of the column throughout the eugeosyncline belt are fairly consistent, and the sequence exposed in the thesis area fits the regional pattern.

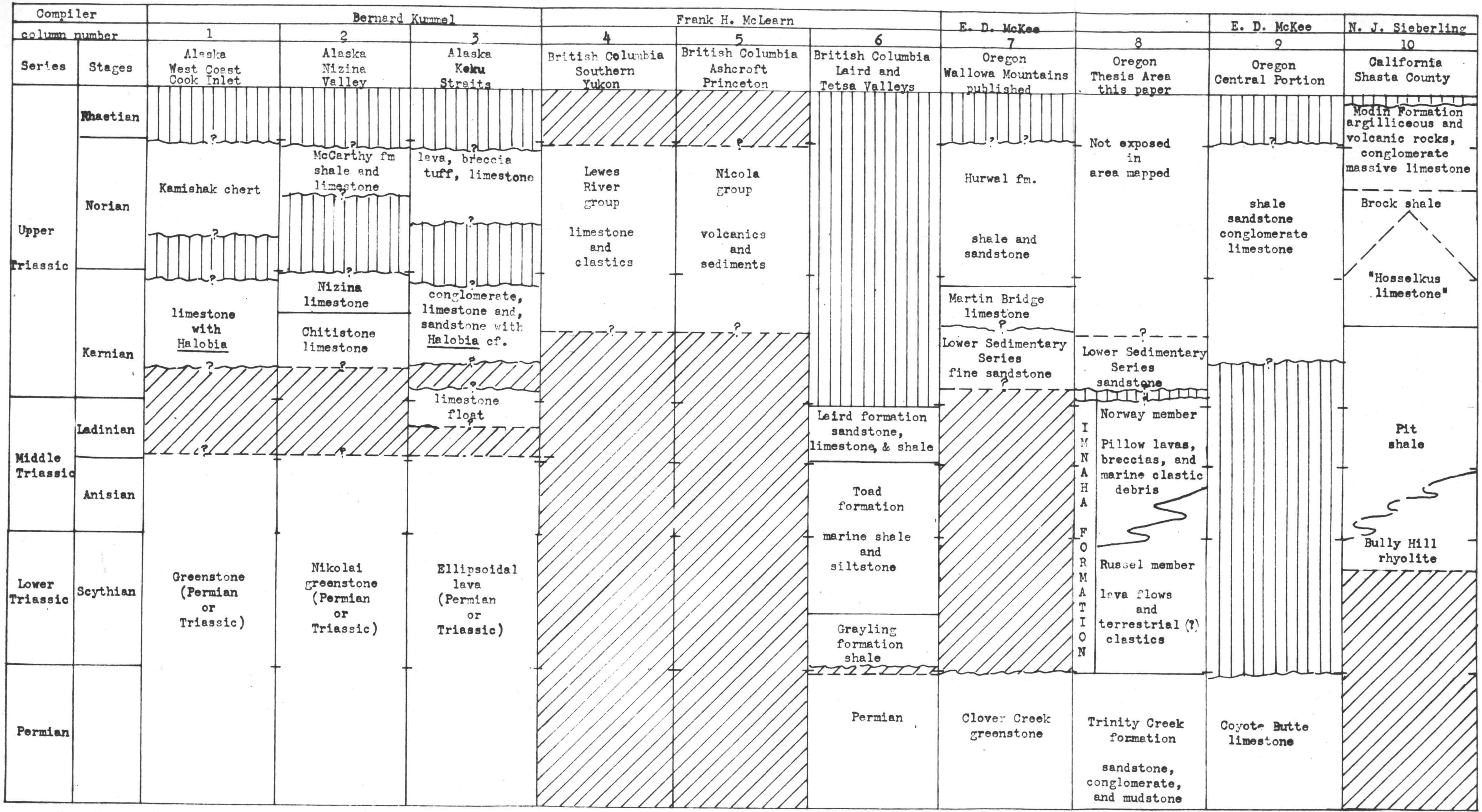


Fig. 2 Correlation chart showing relations between the thesis area and other parts of the Frazer belt. Vertical lines represent known unconformity. Slanted lines indicate lack of information. Columns 1-3 7,9&10 from (*20*, p. 1451-1514) Columns 4,5 &6 from (15, p. 1205-1228)

STRATIGRAPHIC UNITS

The lithology and stratigraphic relations of each stratigraphic unit shown on the geologic map (Pl-1) are described below. Correlation of these units with the regional stratigraphy and structure is discussed in separate sections.

Marble

This section concerns only those isolated bodies around the perimeter of Clear Creek stock; it does not include marble lenses, or calcareous sediments found in other stratigraphic units.

Distribution and Expression

Six small irregular units of contact marble are present at intervals around the Clear Creek stock. Reid (21) mapped similar marble units along the borders of a gabbroic stock east of the thesis area. The marble is exposed in low, rounded outcrops with distinctive weathered surfaces. Gradation from marble to skarn exists in the only outcrop where the two are in contact, in the NW¼ sec. 17, T. 6 S., R. 46 E.

Petrography

The marble is light blue gray with irregular dark streaks and patches present in a few outcrops. Weathering has roughened the surface, producing fluted grooves. Jointing is well developed, generally parallel to foliation of the dynamo-thermal aureole. Reid (11, p.34) described isoclinal folding in the marble, but the writer failed to recognize any bedding or other markers by which folding could be traced.

The marble effervesces freely in dilute HCl. Texture is granular, but individual grains are generally too small to recognize with a hand lens. Rarely the marble is coarsely crystalline with calcite crystals up to 3/4 inch across.

C. P. Ross (22, p. 29) described a chemical analysis of the marble from T. 6 S., R. 46 E. as follows: "The marble contains 32.84 percent lime, 20.52 percent magnesia, 46.60 percent carbon dioxide, with traces of iron oxides and water, a total of 99.96 percent."

The assemblage fosterite-periclase-calcite, typical of magnesian marbles of the pyroxene hornfels facies (30, p. 429), is characteristic of these units. Twinned calcite, in anhedral to subhedral grains, constitutes about 90 to 95 percent of the rock. Only occasional remnants of isotropic periclase are present in conspicuous rounded patches of brucite. Small drop-like crystals of fosterite and garnet, revealed by high relief, are scattered throughout the rock. Fosterite is largely altered to irregular "veined" patches of antigorite; commonly only several isolated fragments of the original crystal remain "floating" in the fibrous mass. Garnet, clear, unzoned, and isotropic, is rimmed by chlorite. Chemical composition of the garnet was not determined.

Accessory minerals are clinohumite, pyrite, and magnetite. Clinohumite forms clear to very pale yellow crystals with fine polysynthetic twinning. Euhedral pyrite cubes are partially altered to limonite.

Thickness

Maximum thickness of the marble is probably less than 300 feet. As no bedding was recognized, accurate measurements were not possible.

Fossil Content

Within the thesis area, marbles are nonfossiliferous because of complete recrystallization. A limited fauna, discovered by W. H. Taubeneck, was collected from similar marble near Twin Lakes. The precise fossil location is SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 2, T. 6 S., R. 14 E. about 50 feet east of the new Twin Lakes road. The fossils were collected from a single stratum near the southern edge of the exposure.

No age has as yet been determined for the fauna.

Age and Stratigraphic Relation

Distribution of the marble around stocks of the Fish Lake complex, and only around the two largest stocks, leaves little doubt that the present position of the marble resulted from intrusion of the stocks. Marble units may be either (a) portions of an underlying stratum, broken and carried up with magma, or (b) a calcareous lens or lenses "shouldered" aside by the intrusive.

The second possibility is open to serious doubt. If the marble units represent lenses in the "greenstone," they would not reasonably be restricted to intrusive borders; similar lenses should be present away from the stocks. Also, lenses should be conformable with surrounding units. Only one of the marble lenses suggests the possibility of conformity with surrounding rock, the elongate mass in NE$\frac{1}{4}$ sec. 17, T. 6 S., R. 46 E., and as it is gradational into skarn which is definitely included in the stock, conformity with the "greenstone" is doubtful. Lenses of equal size were not found in the Imnaha formation; calcareous lenses mapped are much smaller than most of the marble units, and invariably contain scoriaceous cobbles.

No limestone older than Triassic is known in the Wallowa Mountains, but some Permian limestone is known in the Elkhorn Mountains near Sumpter. The nearest known exposure of limestone, in the upper Triassic Martin Bridge formation, lies about 7 miles west of these lenses. If the marble lenses are related to the Martin Bridge or other Triassic limestone, they could only have originated from a lower thrust plate. A regional thrust is described by Livingston (14, p. 32-36) trending northeast from Burnt River, Oregon, to Cuddy Mountain, Idaho, along the Oregon-Idaho border. Along this fault, Paleozoic (?) argillites have been thrust from the northwest over Jurassic shales. The fault can be traced for 40 to 50 miles, and is postulated to extend possibly 125 to 130 miles.

Thrusting of such scale could involve units within the thesis area but no thrusting of such magnitude was recognized during the field work.

If the marble lenses were derived from a thrust plate, the most likely parent would be the Triassic Martin Bridge limestone. However, until a definite age has been determined for the fauna collected from the limestone lens near Twin Lakes, or until further mapping has indicated a thrust fault, no conclusions can be reached as to the ultimate origin of the marble. The lenses are definitely considered to have been carried into place by the intruding magma, but their age may be either pre-Permian, Permian (but pre-Trinity Creek), or Triassic.

Trinity Creek Formation

For purposes of this thesis, the name Trinity Creek formation is proposed informally to designate a thick group of assorted sedimentary rocks, mostly sandstone and conglomerate, which have not heretofore been designated as a stratigraphic entity. This formation was previously included in the Carboniferous (?) sediments by Ross. (12) The double name is retained because "Trinity formation" has been used elsewhere. No permanent formal name is suggested here because total thickness and areal extent of the formation are not yet known. The most typical and consistent outcrops of the formation in the thesis area are found in secs. 16, 21, and 27, T. 6 S., R. 46 E., along Trinity Creek. Attitudes are consistent within the area mapped, but the formation continues for an unknown distance to the south, so that total thickness cannot be computed from known data.

Topographic Expression and Areal Distribution

Outcrops of the Trinity Creek formation are irregular and discontinuous. They occur generally as low rounded protuberances on the tops of ridges and as precipitous bluffs. Because of their extreme induration and extensive jointing, the sedimentary rocks lack any distinctive outcrop pattern or character by which they can be recognized at a distance.

This formation covers the southeastern portion of the thesis area, and occupies a small window exposed through Columbia River basalt near the head of Trail Creek. Outside of the thesis area, the formation extends for an unknown distance to the east and south. It is also exposed near the junction of Trail and Clear Creeks, where the best outcrops along Trail Creek are at elevations between 4800 and 5000 feet. Sandstone, thought to belong to the Trinity Creek formation, is exposed south of Simmons Mountain in the NE$\frac{1}{4}$ sec. 27, T. 6 S., R. 45 E.

Petrography

Lithology of the Trinity Creek formation is extremely varied, both vertically and laterally. Because of variation and discontinuous outcrops, it was not possible to trace any individual unit for more than a few hundred yards laterally. Medium to coarse feldspathic sandstone is the most common rock type. Several different types of conglomerate, in a wide range of size and sorting, are present. Siltstones and mudstones are interbedded with coarser clastics at infrequent intervals, and typical outcrops consist of interbedded sandstone and conglomerate, usually with indefinite gradation between individual beds. Large exposures consisting entirely of one rock type are rare.

To avoid confusion, the major rock types are discussed individually.

Sandstone. Sandstones of this formation are feldspathic and lithic graywackes according to the classification proposed by Gilbert (33, p. 293). Proportions of the main constituents are shown in Figure 3; as can be seen from this diagram, two samples, C-377 and C-378, show a marked increase in quartz content. The quartz content of these two samples becomes more significant when one realizes that they are stratigraphically the lowest samples from the formation; therefore, these two samples are described separately.

The sandstone is usually gray to dark green, depending on the abundance of rock fragments and chloritic material, but light tan to buff beds are common, and distinctive bluish to purple horizons are rare. Coloration is little different on the weathered surfaces than on freshly broken surfaces. Induration is extreme, and therefore true bedding surfaces are difficult to find, though the trace of the beds is often clearly visible. Joint surfaces are extremely smooth, without deflection around the particles; intersecting joints commonly produce sharply mitered corners.

Units of the feldspathic wacke vary from thin beds of sandy material interbedded with coarser conglomerate to

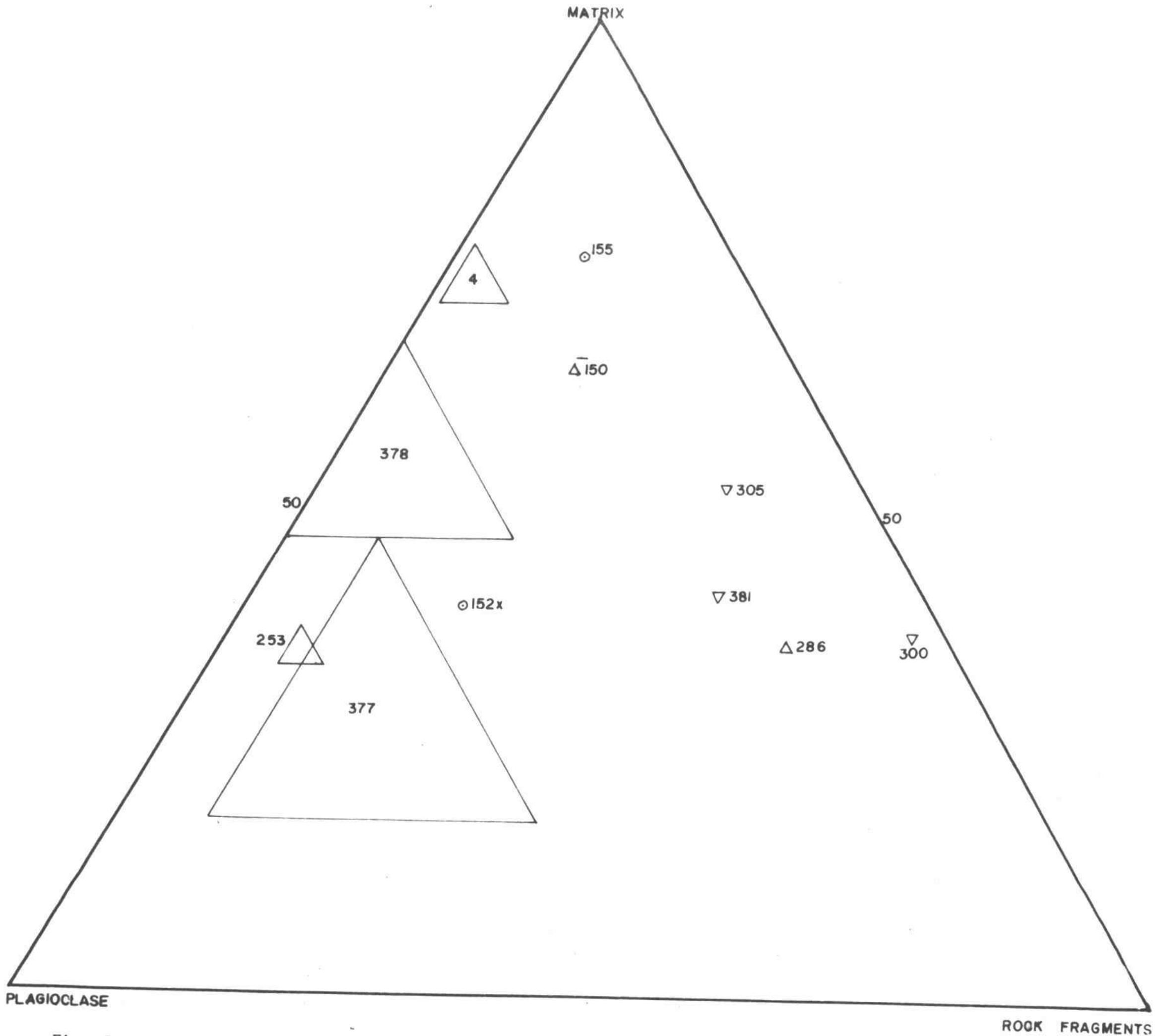


Fig. 3 Triangular diagram showing modal analysis of typical samples of the Trinity Creek formation. The percentage of quartz is indicated by the size of the triangle. Numbers are for samples. Note the large difference in percentage of quartz for 377 and 378.

massive cross-laminated layers 30-50 feet thick. Sorting within individual units or beds is generally moderate to good, or else distinctly graded. Graded bedding is commonly very well defined, but is by no means a universal or characteristic feature of the wackes in this unit. Outcrops of sandstone which grade gradually upward into grit, pebbly sandstone, and conglomerate are common in this area.

Sorting has been most effective in cross-bedded units. In these units, the bedding is defined by thin, dark colored streaks. Most cross lamination is in small lenticular to wedge-shaped units less than 4 feet long, and 1 to 2 feet thick. Outcrops of cross-laminated sandstone are shown in Figures 4 and 5.

Microscopically the sandstones are seen to consist of fragments of plagioclase, fine-grained volcanic rocks, and quartz, in a silicified matrix of finer grains and a recrystallized equi-granular mosaic of quartz and albite with abundant finely divided sericite, chlorite, leucoxene, and occasional irregular crystals of calcite. Relative abundance of the constituents varies, but plagioclase and lithic fragments predominate. The degree of rounding varies from moderate to poor, but in general the scattered quartz grains are somewhat better rounded than either plagioclase or lithic fragments.

Lithic fragments, generally subangular to subrounded

Figure 4. Cross-laminated sandstone in Trinity Creek formation. Location: NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 22, T. 6 S., R. 46 E.

Figure 5. Cross-laminated sandstone of the Trinity Creek formation, immediately overlying coarse well-rounded conglomerate at 6850 feet elevation in SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 22, T. 6 S., R. 46 E.

in these rocks, are predominantly fine-grained or porphyritic volcanics, but chert grains, most abundant in C-305, are present in a few of the slides studied. Volcanic fragments are marked by pilotaxitic or felsitic plagioclase microlites set in a dense accumulation of chlorite and iron ore, or of iron ore alone. Phenocrysts of plagioclase are infrequent, marked by crystal fragments partially enclosed in a much finer ground mass. Only rarely, in some of the larger grains, is a whole phenocryst present. Parent volcanics are believed to have ranged from basaltic to trachytic, as indicated solely by abundance and texture of plagioclase microlites. All mafics have apparently been removed by metamorphic or diagenetic processes, for none were recognized in thin section.

Plagioclase fragments are generally angular to subangular, and have occasionally been crushed after deposition. Twinning and progressive zoning is common. Alteration has frequently obscured grain outlines, and not uncommonly has formed selectively in zones of the plagioclase. Incipient recrystallization of plagioclase to albite was seen in all slides examined, and in some it has progressed to a stage where the outline of original plagioclase is revealed only by an indistinct border. Early stages of recrystallization are revealed by irregular patches with individual extinction and a general hazy appearance of the crystal under crossed nicols. Feathery crystals of albite, without any visible relation to the original plagioclase, occur frequently in the matrix.

Quartz is a minor constituent in most of the sandstone, and is absent in many thin sections. In general, quartz is somewhat better rounded than other grains, although rounding may have been caused by partial replacement by the siliceous matrix. Partial replacement is shown by fritted borders and infrequent embayments. Authigenic overgrowths formed on quartz in C-304 prior to recrystallization of the matrix. Irregular "dust-trails" and general lack of inclusions indicate that the quartz is of igneous origin. Wavy extinction is characteristic of these quartz grains, but may have resulted from forces acting either before or after deposition.

Tuffaceous origin is suggested for two samples, C-155 and C-4, by texture and mineral content, but metamorphic processes have so obscured the relations that positive identification is not possible. Irregular and discontinuous sinuous stringers and arcuate patterns of hematite are present in C-155. Hematite constitutes about 30 percent of the rock, thus causing a distinctive purple coloration. C-4 is similar to distinctive rocks of the Blue Creek lentil which are interpreted as crystal tuffs. The close relation of C-4 to these rocks is also indicated by its position on the triangular diagram (See Figure 31). Therefore, pyroclastic activity may have been a contributing, though minor, factor in the history of this formation.

A sharp change in rock type is represented by samples C-377 and C-378. As noted in Figure 3, the percentage of quartz increases rapidly, and though less definitely indicated in the diagram, sorting is much better. The matrix is free of finely crushed rock and feldspar, consisting of recrystallized chlorite-hematite-calcite in C-377, and quartz-albite-sericite in C-378; in both samples the matrix shows replacement of the larger grains, including quartz. These samples cannot, therefore, be considered true graywackes, but feldspathic arenites.

Sample C-377 contains chert and siltstone fragments in addition to volcanic rock grains; one chert grain contains angular inclusions of quartz. Another feature not noted in other samples is inclusions of zircon in the quartz and plagioclase grains of both C-377 and C-378.

Conglomerate. Conglomerates in the Trinity Creek formation are irregular and discontinuous, both laterally and vertically. No particular conglomeratic horizon could be traced laterally for more than 100-150 yards. Fine, angular, non-bedded, pebble to cobble conglomerate, in zones varying from 3 to 25 feet thick, are most common, but lenticular areas of coarse, well-rounded, cobble to boulder conglomerate are scattered throughout the formation. In such outcrops, sorting is generally good; boulder size reaches a maximum diameter of 14 inches, but cobbles 4 to 8 inches in diameter are predominant. Commonly the lenticular conglomerates are immediately overlain by cross-bedded sandstone. However, most of the outcrops show irregular gradations between coarse pebbly sandstone and conglomeratic facies.

Cobbles and boulders in the conglomerates are predominantly fine-grained or porphyritic volcanic detritus. Vesicular volcanic cobbles and fragments of sedimentary rocks occur locally as the dominant clast type in a given outcrop. Occasional rounded boulders of strongly porphyritic volcanic rock, typical of the overlying member of the Imnaha formation, are present in the upper portion of the Trinity Creek formation. A single "granitic" cobble, C-198, was found in the formation.

Several lenticular areas of coarse, well-rounded boulders contain a high percentage of a single rock type; in two counts of 200 pebbles each, a fine-grained porphyritic rock of andesitic character was the only rock type present. However, not all conglomerates in the formation are monolithic, nor is the same rock type present in all outcrops which show a tendency toward monolithic content. Variety is especially conspicuous in the finer, more angular conglomerates. Because of extreme lateral variation in conglomerate from outcrop to outcrop, pebble counts are characteristic only for the particular outcrop concerned.

A distinctive intraformational conglomerate, containing randomly oriented, 1 to 3 inch fragments of bedded siltstone and mudstone crops out at 7060 feet elevation in the NW$\frac{1}{4}$SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 16, T. 6 S., R. 46 E. Large irregular solution cavities, 8 inches to 2 feet wide, mark the position of calcareous lenses or boulders. The matrix, about 60 to 80 percent of the rock, is composed of dark grayish green sand to silt sized grains with crude bedding.

A few scattered outcrops of conglomerate suggest deposition by mudflow. Such an outcrop occurs in the NE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 16, T. 6 S., R. 46 E. where a narrow bench is composed of angular vesicular boulders in a very coarse feldspathic matrix. A reddish, baked appearance, and extreme surface irregularity serve to distinguish the rock from the more common conglomerate types. In general appearance, this outcrop is similar to many of the mudflow breccias in the Clarno Basin of central Oregon.

<u>Mudstone</u> <u>and</u> <u>Siltstone</u>. Fine-grained greenish to buff mudstone and siltstone, with individual grains too small to be distinguished in hand specimen, occur in scattered localities throughout the Trinity Creek formation, but are

best exposed on the ridge immediately south of Fish Lake, where they are the dominant rock and can be traced for about half a mile without interruption, except for minor sandstone and conglomerate lenses. Bedding is usually well defined by color changes; individual beds vary from ½ to 4 inches in width. The light gray rock has a slight greenish cast, is siliceous, and breaks with a subconchoidal to irregular fracture without reference to the bedding. Microscopically the rock is seen to contain scattered, well-sorted, angular grains of quartz, plagioclase, and an occasional, recognizable volcanic fragment in a dense recrystallized matrix of sericite, leucoxene, chlorite, and microcrystalline quartz. Modes are shown in Figure 3.

Graded bedding and load casts are present in some outcrops of the siltstone. Striking features of penecontemporaneous deformation, including load casts and slumping are exposed in a series of irregular mudstone beds about 6 feet thick, overlying about 30 feet of well-bedded coarse sandstone, in SW¼NW¼ sec. 28, T. 6 S., R. 46 E. at an elevation of 6000 feet. (Figures 6 and 7) Unsorted angular pebbles and cobbles of vesicular volcanic rock, probably of pyroclastic origin, were dumped onto unsolidified muds, and minor slumping further contorted the beds. The structure could have resulted either from a pyroclastic shower or turbidity current.

Figure 6. Penecontemporaneous deformation of fine grained beds in the Trinity Creek formation; cobbles in lower bed probably of pyroclastic origin; note angularity

Thickness

A section of the Trinity Creek formation between 6500 and 7000 feet thick is exposed in the thesis area. The total thickness is unknown, but similar sedimentary rocks are exposed southward along the road to an elevation of about 5000 feet. Therefore, the total thickness may approach 8000 to 10,000 feet. Thickness was computed from the map by using an average dip of 30°. No sections were measured with a chain.

Depositional Environment and Provenance

Coarse boulders in discontinuous lenticular bodies frequently overlain by well sorted cross-laminated sandstone indicate rapid deposition by strong currents with subsequent reworking by waves or currents. The fluctuation of grain size through a vertical sequence, so characteristic of the Trinity Creek formation, and thin discontinuous accumulation of fine-grained siltstone and mudstone indicate variation in competency and capacity of transporting currents, or variation in the amount of available detritus in the source area. Compositional immaturity indicates little transportation or sorting prior to deposition. All of the above conditions can be satisfied only by deposition in shallow water near a land mass or group of islands with moderate to high relief, in which mechanical breakdown of parent rock was more active than chemical decay.

The occasional occurrence of tuffaceous (?) textures, mudflows, and coarse, angular, vesicular debris (Figures 6 and 7) suggests explosive eruptions in adjacent areas, and the dominance of volcanic grains proves that the source area was predominantly composed of volcanic rocks.

Therefore, the bulk of the Trinity Creek formation, is considered to have been deposited in shallow seas adjacent to a land mass or group of islands on which vulcanism was active. The attitude of cross-lamination in the sandstone suggests that the source area was to the southeast.

Onset of extensive vulcanism may be recorded by the sharp break in sedimentary types (C-377 and C-378). The increased percentage of quartz with inclusions typical of acid plutonic rocks, and the presence of chert and siltstone fragments in the two stratigraphically lowest samples leave no doubt that sedimentary and probably crystalline rocks were exposed in the early source areas. However, definite conclusions would require additional mapping and sampling in the Trinity Creek formation south of the thesis area to establish the extent of the arenites.

Fossil Content

Eight fossil localities are plotted on the accompanying map. A varied and well preserved fauna was collected from Fl-1, Fl-3, and Fl-8. Other localities yielded limited fauna usually consisting of poorly preserved casts.

The following forms were identified by Dr. S. W. Muller: (16)

Fl-3	1. <u>Neospirifer</u> sp.	Penn-Perm
	2. <u>Chaoiella</u> sp.	
Fl-8	1. <u>Punctospirifer pulcher</u>	Permian (Phosphoria)
	2. <u>Dictyoclostus</u> sp.	Miss-Perm

<u>Age and Stratigraphic Relation</u>

The Trinity Creek formation is the oldest unit recognized in the area; it is dated as Permian on the basis of the previously listed fauna, and is conformably overlain by the Imnaha formation. Upper portions of the Trinity Creek formation and "greenstones" of the Imnaha formation interfinger on the crest of the ridge immediately south of Fish Lake. Other small bodies of "greenstone" within the Trinity Creek formation crop out near the head of East Pine Creek in the NE$\frac{1}{4}$ sec. 21, T. 6 S., R. 46 E. The exact nature of these small bodies is not definitely known, but both intrusives and flows are probably present.

Definite intrusive contacts may be seen on the ridge immediately south of Fish Lake and in the eastern edge of East Pine Creek (Pl-1), where a narrow ribbonlike dike of "greenstone" has been injected into the older rock. Contacts of the other bodies of metavolcanics are obscured, but there is no indication of intrusion.

Figure 7. Minor faulting in same outcrop of Figure 6 with boulder of similarly deformed strata in conglomerate of downthrown block.

Imnaha Formation

The name, Imnaha formation, is proposed for "greenstones" and associated sedimentary rocks exposed in a wide belt trending northeast through the south central portion of the Cornucopia quadrangle. (Pl-1) These rocks have previously been thought to be a part of the Permian Clover Creek greenstone. (21) However, lithology and fossil content indicate that these rocks form a separate stratigraphic unit.

The formation is named for exposures rimming the Imnaha canyon for several miles east from the junction of the Imnaha and Cliff Rivers. A typical section is present in nearly continuous exposures along the south rim of the Imnaha canyon.

The Imnaha formation is divided into two members on the basis of lithology and inferred depositional environment. Each member contains a single lentil of restricted areal extent but distinct character. The two members, with their included lentils, are the Russel member, including the Sugarloaf lentil, and the Norway member, including the Blue Creek lentil.

Russel Member

The Russel member consists of a series of thick lava flows, intercalated breccia and conglomerate, and minor pods of recrystallized limestone. It is named for typical exposures in Rock Creek canyon, north of Russel Mountain. (Figure 8) This member occupies a linear belt about 3½ miles wide, comprising most of the northeast portion of the thesis area. Bold outcrops, rounded roches moutonnees, steplike cliffs, long smooth benches, and strong persistent joints are typical of this member. Most outcrops are cut by one or more dikes which cause extreme difficulty in detecting structural continuity.

Petrography. Both fragmental and flow rocks are dark green, or blue to blue-black, blotched with white phenocrysts and glomeroporphyritic rosettes of plagioclase. The strongly porphyritic nature of the volcanics in this sequence is distinctive—non-porphyritic rock is almost totally absent, even in the intercalated clastics.

The rocks are nearly structureless and lineation of any sort was rarely noted. Pillow structure was noted at a single locality, the small lenses of "greenstone" interbedded with the Trinity Creek formation south of Fish Lake. Vesicular pillows are well formed, but obscured by erosion, and are separated by thin septae of dense, devitrified chloritic material without phenocrysts. Content of vesicles increases toward the top of the exposure, but within individual pillows, the vesicles, now filled with calcite, are concentrated in concentric zones near the edge of the

Figure 8. "Greenstone" outcrops in Rock Creek canyon, type locality for Russel member.

Figure 9. Typical exposure of eastern portion of the Norway member. Note dikes.

pillows. Pillow structure is best exposed on the north face of the outcrops.

Flow Rock Porphyritic and glomeroporphyritic meta-andesites and metabasalts with plagioclase phenocrysts set in a dense green to black groundmass, are composed of plagioclase, augite, chlorite, actinolite, epidote, and calcite plus accessory magnetite, quartz, apatite, hematite, and sphene. Plagioclase and augite are relict; primary magnetite and apatite are also present. Other minerals are the result of low grade regional metamorphism.

Metamorphism has not reached equilibrium in the greenschist facies, for relict augite and plagioclase are recognizable. An equilibrium assemblage should also include albite instead of the calcic andesine and labradorite. Thus low grade regional metamorphism, sufficient to allow the formation of epidote, chlorite and actinolite, but not sufficient to completely remove augite or to allow recrystallization of plagioclase to albite, is indicated.

Plagioclase composition varies from calcic andesine, An_{42-44}, to sodic labradorite, An_{54-58}. Complex carlsbad, albite, and occasionally pericline twinning is visible in all but the most altered crystals. Zoning is not common, being present only in the outer portions of some phenocrysts. Unaltered patches of the phenocrysts are present in most thin sections; frequently the groundmass feldspar is less altered than the phenocrysts. Alteration products include sericite, epidote, chlorite, prehnite, lawsonite (?), and a dark brown to black "scumlike", nearly opaque aggregate of dustlike particles. Prehnite and sericite form minutely crystalline scaly overgrowths dotted with granular epidote. Chlorite is present within the plagioclase as small infrequent green flecks. The dark formless aggregate usually shows no optical properties, but sometimes anomalous berlin blue, typical of clino-zoisite, and a few brightly colored specks of epidote (?) may be seen under crossed nicols.

Borders of the phenocrysts are usually well defined, and in several slides the pilotaxitic groundmass has flowed around the larger crystals; a few broken crystals have been intruded by the groundmass. In the more altered rocks phenocryst borders are indistinct, and groundmass plagioclase is detected only as rectangular patches of light.

The large feldspar crystals common in the Russel member were described by Ross as porphyroblastic. (22, p.22) Staples (26, p. 7) found no evidence to indicate that they were not phenocrysts. Careful examination in the field failed to reveal a single instance where the feldspars could be seen to cross clast boundaries, but hundreds of instances were found where feldspars were truncated by the clast boundary. In addition similar porphyritic boulders occur in other sedimentary units, and not all boulders are porphyritic in a given outcrop, as seems unlikely if the feldspars were porphyroblastic. Microscopic evidence that the groundmass has flowed around and even intruded these large crystals leaves no doubt that they are phenocrysts.

Augite was recognized in only one thin section, C-217, as small remnants, the original crystal being almost entirely replaced by clustered actinolite. Many similar groups of actinolite likely mark completely altered pyroxene crystals. No other primary mafic minerals were recognized.

Chlorite, actinolite, and epidote cause the dark green color of the rock. The chlorite forms minute flaky crystals intergrown between the actinolite fibers, or occurs in distinct rounded patches, either alone or with epidote. It is yellowish to emerald green under plain light, and under crossed nicols it varies from bright blue to deep purple. Strongly pleochroic actinolite, changing on rotation from pale yellow to bright blue-green, is usually present as a mass of felted fibers intergrown with granoblastic quartz. Epidote, pleochroic in shades of yellow, is present in aggregates of granoblastic grains and subhedral crystals.

Quartz and calcite are present in most slides as rounded clusters and veinlets of granoblastic grains. Prehnite veinlets occur, but are not common. Calcite occurs also as vesicular fillings. Magnetite is present as an accessory in all samples examined; in some thin sections it constitutes 10 to 12 percent of the rock. Other minor minerals are biotite, apatite, hematite, and sphene. Both brown and green biotite are present in small amounts; but the brown variety probably indicates thermal effects, as brown biotite is characteristic of thermal aureoles in northeastern Oregon. (28, p. 1650)

Relict pilotaxitic and felsitic textures are common in the groundmass. Hyalopilitic and intersertal textures are suggested by the abundance of chlorite patches and the wide spacing of feldspar laths in the groundmass, but similar textures could also result from the replacement of original mafic minerals. Vesicular texture is rare.

<u>Clastic Rocks</u> Clastic rocks, ranging from fine angular breccia to very coarse well-rounded conglomerates comprise most of the Russel member. The most striking feature of these clastic rocks is the monolithic character of the contained fragments. These fragments are indistinguishable in the field from the intercalated flow rocks described above. Induration is extreme, so that the clasts are usually visible only on weathered surfaces, and it is often necessary to examine outcrops in detail to be certain of clastic composition. Clastic units are variable and discontinuous; therefore, descriptions of several varied

occurrences are given.

In the SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 17, T. 6 S., R. 46 E., a coarse, extremely angular breccia outcrops in a series of narrow exposures trending northwest for about 500 feet. The rock is mottled white and dark greenish black; irregular rust-colored patches of iron stain cover most of the weathered surface. The fragments are dark green to black, fine-grained porphyritic and glomeroporphyritic volcanics, broken into angular pieces averaging $\frac{1}{2}$ inch to 2 inches across. The phenocrysts are subhedral to euhedral plagioclase crystals occurring both singly and in groups; individual crystals up to an inch long are common. Feldspar fragments and feldspathic sand-sized rock fragments form the matrix.

An exposure approximately 100 to 150 feet wide, exposed in NW$\frac{1}{4}$ sec. 8, T. 6 S., R. 46 E., is composed of fine angular to subrounded basaltic fragments averaging $\frac{1}{2}$ inch to 2 inches across. Some white phenocrysts are present in the fine fragments, but are less common than elsewhere in the member. Occasional cobbles 6 to 10 inches across show development of large phenocrysts up to an inch long. An arcuate, coarsely porphyritic boulder resembling the outer "rind" of spherulitic weathering is tightly packed in the finer angular matrix. (Figure 10) A boulder could not retain this shape through much transportation. No trace of bedding was found in approximately an eighth of a mile of continuous outcrop. Sample C-101, described under the heading "Dynamo-thermal Aureole," was taken from the west end of this outcrop. Similar breccias occur frequently throughout the formation; and another distinctive angular boulder, broken during the compaction of the sediments, is shown in Figure 11.

A more extensive, bedded breccia unit crops out in several localities in the long tongue extending into the Norway member (Pl-1) in secs. 1 and 2, T. 6 S., R. 46 E. Thick, rudely defined beds of medium to coarse, blocky breccia containing clasts up to 8 inches across are interbedded with coarse feldspathic sandstone and angular conglomerate. The breccia beds, 6 to 30 feet thick, strike N. 15° E., and dip 20° WNW. They are separated by sandstone and conglomerate beds 1 to 4 feet thick. The sandy calcareous matrix shows patchy differential weathering, but usually the matrix is distinguishable only by texture from the larger porphyritic and glomeroporphyritic volcanic fragments. The clastic nature of the rock is not always evident, for the rock breaks irregularly across fragments. Smooth joint faces and steplike outcrop pattern cause confusion with similar flow rocks under superficial examination.

The groundmass of the fragments is dense, dark green

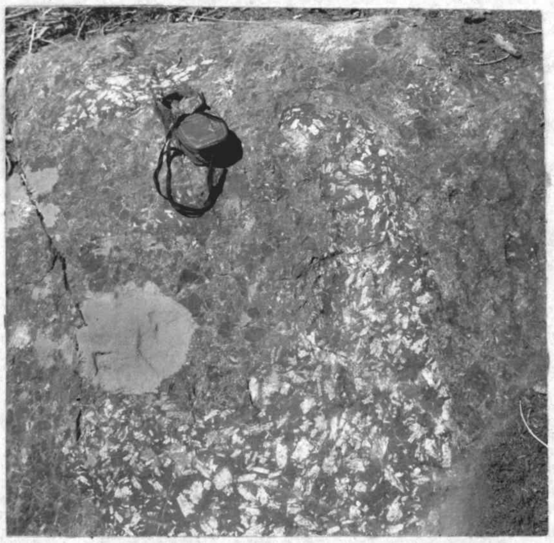


Figure 10. Arcuate boulder in matrix of angular breccia, proof of lack of transportation. Note injection of fine matrix into fracture near top. Location: NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 8, T. 6 S., R. 46 E.

Figure 11. Broken irregular boulder in fine angular breccia. Filling of fracture by finer matrix indicates compaction before complete cementation. Location: about 7000 ft elevation, NW$\frac{1}{4}$ sec. 9, T. 6 S., R. 46 E.

or black to blue-black. Rusty iron stain is sparsely present, but not generally conspicuous because of the sharply contrasting white and dark colors; plagioclase phenocrysts range from 1/8 to 1½ inches long. White radiating rosettes of plagioclase up to 3 inches across, constituting nearly the entire clast, are abundant and give the rock a distinctively spotted pattern. (Figure 12) Stratification of the rosettes is exposed at an elevation of 7300 feet in the NW¼NW¼ sec. 12, T. 6 S., R. 46 E. (Figure 13)

In the saddle between Clear and Soldier Creeks, the distinctive "rosette-breccia" is interbedded with very coarse boulder conglomerate consisting of porphyritic boulders in a feldspathic, sandy or gravelly matrix. Similar boulder conglomerate is the most abundant rock type in the Russel member. Conglomerate forms most outcrops from this saddle northwest to Deadman canyon, and is exposed in a wide belt across the upper part of Rock Creek canyon. Further exposures are present northeast of Fish Lake and south of Russel Mountain between the road and the summit.

The clastic nature of these conglomerates can usually be seen only on weathered surfaces where the boulders generally show as dark blue, green, or black zones thickly spotted with white plagioclase phenocrysts in a rusty matrix, but may be vaguely defined, spotted zones on a less spotted background.

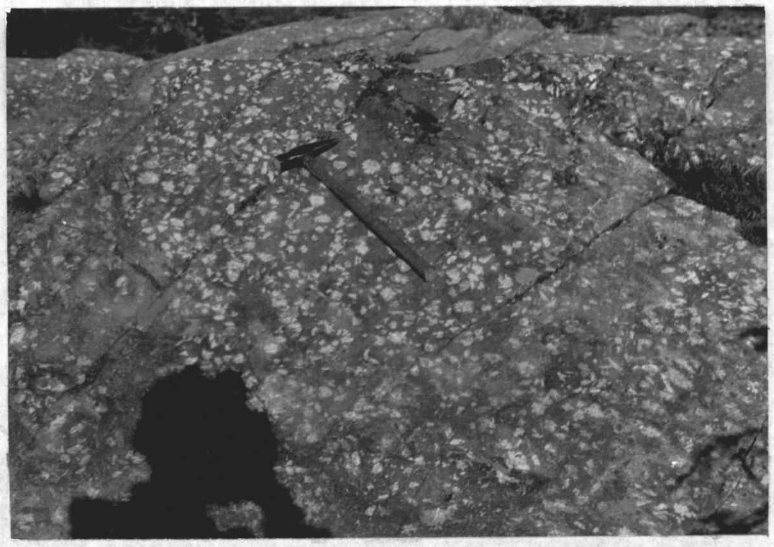


Figure 12. Unusual breccia west of Clear Creek Reservoir. Individual fragments visible only on close examination, and do not stand out in the photograph. Note size of glomeroporphyritic cluster. (Hammer handle 20 in.)

Figure 13. Bedding defined by accumulation of glomeroporphyritic cobbles in angular conglomerate. Location: 7320 feet elevation $NW\frac{1}{4}NW\frac{1}{4}$ sec. 12, T. 6 S., R. 45 E.

These conglomerates vary in grain size, angularity, and ratio of boulders to matrix. The smallest cobbles noted were about 3 inches in diameter; the largest boulders were about 24 inches in diameter, but within an individual outcrop the size range and degree of rounding remain fairly uniform. Typical outcrops, chosen to show differences in size and angularity, are shown in Figures 14 and 15.

Two unusual outcrops in SW$\frac{1}{4}$NE$\frac{1}{4}$ sec. 1, T. 6 S., R. 45 E, and NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 12, T. 6 S., R. 45 E., deserve special mention. Both are thick units (75 to 100 feet) of medium to coarse grained, angular feldspathic sandstone containing large well rounded blue-black, white spotted porphyritic "greenstone" boulders which appear to float in the sandstone. Only rarely are two boulders in contact; they occur usually as singles, but may be in streaks and occasionally in groups. A rough parallelism exists between boulder streaks and bedding in the sandstone, but no definite horizons exist at which boulders are most frequent. Joint surfaces cross boulder faces smoothly and without deflection. (Figure 16) In the northern exposure cobbles are small, only about 6 to 8 inches in diameter; boulders in the southern exposure average 1 to 2 feet in diameter.

<u>Limestone</u> Recrystallized limestone occurs in the Russel member as small lenticular pockets, most of which were too small to show on the map. Such pods occur

frequently only in secs. 32 and 35, T. 6 S., R. 46 E.

The limestone is light gray to dirty white streaked with pale green. Fine sugary texture is predominant; calcite grains average 1 to 3 mm across, and on weathered surfaces bear a strong resemblance to poorly formed concrete. Figure 18 shows a typical outcrop of such conglomerate, and Figure 19 is a close-up view of the same beds. Such rock may be called calcareous conglomerate, but distance between beds varies widely and in many outcrops the calcareous "matrix" forms by far the major portion of the rock.

A single, poorly preserved ammonite (?) was taken from mudstone beds within the northernmost limestone pod. (Pl-1) The mudstone occurs as a series of thin beds totaling about 4 feet in thickness near the middle of approximately 50 feet of limestone. The fossil was taken about 50 feet from the west end of the exposure near the top of the mudstone beds. Vesicular cobbles in a calcareous matrix form the lower 8 to 10 feet of the limestone pod; above the mudstone, limestone shows very thin, shaly partings parallel to bedding in the mudstone. No pillow structures are present in the overlying flow rock.

Thickness. As structure is inadequately known in the Russel member, its thickness cannot be computed. Estimated thickness, based on available structural data, is 10,000 to

Figure 14. Exposure of coarse angular breccia in lower portion of Russel member. Location: $SE\frac{1}{4}SE\frac{1}{4}$ sec. 9, T. 6 S., R. 46 E.

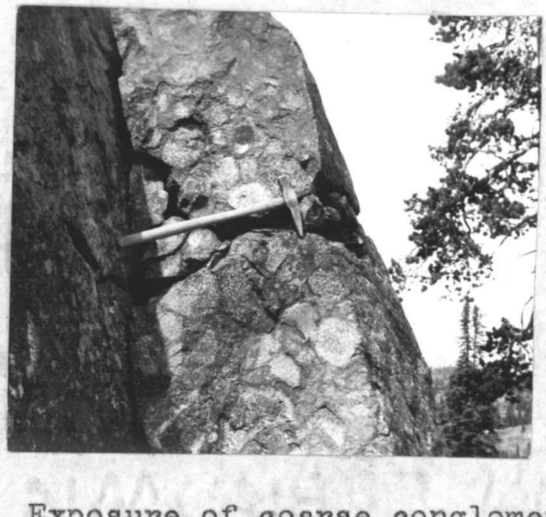


Figure 15. Exposure of coarse conglomerate typical of large portion of Russel member.

Figure 16. Unusual conglomerate with huge boulders "floating" in sandy matrix. Location: $NW\frac{1}{4}NW\frac{1}{4}$ sec. 12, T. 6 S., R. 45 E.

Figure 17. Close-up view of poorly sorted, heterogenous conglomerate in the Sugarloaf lentil with porphyritic boulder similar to lavas of Russel member. Note truncations at boundary of boulder.

Figure 18. Pyroclastic conglomerate in a calcareous lens of the Russel member.

Figure 19. Close-up view of same unit to show texture of conglomerate.

15,000 feet, but the margin of error may be wide.

Provenance and Depositional Environment. The following conditions must be considered to determine the depositional environment of the Russel member:

1. Extreme discontinuity of recognizable rock units both vertically and laterally.
2. Almost total lack of sorting or bedding in clastic units, coupled with the extreme angularity of the finer breccias.
3. Pillow lavas limited to a single occurrence of undoubted submarine origin.
4. Discontinuity and irregularity of limestone lenses, without evidence of extreme deformation.
5. Sharply defined change in lithologic aspect and both sedimentary and igneous structure from known marine units above and below.
6. Lithosomal interfingering with overlying marine member.

To explain these features, a terrestrial and littoral strand line depositional environment is postulated for this member. Sediments and intercalated flows probably originated from nearby volcanic areas of high relief and fluctuating coastline. The extremely angular and poorly sorted breccias are thought to be mud flows and/or talus accumulations; the coarse, rounded conglomerate to be beach accumulation; and the calcareous lenses to be lagoonal deposits.

Gilluly (7) attributed discontinuity of limestone in the Clover Creek greenstone to extreme deformation. Such deformation seems to be ruled out for limestone pods in the thesis area, because the interbedded mudstones and conglomerates are not greatly deformed, nor can the vesicular volcanic cobbles be traced laterally into the surrounding rock as would be expected if both had been deposited on the sea floor.

Boulder accumulation on beaches bordered by volcanic highlands occurs today, as at Yaquina Head on the Oregon coast, where the boulders are also nearly all similar in composition to the surrounding highlands. If the clastic units of the Russel member had been deposited in a normal marine basin, they should contain a much higher percentage of "foreign" fragments.

Age and Stratigraphic Relation. The Russel member is Triassic; and possibly a large portion of the lower Triassic is included in this great thickness of volcanic flows and detritus. A Triassic fauna, probably upper Triassic (16) was collected from the Sugarloaf lentil, which is near the center of the member.

The Russel member conformably overlies the Trinity Creek formation and interfingers lithosomally with the Norway member. In the area just east of Clear Creek Reservoir, known locally as "the Pothole," bedded units of the Norway member are exposed under portions of the Russel member. Gradation between the two members is best exposed along the northern edge of the Potholes, where the contact is arbitrary. The true relation of the two units is best exposed on the divide between Soldier and Blue Creeks where a long tongue of porphyritic metavolcanics extends into the Norway member.

An angular unconformity exists between all units of the Imnaha formation and Tertiary basalt flows.

Sugarloaf Lentil

The Sugarloaf lentil, a steeply dipping band of deformed fossiliferous siltstone, sandstone, and conglomeratic limestone, liberally interspersed with irregular pods and stringers of coarse boulders, is exposed for about half a mile along the southern flank of Sugarloaf Mountain, and is completely enclosed by the remainder of the Russel member. Local contortion within the unit is suggestive of a very tightly folded syncline, but probably results from a crumpling.

Petrography. Varicolored thin-bedded siltstone exposed in discontinuous outcrops is characteristic of this unit. Most siltstone is green, but blue to purple beds occur frequently. Bedding is emphasized by differential weathering, as fine grained beds, ½ inch to 4 inches thick, stand out in relief, separated by ¼ to 1 inch partings of sandy material. Irregular pods and streaks of cobbles, and scattered well-rounded boulders in ill-defined zones are intercalated in most outcrops. (Figure 20)

The main constituents of the siltstone are angular to subangular quartz and plagioclase grains with less abundant lithic fragments set in a dense matrix of biotite, magnetite, and very minor chlorite. Only volcanic textures were recognized in the lithic fragments; many contain abundant microvesicles. Chloritic alteration and formation of secondary iron ore have obscured much of the original texture in the lithic grains, but twinning is sharply defined on many plagioclase grains.

Bedding is well defined in this section as chloritic partings. Metamorphism equivalent to greenschist facies is indicated by the assemblage biotite-chlorite-epidote-actinolite. All minerals except biotite are present in minor amounts. Calcite is also present, but was probably an original component.

Conglomerates are extremely discontinuous and varied (Figure 17); no single type can be called characteristic, but rounded to subrounded cobble conglomerate with irregular calcareous lenses, in which individual cobbles are separated by gray carbonate matrix, is distinctive.

Calcareous deposits range from conglomeratic lenses to "beds" 12 to 25 feet thick, of about 50 percent

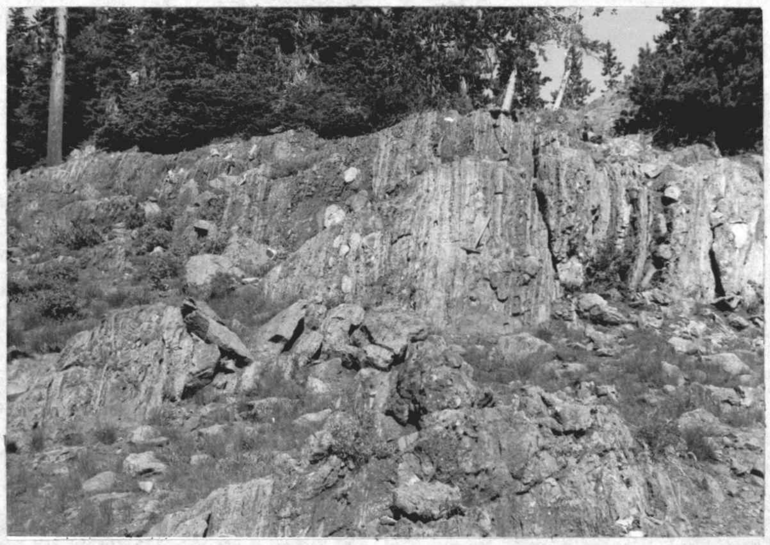


Figure 20. Outcrops of near vertical fossiliferous siltstones and scattered boulders with minor lenticular groups of cobble conglomerate in the Sugarloaf lentil. Most fossils were taken from the outcrop in the foreground.

Figure 21. Small anticlinal flexure in calcareous siltstones of the Norway member. Location: 7430 feet elevation, SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 2, T. 6 S., R. 45 E.

carbonate, containing both dense and vesicular, angular volcanic fragments scattered throughout. Outcrops of conglomeratic limestone are extremely rough, as though the dark clasts had been sprinkled on the white surface of the carbonate.

Sample C-157, taken from limestone containing fine gravel, is composed of slightly rounded rock fragments, quartz, plagioclase and possibly detrital calcite in a thick calcareous matrix. Most rock fragments are metavolcanics, either thickly dusted or almost completely replaced by iron ore. Plagioclase microlites are aligned in some clasts, randomly oriented in others; a few fragments are so fine-grained that plagioclase is not distinguishable. Chlorite, biotite, calcite, and very minor epidote are additional alteration products.

A few grains appear to be fragments of sedimentary rocks; very fine-grained quartz and possibly albite form a mosaic which is irregularly dusted with hematite and magnetite.

Angular plagioclase grains showing strong oscillatory zoning are common and are characterized by very little alteration. Unzoned grains are more highly altered to sericite and show incipient recrystallization to albite.

Recrystallized calcite in small xenoblastic crystals constitute 50 percent or more of the rock, but several large crystals are completely surrounded by rims of much finer grained calcite mixed with hematite and biotite. Such crystals may have been original clastic grains.

Formation of albite, chlorite, epidote, and secondary iron ore, accompanied by recrystallization of calcite, indicates low grade metamorphism. However, presence of relict minerals shows that equilibrium was not reached.

Thickness. The Sugarloaf lentil is about 600 to 800 feet thick and was included in the estimate of thickness for the entire Russel member.

Fossil Content. A poorly preserved, but varied fauna was collected from the Sugarloaf lentil (Fl-5). Muller (16) states: "I have pretty good indication that lot Fl-5 is Triassic, probably Upper Triassic." The fauna consists of pelecypods, gastropods, and a single coral.

Provenance and Environment of Deposition. Large boulders scattered through fine-grained sands and silts which show no evidence of scour could only have been emplaced by gravity. Any current sufficient to transport them would erode the finer deposits. Regularly bedded, fine-grained sediments accumulate in quiet water below wave base (18, p. 593), yet the presence of carbonates and pre-Cretaceous lime-secreting fossil forms indicate shallow water deposition. (10, p. 596) Therefore, the Sugarloaf lentil is believed to have accumulated in a narrow coastal embayment protected from wave action and closely bordered by rugged highlands. The bottom of the bay or arm may have contained irregular potholes where fine muds accumulated between intermittent deposition of sand.

Most sediment was derived from the surrounding land through erosion and volcanic activity. Micro-vesicular to pumiceous fragments prove explosive vulcanism, and it seems unlikely that the larger boulders could have accumulated except by rapid dumping into quiet water. No indication of turbidity currents was found.

Age and Stratigraphic Relation. The Sugarloaf lentil is tentatively dated as Triassic on the basis of the above fauna.

The unit is cut off on the north by unconformably overlying Columbia River basalt. A narrow spur, extending southwest from the west end of the lentil, and another isolated outcrop to the west suggest original continuity with the lower portion of the Norway member. Similar lithology further suggests such a relationship.

Norway Member

The name Norway member is proposed to designate a thick marine sequence of heterogeneous clastic material and intercalated pillow lavas. The member constitutes the upper portion of the Imnaha formation, and is best exposed on the ridges enclosing Norway Basin in the west central part of the thesis area. Structure is well defined only in the lower portion of the member.

Distribution and Expression. Total distribution of the Norway member is unknown; the unit occupies a north-south belt about 3 miles wide in the thesis area (Pl-1), extends south to Simmons Mountain, and appears north of the Imnaha River on Marble Mountain. Typical exposures are rugged blocky outcrops and steep ridges. (Figures 22 and 23) Dark colorations and bold cliff-forming outcrops permit easy recognition.

Petrography. For ease of description the Norway member is divided into three parts: bedded units, pillow breccia, and pillow lava. It must be emphasized, however, that no stratigraphic division exists between the parts. Bedding is found irregularly throughout the member, but is a common and consistent feature only in the lower portion. Jumbled, massive breccia becomes more abundant in the upper portion. Pillow lavas are a frequent and persistent feature of the member at all levels. Scattered irregular boulders of dark red chert occur as talus on the west side of Bear Creek canyon, but none was found in place, so the exact relation to the bedded units and pillow lavas is not known.

Figure 22. Typical outcrops of the Norway member, highly epidotized at this locality. Contact with overlying Lower Sedimentary Series drawn in upper left corner.

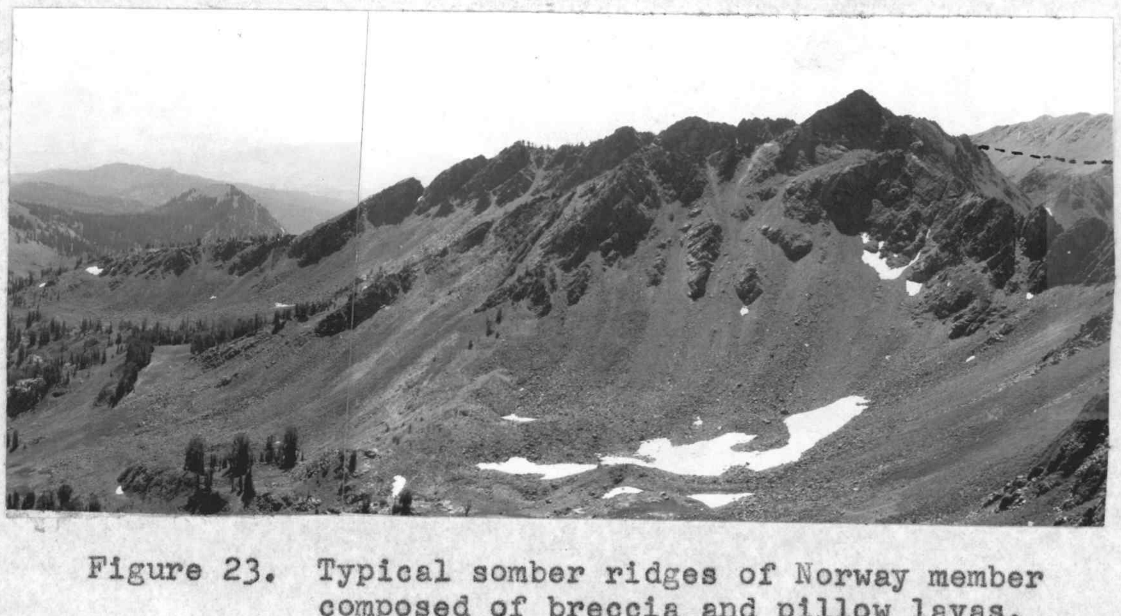


Figure 23. Typical somber ridges of Norway member composed of breccia and pillow lavas. Contact with overlying Lower Sedimentary Series drawn in upper right corner.

<u>Bedded Units</u> Thin bedded light gray, green, and purple siltstones, sandstones, gravels, and calcareous conglomerates are characteristic of the lower Norway member. The best exposures are in the Potholes, east of Clear Creek Reservoir. (Figure 9) The beds vary in thickness and sequence but series of fine-grained green and purple siltstone beds 1 to 4 inches thick are generally separated by 1 to 6 feet of calcareous conglomerate. The calcareous content varies from minor cementing material in the gravel to more than 50 percent of the rock. Fine conglomerates with few clasts longer than 1 inch across occur at infrequent intervals in beds from 1 to 12 feet thick. From Bear Creek west, bedding decreases rapidly in frequency and continuity. Local flexures are common. (Figure 21)

The siltstones are feldspathic and lithic graywackes composed of fine, subangular to subrounded quartz, plagioclase, and lithic grains embedded in a recrystallized matrix clouded by leucoxene. Quartz is a minor constituent which seldom comprises 10 percent of the rock. Plagioclase is generally highly altered to calcite-albite-sericite intergrowths with only an outline of the original grain preserved; a few grains with sharp twinning and progressive zoning appear unaltered. However, such crystals generally have an index of refraction less than balsam so original composition is doubtful. Lithic grains are predominantly highly altered volcanic fragments, recognized only by heavy matted alteration products and microlitic plagioclase. Most fragments contain micro-vesicles filled with calcite and greenschist assemblages. In C-220, recrystallized calcite constitutes more than 50 percent of the rock, but whether the calcite represents original grains or cement is not clear.

The sandstones are typical feldspathic and lithic graywackes differing from siltstones only in size of constituent grains. Lithic grains are prodominantly volcanic, but infrequent sedimentary fragments occur. A high percentage of magnetite is present in C-224, causing strong deflection of a compass needle in the field.

The rock most characteristic of the lower portion of the Norway member is a recurring conglomerate composed of angular, scoriaceous cobbles which are generally separated by calcareous cement. These conglomerates generally occur in strata less than 10 feet thick with strong blue to purple coloration on the weathered surface. Freshly broken rock has a reddish-white matrix and dull gray to black clasts. More rapid weathering of the calcite matrix caused extremely rough, pitted surfaces.

Thin sections from finer portions of such conglomerates are largely calcite and altered micro-vesicular volcanic fragments. Hematite produces the red coloration.

Nearly all clasts contain microlites or crystallites of altered plagioclase but no other original minerals are recognizable. Iron ore is usually concentrated around outer rims of the clasts and around the vesicles. Biotite, chlorite, and calcite occur as alteration products of the clasts, but are best formed as vesicle fillings. In C-187, fine biotite flakes are extremely abundant and thickly matted throughout the slide.

Hematite and calcite were original cements, but it is not certain whether calcite grains also existed. Other minerals typical of the greenschist facies have formed during low-grade metamorphism. The abundance of secondary magnetite and the microlitic texture suggests that the clasts may have been glassy.

Minor amounts of pyrite, apatite, and zircon are present. Pyrite occurs infrequently as euhedral cubes up to 0.5 mm. Apatite is a common accessory. A single detrital grain of euhedral zircon is present in section C-205F.

Textures, although greatly obscured by alteration products are sufficiently recognizable to be placed in two classes: clastic and pyroclastic. Typical sandstones and conglomerates fall into the first group and are discussed no further. Many dark-colored, fine-grained beds contain shardy patterns, pumiceous fragments, and dark-rimmed, scoriaceous clasts indicative of pyroclastic origin. (Figure 24) Rounded blebs and sinuous ribbons of magnetite form outlines closely resembling vitroclastic texture as pictured in Williams, Turner, and Gilbert. (33, p. 151) Lacy pumice shards are shot through with tiny vesicles, and contain hairlike plagioclase microlites, but are otherwise completely altered to chlorite and magnetite. (Figure 25) Larger clasts frequently rimmed by heavy accumulations of magnetite are suggestive of original palagonitic material in lithic tuffs. (C-231)

As these rocks are usually bedded and show all field indications of water deposition, they should properly be called volcanic siltstones after Hay. (10) Two particular rocks, apparently actual tuffs, deserve special description because of lithologic peculiarity and structural significance: (1) fine lithic tuff, and (2) welded or crystal tuff. They are exposed together in two localities, and in each occurrence the first is stratigraphically approximately 50 feet beneath the second.

(1) A highly sheared, fine-grained purple rock with sinuous gray patterns on the weathered surface crops out in ledges 15 to 20 feet thick below East Lakes Reservoir and along the Ice Creek Trail. On fresh surfaces the sinuous gray ribbons are not visible, and the purple coloration is less pronounced.

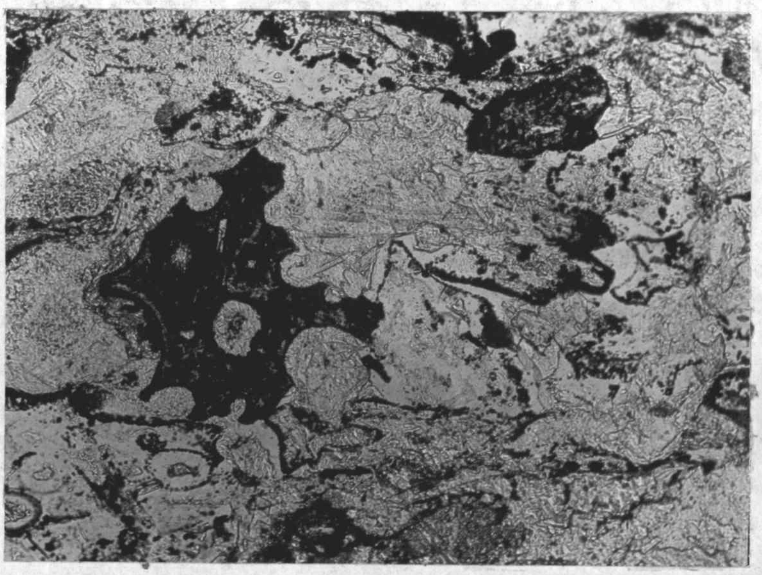


Figure 24. Photomicrograph showing typical microvesicular clast and tuffaceous (?) texture of fine-grained beds in the lower Norway member. (X 130) plain light.

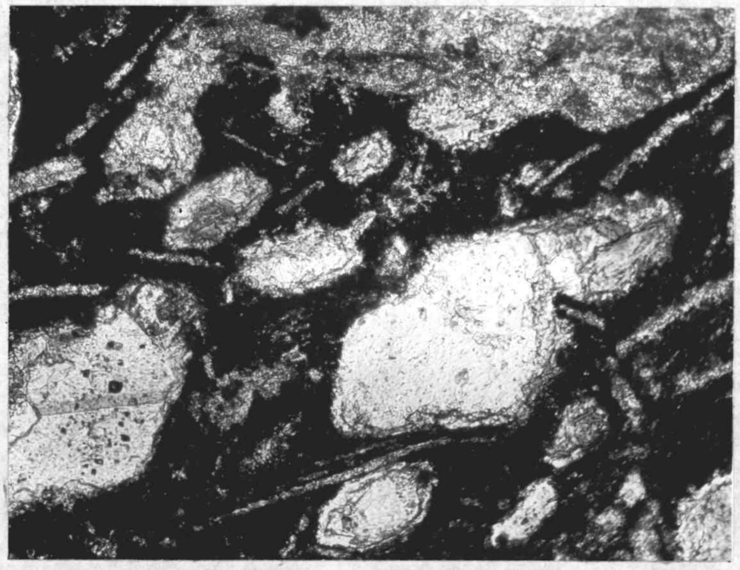


Figure 25. Photomicrograph of microvesicular pumice clast in siltstone of Norway member. Note altered plagioclase microlites and heavy accumulation of magnetite. (X 130) plain light.

Microscopically this rock consists of albite, calcite, hematite, chlorite, and quartz, none of which is primary. Outlines of original plagioclase, now filled with a fine albite mosaic or albite-calcite intergrowths, show definite preferred orientation roughly parallel to shearing. Hematite is concentrated in thick bands and streaks of finely divided, dustlike particles, and accompanies magnetite as heavy borders around prismatic areas which are filled by fine intergrowths of quartz, calcite, chlorite, and rare albite. The outline and alteration products are suggestive of original pyroxene. Relations are obscured by a finely divided, scaly mat of chlorite and sericite (?). Granoblastic quartz forms small lenses and irregular bands through the rock.

Elongate volcanic grains are revealed by vague outlines and microlitic texture. Grain borders are very irregular, but may have been partly replaced. Circular areas of quartz-chlorite-calcite within the grains show suggestion of flow around clasts, but matted accumulation of chlorite prevents certain identification.

The texture is cataclastic to schistose, marked by twisted calcite cleavage and twinning and by hematite streaks. Sinuous bands of hematite form bulbous and arcuate patterns (vitroclastic texture) which interrupt alignment of plagioclase microlites. Such disruption would not be likely if the microlitic alignment was the result of shearing stress.

The rock is therefore thought to be a lithic tuff now metamorphosed to greenschist. Metamorphic recrystallization and shearing have so altered the relations that a definite origin cannot be stated. Shearing is believed to have resulted from movement along the Bear Creek Fault.

(2) A light gray band of crystal or welded tuff 10 to 15 feet thick can be traced continuously for half a mile southwest along the east side of the ridge from the point where Ice Creek Trail crosses the 7520-foot contour, but ends abruptly near the edge of a shallow ravine west of East Lakes Reservoir. (Pl-1) A similar but slightly thicker unit crops out at an elevation of 7250 feet immediately northeast of the reservoir, but can be traced laterally for only about 200 feet.

Microscopically the two rocks are indistinguishable except for degree of alteration. Both thin sections, C-218 and C-226, are composed of large (0.25-2.5 mm) quartz and sodic oligoclase grains set in a fine granoblastic quartz-albite-sericite matrix. (Modes in Figure 26) Two keratophyre grains are present in C-218, none in C-226. Most of the grains "float" freely in the matrix, but occasionally two or more grains are in contact.

Quartz grains have been corroded and embayed by the

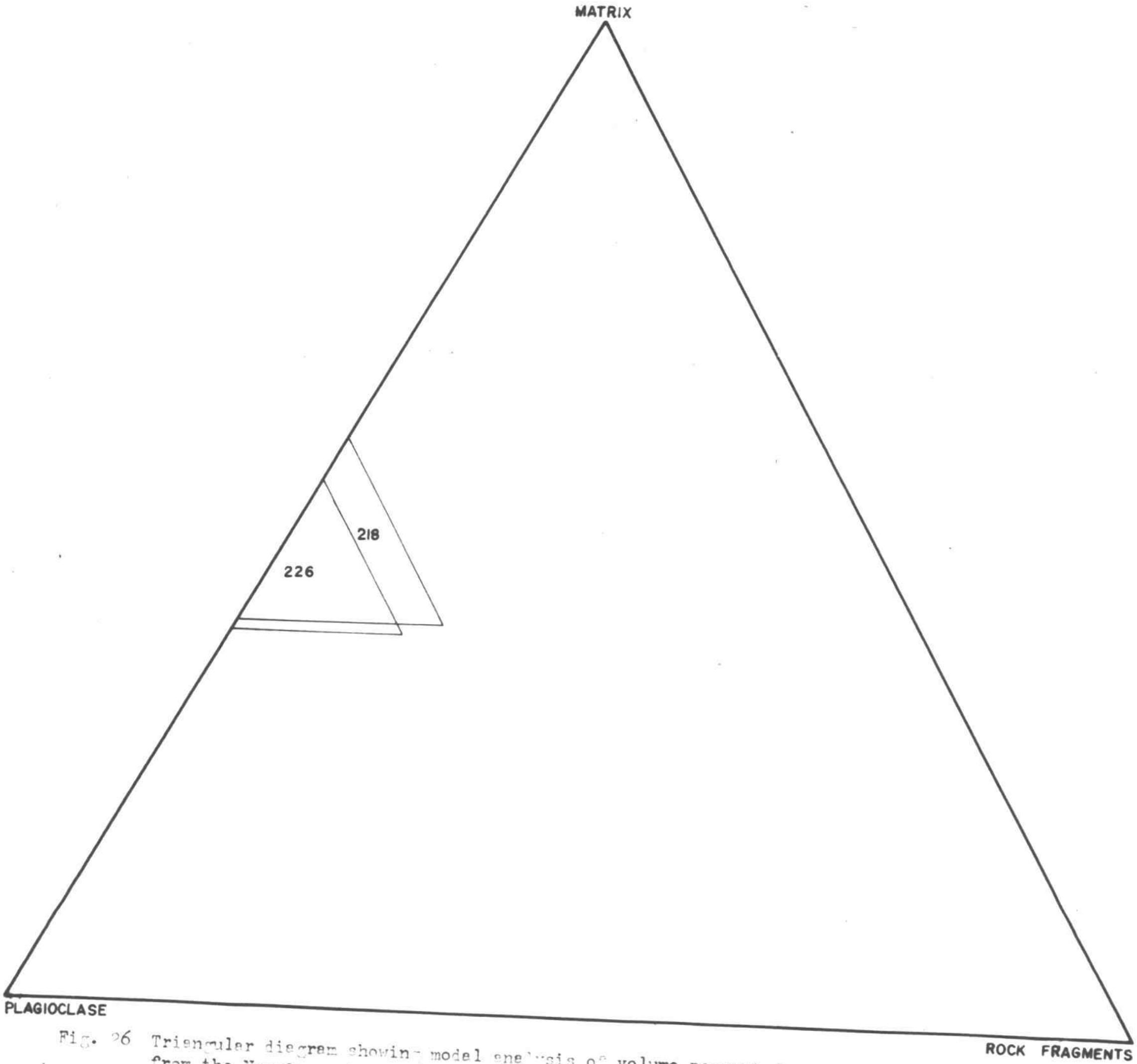


Fig. 26 Triangular diagram showing model analysis of volume percent for crystal tuff samples from the Norway member. Numbers are sample numbers. Percentage of quartz is indicated by the size of the triangles.

recrystallized matrix. Narrow, rounded embayments extend to the centers of many grains, and irregular, rounded cores of the matrix are common in quartz. Serrate cusped borders on quartz grains indicate replacement by the matrix, but replacement has generally been most active along fractures in the quartz, and frequently several tongues join to isolate fragments of the original quartz crystal.

Crystals of albite-oligoclase, An_{8-12}, appear only slightly altered with sharply defined complex twinning under crossed nicols. However, under plain light they appear clouded and patchy. Because of the complex twinning, unlikely in metamorphic crystals, albite-oligoclase is considered to be original.

The matrix is predominantly quartz and albite, but finely divided sericite is also an important constituent. Very fine, scattered iron ore and irregular clusters of chlorite and epidote are minor. Chlorite tends to be concentrated as narrow borders on plagioclase, showing preference for alternate twin lamellae.

The southern outcrop contains irregular nodules which appear to be pale bluish chert in hand specimen. Microscopically they are similar to the matrix just described. Fine grains of quartz and plagioclase are visible, but feathery albite is the dominant mineral. C. S. Ross (24) lists corroded quartz grains as characteristic of acid tuffs. Corroded quartz grains and euhedral plagioclase are known also from welded tuffs near Bishop, California. (33, p. 155) A quartz-albite-sericite matrix is common in slightly metamorphosed tuffs. (33, p. 154) Therefore, this rock is considered to be crystal tuff.

The relation of the two exposures is not certain, but they are thought to be faulted sections of the same bed, because of the similar occurrence of the highly sheared purple beds beneath both exposures.

Two additional bedded units deserve special consideration because of their isolated occurrence and structural significance.

Silicified mudstone crops out in a series of laminated beds 20 to 25 feet thick at an elevation of 8750 feet on the ridge southeast of Red Mountain. (Pl-1) These beds provide the best clue to structure in the upper portion of this member. (Figure 27) The rock breaks into sharp irregular fragments without reference to bedding. Angular fragments of quartz and plagioclase with minor elongate sedimentary grains are enclosed in a silicified matrix. The relations and textures are greatly obscured by the formation of chlorite and leucoxene, but definite laminae averaging 5 mm thick are still visible. Grading was not recognized.

Exact origin of the beds is not certain, but they

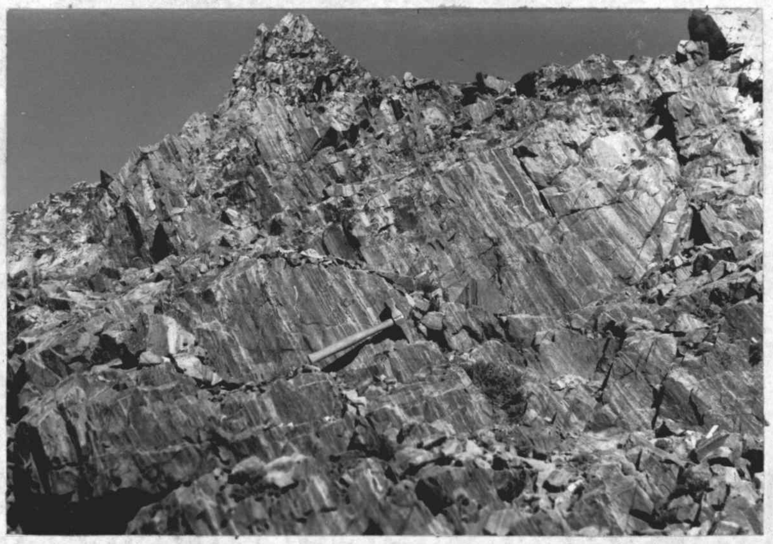


Figure 27. Silicified mudstone dipping away from Pine Creek Fault. Location: 8750 feet elevation, half a mile east of Red Mountain

Figure 28. Pillow lavas characteristic of the Norway member. Note concentric structure. Location: 7300 feet elevation $NE\frac{1}{4}SW\frac{1}{4}$ sec. 6, T. 6 S., R. 46 E.

probably represent action of turbidity currents as there is no other indication of deep water deposition.

A small lens of thin-bedded brown siltstones about 25 feet thick, which appears unconformable with the breccias, occupies a shallow swale on the crest of the ridge east of Norway Basin (7850 feet elevation, NW¼NW¼ sec. 10, T. 6 S., R. 45 E.) The lens is so small (only about 350 feet long by 200 feet wide) that its true significance is unknown, but the dip is nearly at right angles to reliable dips northeast of East Lakes Reservoir.

<u>Pillow Breccia</u> Pillow breccia is a name coined by Henderson (11, p. 29) to designate angular, unsorted breccias intimately associated with pillow lavas in the Yellowknife district, and considered by him (11, p. 31) to have formed by the ejection of hot lava into water.

The upper portion of the Norway member is composed predominantly of angular to subrounded, unsorted vesicular breccia. Vesicular to scoriaceous boulders and fragments of dark colored aphanitic lava are virtually the only rock type present in the breccia. They are set in a sandy, usually somewhat calcareous matrix. Bedding is uncommon, but occurs at scattered localities. Boulders reach 14 to 18 inches in diameter, but cobbles 4 to 8 inches are dominant. Many of the larger boulders are indistinguishable from associated pillows; others containing arcuate bands of vesicles are clearly fragments of pillow structure, but vesicles form no recognizable pattern in some bomblike clasts.

Thin sections of finer portions contain sand to grit-sized, microvesicular, volcanic fragments. Rounded to elliptical vesicles filled with greenschist mineral are very abundant. Most clasts contain thin needlelike microlites of plagioclase, but many are altered to a dense mass of iron ore thickly sprinkled with rounded vesicles. Vesicles are generally rimmed by concentrations of iron ore which thin out gradually into the rock.

Typical assemblages of both greenschist subfacies are common. The biotite-chlorite subfacies is represented by assemblages:

(1) epidote-albite-chlorite-(quartz-biotite)
(2) actinolite epidote-albite-chlorite-(quartz-biotite)

The muscovite-chlorite subfacies is represented by:

(1) muscovite-epidote-chlorite-(quartz-albite)
(2) epidote-chlorite-calcite-(quartz-albite)

Both biotite and muscovite are present in some samples and indicate a transition between the two subfacies.

Mineral characteristics are typical of the greenschist facies. Chlorite is very abundant in bright green to yellow-green patches and rounded aggregates which show no reference to clast borders. Interference colors vary from dull olive-brown to bright purple. Chlorite is best formed as blades intergrown with biotite in vesicles. Biotite is light green to dark brownish green; it occurs as vesicle fillings, fine borders on clasts, and in finely divided, extensive aggregates. Epidote forms irregular grains, euhedral laths, and distinctive spherulites; amounts vary, but partial vesicle fillings of epidote are common. Blue-green actinolite is usually minor in amount, occurring most frequently on the clasts in irregular needles and tufts. Feathery aggregates of albite and albite-sericite-calcite pseudomorphs after plagioclase are generally present. Relict, highly altered plagioclase is present in C-275; epidote, sericite, and a dark brown amorphous mat cover most grains.

Hematite is the only other original mineral recognized. It is considered to have formed a partial cement in local areas of the original rock. Quartz is a common but minor constituent, usually occurring as lenticular groups of granoblastic grains. Accessory apatite and sphene also occur frequently.

<u>Pillow Lavas</u> Dark, fine-grained, vesicular, spilitic pillow lavas occur frequently in the Norway member; lava without pillow structure is rare. Individual pillows are rounded ellipsoids 8 to 60 inches long, and typically defined by concentric vesicular bands and spongy cores. No

connection was observed between pillows; irregular moulding around adjacent pillows is common. Continuous, dense "cell-walls" frequently separate individual pillows (Figure 28), and interstices filled with breccia or calcite are common. Calcite fillings of interpillow spaces, broken pillows, and spongy pillow cores are common in the vicinity of East Lakes Reservoir.

Well defined pillows are generally localized in lenticular or irregular areas. Where exposures are continuous, as along the ridge east of Red Mountain, pillow structure grades imperceptibly into coarse angular breccia. Because of extreme jointing in the area, to distinguish between pillow lava and associated breccia is difficult.

A series of unusual outcrops, believed to be profile sections across individual flows, occurs in W$\frac{1}{2}$ sec. 6, T. 6 S., R. 45 E. Well-formed pillow lavas in rounded "wedges," 75 to 150 feet thick by 200 to 300 feet wide, are separated and enclosed by cross-bedded sediments. Parallel groups of foreset beds dip into the "valleys" between flows at nearly right angles to the regional dip. (Figure 29) The sides of the flows are steep, 40 to 60°, but show no evidence of intrusion. It seems certain that parallel tongues of viscous lava flowed from the east, leaving narrow ridges to be covered by sediment.

The pillow lavas were originally of andesitic composition; albite has partially or entirely replaced original plagioclase to form spilite. Composition of recognizable relict plagioclase varies from An_{30-40} to An_{36-40}. No relict mafic minerals were recognized.

Albite-calcite-sericite pseudomorphs are best developed after plagioclase phenocrysts, but also replace microlites of plagioclase. Generally calcite and sericite form borders around centers of clear, infrequently twinned albite. Sericite is less abundant than either calcite or albite, but well-formed tabular crystals up to 0.3 mm long, more properly called muscovite, are present in several sections.

Biotite-chlorite intergrowths in rounded aggregates and scattered irregular patches are common throughout the rock, but are best developed in vesicles. Chlorite is often concentrated as narrow bands around inside edges of vesicles. Biotite varies from pale green to brown, but dark green biotite with brown tints is typical. Small tabular crystals of both minerals form radiating sheaves either alone or as intergrowths. None of the sheaves show deformation.

Blue green actinolite occurs frequently, either as individual needles, fibrous laths, or tufted clusters. It often extends into vesicles from the surrounding rock.

Epidote is present in nearly every slide in widely

Figure 29. Crossbedding near pillow lavas of Figure 28. Hammer rests on bedding plane; handle bisects foreset beds (fine gravel streaks). Location: 100 yds SW of Figure 22.

Figure 30. Outcrop of strongly sheared crystal tuff in the Blue Creek lentil. Note stretched grains. Location: 7500 feet elevation, ½ mile W. of Blue Creek.

varying amounts. Euhedral laths, anhedral grains, clusters, and spherulites are all common forms of epidote in the spilitic lavas.

Iron ore is very abundant; magnetite, pyrite, and leucoxene are all present. Magnetite grains occur throughout the rock, but are conspicuous as heavy rims around vesicles. Spongy leucoxene forms an obscuring mat, often over large areas. Pyrite occurs in conspicuous, but never abundant, small euhedral cubes.

Other minerals occur frequently, but are not present in all rocks. Quartz generally forms clear lenticular patches of granoblastic grains, either alone or intergrown with albite and calcite. It is definitely secondary in all slides but C-274, where two large (2 to 6 mm) grains are rimmed by chlorite. The relation is not certain; these crystals could be either phenocrysts or vesicle fillings. However, vesicle fillings composed of single grains are rare, and these grains are thought to be phenocrysts. Clinozosite occurs in a single slide, C-274. Other minor minerals are sphene and apatite.

Vesicles are filled with intergrowths of two or more greenschist minerals; biotite-chlorite-epidote aggregates occur most frequently. The bladed minerals occur in rounded undeformed sheaves. Well-formed, radiating spherulites of epidote fill smaller vesicles and in many sections are the major vesicle filling. Vesicles in C-349 are almost entirely filled with albite; epidote is uniformly concentrated along the same side of nearly all vesicles in the rock. Indication that vesicles were filled after solidification of the rock is seen in C-344 where concentric hemispherical bands of hematite marked the outlines of progressive filling of vesicles with calcite.

Blastoporphyritic vesicular textures with plagioclase phenocrysts less than 2 mm long are characteristic of these pillow lavas. Glomeroporphyritic clusters of plagioclase are rare (C-347), and no coarse clusters, so characteristic of the Russel member, were seen in the Norway member. Groundmass microlites are small laths to needles set in thickly matted chlorite-biotite-actinolite-iron ore aggregates. Streaming of the microlites is not usually well developed. The original rock may have contained glass, but alteration products are too extensive to be certain. However, concentration of magnetite as vesicle rims is suggestive of glassy textures.

Metamorphism is more advanced, though spotty, in the Norway member than in the Russel member; this condition is particularly noticeable in the spilitic lavas where equilibrium in the greenschist facies has generally been achieved. Albite is much more abundant in this member. No certain explanation can be formulated without more detailed work, but reaction of the lava with Na available in the sea water at the time of extrusion is suggested. Turner and Verhoogen (30, p. 209) suggest that albite can form as the result of sea water streaming up through hot lavas.

Thickness. Computations from the map indicate a thickness of about 8500 feet for the Norway member. However, some repetition has been produced by faulting, and scanty structural information limits accuracy. Therefore, the Norway member is estimated to be between 6000 and 8000 feet thick.

Depositional Environment and Provenance. The Norway member is considered to have been deposited in moderately deep to shallow coastal seas with adjacent volcanoes. As the great thickness could only accumulate in a sinking trough, volcanic islands are more likely than a continental mass.

Well stratified sedimentary units with intercalated calcareous beds indicate marine conditions and deposition in quiet water below wave base. Decreasing regularity and frequency of recognizable beds may indicate decreasing depth and greater turbulence. However, an increase of frequency and size of lava flows forming both breccia and pillow lava seems more likely. Henderson (11, p. 29) suggested that coarse breccia associated with pillow lava merely represents granulation and shattering of lava ejected into water, and that pillow lava and pillow breccia differ only in degree of shattering. Because of the general lack of stratification in the breccia and the indistinct contact between lava and breccia, this seems a satisfactory hypothesis for the Norway member. Part of the breccia was undoubtedly formed from the breakup of pillow lava as partial pillows can be recognized in the breccia. The immense volume of the breccias relative to lava rules out complete derivation from the breakup of associated pillow lava after solidification.

Henderson (11) considers pillow lavas as merely a distinctive type of breccia. This conclusion seems warranted for the Norway lavas because concentric bands of vesicles could have formed only if each ellipsoid was an entity. Similar, concentrically banded pillows have been described from various parts of the world (13), and have generally been attributed to individual globular masses formed upon ejection of hot lava into water.

Age and Stratigraphic Relation. The lower Norway member is considered equivalent to the Sugarloaf lentil, probably Upper Triassic (16). The entire member is ~~younger~~ older than the Lower Sedimentary Series which is known to be Upper Triassic (26, p. 8).

The Norway member is in faulted contact with the Upper Triassic Lower Sedimentary Series except for a small area east of Red Mountain. In this locality the younger formation occupies a small shallow syncline resting unconformably on breccias of the Norway member; crumpled silicified mudstone of the Norway member exposed within 150 feet of the contact dips steeply northeast. (Figure 27) However, such angular unconformity may not be consistent for the entire formation. Shear planes in the overlying unit tend to obscure bedding, and full effects of the adjacent Pine Creek fault are not known.

The Blue Creek lentil is enclosed and interbedded with breccias and lavas of the Norway member.

Blue Creek Lentil

The name Blue Creek lentil is used to designate a small area of highly indurated clastic rocks which are lithologically distinct from interfingered and surrounding breccias and lavas. The lentil is well exposed in rounded outcrops between Blue and Fly Creeks on the south side of the Imnaha Canyon. Light colors and "clean" appearance set this unit apart from the dark-colored, "dirty" breccias.

Petrography. The lentil is composed predominantly of fine light-colored conglomerate and coarse sandstone. Angular to subrounded volcanic and sedimentary rock fragments are tightly compressed in a siliceous matrix to form a dense hard rock which breaks across grains. Weathered outcrops are smoothly rounded; surface irregularities are pronounced only where lenticular calcareous areas have been partially removed by weathering. Matrix forms a very low percentage of the rock in most conglomerate outcrops; extreme compaction is characteristic.

As seen microscopically, sandstones are composed of slightly rounded, porphyritic, and pilotaxitic volcanic grains. (Modes in Figure 31) Several textural varieties can be recognized, but actual composition cannot be determined. Much of the plagioclase has been altered to albite, sericite, and calcite; no relict mafics are present. Vesicular clasts are rare. Green biotite, chlorite, and epidote are thickly scattered through all clasts. Quartz and calcite are well developed in the cementing matrix, but granular epidote and aggregates of biotite and chlorite are also common in the matrix, especially as rims and extensions of the clasts. Fragmental detritus of larger grains is notably lacking in most conglomerate, thus causing the "clean" appearance. Sedimentary rock fragments were not recognized in thin section, but are occasionally present in outcrop in the western portion of the lentil.

Thin, 1 to 4-inch, gray-green and dark, reddish purple beds of fine tuffaceous (?) siltstone alternate at irregular 6 to 18-inch intervals with crystal tuffs and lenticular conglomerate through about 150 feet of section on the

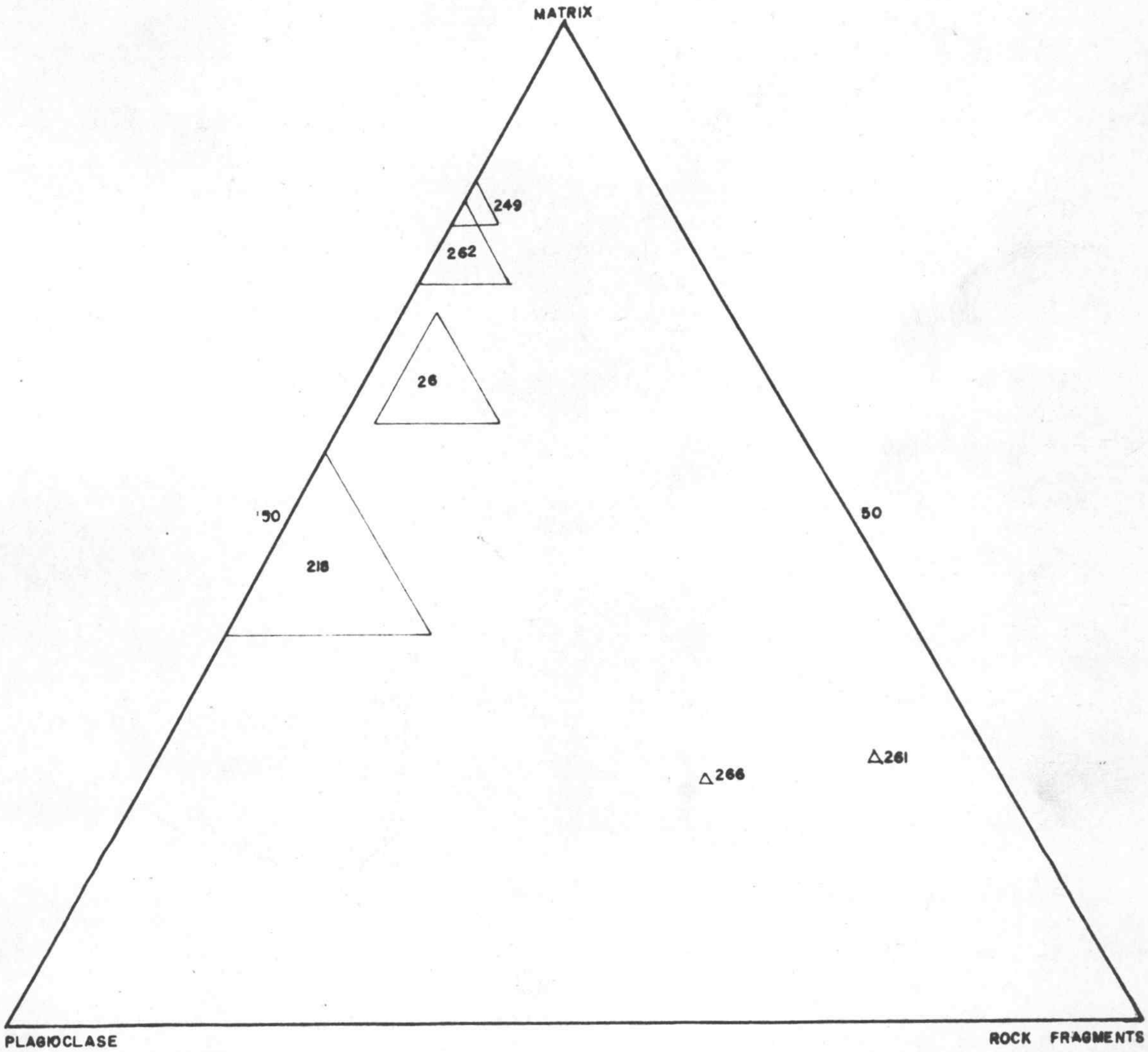


Fig. 31 Modal analysis of typical samples from the Blue Creek lentil by volume percent. Quartz is indicated by the triangles. Sample 218 from the Norway member is plotted to show the relation to the crystal tuffs grouped in the upper left side of the diagram.

west side of Blue Creek (7200 feet elevation). Lateral gradation is well developed; sequences cannot be traced from outcrop to outcrop, but persistent purple bands mark all outcrops in a local area. This purple rock contains fine needlelike plagioclase which was recognized by pseudomorphous aggregates of albite-sericite-calcite and grain outline. Formation of matted chlorite has so obscured original textures that no other clasts are recognizable. Secondary calcite, epidote, and quartz have developed in minor amounts.

Needlelike plagioclase grains seem incompatible with reduction of grain size produced by abrasion during water transportation. However, such forms could easily result from eruption and transportation by air. The thin purple bands are interbedded with crystal tuffs; therefore, they are called tuffaceous (?) siltstones.

Rounded concretionary masses of calcite 1/16 to ¼ inch in diameter are liberally sprinkled through an exposure of similar rock at 7500 feet elevation half a mile east of Fly Creek. Chlorite has grown between calcite grains in the concretions, but no definite cause for the concretions can be recognized. The rock is an altered feldspathic siltstone without definite tuffaceous features. However, Ross (23, p. 182) described somewhat larger calcareous concretions in tuff.

Crystal tuff beds, microscopically identical to those in the Norway member proper, are very common in the Blue Creek lentil. The tuff is generally exposed in unstratified outcrops 10 to 50 feet thick. Bedding is never present within the tuff, and only the surrounding beds reveal structure. In hand specimen the rock appears to be a quartz-bearing, feldspathic sandstone, colored light bluish gray on fresh surfaces. Quartz grains are large, 1/8 inch or more, and sufficiently abundant to be striking. These grains, microscopically revealed to be corroded, are a distinctive feature of all thin sections. Crystal tuff is found throughout the lentil, but no single bed or horizon could be traced for correlation.

The strong resemblance between these tuffs and similar tuffs in the Norway member proper is graphically shown in Figure 31. All samples form a closely compact group on the chart. Sample C-4 from the Trinity Creek formation also falls in this group.

Sample C-264, strongly deformed by shearing, was taken from about 7500 feet elevation immediately west of Blue Creek. (Figure 30) Clasts are stretched and dragged out, but lenticular groups of alteration products contain undeformed biotite.

<u>Thickness</u>. The Blue Creek lentil has a maximum thickness of about 1400 feet. No repetition is indicated by structure so the computations should be accurate.

Depositional Environment and Provenance. The exact environment in which this lentil formed is not certain. Flows which formed breccia pillow lavas were for some unknown reason absent from the area of accumulation. Because of the general lack of extensive calcareous units, and an abundance of slightly rounded, generally well sorted conglomerates, a shallow coastal lake or lagoon fed by small streams is postulated as the depositional environment. Another possibility is a small bay at a river mouth. However, no crossbedding typical of deltaic deposits was found in the field. It seems certain that the area was fed by streams because of the much larger accumulation of crystal tuff than in the surrounding portions of the member, and the better sorting definitely indicates greater reworking by water.

The provenance area was nearby, and vulcanism was active. Such conditions are clearly indicated by abundance of tuffs, slight rounding of clasts, and compositional immaturity of the rock. Mechanical breakdown more effective than chemical decay is indicated by the feldspathic detritus.

Lower Sedimentary Series

Upper Triassic units stratigraphically underlying the Martin Bridge limestone were called the Lower Sedimentary

Series by Smith and Allen. (26, p. 8) The designation is retained in this thesis for a tightly folded, sedimentary sequence which is well exposed on both sides of Cliff River, and which underlies Martin Bridge limestone. Outcrops are easily recognized by the characteristic rusty brown weathered surfaces; Red Mountain takes its name from this coloration.

Petrography. The Lower Sedimentary Series in the thesis area is predominantly composed of thin repetitious beds of fine-grained pyritiferous sandstone. Large areas of coarse, jumbled conglomerate are also present; most of the area south of Red Mountain summit is devoid of recognizable bedding. Fine, bedded conglomerate occurs in the formation, but is far less abundant than the finer thin-bedded sandstone.

Sandstone. Fine-grained pyritiferous sandstone is typically exposed in thin, well defined beds. Individual beds, characteristically ½ to 2 inches thick, reach 1 foot in thickness. Each bed is sharply defined, usually by a dark line or sharp change in grain size. Typical outcrops contain hundreds of beds. Generally the grains are too fine and too well sorted to permit field recognition of graded bedding, but most of the thicker beds are distinctly graded.

Freshly broken surfaces are dark gray to black with a fine, grainy texture. The characteristic rusty brown color is present only on weathered surfaces. Discoloration is caused by the breakdown of pyrite to limonite, but the dark browns or grays result from a high content of volcanic rock fragments.

The sandstones are lithic and feldspathic graywackes, firmly cemented by recrystallization of the chloritic matrix. A high degree of compaction suggests that the original matrix was relatively minor. Most samples studied were inadvertently collected from within thermal aureoles of the Cornucopia or Coral Creek stocks, and show thermal conditions superimposed on regional greenschist metamorphism. These specimens are so altered that accurate modes for the original sandstone can not be determined.

Recognizable constituents include rock fragments, and grains of plagioclase and quartz. Plagioclase and rock fragments are about equally divided, but quartz is minor. Volcanic rock fragments contain no relict minerals except microlitic plagioclase, and albitic replacement is far advanced in the microlites. Detrital grains of plagioclase are also in an advanced stage of albitization. All textural relations are greatly obscured by a matrix consisting of chlorite, green biotite, actinolite, and quartz, but in the least metamorphosed samples, individual grain outlines are recognizable. In more altered samples, blastopsammitic to hornfelsic textures, in which only bedding can be recognized, are more common.

Assemblage of the hornblende hornfels facies, marked by dark red-brown biotite and plagioclase more calcic than albite, are present in all samples taken south of the summit of Red Mountain. Bedding is marked by color, texture, and mineral content. In these samples, biotite is restricted to certain laminae, indicating that the assemblages have developed in response to bulk composition of individual beds. However, a narrow gradational zone in which biotite gradually disappears, not a sharp break, mark the division between assemblages. Amphibole is much less abundant in beds where biotite has formed. Definite identification of actinolite or aluminous hornblende could not be made, but aluminous hornblende is more compatible with the hornblende hornfels facies.

Characteristics of the individual minerals are typical of the hornblende hornfels facies. Biotite forms tiny brown to red-brown disoriented laths, usually alone, but in C-237, biotite is formed from chlorite. Amphibole is typically developed as pale to dark green tufts and fibrous laths, but small fibers are also present. Plagioclase is rarely twinned, has "n" greater than balsam, and commonly occurs as granoblastic groups within recognizable outlines of original crystals. Granoblastic quartz occupies rounded areas, and may have formed from original grains. Irregular grains of potash feldspar and apatite are minor accessories which do not occur in all samples.

Abundance of pyrite is a distinctive and characteristic feature of the fine clastics. Euhedral pyrite cubes are present in both greenschist and hornfelsic samples, but have been largely altered to limonite. They are generally also visible in hand specimen as cubes averaging about 1/8 inch across.

Mudflow Conglomerate. Much of the jumbled conglomerate exposed on the south flanks of Red Mountain contains extremely coarse boulders, commonly 1 to 3 feet in diameter, scattered through a sandy, or gravelly matrix which constitutes by far the largest portion of the rock. The most persistent rock type is a fine-grained dioritic rock with faintly mottled surfaces. Although the conglomerate has an estimated thickness of several hundred feet, no bedding was found, and the rock is similar in outcrop to morainal deposits. Extremely rugged exposures and loose talus prevent accurate delineation of the breccia unit or units. This area closely fits a description of mudflow breccia by Keunen and Carrozzi: (12, p. 367)

> "Slide conglomerates or breccias occur interbedded among normal rocks. These conglomerates can be entirely isolated, or they may be present in groups with or without graded beds and 'pelagic' beds between them. Although usually emplaced

> without marked erosion of the underlying beds, local stripping of some thin beds for laminae of underlying deposits may occasionally be noted..."

Conglomerates. Finer conglomerates intercalated with thin-bedded sandstones are well exposed on the west side of Red Mountain between elevations of 8000 and 8500 feet. Randomly oriented angular clasts of bedded shale scattered through a sandy matrix are exposed at an elevation of 8200 feet about half a mile N 10° W from the summit of Red Mountain. Similar fragments are common in the general area, but are more frequently associated with assorted volcanic cobbles in conglomerate. Scour is common in the finer conglomerate beds and associated sandstone, but was recognized nowhere else in the formation. In general, conglomerate beds are much thicker than sandstone beds; they average 1 to 6 feet.

Thin sections of grit-sized fragments show volcanic textures denoted now only by abundance and relation of plagioclase microlites and phenocrysts. The cementing matrix is composed of granoblastic quartz and albite, abundant chlorite, actinolite, biotite, and fine fragments of plagioclase and lithic grains. Detrital hornblende shows fibrous overgrowths on deformed crystals in C-356.

Thickness. About 3000 feet of the Lower Sedimentary Series is exposed in the canyon of Cliff River. As the eastern contact is faulted, true thickness cannot be measured in the thesis area. However, as the contact with the Martin Bridge limestone lies just west of the thesis area, the Lower Sedimentary Series is estimated to comprise 4000 to 6000 feet.

Fossil Content

Fossils were discovered at a single locality in this formation west of the thesis area. A small fauna was collected from a series of paper-thin, brown calcareous shale laminae at the contact against the Martin Bridge limestone in the canyon of East Eagle Creek.

This locality, first discovered by D. E. Ogren and the writer during a preliminary reconnaissance in the summer of 1957, is between 6800 and 6850 feet elevation, 3800 feet west of the summit of Krag Peak.

Depositional Environment and Provenance. The Lower Sedimentary Series is regarded as an offshore facies which accumulated in a moderate to deep basin beyond the shelf. Many features of this formation are indicative of deposition from turbidity currents: (12, p. 364-367)

1. Regular bedding
2. Each bed maintains features through exposure
3. Sharply defined beds
4. Absence of scour in most beds
5. Coarse-grained beds thicker
6. Absence of crossbedding and other shallow water features

7. Graded beds
8. Cementing matrix
9. Associated mudflow conglomerate

Therefore, there is little doubt that turbidity currents were the depositing agent for at least part of the formation. The coarse jumble of unsorted conglomerate south of Red Mountain probably represents a submarine landslide. Though more commonly associated with finer sediments the abundance of pyrite is a further indication of deposition in a deep, poorly ventilated basin. (31, p.333)

Age and Stratigraphic Relation. The small exposure of the Lower Sedimentary Series east of Red Mountain overlies the Norway member with angular unconformity. Sandstone of the Lower Sedimentary Series lies topographically over, but stratigraphically under overturned Martin Bridge limestone in the east wall of East Eagle canyon. As this area was not mapped, relations cannot be definitely stated, but a superficial reconnaissance revealed no indication of unconformity. Smith and Allen (26, p. 8) reported an "apparent strong unconformity" between the two units in the northern Wallowas.

Columbia River Basalt

The youngest rocks in the area are a series of basalt flows which cap the ridges in the eastern part of the thesis area. They have been included in the Columbia River basalt by Ross (22) and by Smith and Allen (26). The basalt forms relatively smooth, rounded ridges and precipitous canyon walls. Parallel flows and dark reddish coloration make the basalts easily recognizable for long distances. (Figure 32)

Petrography. Columbia River basalt is typically exposed in a series of slightly dipping flows which weather to shades of red or brown; dense flows with poorly formed platy structure or columnar joints are most typical, but abundant vesicles partially filled with zeolites are characteristic of some flows. Pillow structure was discovered at a single locality. (Figure 33) Most flow surfaces are rather sparsely timbered, and are marked by accumulations of loose, angular to subrounded boulders. Large dikes of similar basalt as wide as 50 feet are very common in the western part of the area where all flows have been removed by erosion.

The rocks are composed of labradorite, pyroxene, and olivine, with accessory magnetite, apatite, and glass. Modes of three typical samples are shown in Figure 34.

Labradorite, An_{50-54} to An_{68-70}, shows complex twinning and only slight zoning. Phenocrysts rarely reach 8 mm in length, but average 0.5 mm to 1 mm in length. Labradorite forms small disoriented laths which are sometimes partially surrounded by augite.

Figure 32. Exposure of Columbia River basalt flows on the west side of Deadman Canyon which show minor faulting.

Figure 33. Crudely formed pillow structure in Columbia River basalt. Location: NW$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 3, T. 6 S., R. 45 E.

Sample No.	C-144	C-214	C-216
Labradorite	61.0	41.3	49.2
Pyroxene	17.5	24.7	25.1
Olivine	9.9	4.3	3.6
Apatite	0.4	0.5	1.1
Fe ore	5.2	8.2	11.3
Alteration products	6.0	10.9	
Glass	---	10.1	9.7
Total	100.0	100.0	100.0

Figure 34. Modes of three typical samples of Columbia River basalt. Alteration products include serpentine after olivine and devitrification products after glass.

Titaniferous augite and pigeonite are present and irregular grains of both pyroxenes are commonly associated with olivine in the groundmass. Pale purple augite occurs as twinned phenocrysts and as tiny grains in the groundmass. No augite phenocrysts larger than 0.3 mm long were found. Pigeonite was recognized only by its low 2V.

Olivine occurs as scattered irregular grains in the groundmass. Although generally somewhat altered to serpentine and iron ore, unaltered grains are present.

Dark brown, isotropic glass occurs in nearly every slide as irregular patches and fillings between labradorite laths and surrounding augite. Glass, in C-214, is altered to a fibrous red palagonitic mass which produces megascopic red spots, and in C-193 a devitrification product similar to chlorophaeite is extensive. Small rounded areas are composed of spherulitic fibers that superficially resemble chlorite, but their birefringence is too high for chlorite. Relations to surrounding minerals are identical to those of glass, and glass is occasionally seen in the process of alteration to these spherulites.

Thickness. The ridge west of Clear Creek Reservoir contains about 1500 feet of nearly horizontal lava flows. Elsewhere in the thesis area, basalts are thinner or absent.

Age and Stratigraphic Relation

No definite age can be given from the thesis area. If these lavas are indeed Columbia River basalts, then a Middle Miocene age is well established (2, p. 83). Except for Quaternary deposits, they are the youngest rock in the area. Basalts cover an irregular erosion surface on tilted and folded strata of the Imnaha and Trinity Creek formations.

Quaternary Alluvium

Quaternary alluvium is widespread; nearly every canyon floor is choked with coarse debris, probably derived in part from glacial action and in part from rapid erosion of the high ramparts. Subdivision into deposits of purely glacial origin and deposits transported by water was attempted during field mapping. Landslide deposits are also shown on the map.

Glacial Moraines

Morainal deposits are divided into lateral moraines and ground moraines. Glacial veneer is very widespread in the area, and caused difficulty in mapping. Veneer is not shown on the map, as to do so would obscure relations of the principal map units.

Lateral Moraines. The best formed lateral moraines are on East Pine Creek, where blocky boulders, predominantly from the gabbroic stock, are piled into a long narrow ridge. Topographic expression, lack of sorting, angularity of fragments, and frequent striations on fragments definitely mark this deposit as morainal. Position with reference to the canyon indicates lateral relation to the former glacier.

Less obvious moraines in Clear Creek have been altered by postglacial erosion. Ross (22) referred to the deposits on the east wall as "high gravels." Blocky gabbroic boulders, as much as 8 feet in diameter, are scattered from the brink to the floor of the canyon for about $1\frac{1}{4}$ miles. Such large boulders could not have been transported the two or more miles from their source by water because they are deposited at nearly the same level as the source. Water or gravity transport would have carried boulders into the canyon, not laterally along the rim. Post glacial erosion cut notches into the moraine and removed much of the fines, leaving areas composed entirely of huge boulders. This material was redeposited as small fans at the end of shallow gullies.

A sharp "headland" composed of loose boulders juts into Clear Creek Canyon at the extreme south edge of the map. The form and position at the end of a long morainal wall suggest a breached terminal moraine.

Morainal material on the west side of the canyon spilled out over Columbia River basalt, and stands now as a small ridge of loose, jumbled material. The slopes into Clear Creek are covered with a dense growth of willow underbrush, but no outcrops of solid rock were found.

Other lateral moraines were recognized by characteristic tongue shape, but are so similar to those described that no special discussion is warranted. Many are too small to have topographic expression on a map with an 80 foot contour interval.

<u>Ground Moraine</u>. The floor of the shallow bowl immediately northwest of Fish Lake is covered by hummocky accumulations of detritus. Large erratics are frequent; the largest recognized was over 20 feet in diameter. Most of the deposit has no form, but two narrow ridges extend into the bowl. These ridges are accumulation of unconsolidated

material behind abutments of resistant rock. Downstream terminations are steep faces, and consolidated rock is usually exposed for only a short distance, with rounded and polished upper surfaces. Striae indicate movement parallel to the ridges. Therefore, the ridges clearly were formed by accumulation of englacial detritus on the upstream side of the abutments contemporaneously with downstream plucking.

Water-laid Deposits

Water-laid alluvial deposits are divided into three categories: valley fill, alluvial fans, and alpine meadows.

Valley Fill. Narrow valley fillings have accumulated at the base of steep canyon walls, indicating a greater supply of sediment eroded from the highlands than the small streams have been able to carry down relatively flat glacial canyons. Only Cliff River and Trail Creek have exposed bedrock. Alluvium along Cliff River rests on the flat glacial floor out of reach of the main stream, which is entrenched in a narrow gorge.

A narrow "flood plain," covered by fine silty soil, has formed along Clear Creek, but ends at the upstream side of the morainal "headland" described above. A stream with such a small catchment basin is not likely to produce this "flood plain" from runoff water alone. Coupled with the jutting "headland" of morainal boulders, this "flood plain" gives strong evidence of a small postglacial lake formed behind a terminal moraine.

Alluvial Fans. Near the head of Cliff River, on the west side of the canyon, a large alluvial fan has formed, part of which extends into the extreme western edge of the thesis area. The fan consists mostly of rounded to subangular, poorly sorted, unstratified cobbles and boulders with large amounts of finer material as interstitial filling. This deposit resulted from rapid erosion of adjacent highlands and deposition from torrential runoff. Loose material left by glacial ice may have contributed detritus.

Alpine Meadows. Alpine meadows lend beauty and charm to the area. All sizes and shapes are nestled into little basins. Each is level or nearly so, and represents filling of small postglacial lakes with fine sediment.

Landslide Deposits

Only one landslide was recognized; it forms an elongate scar on the south wall of the Imnaha Canyon, just east of Fly Creek.

Two other deposits, probably derived from repeated snow slides, are shown high on the ridge east of Cliff River. These deposits are slightly arcuate in form, and are composed of semi-circular "bands" of angular boulders. Each "band" is pushed tightly against the preceding one;

crests are separated only by a narrow indentation. However, to one standing on the surface, the composite nature of the deposit is clearly visible.

Each deposit is situated below a steep-walled, west-facing cup in which heavy snow accumulates. This position and the composite nature lead to the belief that these piles of loose detritus are derived from frequent snow slides.

INTRUSIVE UNITS

Varied intrusive units occurring in the thesis area are described in related groups as follows: Metadiorite Group, Quartz Keratophyre, Fish Lake complex, Bostonite Group, Corral Creek stock, Cornucopia stock, and Dikes. The order of description corresponds approximately to age.

Metadiorite Group

A series of small metadiorite stocks crops out along Trail Creek, East Pine Creek, and on Trinity Mountain. None is more than a few hundred yards across, and outcrops are not conspicuous. Exposures are generally in isolated, somewhat rounded blocks.

Petrography

The metadiorite is dull green, blotched with white areas of andesine. Only in the exposures on Trinity Mountain are individual mineral grains recognizable. In this rock, slender andesine laths are loosely interwoven through a dark green background. However, samples from each unit contain two distinct microscopic characteristics: pale lavender, titaniferous augite and well-developed skeletal crystals of titaniferous iron ore.

Essential minerals are andesine, An_{30-34}, pyroxene, and hornblende. Accessory minerals include iron ore, apatite, and rarely zircon. Modes are shown in Figure 35.

Sample No.	C-199-B	C-15	C-368
Andesine	59.4	49.7	47.9
Augite	7.6	5.7	9.5
Hornblende	1.7	18.6	12.4
Epidote	13.9	13.4	3.7
Actinolite	2.3	2.1	2.1
Chlorite	12.8	7.0	10.9
Fe ore	2.3	3.5	13.1
Quartz			0.4
Total	100.0	100.0	100.0

Figure 35. Modal analysis of typical samples of metadiorite by volume percent.

Andesine forms long, slender laths up to 6 mm long and 1 mm wide in C-368. In other slides the slender lathlike form is absent; andesine is more blocky, and euhedral crystals are rare. Complex twinning is often visible through the overgrowth of sericite, epidote, and chlorite, but zoning is not well developed.

Sericite is the most abundant alteration product of andesine; chlorite and rare calcite accompany the seritic mat. Though chlorite occurs in the andesine, it has not formed from andesine. In C-368, small opaque inclusions cloud the andesine, suggesting slight thermal alteration. Two generations of andesine are recognizable in this slide, but no change in composition is noted in the finer grains.

Augite forms pale lavender laths and twinned plates. Hourglass zoning is visible in some sections, and polysynthetic twinning of augite is present in C-197. The augite formed after andesine, and frequently partially surrounds or includes andesine crystals. Augite is usually rimmed by deuteric hornblende, but alteration to fibrous actinolite is commonly developed within the rims.

Hornblende forms either partial or complete rims around augite. The rims are dark green to very light brown, and strongly pleochroic from nearly colorless to dark green. Uralitic hornblende has largely replaced augite in C-15; and only irregular augite cores remain.

Chlorite and epidote are the most common alteration products. Generally chlorite shows no definite relation to any other mineral, but forms irregular patches which usually contain epidote and actinolite. Rounded granular aggregates and euhedral laths of epidote are nearly always present in chloritic patches. Actinolite is usually interwoven with chloritic aggregates, but also forms fibrous mats after pyroxene, and ragged fringes on hornblende.

Skeletal crystals of titaniferous iron ore up to 0.5 mm across are characteristic of these rocks. The crystals are formed of several narrow, metallic bars separated and surrounded by leucoxene. In the modes, leucoxene is included as ore; it averages 39 percent of the iron ore listed for the three samples.

Accessory apatite appears in all sections but did not fall under the cross-hairs in the three slides counted. Zircon, marked by a pleochroic halo, occurs only in C-371.

Contact Relation

Clearly intrusive contacts were observed only along the north side of the stock on East Pine Creek, where the metadiorite cuts the Trinity Creek formation. Exact relations are obscured elsewhere. No metamorphic effects were recognized.

Age

Low-grade regional metamorphism is indicated by the extensive development of chlorite, epidote, and actinolite in the samples. As metamorphism is more advanced in these stocks than other intrusive rocks, they are considered to be the oldest intrusive group. Slight thermal effects in C-368 further indicate that the metadiorite stocks are older than the Fish Lake complex. Only rocks of the Trinity Creek formation are in contact with the metadiorite.

Quartz Keratophyre

A very small but distinctive quartz keratophyre stock protrudes through the Trinity Creek formation in the extreme southeast corner of the thesis area. Weathered surfaces are light gray with indistinct spots, superficially resembling a coarse sandstone. Fresh surfaces are dark gray to brown with distinct white plagioclase and quartz phenocrysts set in an aphanitic gray-brown groundmass.

Quartz phenocrysts are corroded with deep embayments, fritted edges, and generally rounded outlines. The size is relatively constant, 2 to 3 mm across. "Dust trails" and undulatory extinction are characteristic, and scattered inclusions of zircon are present. Portions of the groundmass occupying embayments into quartz are more dense than in surrounding areas.

Albite-oligoclase, An_{8-12}, is euhedral; individual crystals as long as 4 mm are common. Although altered to stringers and patches of sericite, albite and carlsbad twins are distinctly visible. Sericite also generally forms very narrow (0.01 mm) rims around plagioclase phenocrysts. Possible albitization during low-grade metamorphism may have changed the composition of the plagioclase.

The groundmass contains a few plagioclase crystals up to 0.1 mm long and small patches and veinlets of interlocking quartz grains. No other primary minerals, except a single zircon, were recognized in the groundmass. Secondary chlorite and fine sericite are also present.

No mafic minerals, except accessory iron ore, are present. However, clusters of chlorite suggest the previous existence of amphibole or biotite. Such clusters are rectangular to hexagonal in outline, generally rimmed by nearly solid chlorite, and contain intergrowths of chlorite and sericite.

Accessory iron ore, apatite, and zircon accompany the principal minerals. Iron ore is slightly altered to leucoxene. Secondary calcite is associated with veinlets of quartz.

Contact Relation

As only two outcrops of quartz keratophyre were located exact relations are not definitely known. The contact is not visible, but the rock is considered intrusive.

Age

The age cannot be definitely stated from such isolated exposures. However, this stock is assumed to be early in the sequence of intrusion, probably before the Fish Lake complex.

Fish Lake Complex

The Fish Lake complex comprises a group of small basic stocks in the eastern part of the area. Several individual stocks are composite, consisting of two or more magmatic units, which were emplaced in mafic to felsic sequence. The complex was first reported by Ross. (22) Reid (21) differentiated four large stocks of the complex, one of which lies just east of this thesis area. The four largest stocks in the thesis area are designated by topographic features as follows: Clear Creek stock, Fish Lake stock, Russel Mountain stock, and Melhorn stock. Smaller bodies are unnamed; where specific references are made to them, their locations are given. An attempt to map individual magmatic units was deemed inadvisable at the map scale, and for the scope of the thesis.

Petrography and relations of the units are discussed individually, but metamorphic effects are described for the complex as a whole.

Hyperite

The hyperite is composed of quartz-bearing hornblende norite and gabbro, gradational in all proportions; slight changes in pyroxene ratio is megascopically imperceptible.

Petrography. The rock is mottled gray to black in varying shades; texture and grain size also vary. In addition to essential labradorite, pyroxene, hornblende, and their alteration products, the rock contains accessory apatite, iron ore, quartz and olivine. Deuteric hornblende, cummingtonite, and biotite are characteristic as shown by modes. (Figure 36)

Plagioclase varies in composition from labradorite, An_{58-62}, to bytownite, An_{68-72}. The more calcic varieties occur in samples containing less amphibole. The crystals are subhedral to anhedral, complexly twinned, and frequently zoned. Combinations of carlsbad and albite twinning are most common, but pericline twinning occurs infrequently. Zoning is generally not well defined; however, some samples show well defined progressive zoning with 8 to 10 bands. No correlation between plagioclase zoning and bulk composition of the rock was recognized.

In many samples, the plagioclase is so altered that the composition could not be determined. A nearly opaque, fibrous to scaly mat of chlorite, "white mica," epidote, prehnite (?), and leucoxene obscures the crystals. Such alteration is probably the combined result of deuteric "saussuritization" and low grade metamorphism. Shand (25, p. 172) describes saussuritization as follows:

> "...the anorthite fraction of a calcic plagioclase is converted by the addition of water into an aggregate of zoisite and sericite, with which calcite and chlorite are often associated....... Plagioclase crystals, which have suffered this alteration become semi-opaque by the development of minute scales of sericite and granules of epidote or zoisite."

Prehnite may replace plagioclase during the early stage of

Phase	Hyperite					Tonalite		Trondjemite
Sample No.	C-33	C-158	C-78	C-292	C-202	C-294	C-166	C-201
Quartz	0.7		0.6			22.7	14.2	33.3
Plagioclase	13.2	37.7	61.3	48.1	67.9	50.7	55.1	55.6
Potash feldspar						3.7	0.1	4.0
Hypersthene	10.0	7.4	3.7	25.3	10.9			
Augite	42.7	3.2	5.9	19.9	4.7			
Hornblende	24.7	48.4	18.8	4.0	6.2	13.2	22.2	
Biotite		0.1	0.2		0.3			4.0
Actinolite	4.7	0.8		1.1	1.9			
Cummingtonite	1.1	1.2	5.5	0.6	4.8			
Iron ore	1.5	0.7	2.9	1.0	3.1	0.1	0.7	0.2
Talc	0.6	0.1	0.5		0.1			
Olivine	0.1							
Serpentine	0.6	0.3	0.4					
Apatite	0.1	0.1	0.1			0.1		
Chlorite			0.1		0.1	6.9	7.0	2.2
Epidote						2.3	0.7	0.7
Muscovite						0.3		
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Figure 36. Modal analysis of typical samples of the Fish Lake complex.

regional metamorphism (6, p. 170, but is not a deuteric mineral. Therefore, both saussuritization and low grade regional metamorphism seem to have affected the plagioclase. Large blades of "white mica" as long as 1.3 mm occur in C-X-3 as alteration of plagioclase; they are thought to be paragonite instead of sericite.

Pink, strongly pleochroic hypersthene, Fs_{25-28}, is characteristic of the hyperite phase, but varies widely in abundance. Both euhedral crystals with well developed lamellar exsolution and irregular grains are common. Deuteric rims of cummingtonite enclose most hypersthene; rarely, only isolated remnants of hypersthene remain in pseudomorphs of cummingtonite. Alteration to talc and bastite is occasionally well developed. Cores of hypersthene occur in augite without sharp demarkation, but are easily distinguished by the strong pleochroism of hypersthene. Such inclusions are sometimes separated from surrounding augite by a rim of iron ore.

Augite is distinguished from hypersthene by its lack of pleochroism, tabular form, and characteristic partial alteration to hornblende. Twinning is well developed, hourglass structure is occasionally present, and zoning is rarely observed. Crystal size varies largely in relation to the degree of replacement by hornblende; large augite grains with narrow hornblende rims, and small irregular cores of augite in hornblende are both common. Outer borders of augite are generally granular with spongy, optically continuous grains of hornblende embedded through a wide zone. However, few augite crystals show sharp contacts against hornblende. Augite composition ranges from 26 to 40 percent $CaFeSi_2O_6$ molecule in four typical samples. Alteration of augite to actinolite is occasionally far advanced.

Strongly pleochroic, dark brown hornblende was formed in response to increasingly hydrous conditions during late magmatic stages. Its color grades outward from dark brown to pale bluish green in large crystals. Lack of any semblance of crystal form, and thickly scattered, rounded inclusions of all principal minerals are characteristic of the hornblende. Narrow rings of cummingtonite separate hypersthene inclusions from hornblende. Augite inclusions are seldom rounded; the zone of contact is irregular. Some small cores of augite remain even in the most hornblende-rich samples. Alteration of hornblende is usually not far advanced, but small amounts of chlorite are typically present.

Cummingtonite has a similar role in relation to hypersthene as hornblende has to augite; narrow rims of cummingtonite around hypersthene are characteristic even in the most basic samples. Where amphibolitic alteration of hypersthene has taken place, the secondary mineral is cummingtonite. No hornblende has formed from hypersthene.

Dark red-brown biotite is usually minor, formed after hornblende, and around iron ore, but is occasionally a major constituent. (C-X-1) Where biotite is abundant, the rock is generally finer grained, and contains only minor pyroxene and more sodic plagioclase. Pale green, bladed to fibrous hornblende is also usually present. However, only the finer texture is megascopically recognizable.

Accessory minerals, except for the simultaneous occurrence of quartz and magnesian olivine, are typical of gabbroic rocks. Apatite is consistently present, often in large crystals up to 1.3 mm long. Magnetite is abundant; and skeletal crystals of titaniferous iron ore are infrequently present. Interstitial quartz is slightly more abundant and widespread than olivine.

Olivine occurs only as rounded blebs and corroded crystals, usually in an advanced state of alteration, included either in single crystals, or tightly packed aggregates of augite or hypersthene. Dark red-brown serpentinous pseudormorphs are more common than the parent olivine. Talc and serpentine have formed along fractures, and all fragments are rimmed by heavy bands of iron ore. Olivine composition (Fa_{15-25}) is based on a negative optic axis figure with an estimated 2V of 85-90°.

Shand (25, p. 120-121), in his discussion of incompatible phases states:

> "If the magma is cooled rapidly after olivine has begun to crystallize, then the reaction between olivine and silica is prevented and we have a rock composed of a few crystals of olivine with or without other minerals embedded in a siliceous glass.... A similar effect may be produced by the olivine reacting with the siliceous residual magma; the latter, if it crystallizes completely, must then yield some quartz."

The second effect is well illustrated in the Fish Lake complex. Olivine crystallized early, and was incompletely resorbed before becoming isolated from the magma by formation of the surrounding pyroxene. No evidence exists that either quartz or olivine originated by contamination in the rocks of the Fish Lake complex.

Erratically shaped, glossy-black schlieren, characterized by coarsely crystalline texture and brownish weathered surfaces, occur in hyperite throughout the complex. (Figure 37) Schlieren composition is usually melagabbro, but hornblendites also occur. Extensive replacement of augite by poikilitic hornblende is characteristic of these "inclusions" and hornblende is much more abundant in the schlieren than in the surrounding rock. Individual crystals of both pyroxene and hornblende one-quarter to one-half inch across are typical of the schlieren.

If these "inclusions" were remnants of an earlier

Figure 37. Erratically shaped schlieren typical of hyperite in the Fish Lake complex. Location: center NW$\frac{1}{4}$ sec. 7, T. 6 S., R. 46 E.

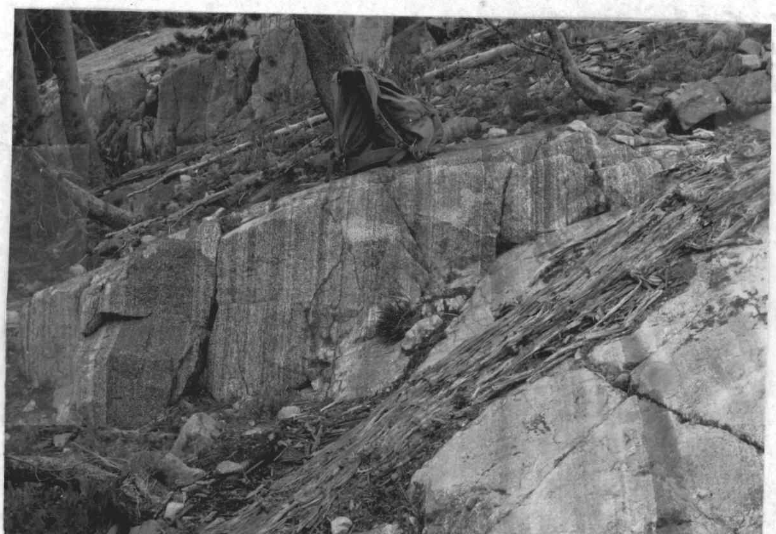


Figure 38. Planar flow banding in hyperite of the Fish Lake complex. Location: SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 7, T. 6 S., R. 46 E.

phase which was dragged out into such weird patterns, large tabular minerals should record the deformation, but no such deformation is present, even biotite does not have bent cleavage. The schlieren, therefore, are not believed to be inclusions in the ordinary sense; either they were a part of the parent magma or chemical assimilation has reached complete equilibrium with the magma.

Local concentrations of water could cause replacement of augite by hornblende without change in temperature. Complex patterns developed in the schlieren are more suggestive of the diffusion of one fluid through another than of deformation produced by shearing or pressure. (Figure 37) It is therefore suggested that the schlieren represent local concentrations of water vapor and volatile constituents in the crystallizing magma.

Flow Banding. Planar flow banding is well developed in several parts of the complex. (Figure 38) The most striking exposures are in the northern part of Clear Creek stock where a zone 100 to 150 feet wide can be traced continuously for about half a mile. Other areas with well developed flow banding are in the center SW¼ sec. 16; SW¼ SW¼ sec. 17; and E½NW¼ sec. 9, T. 6 S., R. 46 E. and also in the small gabbroic bodies east of Deadman Point. Banding is caused by segregations of hornblende and labradorite. Individual bands are well defined in outcrop, but scarcely visible in thin section. Relative concentrations of hornblende grade into feldspathic areas on both sides. Dark bands generally 1/16 to ¼ inch wide are separated by a maximum width of 2 inches; a few dark bands are several inches wide. No preferred orientation of the minerals was observed in the bands.

In all occurrences, the banding roughly parallels the borders of the stock, though in the Clear Creek stock the banded zone is in places 100 to 150 yards from the contact. Swirls and eddies on horizontal surfaces suggest a slow moving stream (Figures 39 and 40), but on exposed vertical surfaces the lineation is regular. (Figure 38) Wagner and Deer (32, p. 27) interpret greater vertical regularity in flow banding along the border of the Skaergaard Intrusive to flowage either upward or downward, not horizontally. They believe that greater irregularity would result on vertical surfaces from horizontal movement. Platy flow banding of disoriented mineral grains is a common feature of basic plutons. (3, p. 16)

<u>Inclusions</u>. Hyperite contains ultrabasic and skarn inclusions which are large enough to show on the map. Other small rounded xenoliths of uncertain parentage are scattered through the complex at random intervals, generally near the borders. Each type is described individually.

Figure 39. Irregular swirls suggestive of sluggish stream in zone of planar flow. Location: 6640 feet, NE¼SW¼ sec. 7, T. 6 S., R. 46 E.

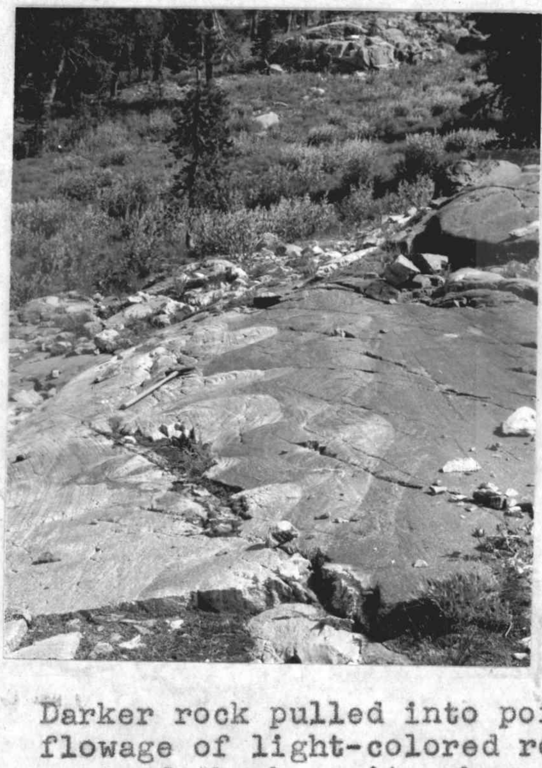


Figure 40. Darker rock pulled into pointed "cusps" by flowage of light-colored rock. Both are part of the hyperite phase. Location: 6800 feet, NW¼NW¼ sec. 7, T. 6 S., R. 46 E.

<u>Ultrabasic Inclusions</u> Ultrabasic inclusions are marked by distinctive, weathered surfaces; deep reddish brown coloration contrasts sharply with grays of the surrounding rock. Many of the ultrabasics are streaked on weathered surfaces with closely spaced parallel bands superficially resembling bedding. The bands are composed of chalky white fibers, marking a high serpentine content. The rock on fresh surfaces is jet black, and generally fine-grained; blocky, prismatic cleavage faces typical of freshly broken schlieren are absent.

These inclusions are usually rounded to elliptical in form, but irregular shapes also occur. Contacts are generally sharp, although some assimilation has undoubtedly taken place. The largest ultrabasic inclusions are 250 to 300 feet long by 100 to 150 feet wide. (1-1)

Thin sections of typical inclusions are classified as amphibole olivinites, peridotites, and serpentinites. Olivinites and peridotites are gradational as only the ratio of olivine to pyroxene changes. Deuteric hornblende and cummingtonite rim the pyroxenes in both rock types. Basic plagioclase is accessory, but is so much altered that composition could not be determined. Coronas formed at the contact of olivine and plagioclase. Other accessories are foxy-red biotite, apatite, and iron ore. Alteration products are similar to those described in the hyperite phase.

Serpentinites are composed of myriad veinlets of antigorite and magnetite. Fibrolamellar banding is distinct in some thin sections. In others subcircular patches of antigorite are sometimes interfingered, sometimes separated by thin partitions of magnetite. Deep foxy-red biotite partially replaced by chlorite infrequently encircles magnetite; rims of biotite probably indicate primary rather than secondary magnetite.

<u>Rounded Xenoliths</u> Small, rounded xenoliths, usually less than a foot in diameter occur in scattered zones around the stock borders. Though xenoliths are not common, where one is noted, several can usually be found in the vicinity.

The most distinctive type (Figure 41) contains large laths of hornblende 1 to 3 inches long in a matrix of highly altered plagioclase. A dense white border ½ to 2 inches wide encircles inclusions of this type, which are generally associated with banded portions of the hyperite phase.

Dark, fine-grained xenoliths, apparently fragments of the country rock, are generally within a few feet of contacts with "greenstone."

<u>Skarn Inclusions</u> Skarns are present as inclusions in both the hyperite and tonalite phase. They are discussed in detail under metamorphic units because some skarn localities are not inclusions.

Figure 41. Xenolith in hyperite of the Fish Lake complex. Note formation of heavy rim, and long crystals of hornblende.

Figure 42. Pegmatitic dike cutting gabbroic rock of the Fish Lake stock. Note heavy margins of coarse hornblende. Location: 6700 feet elevation at west end of Fish Lake.

Pegmatitic Dikes. Small, irregular, pegmatitic dikes are infrequently developed in the hyperite. (Figure 42) The best exposures are at the west end of Fish Lake at an elevation of 6850 feet, and in the small elliptical stock in SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 16, T. 6 S., R. 46 E.

These dikes are coarse-grained, mottled black and white, and generally very irregular in pattern. Ribbonlike patterns cut planar flow bands in the small stock. Laths of randomly oriented hornblende up to 2 inches long are present in many such dikes. Others are bordered by heavy rims of coarsely crystalline hornblende. Plagioclase is the principal light-colored mineral. No thin sections of these dikes were prepared.

Contact Relations. The contact between the hyperite phase and "greenstone" is exposed at a single locality along the north side of Fish Lake stock (Figure 43), and around the small dikelike body near the center of sec. 9, T. 6 S., R. 46 E. Slight chilling effects produced a "groundmass" of rounded granular augite, hypersthene and labradorite. Large phenocrysts of dark brown hornblende formed later, and poikilitically include grains of the early minerals. Chilling is not readily apparent in hand specimen because of the large prismatic hornblende crystals which frequently reach a half inch in length.

Stoping or brecciation of enclosing "greenstone" is

Figure 43. Contact with metamorphosed "greenstone" on the north side of Fish Lake stock. The pocket knife lies on the contact, with chilled border facies of the stock on the right. Location: 6850 feet NE$\frac{1}{4}$SW$\frac{1}{4}$ sec. 9, T. 6 S., R. 46 E.

Figure 44. Large boulder composed of intrusive breccia typical of the marginal tonalite in the Fish Lake complex. Location: 7000 feet NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 17, T. 6 S., R. 46 E.

suggested only at the southeastern corner of the small stock south of Russel Mountain. About 200 feet north of the road, angular xenoliths of "greenstone" occur in a gabbroic matrix, and 100 to 125 feet inward, dark, rounded xenoliths are scattered through outcrops of hyperite.

Near the contact with later tonalite, thermal metamorphism of hyperite is denoted by the appearance of anthophyllite.

Tonalite

Tonalite was generally recognized in the field only by its characteristic intrusive breccia. The rock is lighter than the hyperite when the two are viewed together, but the difference in color was not sufficient to allow the writer to map with confidence. Intrusive breccias with dark inclusions in the lighter tonalite are distinctive (Figure 44), and occur with sufficient frequency to indicate that the tonalite is extensive. However, breccia could not be traced continuously, so the tonalite units may be discontinuous within the Clear Creek stock. Although best exposures are in the eastern part of Clear Creek stock, most of the small stocks also contain breccias where tonalite has intruded the older hyperite. However, no tonalite was recognized in the Melhorn, Fish Lake, or Russel Mountain stocks.

Petrography. Andesine, quartz, and hornblende are major components of the tonalite (Figure 36). Chloritic pseudomorphs have replaced nearly all of the original biotite, therefore biotite does not appear in the mode though it was an original component. Zircon, sphene, and allanite also failed to fall under the cross-hairs during counts, but are accessory minerals in addition to the apatite shown.

Andesine is generally so altered as to make determination of composition difficult; An_{44-47}, and An_{36-38}, mark the range of determined composition. Complex carlsbad and albite twins are common; pericline twinning rarely occurs. Strong progressive zoning is still visible in many crystals. Alteration has progressed by zones, and frequently is restricted to the more calcic cores. The most consistent alteration products are "white-mica" and epidote, but minor calcite has formed on a few grains. Prehnite (?) and the opaque spongy mass so characteristic of plagioclase alteration in the thesis area are also present.

Green hornblende is euhedral to subhedral; long prisms and euhedral cross-sections are common. Color changes on rotation from bright green to pale yellow-green. Small cores of augite are rarely present, and hornblende is commonly rimmed by chloritic pseudomorphs of biotite; less commonly partially altered to chlorite.

Quartz is anhedral, occurring only as interstitial grains. Coarse grains up to 1.5 mm across show well developed "dust trails" and undulatory extinction. Small inclusions of euhedral zircon and apatite are characteristic of the quartz grains.

Biotite is seldom unaltered; it is generally recognized only as dark brown remnants in pseudomorphous aggregates of chlorite, epidote and rutile. Alteration has proceeded inward along cleavage planes from the outer borders, and distinct stages of alteration are recognizable. The biotite first bleaches, then alters to strongly pleochroic chlorite with granular aggregates of epidote concentrated along cleavage traces, often completely separating the shreds of chlorite. Minute scaly aggregates of leucoxene and rutile form dark patches in the chlorite. The final product, under plain light, is a rectangular patch either of banded, green and black, shreddy fibers separated by broader bands of yellowish epidote, or irregular grains of epidote completely surrounded by fibrous masses of chlorite. Irregular calcite grains are infrequently associated with alteration products of biotite. The pseudomorphs occur alone or less frequently as partial rims and replacement of hornblende.

Two types of chlorite are present: (1) formed after biotite, strongly pleochroic, tan to bright green, in shreddy aggregates with deep purple interference colors, and (2) formed after hornblende, slightly pleochroic, light green to nearly colorless, in rounded aggregates which show polarization crosses.

Contact Relations. Wherever the contact is exposed, the tonalite brecciated the surrounding rock. Intrusive breccia is best exposed along the west side of East Pine Creek, where the inclusions are well rounded (Figure 44). At several other localities angular fragments of the gabbroic phase show little displacement. Interlocking pieces are separated only by narrow injections of tonalite. The degree of rounding increases away from the contact. Similar relations are exposed where the tonalite cuts deformed "greenstone" of the thermo-dynamic aureole (Figure 45). Well developed breccias indicate rapid, forceful injection with subsequent stoping and partial assimilation to round the innermost inclusions.

Inclusions. Xenoliths of other than hyperite and skarn were noted only at the head of East Pine Creek where angular fragments of country rock are included (Figure 45). Reid (21, p. 73) reported inclusions of pyroxenite, gabbro, skarn, and greenstone, but does not cite localities. Petrographic studies of the breccia were considered beyond the scope of this thesis.

Figure 45. Angular blocks of "greenstone" included in the tonalite phase of the Fish Lake complex. Location: 7120 feet, center of $NW\frac{1}{4}$ sec. 17, T. 6 S., R. 46 E.

Figure 46. Angular fragments of the hyperite phase brecciated by the intrusion of the tonalite.

Trondjemite

Trondjemite is conspicuous by its very light color; white weathered surfaces stand out sharply against the darker surrounding rocks. Only a small area, 600 to 800 feet long by about 200 feet wide, was found. The exposures are near the bottom of Clear Creek canyon at an elevation of 6000 feet in the SW¼NW¼ sec. 18, T. 6 S., R. 46 E.

Petrography. Large anhedral crystals and interstitial grains of quartz are very abundant. Inclusions of zircon and apatite are generally present in the quartz grains, and irregular grains of potash feldspar are associated with quartz.

Andesine, An_{30-34}, is complexly twinned and strongly zoned; outer zones show parallel extinction. Alteration to "white-mica" and epidote is concentrated in cores and along preferred zones.

Dark brown biotite is the only mafic present. Alteration to chlorite, epidote, and rutile is far less advanced than in the tonalite. Some crystals show slightly bent cleavage.

Accessory minerals are apatite, zircon, and iron ore. Zircons are well formed, large, and relatively abundant; individual crystals attain a length of 0.15 mm. Modal analysis is shown in Figure 36.

Contact Relation. Intrusive breccias are present in the southeast end of the exposure, but are less well developed than in the tonalite phase. The inclusions are slightly rounded. Knife-edge contacts between trondjemite and tonalite are not exposed, but the contact can be placed within three to five feet. Abrupt change in color and in megascopic quartz content allows easy recognition.

Metamorphic Aureole

No attempt was made to sample sufficiently to make a detailed study of metamorphic aureoles around units of the Fish Lake complex, but samples were taken immediately adjacent to the contact of the Fish Lake stock and the narrow dikelike unit near the center of sec. 9, T. 6 S., R. 46 E. The precise contacts are not visible around other units. The dynamo-thermal aureole around the western two units is discussed in detail under metamorphic units (Page 159).

Pyroxene Hornfels. Pyroxene hornfelses were formed within a few inches of the contact, but probably do not extend more than 3 to 5 feet from it. The extreme outer limit is certainly less than 50 feet, because samples taken at that distance were hornblende hornfelses with relict plagioclase. Rounded hypersthene inclusions, largely altered to cummingtonite and iron ore are present in one slide, and cummingtonite-hornblende intergrowths in another, each taken within 5 to 8 feet of the contact. The hornfelses are dark, medium-grained, irregularly spotted rocks with indistinct streaking parallel to the stock, and are difficult to distinguish by eye from the similarly spotted chilled border of the intrusive (Figure 44).

The assemblage diopside-hypersthene-plagioclase is characteristic of the pyroxene hornfels facies (30, p. 442). In the thin sections examined, hypersthene and diopside occur as xenomorphic grains and partially formed laths, and as rounded inclusions in hornblende. The hypersthene is strongly pleochroic from pale green to pink. Colorless or pale green diopside is closely associated with hypersthene and hornblende, but is distinguished by its total lack of pleochroism. Some larger crystals of diopside display sieve structure. Both pyroxenes are somewhat altered, hypersthene to cummingtonite and biotite, and diopside to actinolite and hornblende.

The plagioclase varies in composition from calcic andesine, An_{46-50}, to labradorite, An_{55-59}. Recrystallized xenoblastic plagioclase is clouded with tiny rodlike inclusions, in part apatite, but most commonly too small to identify, aligned parallel to crystal axes. Usually the crystal borders are free of inclusions but the core may be quite dark. Orientations of the inclusions commonly vary in adjacent twin lamellae. Dense rounded intergrowths of sericite, epidote, prehnite, and lawsonite are common in the plagioclase, usually accompanied by minor flaky chlorite.

Cummingtonite and biotite are commonly intergrown as replacements of hypersthene. Cummingtonite, dusty with iron ore, usually rims hypersthene, but complete pseudomorphs are less common. Small blades of dark red-brown biotite have formed with cummingtonite and occasionally directly replace the hypersthene. Biotite also occurs as rims on iron ore.

Minerals present in minor amounts include chlorite formed on hornblende; fibrous blue-green actinolite formed from diopside; and granular epidote associated with densely matted alteration products of plagioclase. Calcite is present in a single section, but apatite and iron ore are constant accessory minerals; skeletal crystals of titaniferous iron ore are present in C-75.

Amphiboles are not characteristic of the pyroxene hornfels facies, but are indicative of lower facies (30, p. 443). Therefore, the assemblage described above does not indicate equilibrium in the pyroxene hornfels facies. The dark hornblende may indicate transition between hornblende hornfels and pyroxene hornfels. Alterations of pyroxene to amphibole, and amphibole to chlorite are indicative of retrograde adjustments to waning temperature or continuing low-grade regional metamorphism. The presence of sericite, epidote and other alteration products on the plagioclase of both the stock and thermally reconstituted rock is probably indicative of deuteric alteration and slight regional metamorphism after emplacement of the stocks.

Hornblende Hornfels. Hornblende hornfelses, marked by the abundant formation of green hornblende, recrystallized plagioclase, and granoblastic quartz, are found outside the pyroxene hornfels zone. Most sections contain altered relict plagioclase, and varying amounts of actinolite, chlorite and other greenschist minerals.

A detailed discussion of samples of the hornblende hornfels facies is given in the description of the dynamothermal aureole around the Clear Creek and Melhorn stocks.

Limits of Aureole. The outer limits of the thermal aureole are not known. Samples taken up to a quarter of a mile from intrusive contacts show incipient recrystallization of clouded plagioclase to albite, and contain brown biotite in addition to greenschist minerals: actinolite, chlorite and epidote. Clouded plagioclase alone cannot be used as a criterion for thermal metamorphism (19, p. 76). Taubeneck (28, p. 1650) indicates that brown biotite is characteristic of thermal aureoles in northeastern Oregon. Albite is not found in other samples of the Russel member which were taken at greater distances from the contact. Therefore, thermal aureoles around the Fish Lake complex are believed to extend at least one quarter mile from the outer contact of the stocks.

Age

The Fish Lake complex cuts through all units older than the Lower Sedimentary Series. Thermal effects from the stocks have been imposed on regional metamorphism in the surrounding rocks, and regional metamorphism of the stocks is not well developed. Therefore, the complex was intruded after metamorphism had begun in the Imnaha formation, but before all regional metamorphism had ceased. However, no definite age can be given. This complex may be related to early units of the Wallowa batholith to the west, generally considered to be Cretaceous.

Bostonite Stocks

A small stock of bostonite about one-half square mile in extent protrudes through breccias of the Norway member just west of Norway Basin and occupies most of an area known locally as Clipper Basin. Two smaller bostonite intrusives are located about 1 mile west and 1½ miles north, respectively. The main stock is exposed in a series of roches moutonnées and is recognized from a distance by white weathered surfaces. The small exposure west of Clipper Gap (Pl-1) is marked by rusty-red discoloration on weathered surfaces.

Petrography

The bostonite is a finely porphyritic, dense siliceous rock with tiny white albite phenocrysts as long as 1.5 mm scattered through a blue-black to faintly purple groundmass. Components are albite and quartz with secondary green biotite, epidote, calcite, and pyrite as minor constituents, but the rock is too fine-grained for accurate modal analysis.

Albite phenocrysts, An_{6-10}, are set in a very fine groundmass of cryptocrystalline quartz and microlitic albite. Flowage is indicated by poorly developed streaming of microlites around phenocrysts, but is not developed in all slides. All albite is clouded with sericite and "dusty" alteration products. The composition was determined from symmetrical extinction of albite twins, which are well developed and show no indication of replacement.

Quartz, where large enough to be recognized as individual crystals, occurs as rounded to elliptical aggregates of sutured grains.

Fine flakes of green biotite are scattered through most slides, but biotite is a very minor constituent, and is not regarded as primary. Pyrite in the main stock occurs as sparsely scattered euhedral cubes less than 0.5 mm across, but is very abundant in portions of the west intrusion. Widely scattered irregular grains of calcite occur in some slides, but are not consistently present.

Brecciated portions of the stock contain angular to slightly corroded fragments separated by thin bands of microcrystalline quartz, albite, green biotite, and pyrite. Some fine magnetite may also be present. Albite microlites are frequently in clusters which are thought to be fine fragments of the original rock. Biotite, most abundant along fragment borders, decreases rapidly in size and frequency toward the center of the fragments. Epidote is also more abundant in the inter-fragment bands.

In contrast to the main stock, the west intrusive is more brecciated, contains more and larger pyrite, and has dark red-brown biotite. However, the abundance of twinned albite laths in a siliceous matrix leaves no doubt that this rock is related to the main bostonite. The exact cause of the red-brown biotite and pyrite cubes up to 4 mm across is not known. Red-brown biotite, not a primary constituent in this rock, indicates either thermal or intensive dynamic metamorphism.

Contact Relation

The contact of the bostonite, well exposed in several places, cuts steeply through the older rock on the south. The upper surface is exposed in a vertical face on the north, and dips slightly to the east. Shearing and deformation are well developed in a narrow belt parallel to the stock. Deformation and stretched cobbles within three feet of the contact are shown in Figure 47. Closely spaced, nearly vertical shear planes are revealed about 15 to 20 feet from the southwest contact. Maximum width of shearing is 50 to 75 feet around the main body and 10 to 15 feet around the smaller bodies. Attitude of shearing and deformation on the north side of the main stock suggests that the present exposures are near the top of the intrusive.

A wide zone of intrusive breccia is present in the marginal bostonite of the main stock. The breccia zone, varying from 8 to 100 feet in width, consists of white angular clasts separated by dense dark blue to black bands. The clasts are thick and well defined at the contact but gradually thin out and become less distinct toward the center of the intrusive (Figures 48-50). Where the stock is in contact with well defined older breccia, a replacement contact is suggested, but clasts in the stock are nonvesicular and those in the older formation are vesicular to scoriaceous. Microscopic examination proves that clasts

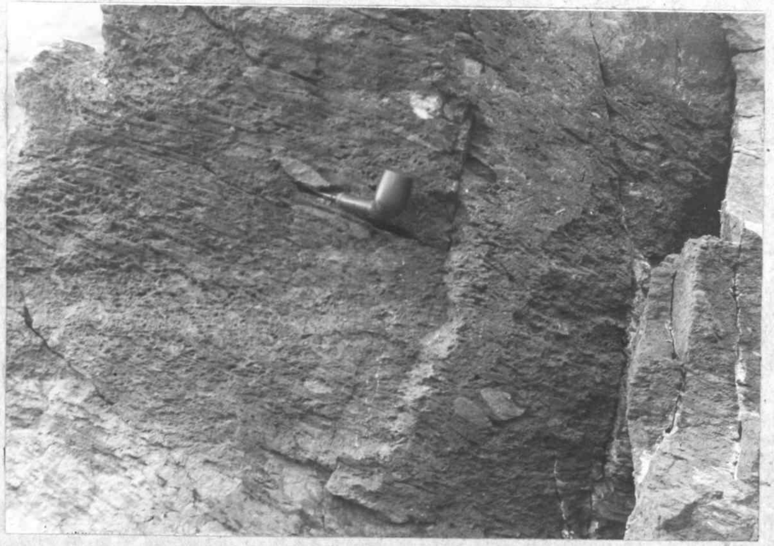


Figure 47. Stretched cobbles in deformed zone bordering the main bostonite stock. Note long pebble above pipe bowl.

Figure 48. Large exposure of intrusive breccia near south contact of main bostonite stock.

Figure 49. Close-up view of coarse angular intrusive breccia in main bostonite stock showing well defined clasts. Within 5 feet of the contact.

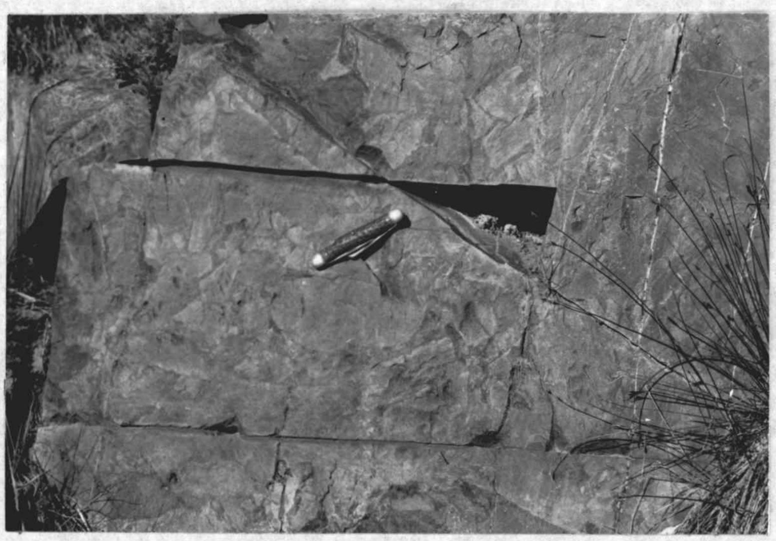


Figure 50. Similar intrusive breccia in the small northern bostonite unit. Note indistinct character of clasts.

and enclosing siliceous matrix are related.

Intrusive breccia indicates that the stock was forcefully emplaced in two or more pulses which were far enough apart to allow solidification of the first phase. No stoping is evident; the deformed zone around the stocks shows that older rocks were shouldered aside by the intruding magma. Thermal effects on country rocks are negligible, but a darker colored biotite and more advanced albitization occurs in samples taken within 100 yards of the contact.

Age

As the bostonite group is in contact only with rocks of the Norway member, it cannot be closely dated. Low grade metamorphism is considered responsible for the presence of green biotite in the bostonite, so it seems likely that the stocks were emplaced during early stages of the orogenic cycle.

Corral Creek Stock

The Corral Creek stock is a small, irregularly shaped, simple trondjemite stock exposed south of Corral Creek on the west side of Cliff River. The stock has an areal extent of about half a square mile, with about 1650 feet of relief between the upper and lower contacts. Nearly all of the stock lies within the thesis area; only irregular dikelike salients extend beyond the map borders.

Petrography

The milky-white rock, lightly flecked with black, is exposed in moderately jointed, rounded, blocky outcrops and smooth flat faces. Extreme abundance of coarsely crystalline quartz is a striking feature of the stock; crystals 5/8 inch in diameter were measured. Concentration of quartz varies, and crystals are larger in localities of higher concentration.

Narrow hair-like quartz veins, bordered by pink bands, ½ to 2½ inches wide, of potash feldspar, mark irregular lines of healed joint planes. When broken, these quartz stringers show a thin central layer of faintly bronze muscovite. Near the borders of the trondjemite, stockwork quartz stringers ½ to 8 inches wide locally are concentrated so as to make up nearly 50 percent of the rock (Figure 51). The veins cut both trondjemite and the surrounding country rock. An increase in potash feldspar and muscovite occurs in the trondjemite near these stockworks. At an elevation of 7200 feet along the north contact, flakes of muscovite were noted in a quartz vein. Quartz veins are common throughout the stock, but such intense concentrations are formed only near the periphery on the north and east.

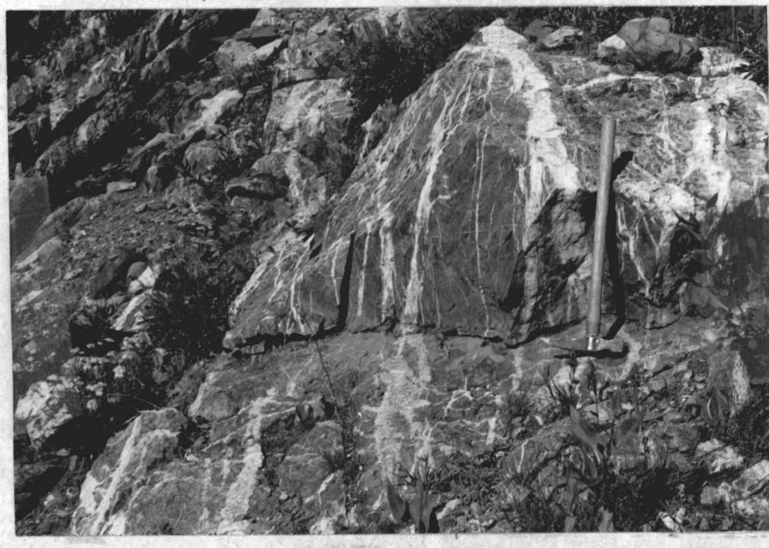


Figure 51. Stockwork maze of postmagmatic quartz veinlets in country rock near the contact of Corral Creek stock. Location: 7220 feet elevation in bed of Corral Creek.

Figure 53. "Knife-edge" contact on Corral Creek stock. Note deformed beds to left of pick. Location: 7200 feet elevation on west side of Cliff River.

The principal minerals are quartz, potash feldspar, zoned oligoclase, biotite and muscovite. Accessory minerals are zircon, apatite, monazite, epidote and iron ore. Modes are shown in Figure 52.

Sample No.	C-321	C-316-B	C-320-A	C-354	C-327-A
Quartz	40.5	30.5	30.3	31.5	30.9
Plagioclase	49.2	47.8	58.6	58.4	58.3
Potash feldspar	1.6	13.1	3.4	3.4	6.1
Biotite	3.2	1.1	4.5	3.8	3.3
Muscovite	4.6	7.0	1.7	2.0	0.4
Fe ore	0.2	0.1	0.4	0.2	0.2
Apatite	0.1				
Chlorite	0.4	0.2	0.7	0.6	0.8
Epidote	0.1		0.2		
Sphene	0.1	0.1		0.1	
Zircon		0.1	0.2		
Total	100.0	100.0	100.0	100.0	100.0

Figure 52. Modal analysis of trondjemite in Corral Creek stock. Percentage is by volume.

Quartz is the most abundant mineral, occurring in subhedral to anhedral grains, irregularly interlocked with potash feldspar. Minor "dust trails," irregular wavy extinction, and inclusions of apatite and zircon are characteristic of quartz. Grains join along irregularly sutured contacts as in vein quartz.

Anhedral, extremely irregular, interstitial grains of potash feldspar show faint traces of microperthitic exsolution lamellae. Immediately adjacent to the contact, the potash feldspar increases in size and frequency, exsolution becomes stronger, and the lamellae appear as irregular stringers and patches. Potash feldspar has partially replaced oligoclase, and optically continuous, irregular inclusions of oligoclase are common in potash feldspar. The potash feldspar shows slight alteration to kaolin. Along the contact and in the pink bands, replacement of oligoclase is advanced, and sufficient potash feldspar is present to give the rock a local composition of granodiorite.

Oligoclase An_{28-30}, shows oscillatory zoning; the inside of a given zone has a more calcic composition than the outer edge of the preceding zone, but the average composition of each zone shows a gradual decrease in An content. Albite twinning is most common, but pericline and carlsbad twinning are also present. Differential alteration of oligoclase to micaeous aggregates is generally confined to certain zones, or to the cores.

Light brown, strongly pleochroic biotite is the most common mica, except along joint planes where late crystallization of muscovite has taken place. Biotite alters to dark green, strongly pleochroic chlorite; random crystals show formation of secondary epidote along cleavage traces. In a single thin section from near the contact, chlorite, formed after biotite, contains sagenitic and radiating needles of rutile. Biotite commonly interfingers with muscovite.

Muscovite is nearly colorless, but shows slight pleochroism, changing to a very pale bronze on rotation. Abundance varies widely, but small amounts are generally present. Concentrations are characteristic along healed joints and as large clots in pegmatites.

Zircon, apatite, and iron ores are the most common accessory minerals. Doubly terminated euhedral crystals of zircon are abundant, occurring most frequently as inclusions in quartz and biotite. Apatite is present in small euhedral crystals and large irregular masses. Irregular massive apatite crystallized as late interstitial filling, but the small crystals were formed early and occur as inclusions in all essential minerals. Small irregular grains of magnetite are common and cubes of pyrite with reddish alteration rims occur occasionally.

Monazite, as anhedral masses from 0.5 mm to 0.75 mm across is present in two slides taken near the outer border of the stock. The number of slides examined is insufficient to reach any conclusions as to the distribution of monazite.

In addition to previously mentioned alteration products, calcite has replaced plagioclase in a sample taken less than two feet from the north contact at an elevation of 7100 feet, and in an area of extensive postmagmatic quartz veins. This thin section (C-317) also shows a more extensive formation of kaolin and micaceous alteration of oligoclase than in other thin sections. The unusual amount of alteration is probably of hydrothermal origin, caused by the formation of stockwork quartz veins.

Aplite Dikes

Aplites and pegmatites occur in the Corral Creek stock in narrow, subparallel dikes less than 100 feet long and 12 inches wide. Aplitic dikes grade rapidly into pegmatitic pockets containing clustered tablets of pale bronze muscovite, coarsely crystalline potash feldspar, and quartz, but pegmatites were not found independent of the aplite dikes. Crude parallelism of adjacent dikes is common, but widely separated dikes are not consistent in direction. The aplites form fine to medium-grained, white to pink saccharoidal dikes; principal constituents are quartz, microperthitic potash feldspar, slightly zoned oligoclase, An_{26-30}, and bladed muscovite. Accessory minerals include apatite, pink garnet and sparse granular iron ore. Modal analysis (Figure 54) shows the rock to be quartz monsonite.

Sample No.	C-365-B
Quartz	34.2
Plagioclase	29.0
Potash feldspar	30.1
Muscovite	6.7
Total	100.0

Figure 54. Modal analysis of typical aplite from Corral Creek stock.

Garnet occurs in a single aplitic dike on the east side of the stock. Pink crystals show poor crystal form, and are slightly altered to chlorite.

Contact Relation

The contact between the Corral Creek stock and the enclosing sedimentary formation is extremely irregular, with numerous dikelike salients extending varying distances into the older rock (Pl-1). Visible bedding in the sedimentary rock has been disrupted where the salients intersected it at high angles, but where intersected at a lower angle, bedding is bent aside to parallel the stock (Figure 55). Excellent exposures of deformed bedding are located along the eastern edge of the stock, where an arm of the older rock is partially enclosed. Near this location, visibly continuous bedding curves through approximately 160° of arc.

Irregular inclusions of country rock as much as 6 inches in diameter are exposed in the bed of Corral Creek within 12 feet of the contact. Chilled margins were not observed, although a "knife-edge contact" is visible in several places. In thin section, a slight increase in microperthitic exsolution is shown for a distance of at least 1 cm, but the igneous border is sharply defined against the granoblastic texture of the hornfelsic country rock.

Metamorphic Aureole

Hornblende hornfelses were formed adjacent to the Corral Creek stock; but the width of the aureole is not definitely known. Sampling revealed two distinct types of hornfels immediately adjacent to the contact, one an equilibrium assemblage and the other a disequilibrium assemblage.

Equilibrium Assemblages. Most country rock at the contact is dark gray to black, and very fine-grained. Although bedding is still visible, other sedimentary textures have been lost. Small flakes of biotite reflect light from freshly broken surfaces.

Complete recrystallization of the sediments produced the following assemblages indicative of equilibrium in the hornblende hornfels facies:

(1) biotite-plagioclase-garnet-quartz
(2) hornblende-plagioclase-biotite-quartz
(3) hornblende-diopside-plagioclase-quartz

Amounts of the constituents vary, but in general individual characteristics are similar. Plagioclase is the only critical mineral of the facies which appears in all samples studied; its grains are anhedral, rarely twinned, and characteristically slightly clouded or altered. Clouding consists of aligned opaque inclusions. Slight alterations to sericite and epidote is common. The composition, An_{26-30}, could be determined by twinning only in C-317-A.

Dark brown biotite is well formed in elongate blades and clusters. Green tints are revealed in some orientations. Amounts vary; in C-317-A, biotite is the only mafic mineral, elsewhere it occurs with hornblende. Lepidoblastic alignment is characteristic of both biotite and hornblende.

Elongate, anhedral grains of green hornblende are characteristic, but crystal form is well developed in some samples. In C-327-B hornblende is restricted to certain bands, which probably mark original bedding. Other bands in the same thin section contain anhedral droplike grains of diopside associated with sphene and minor actinolite.

Garnet, generally in small clusters, is present as clear rounded grains in C-317-A. Though generally isotropic, a few grains show slight birefringence around the outer edges. Its composition was not determined.

Chlorite has persisted in many samples. Lenticular masses, fibers, and spherulitic aggregates are common. Minor amounts of epidote also persist. Small euhedral crystals of apatite are characteristic.

Disequilibrium Assemblages. Dense, dark green rocks containing megascopic garnet are exposed in contact with several dikelike salients of the stock in the bed of Cliff River. A maze of thin quartz veins is almost always present in areas where these distinctive green rocks occur.

Under the microscope samples of the dense rock are seen to contain hornblende hornfels assemblages and a later zeolite assemblage. The hornfels assemblages are:

(1) hornblende-diopside-plagioclase
(2) hornblende-diopside-plagioclase-garnet
(3) diopside plagioclase-garnet-potash feldspar

The later assemblage is zeolite-calcite-epidote.

Diopside and hornblende are generally matted in aggregates so thick that individual minerals are difficult to distinguish. Small hornblende crystals are also present. The larger crystals show faint pleochroism, green to yellow-green.

Plagioclase is minor, usually untwinned, but generally altered to sericite, calcite, and epidote. The plagioclase is thought to be recrystallized, but the relations are not definite.

Garnet forms stout, reddish-brown, anhedral grains with conspicuous sieve structure. Alteration to rounded spherulitic chlorite is far advanced in C-326. Sections C-326 and C-328 are predominantly garnet.

Zeolites have formed in the rounded "cavities" of the garnet, between garnet crystals, and in large "open" patches. Chabasite and thompsonite were both recognized; chabasite in blocky, pseudocubic crystals and thompsonite in groups of radiating fibers. The relations between garnet and zeolites are suggestive of replacement by the zeolites.

Calcite and quartz are frequently intergrown with zeolites, and occasionally include diopside. Many large crystals of epidote are also surrounded by zeolites; therefore the assemblage quartz-calcite-zeolite is later than epidote and diopside.

Obviously the later assemblage formed under different conditions than the first. Zeolites could not persist at conditions sufficient to form diopside and garnet.

Zeolites are known to form from alkaline solutions at low temperatures (27, p. 662). As the samples were taken in close conjunction with postmagmatic quartz veins, the zeolite assemblages can be explained as hydrothermal alteration of the hornfelses which took place after metamorphic recrystallization. The lowering of temperature sufficient to allow formation of zeolites would also be conducive to deposition of quartz from solutions percolating along the fractures.

Age

The Corral Creek stock is similar to one of the latest units of the Wallowa batholith (29), and therefore probably early Cretaceous.

Cornucopia Stock

A small salient of the Cornucopia stock extends into the extreme southwest corner of the thesis area and although no detailed work was attempted, the outer contacts were mapped. On the geologic map (Pl-1) the rock of this salient is called the Cornucopia trondjemite.

Goodspeed (9, p. 55-78) postulated granitization as the origin of the Cornucopia stock. As only an extremely small part of the stock is within the thesis area, no conclusion concerning its origin is justified here and the stock is not considered any further in this thesis.

Dikes

The thesis area is replete with such an assortment of dikes that only by detailed, large scale mapping could they be depicted. Therefore, none were plotted on the accompanying map. Local areas contain such a bewildering maze of dikes that only with difficulty can country rock be positively identified. Outcrops which do not contain one or more dikes are rare in formations older than the Lower Sedimentary Series.

Systematic study of the dikes was beyond the scope of this thesis; but a few samples of lamprophyres and unusual dikes were taken for microscopic examination. The largest dikes are Tertiary basalt, and occur only in the western part of the area. Large dioritic dikes in a narrow belt trending N. 35° W. can be traced for more than 1 mile across the head of Clear Creek canyon. Others are too varied to permit discussion.

Lamprophyre

Lamprophyric dikes are generally narrow and irregular; widths change abruptly, and irregular projections into the country rock are common (Figure 55-56). Angular blocks of country rock are occasionally included in the dikes. Chilled margins are not always visible in irregular lamprophyric dikes, but generally a definite decrease in grain size is visible toward the contact. Preferred orientation of phenocrysts parallel to the dike walls is much more apparent in the center of the dikes, as would be expected if the borders crystallized more rapidly. Larger lamprophyre dikes occur less frequently, but are much more regular in form and width (Figure 57), and characteristically reveal flow structure and chilled margins.

All lamprophyres studied are spessartites, characterized by large phenocrysts of zoned hornblende and highly altered plagioclase. The groundmass is composed about equally of hornblende and plagioclase.

Dark, greenish-brown hornblende phenocrysts have well developed crystal outlines, and are strongly pleochroic.

Figure 55. Irregular spessartite dike cutting small stock of metadiorite in bed of East Pine Creek.

Figure 56. Spessartite dike showing typical irregular borders in contact with "greenstone."

Figure 57. Larger lamprophyric dike with smooth regular borders typical of the larger dikes. The pocket knife lies on the contact with gabbroic rock of the Fish Lake complex.

Figure 58. Xenolithic dike. Note rounded inclusions. Location: SE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 9, T. 6 S., R. 46 E.

Concentric zones are distinctly marked by variations in birefringence and pleochroism. Hornblende phenocrysts are unaltered. In the groundmass, hornblende occurs as slender laths as long as 0.5 mm.

Plagioclase phenocrysts are recognized only by dense matted alteration. Sericite, chlorite, epidote, leucoxene, and minor lawsonite (?) make up the alteration aggregates. Strongly zoned, clear plagioclase crystals in the groundmass have a composition of andesine, An_{42-46}, to labradorite, An_{52-56}.

Accessory quartz and apatite are present in most spessartite samples. Dark brown biotite, chlorite, and slightly clouded plagioclase are characteristic of samples taken within metamorphic aureoles of the Fish Lake complex.

Lamprophyres are of several ages. Some are older than the Fish Lake complex, others are younger. No better dating can be given without more detailed study of the dikes.

<u>Aplite in Gabbro</u>

An aplitic dike of tonalite about 8 inches wide cuts an outcrop of the Fish Lake complex, at the northwest corner of Fish Lake. The fine-grained saccharoidal dike contains abundant quartz and plagioclase, little biotite, and accessory apatite, zircon, and muscovite. Interstitial quartz contains small inclusions of zircon and apatite.

Plagioclase is so altered to epidote, sericite, and lawsonite (?) that its composition could not be determined. Biotite is foxy-red, strongly pleochroic, and generally altered to epidote and chlorite along the cleavage planes. Muscovite occurs in small clusters of subradiate blades. Small veinlets of prehnite cross the thin section. No other dikes of similar composition were recognized, so the relation to the Fish Lake complex is not known.

Pegmatite

In the northern part of Clipper Basin, half a mile north of Red Mountain summit, several coarse-grained pegmatite dikes, 2 to 6 inches wide, cut bedded sandstone of the Lower Sedimentary Series. The narrow dikes form two or more intersecting sets, but individual dikes are extremely regular in width and direction. Well formed orthoclase crystals as long as $1\frac{1}{4}$ inches are common, usually concentrated along the dike margin. Crystalline quartz forms the centers. No parent intrusive body is visible.

Xenolithic Dikes

A spectacular xenolithic dike cuts through gabbroic rock in the northwest edge of the Fish Lake stock at an elevation of 6800 feet (Figure 58). Hundreds of dark, rounded xenoliths, comprising about 60 percent of the dike are enclosed in a dioritic matrix. The 3-foot wide dike can be traced N. 70° E. for about 100 to 150 feet before it disappears under cover.

A similar dike, about 30 inches wide, containing separated clusters of dark xenoliths, crops out about 2000 feet north, at an elevation of 7240 feet. About 200 feet of the dike is exposed, striking N. 85° E. As the two dikes are approximately parallel and of similar lithology they may be related.

METAMORPHIC UNITS

Metamorphic processes within the area have produced two mappable nonstratigraphic units, a dynamo-thermal aureole around Clear Creek and Melhorn stocks, and an epidotized zone along the Pine Creek fault. Skarn deposits are included in this section, but not all outcrops are of sufficient size to map. All skarn deposits shown on the map (Pl-1) are inclusions in the Clear Creek stock.

Dynamo-Thermal Aureole

A strongly deformed, schistose border of varying width and intensity is almost continuous around the Clear Creek and Melhorn stocks. On the east side of Clear Creek stock a narrow salient of the stock severs the deformed band. Foliation is indistinct and local along the south and east borders of Melhorn stock. Alluvium and Tertiary lavas cover portions of the aureole. Schistosity in the deformed zone maintains a position subparallel to the outer border of the stocks. In most of the unit, foliation is nearly vertical, but in a small area at the southern corner of the zone, the foliation dips 12° toward the stock (Figure 59).

Petrography.

The outcrop appearance varies with the intensity of deformation from "gneissoid," with distinct subparallel

Figure 59. Foliation of "greenstone" in the dynamo-thermal aureole.

Figure 60. Stretched cobbles in deformed conglomerate at east of dynamo-thermal aureole.

banding and lenticular augen, to indistinct shearing with laminae revealed by preferred cleavage, differential weathering of certain bands, and particle elongation. The augen are large phenocrysts and glomeroporphyritic clusters of plagioclase, and also dark areas which seem to be groundmass of the original lava. Augen frequently tapers out into discontinuous "trails" caused by crushing and dragging, but plastic deformation has also been active. In some augen, remnants of euhedral crystals may be seen, and surrounding elongate minerals swing around the periphery of the augen so as to indicate probably movement. Rotation of elongate masses of relict plagioclase has left S-shaped trails of fragments and swirls in the schistosity (C-37). Deformation is most intense in the portion caught between the Fish Lake and Clear Creek stocks.

To determine the grade of metamorphism in the dynamothermal aureole, thin sections of 15 samples were examined. The hornblende hornfels facies has been reached in 10 sections, a lower intermediate stage in 1 section and greenschist facies in 4 sections.

Hornblende Hornfels. The hornblende hornfelses are intensely deformed, dark green to black rocks, frequently containing streaks and augen of crushed feldspar. They are lepidoblastic to schistose with slight to definite banding of mafic minerals. Schistosity is more pronounced toward the outer perimeter of the deformed zone.

Typical assemblages are:

(1) hornblende-plagioclase-biotite-quartz
(2) hornblende-plagioclase-diopside-quartz
(3) hornblende-plagioclase-quartz

Relict plagioclase is common. In addition, one or more of the minerals chlorite, calcite and epidote, is present in all thin sections. Secondary iron ore is present in each sample studied.

Strongly pleochroic hornblende occurs in elongate grains, prisms, and tabular poikiloblastic laths. Color changes on rotation from pale yellowish tan to dark blue-green or dark brownish-green. Preferred orientation of elongate crystals and segregation into rude bands or closely packed lenticular masses is common. However, irregular poikiloblastic hornblende containing rounded inclusions of plagioclase and iron ore shows no evidence of lineation or segregation.

Recrystallized plagioclase may be distinguished from relict plagioclase by several features. Generally, the metamorphic plagioclase has irregular crystal outlines, is clear of alteration, and interlocks with surrounding minerals. Relict fragments and clusters of plagioclase are either highly altered to a dense, finely crystalline mat of epidote, chlorite, prehnite, sericite and lawsonite (?), or are clouded.

Plagioclase composition ranges from An_{36-40} to An_{48-52}. Where the composition of both relict and recrystallized plagioclase could be determined in the same slide, relict crystals are more calcic.

Within 50 feet of the stock, crushed glomeroporphyritic rosettes of plagioclase have been partly replaced along fractures and borders by clear zones of more sodic plagioclase and quartz. Replaced zones stand out sharply against clouding and local alteration of the original plagioclase.

Dark brown biotite occurs most commonly as small elongate blades, or irregular tabular aggregates, but near the contact it forms well developed plates which are sometimes poikiloblastic. Pleochroism is from nearly colorless to a very intense brown. Biotite is usually in close association with hornblende, but is also present as rims around iron ore, and in irregular segregations of quartz and plagioclase. Alteration of biotite is uncommon, but in C-37 chlorite, epidote, and sphene have grown along cleavage traces.

Diopside is present as bright green or colorless xenoblastic grains with a maximum size of about 0.2 mm. In some sections diopside is included in hornblende. It occurs at irregular distances from the stock, and is not alone indicative of higher metamorphic effects, though it is often present in slides of the highest grade.

Actinolite occurs in abundance in only two slides, C-372 and C-373, taken about 150 to 100 yards, respectively, from the south side of Clear Creek stock. Hornblende is also present in both slides, but less common than actinolite. The two minerals were distinguished by the extremely fibrous nature of the actinolite, and lower 2V of the hornblende. The color and pleochroism of hornblende and actinolite in these sections are so nearly identical as to make them almost indistinguishable.

Granoblastic quartz in mosaic aggregates, irregular crystals, or veinlets is present in all slides studied. It occurs both as segregations, and in association with all other minerals; intergrowths with plagioclase are common.

Iron ore is generally most prevalent in slides containing relatively large amounts of calcite, epidote, and chlorite. Dark brown to reddish spherulitic masses of limonite are present in two slides, usually in close association with other iron ore.

Potash feldspar was recognized in only two slides. It occurs as small irregular grains in the recrystallized matrix, usually associated with granoblastic quartz.

Calcite and sphene commonly occur together. Calcite forms anhedral, coarsely twinned grains with well defined cleavage, and varies in amount. Amounts vary from scattered crystals to about 10 percent of the rock. Sphene occurs as euhedral crystals, irregular aggregates, and drop-like grains, and occasionally forms narrow rims around iron ore. Euhedral sphene is abundant, generally forming 3 to 5 percent of the slides in which it occurs.

Epidote and chlorite are present in most sections, but usually minor in amount. Epidote is generally more abundant than chlorite. Veinlets filled with quartz, calcite, epidote or a combination of these minerals are common in the hornblende hornfelses. A significant veinlet, filled with prehnite, epidote, calcite, chabasite, and pistacite, occurs in C-373. This assemblage as a vein filling indicates either low grade metamorphic conditions after the formation of the hornblende hornfelses, or retrograde metamorphism.

Transitional Facies. In C-90, epidote is the most abundant mineral; no recrystallized plagioclase was recognized, and greenschist minerals are as prevalent as those of higher metamorphic grade. Plagioclase is almost completely obscured by matted alteration products. Diopside occurs as inclusions in poikiloblastic hornblende and as scattered rounded to irregular grains. Chlorite is present but minor; sphene is abundant. The assemblage diopside-hornblende-epidote-chlorite is not in equilibrium with any metamorphic facies, and therefore the rock is probably transitional between the albite-epidote amphibolite facies and the hornblende hornfels facies.

Greenschist Facies. Three samples which show metamorphism of only greenschist facies are discussed individually. One, C-101, was taken just outside the mapped aureole, but shearing effects are visible in thin section; a second, C-190, was taken near the center of the aureole and is intermediate in distance from the stock; the third, C-115, came from within 100 feet of the north edge of Clear Creek stock. Foliation in this portion of the aureole is less well defined than in other parts, but can be distinguished in outcrops approximately 125 yards from the contact of the stock.

Sample C-101, taken east of Melhorn stock in the SE$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 8, T. 6 S., R. 45 E., is an angular sedimentary breccia consisting of altered lithic fragments in a sand to silt-sized feldspathic matrix. Meta-andesite is the dominant rock type in the fragments, but one subrounded "granitic" pebble about 5 mm in diameter is present in the thin section.

The "granitic" granule consists of quartz, potash feldspar, and altered plagioclase with irregular patches of minutely crystalline intergrowths of actinolite, epidote and white mica.

At least two lava types are represented in the lithic grains: coarsely prophyritic meta-andesite and a fine-grained pilotaxitic metavolcanic of uncertain composition. Plagioclase crystals in the clasts are severely altered, but twinning can be seen in many crystals. Alteration products include white mica, epidote, chlorite, and scattered clusters of prehnite.

Alignment is conspicuous in the matrix; large grains of plagioclase are crushed and the smaller fragments dragged out in trails. Finer grains, mostly quartz and iron ore, have been forced into streaks similar to flow structure. Rock fragments have smooth elliptical outlines drawn out parallel to the streaming. Large areas in the matrix are filled with coarsely crystalline epidote, calcite, actinolite, and granoblastic quartz, which do not show any relation to the streaming, and therefore, are thought to have formed after the principal deformation.

Epidote is the most common mineral, and large crystals are molded around meta-volcanic clasts, occasionally forming nearly complete borders. Much of the matrix is nearly opaque because of thick accumulations of finely divided iron ore. Recognizable plagioclase in the matrix is twinned and highly altered.

In sample C-190, a coarse sandstone, foliation is not well defined in thin section, but was evident in outcrop.

However, foliation is visible only in the more competent beds; outcrops of associated calcareous sediments fail to show distinct foliation in the field. A deformed cobble conglomerate, exposed about 300 feet from the spot where C-190 was taken (6800 feet, SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 12, T. 6 S., R. 45 E.), contains stretched cobbles up to 14 inches long, but only 1$\frac{1}{2}$ inches wide (Figure 60).

This thin section contains subrounded to angular lithic grains, quartz and plagioclase fragments, in a fine matrix of minute green biotite, microcrystalline quartz, and twisted aggregates of sericite. Lithic fragments are fine-grained metavolcanics containing relict plagioclase microlites in a dense chloritic groundmass. Plagioclase fragments are usually highly altered, but a few are nearly fresh with distinct normal zoning. Incipient recrystallization to albite is visible along the borders and in patchy areas of the plagioclase. Epidote, calcite, and chlorite also occupy irregular patches. The form of the micaceous minerals is the only evidence of foliation. Tiny sericite crystals form narrow, highly birefringent stringers which separate the larger clasts, often entirely enclosing individual grains, and spreading to form a dense nearly solid mat over local areas. Finely tabular green biotite is closely intergrown with the sericite. Variations in orientation of the micas cause the stringers to appear twisted, but definite preferred orientation is shown by nearly simultaneous extinction over large areas. The micaceous minerals probably formed from argillaceous material in the matrix, and grew with elongation normal to the pressure gradient.

Sample C-115, is a coarse sandstone made up of metavolcanic fragments and plagioclase grains in a very fine, recrystallized matrix of mosaic quartz and possibly plagioclase. Alteration is extensive, but individual grains are still visible. The clasts are dark with secondary iron ore, and contain large amounts of chlorite and blue green actinolite. Chlorite is practically restricted to the clasts, but actinolite is well developed in both clasts and matrix. Green biotite occurs as tiny randomly oriented crystals and shredded aggregates in both clasts and matrix, but is most extensive in the matrix.

Lineation or shearing is lacking in this thin section, but its absence may have resulted from the random orientation of the thin section. No satisfactory explanation of the lack of thermal alteration so close to the contact is known. Samples taken a greater distance from the stock have been thermally metamorphosed to hornblende hornfels.

Origin

The relation of the deformed zone to the Clear Creek and Melhorn stocks is shown by change in strike of the foliation parallel to perimeter of the stocks except on the east side of Clear Creek stock where a salient of the stock crosses the foliation (Pl-1). From a study of the map alone the disruption of the deformed zone would seem to indicate that the stock was later than the deformation. This is true only of the narrow tonalite arm which actually crosses the aureole, not for the entire stock. Intrusive breccias are well developed near this point where the tonalite phase has intruded the older hyperite phase. A small outcrop of the deformed "greenstone" south of the narrow salient contains foliation parallel to that on the north side. Therefore, the deformation can be safely assigned to the forceful intrusion of early unit of the stock, and disruption of the foliation to later intrusion of the tonalite.

Augen of relict plagioclase and bands of crushed feldspathic fragments within a few feet of the stock indicate that thermal effects lagged behind dynamic granulation and compression. Further, the presence of well defined shearing, crushing and stretching of clasts in samples showing no thermal effects leave no doubt that forces resulting from intrusion were the major contributors to the formation of the dynamo-thermal aureole.

The presence of minerals of low metamorphic grade in moderate to high temperature assemblages might indicate either thermal metamorphism imposed on regional metamorphism, or retrograde adjustment. As there is no indication that the chlorite and epidote have formed from minerals of higher metamorphic grade, and the gabbroic bodies do not show evidence of regional metamorphism equal to that of the surrounding units, the low-grade minerals are believed to be the result of previous regional metamorphism.

Calcite and sphene could be produced either from the bulk composition of the original rock or metasomatic introduction of Ca and Ti. As both occur at irregular distances from the stock, they are thought to be the result of original composition. If they were the result of metasomatic enrichment they should be most common near the contact.

In view of the above evidence it seems clear that the dynamo-thermal aureole around Clear Creek and Melhorn stocks is the result of an interplay of dynamic and thermal metamorphism caused by the forceful intrusion of basic magma into a terrane of slight regional metamorphism. Thermal metamorphism has been imposed over regional, and the forces exerted by the expanding intrusive on the sheared and somewhat plastic surrounding rock induced flowage and shearing resulting in distinctive "gneissoid" banding. The presence of a zone of intense deformation around two stocks in the complex and its absence around others are difficult to explain satisfactorily. As the Clear Creek stock is the largest stock in the complex, likely the deformation is related to bulk of intruding magma, but as the Melhorn stock is small, size cannot be the sole cause. Foliation is more pronounced on the northeast side of Clear Creek stock, and is well developed only on the northwest side of Melhorn stock. Foliation is not present in all of the "greenstone" caught between the two stocks, and therefore may not have resulted from compression between them. All problems concerning the dynamo-thermal aureole cannot be answered, but the positions of the most intense deformation suggests that direction of emplacement; northeast for Clear Creek stock and northwest for Melhorn stock; and the size of Clear Creek stock caused mechanical adjustments in the country rock which took the form of foliation. If the two stocks are considered as a single unit, the greater amount of intruded magma compared with other members of the complex becomes even more significant, and is probably the chief cause of the dynamo-thermal aureole.

Epidotized Zone

A wide zone of epidotization occurs along the upthrown side of the Pine Creek fault. Eastern borders of the zone are arbitrary, drawn to include areas of intense green coloration recorded in the field. Precise limits cannot be defined as the intensity of alteration is gradational. This zone corresponds to the epidote-garnet rock of Ross (22).

Petrography

Outcrops within the zone are generally dull green, but original textures are recognizable. Breccias of the Norway member are particularly distinctive; dull green lava fragments are embedded in a gray to white, recrystallized matrix of calcite. Vesicles are clearly defined in pillow lavas and breccias as dark green spots of crystalline epidote. Epidotization is spotty, as dark areas of variable size are scattered through the area.

Microscopic textures of parent rocks are less well preserved. Blastoporphyritic and blastopsammitic sections are nearly indistinguishable. In other sections, no trace of the original mineral or clastic grains was detected, even though macroscopic texture was well preserved. Shearing is not extensive except in local areas.

Greenschist assemblages are well developed; the two most commonly developed are:

(1) albite-epidote-actinolite-calcite-chlorite-biotite (sphene-quartz)
(2) albite-epidote-actinolite-calcite-chlorite-(sphene-quartz)

The two assemblages are distinguished only by the formation of biotite. Sphene and quartz are usually present, but one or both may be absent. Quartz is especially variable in amounts, it sometimes forms 10 percent or more of the rock. Sphene, usually in well formed crystals, is never a major constituent. Other minerals which appear with these assemblages are relict plagioclase, pyrite, apatite, and potash feldspar.

Epidote is the most persistent mineral formed in the zone; in some samples it comprises 50 percent or more of the rock. Crystal form varies, but usually epidote crystals are larger and better formed where associated with larger amounts of calcite and quartz. Large crystals tend to be clear, strongly pleochroic, euhedral prisms which are frequently twinned. Spherulitic aggregates are characteristic of epidote vesicle fillings. Granular epidote is most commonly formed as alteration of volcanic clasts. Inclusions of iron ore are common, and at times causes grains to be nearly opaque. Tiny beads of epidote are usually congregated around large epidote euhedra included in quartz-rich samples.

Green biotite is present in about half of the thin sections studied. A strong brown tint is present in some biotite, but green is the dominant color. Sheaves and subradiate clusters are characteristic of biotite; the clusters occur as vesicle fillings, patchy replacements of clasts, and isolated groups in the matrix. Intergrowths with epidote and chlorite are common.

Chlorite is very abundant, generally as irregular rounded patches, partial vesicle fillings, and radial aggregates. Chloritic aggregates are usually intergrown with other minerals, and are best developed on volcanic clasts, and in sections of pillow lavas.

Pale green actinolite is generally abundant. In several sections it is more abundant than epidote; however, the samples came from widely scattered locations and cannot be used to determine limits of the zone. Where actinolite and calcite appear in the same slide, they are usually intergrown, with long needles of actinolite thickly woven through calcite crystals.

Calcite is conspicuous only in samples of breccia where it was a constituent of the original rock. In these slides, calcite forms large crystals with inclusions of epidote, pyrite, and small aggregates of biotite and chlorite. Irregularly sutured contacts against quartz grains are common, for quartz is generally more abundant in slides containing calcite.

Albite has partially or completely replaced original plagioclase; it is typically developed as feathery aggregates, often within recognizable outlines of the original crystal, and is generally less abundant in slides containing large amounts of epidote. Radiate patterns between clasts in C-257 suggest zeolites now metamorphosed to albite.

Transition into the albite-epidote-amphibolite facies is marked by the presence of diopside in two sections (C-309 and C-340). Irregular, partially formed diopside tablets are associated with calcite-actinolite intergrowths. Relations are not clear as to which mineral is being replaced, but consideration of metamorphic stability suggests that diopside is later.

Garnet was found at a single locality; in thin section the garnet forms strongly zoned, partial crystals with weak birefringence, usually as narrow rims around cores of quartz and calcite. Crystal form is usually absent, but two or more faces are depicted by sharp angles in the narrow rims. Stringy extensions irregularly protrude into the included minerals from the rims. Inclusions of chlorite are present in larger garnet crystals, but it is not clear whether the chlorite is a replacement or not. As composition of the garnet was not determined, grade of metamorphism indicated is not known.

Areas of intense epidotization marked by strong green coloration contain irregular zones of dark rock, some of which appears to have been a sandstone. Rounded cobbles and boulders, turned dark green by selective epidotization are contained within some dark zones. Other areas of dark rock appear to be merely less altered breccias of the Norway member.

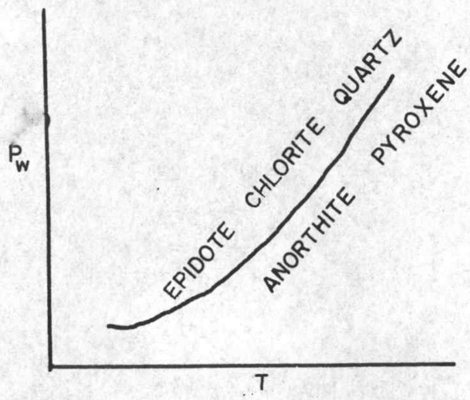
The dark "sandstone" is finer-grained than other parts of the Norway member, but all samples contain the assemblage biotite-muscovite-albite-quartz (chlorite-epidote). Chlorite and epidote are very minor, never more than 1 to 5 percent of the rock. Muscovite occurs with albite and quartz in aggregates, usually bounded by outlines of original plagioclase grains. Biotite is the dominant mineral. Two colors of biotite are present in the same thin section, and brown biotite is characteristic of the "sandstone." Fine blades form rounded clusters, but more typically, biotite flakes are scattered through the rock.

Most of the dark rocks seem to have resulted from different parentage than the ordinary breccia. They may represent either sedimentary rocks incorporated in the Norway breccia or foreign material "mixed" with the breccias by tectonic activity. However, deformation does not seem sufficient in the zone to support the theory of tectonic mixing. Therefore, the dark rock is believed to be materials of different bulk composition than most of the Norway breccia, but originally incorporated in these breccias.

Origin

The epidotized zone is clearly related to the fault zone, but the general lack of shearing, and preservation of macroscopic texture of the original rock indicate that the zone did not form as the direct result of intense deformation.

Greenschist assemblages represent hydrous phases of the chemical components found in rocks of basaltic parentage, and are formed at moderate temperatures and moderately high pressures (14, p. 167-172). Theoretical stability relations can be shown by the following diagram (6, p. 171):



Fyfe and Turner (6, p. 170) suggest several reactions by which epidote minerals might form; all involve water. The third, "anorthite + water + olivine or pyroxene = zoisite + chlorite + quartz," is applicable in the epidotized zone because the minerals on the left side of the equation should have been present in the original lavas. Fyfe and Turner (6, p. 171) state:

"It appears from present knowledge that the dense

> hydrous minerals of low grade metamorphism (e.g., epidote and prehnite) will form rapidly at low temperatures in the laboratory only if pressures are well above 3000 bars....this does not mean that water pressures of this magnitude are necessary. Low partial pressures of water and high load pressure may suffice; for in the case of the epidotes, the molar volume of the hydrous solids is less than that of the anhydrous phase by a considerable amount."

Therefore, to explain the formation of the epidotized zone it is necessary to postulate a hydrous environment with temperatures above 200°C and pressures of 2000 bars, a possible minimal limit of the greenschist facies (6, p.173) suggested as the result of a study in New Zealand by Coombs (5).

In consideration of the above physical relations, the formation of the epidotized zone is considered to have resulted from alteration of basaltic rocks of the Norway member without metasomatic additions except water. Localization along the fault is therefore logical, because avenues for the circulation of water are provided. High pressures are also expected along a fault zone. High permeability of the breccias and pillow lavas allowed the water to spread, but the width of the zone may be in part due to unrecognized cross faulting.

Skarn

Skarn areas are small, many too small to map; the most extensive and well developed areas are inclusions near southeast border of Clear Creek stock. Other areas are localized near the small gabbroic stocks eact of Deadman Point. Skarn is distinguished in the field from contact marble by its color and its content of garnet and epidote.

Field Appearance

Skarns do not form prominent outcrops, but are marked by distinctive color and coarse crystallinity. Colors vary with mineral content, but the most common color is gray with a green or red cast.

In 5 skarn areas along the south and southeast side of Clear Creek stock, the borders are difficult to place precisely, for the original inclusion has been brecciated and irregular blocks are enclosed by narrow bands of dioritic rock. Many dioritic stringers contain flow lines parallel to the blocks, indicating forceful intrusion of the igneous rock. Individual blocks become smaller and generally more rounded towards the outer limits of the skarn areas.

Some smaller blocks near the borders of these areas, especially on the point overlooking the small saddle between Fish Lake and Clear Creek stock (Pl-1), are dark and very irregular in outline. They are predominantly composed of coarsely crystalline black hornblende in blocky crystals about one-half inch long, and small interstitial, milky-white plagioclase.

Garnet is particularly well developed in the southernmost skarn area (P1-1) and on Garnet Butte. It occurs as local nearly pure masses and as intergrowths with calcite and epidote. In the southern locality, lenticular masses several feet in diameter contain coarsely crystalline garnet with only very minor calcite and epidote. Individual garnet crystals in these masses average ½ to 3/4 inch in diameter. The rock breaks along the crystal faces, and tends to crumble into individual grains when struck with a hammer. Garnet-calcite intergrowths are best developed at Garnet Butte. Here dark red garnet, commonly in complex euhedral crystals, is embedded in a matrix of white, coarsely crystalline calcite. Individual crystals of garnet 1½ inches in diameter were measured at this locality. Garnet-epidote intergrowths, with neither mineral showing euhedral form, are common throughout all of the skarn areas. Crystal size varies widely. Both quartz and calcite are common associates of such intergrowths.

Epidote is widely distributed in the skarn, but is rarely euhedral in form. It is best developed in both form and size near the edge of the skarn in the saddle separating Fish Lake and Clear Creek stocks, where bright green prisms up to three-fourths inch long are formed in calcite.

In the skarn locality at the edge of the east salient of Clear Creek stock, garnet occurs as red-brown clusters and zones of fine grains in relatively pure marble. Green areas of epidote and white rhombs of calcite are present in the clusters and zones. One band of nearly pure garnet is 5 to 6 feet wide. A narrow zone in this outcrop shows strong iron and copper stains on weathered surfaces.

In the circular locality in the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 7, T. 6 S., R. 46 E. the relations are different than in most of the other areas. No brecciation of the original inclusion has taken place; three distinct but gradational zones of minerals are present. Black acicular prisms of hornblende up to 3 inches long, with minor interstitial white plagioclase, make up the outer 10-20 feet. The middle zone is composed of white plagioclase, and spotted with scattered crystals of black garnet one-fourth to one-half inch in diameter and euhedral epidote up to one-half inch in diameter. Clear anhedral quartz is also present. The inner zone, about 50 feet in diameter, contains very thick accumulations of crystalline garnet "cemented" by quartz and feldspar. A silicified garnetiferous vein with dark iron stain cuts the center of the outcrop area.

Quartz veins and stringers are common in the skarn outcrops. Iron stain, from pyrite or rarely chalcopyrite, has usually colored the quartz varying shades of dark brown or red. Claim stakes have been errected on nearly all such outcrops.

Petrography

A mineralogical study of the skarns was not attempted; but three representative samples were studied to show their general composition. Two assemblages: (1) diopside-enstatite-garnet-(epidote-hornblende-clinozoisite) (2) diopside-garnet-epidote-(calcite-quartz) are present in the thin sections studied.

In the first, diopside constitutes about 85 to 90 percent of the rock; anhedral garnet, epidote, and clinozoisite are the other principal minerals. Faintly pleochroic enstatite is present but minor, probably less than 2 percent. Both diopside and enstatite form large tightly interlocked plates which are heavily altered and clouded with iron ore. Dark green hornblende occurs as irregular patchy inclusions in diopside. Other alteration minerals are actinolite, iron ore, and chlorite.

In the second assemblage, garnet or epidote constitutes the bulk of the rock. Diopside forms clusters of tabular anhedral crystals. Garnet is in large red-brown, xenoblastic masses and subhedral to euhedral grains, usually formed around or in conjunction with epidote. Dusty accumulations of opaque inclusions darken some of the garnet and most of the epidote. Alteration products are actinolite and chlorite. Pale green, fibrous tufts of actinolite have grown from diopside. Chlorite has formed along the margins of garnet.

Accessories in the skarns include sphene, pyrite, magnetite and apatite. Sphene is usually euhedral, in characteristic diamond-shaped crystals. Apatite forms irregular grains up to 0.1 mm in C-48. Pyrite is in well formed cubic crystals, partially altered to limonite.

Reid, who made a more detailed study of these skarns (21, p. 431) determined the composition of the garnet from these skarns as "35 percent grossularite and 65 percent andradite — according to its specific gravity and index of refraction." He also reported prehnite, vesuvianite and pleonaste in addition to the minerals described above (21, p. 34-35).

GEOMORPHOLOGY

The area mapped may be considered as two physiographic zones: a dissected plateau east of Blue Creek (Figure 61), and a high mountainous zone west of Blue Creek (Figure 62). The Columbia River basalt exerts topographic control only in the plateau zone, where it caps relatively broad, flat ridges. Prominent geomorphic features are the combined result of Tertiary faulting and Pleistocene glaciation. Uplift along a series of intersecting block faults provided elevations from which alpine glaciers moved to carve out much of the present topography. Geomorphic forms are discussed below as glacial and nonglacial forms.

Glacial Forms

Glacial action created most of the land forms found in the area; various forms are described according to classification.

Glacial Valleys

Most stream valleys in the area were formed or modified by glacial action. Clear Creek, Cliff River, Norway Creek, East Pine Creek, and the Middle Fork of Pine Creek all flow in excellent examples of glacially eroded valleys. Figures 63 and 64 show two such valleys with oversteepened

Figure 61. View to east showing typical flat-topped ridges of dissected plateau capped by Columbia River basalt flows.

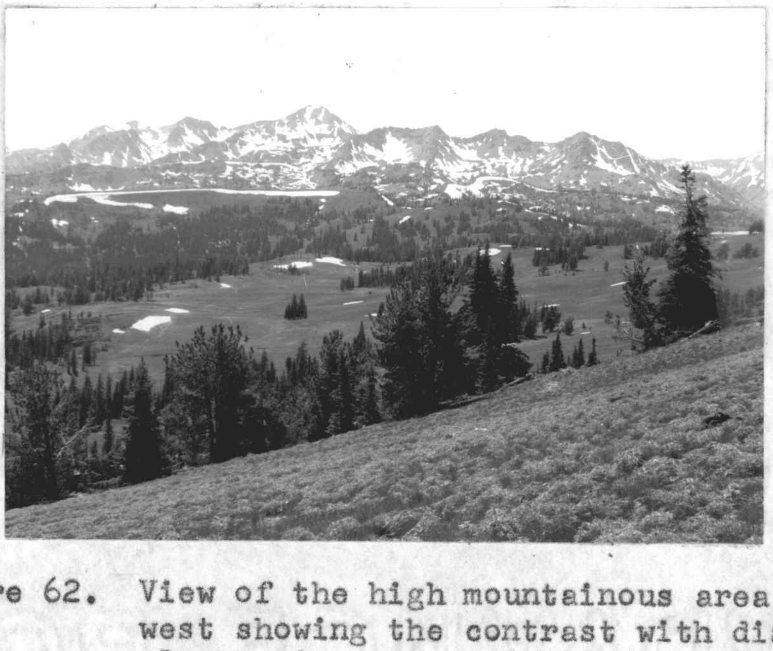


Figure 62. View of the high mountainous area to the west showing the contrast with dissected plateau in eastern part of the area.

Figure 63. Red Mountain Basin, a well developed glacial valley.

Figure 64. Clear Creek canyon, typical U-shaped valley gouged through gabbroic rock of Fish Lake complex.

sides and flattened floors. Both follow a generally straight course to an intersection with a larger valley. In Red Mountain Basin the creek flows across a step profile typical of glacial valleys.

All stream valleys in the area, except Trail Creek, show evidence of glaciation, mostly in the form of striated roches moutonnées, although the typical "U" shape of glacial valleys is less well developed.

Hanging Valleys

The entry of Norway Creek into Norway Basin is an excellent, though small, example of a hanging valley. The creek flows southeast from Clipper Gap over a series of treads and risers to plunge some 300 feet to the floor of the basin in a series of small cascades.

Blue, Bear, Soldier, Deadman and Rock Creeks all enter the Imnaha River from hanging valleys. Postglacial erosion has somewhat obscured relations of these canyons to the larger Imnaha Canyon.

Lake Basins

Fish Lake, Clear Creek Reservoir, Francis Lake and Melhorn Reservoir occupy basins gouged out by glacial ice (Figure 65). Origin of the basins is indicated by the presence of roches moutonnées, striae, and small moraines in positions showing that the ice moved over the basin.

Figure 65. View of Fish Lake showing a typical lake basin of the area.

The dip slope of the Trinity Creek formation along the south side of Fish Lake may have facilitated plucking.

Construction has removed evidence for the origin of the basin containing Sugarloaf Reservoir; East Lake was produced by constructing a dam across the small stream.

Throughout the eastern plateau zone, mountain meadows occur frequently. Mud Lake represents such a "meadow" in the last stages of completion. This very shallow lake, (maximum depth of 18 to 24 inches in the spring), occupies a slight depression surrounded by nearly flat banks of silty mud. Because the lake is situated on the crest of a low divide, sediment has not accumulated as rapidly as in other locations.

Cirques

No well defined cirques are in the thesis area. However, the head of Red Mountain Basin is a modified cirque. The shape has been altered by postglacial crumbling from the headwalls. Talus chokes much of the upper portion of the valley.

Arêtes

Aretês are common in the western part of the area. Ridges on both sides of Red Mountain Basin are excellent examples. Typical arêtes in this area are shown in Figures 66 and 67.

Figure 66. Well formed arête at the head of Red Mountain Basin, on southeast slope of Red Mountain. Note cirques on The Granites in background.

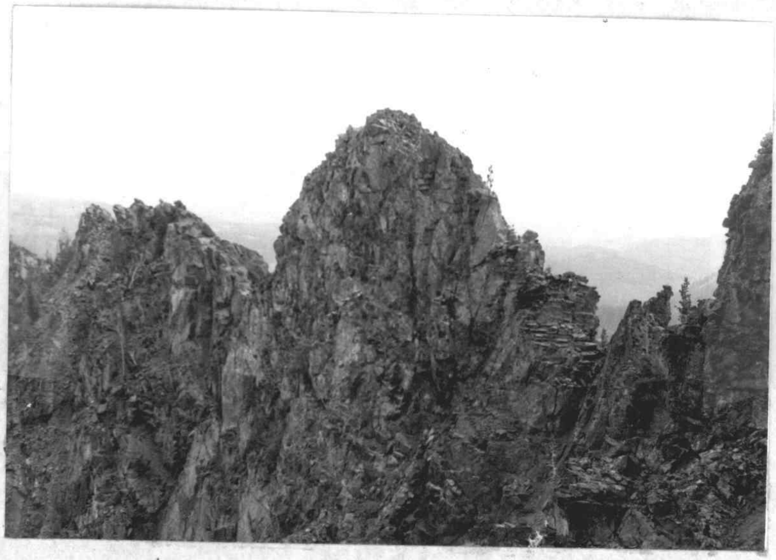


Figure 67. Close-up of portion of arête east of Red Mountain.

Roches Moutonnées and Glacial Striae

Roches moutonnées are common in the more resistant rocks throughout the area, but the best examples are in the "greenstones" and the basic stocks. In the vicinity of Rock Creek, as may be seen from Figure 8, roches moutonnées are the most frequently occurring outcrop form. Good examples are formed in gabbroic rock near the Fish Lake Guard Station.

Glacial striae, up to $\frac{1}{4}$ inch deep and 5 feet long, are conspicuous on roches moutonnées. Between Sugarloaf Mountain and Fish Lake, striae are generally oriented southeast. Within the valleys striations are roughly parallel to the canyon walls. Striae are as common on higher elevations in the eastern part of the area as in valleys. This condition suggests probably existence of a local piedmont glacier which moved away from the high mountains and was not restricted to valleys.

Moraines

Lateral moraines parallel East Pine Creek for nearly a mile, but typical tongue shape is conspicuous only on the east side. This east ridge, separating the two forks of East Pine Creek, is shown in a panoramic sequence in Figure 68. Other small moraines are present along Norway Creek, but are so small as to have little expression at

Figure 68. Long tongue-shaped lateral moraine along East Pine Creek.

Figure 69. View of the upper reaches of Cliff River showing large alluvian fan. Outlines drawn in.

eighty-foot contour intervals.

Nonglacial Forms

Nonglacial geomorphic forms are not well developed in the area, but in the upper part of Red Mountain Basin, the Middle Fork of Pine Creek flows through a gorge some 20 to 30 feet deep, but only 50 to 100 feet wide, cut into sedimentary rock. This gorge has been cut by the stream as a partial adjustment toward base level. Torrential spring melt-waters were probably the main erosion agent.

Trail Creek canyon shows no evidence of glaciation. Lack of glacial striae, roches moutonnées, and "V" shape as opposed to "U" shape of glacial canyons lead to the conclusion that stream erosion, not glacial ice, was the formative agent for this canyon.

STRUCTURAL GEOLOGY

At least two cycles of orogenic deformation are recorded in the thesis area, one during the Tertiary, and one during the late Mesozoic. Mesozoic mountain-building was completed long before outpouring of Miocene lavas. Older deformation may also have occurred, but if so its effects are obscured by later structures.

Mesozoic Deformation

The major folds of the area were produced during the Mesozoic. Folding increases in intensity from east to west, concurrent with a swing in strike from northeast to north. Attitudes are generally steeper toward the west, and the west limb of the asymmetrical anticline exposed along Cliff River is slightly overturned. This anticline has been contorted, and strikes near the summit of Red Mountain suggest that the axis follows an irregular "S" curve, swinging from northeast to southeast and then back to northeast.

Steep dips are recorded in sedimentary portions of the Russel member, but structural information is so sketchy in the northeast portion of the area that the extent of folding is not known.

Faulting undoubtedly occurred during this orogeny, but no faults were recognized which can be assigned definitely to this period. However, the Pine Creek fault, which has been offset in the northern part of the area by later faulting, may have originated in the Mesozoic. This reverse fault crosses the thesis area just east of Red Mountain, and has a minimum vertical displacement of 2500 feet. Sandstones of the Lower Sedimentary Series are exposed under breccias of the Norway member at an elevation of 6000 feet in the gorge of the Middle Fork of Pine Creek, yet at 8800 feet on the upthrown side of the fault, the Lower Sedimentary Series occupies its true stratigraphic position above the Norway member. The trace of the fault is not well exposed, and is visible only on the crest of the saddle east of Red Mountain where gabbroic rock has been dragged into place. This "foreign rock" is highly sheared and partially metamorphosed, but still recognizable as being coarser-grained and distinctly different than rocks of either the Norway member or Lower Sedimentary Series. Shearing developed near the fault in both walls indicates a dip of 55-60° E. for the fault plane.

The age of this fault is not known; it may be either Mesozoic or Tertiary, but this fault is older than a northwest-trending fault which has offset it in the northern part of the area.

The short fault in the Trinity Creek formation is defined by a silicified gouge zone about 4 feet thick which can be traced for only a few hundred feet. Age and displacement are unknown, but the fault is probably pre-Tertiary for feldspar fragments in the gouge zone show partial albitization.

Post-Miocene Deformation

Deformation within the thesis area since the outpouring of the Columbia River basalt has consisted primarily of normal faulting. This faulting was probably contemporaneous with the great uplift along faults which produced the present Wallowa Mountains.

Normal faults of this age trend north and northwest across the area. Each of the faults was recognized only by the relation of basalt flows to older rocks, or as at East Lakes, by offset of a distinctive horizon. No fault gouge or other traces were recognized. Because Tertiary rocks are displaced by some of these faults, parallel faults are considered to be of equivalent age.

Compressional stress has produced broad shallow folds in the basalt flows. Because of the dissected nature of the thesis area, these folds are not readily traced. However, gentle folds in Columbia River basalt are visible outside of the area on the north wall of the Imnaha canyon.

ECONOMIC GEOLOGY

No mineral deposits of proven economic value exist within the thesis area, nor were any deposits of potential value discovered during the field investigation. A combination of short working season, rugged terrain, and inaccessibility weigh heavily against any mining venture within the area. As even a negative report can be of value, the following materials are discussed: Gold, uranium, and limestone.

Gold

Gold mining has long been of primary interest in the region because of the rich mines at Cornucopia, and all of the area has been prospected, probably many times. Innumerable "gopher holes" give mute evidence of the diligence of early prospectors. Only 4 "mines" are shown on the map, and only three of these show indication of production. They were not considered sufficiently significant to search out the history from Baker County records. Each mine is discussed by location.

Carnahan Mine

The Carnahan mine is the only prospect named in previous literature; it is mentioned in Smith and Allen's report (26, p. 58). The "mine" is now merely a shallow hole scooped out on the saddle between Blue and Norway Creeks. There is nothing to indicate that it was ever more than a prospect hole.

<u>NE¼SE¼ sec. 7, T. 6 S., R. 46 E.</u>

A winze, now open to a depth of 35 to 40 feet, has been sunk along a vuggy quartz vein 18 to 30 inches wide which strikes N. 25° W., dips 65° SW. The vein can be traced on the surface 100 to 150 feet through a small pod of limestone enclosed in gabbroic rock. The quartz carries pyrite, hematite, and malachite (?) stain. Waste dumps indicate that the original mine was larger than the open winze.

<u>SE¼NE¼ sec. 18, T. 6 S., R. 46 E.</u>

Two large pits have been sunk, probably on the same vein, about two hundred yards apart. The vein is not visible on the surface, but the direction between pits is N. 15° E. Quartz in the dump contains small amounts of pyrite, scattered garnet, and reddish, encrusting limonite (?) stain. No other sulphides were noted. Some tunneling had been done from the base of the northern pit, but the extent could not be determined.

West of Blue Creek

In the unsurveyed area about one-half mile west of Blue Creek at an elevation of 7400 feet, an adit enters the hillside along a silicified zone varying from $1\frac{1}{2}$ to $5\frac{1}{2}$ feet in width. The zone strikes N. 35° W., dips 40° SW., and can be traced for 200 to 300 feet on the surface; the adit was not explored, but is open for at least 50 feet. Quartz from the shear zone carries heavy pyrite mineralization, but no other sulphides. Weathering of the pyrite has produced a rusty-stained zone several inches wider than the mineralized zone.

Norway Mine

Oregon Metal Mines Handbook (17, p.32) places the Norway Mine in sec. 9, T. 6 S., R. 45 E., but on the present topographic maps, the mine dump falls just inside sec. 15. Therefore, the mine is not shown on the accompanying map.

A large dump, some old track, and a small mill remain on the site. All workings are caved. A tunnel over 1000 feet long is reported to have followed a wide shear zone, which carried "gold of fair grade" (17, p. 32).

Uranium

Extensive claims for radioactive minerals have been staked along the west side of Blue Creek, but no development or production has been carried out. No evidence of uranium mineralization was noted in the area, but no means of detecting radioactivity was used to test the area.

Limestone

Limestone deposits exposed in the thesis area are too small and inaccessible to be considered as economic prospects.

HISTORICAL GEOLOGY

The span of pre-Permian time is unrecorded in the area. During the Permian most of the region was covered by a shallow coastal sea, occupying a eugeosynclinal trough. Vulcanism was active; volcanic material comprises the bulk of the Permian rocks in the region, but sedimentary rocks were also being eroded to contribute fragments to the lower Trinity Creek formation.

Subsidence of the trough was rapid, but failed to pace the volcanic outpour; the seaway filled and terrestrial deposits began to form. Talus and landslide deposits accumulated between periodic expulsions of lava to form the thick, jumbled sequence of the Russel member.

Shallow marine embayments and lagoons remained, marked by irregular limestone pods, and during the Triassic, probably in early Upper Triassic time, the sea again spread over the entire area. Pulsations of the sea are recorded by lithosomal intertonguing of marine and terrestrial members of the Imnaha formation. Extensive vulcanism continued beyond the time of terrestrial deposition, resulting in the thick breccia and pillow lava of the Norway member. Part of Upper Triassic time is unrecorded in the thesis area. During this emergence minor orogeny may have taken place to produce the angular unconformity between the

Norway member and the Lower Sedimentary Series.

When the sea again swept over the area in Upper Triassic time, vulcanism was no longer so active. The water was deeper, receiving mostly fine sediment. Large boulders in mudflow conglomerate suggest that the source of the sediment was not far removed. Marine deposition apparently continued through Upper Triassic time to form the Martin Bridge and Hurwal formations, though these formations are not present in the thesis area.

Orogeny, with plutonic intrusion, deformation, and regional metamorphism took place in northeastern Oregon during the late Mesozoic, and this was probably the time when most of the intrusive units were emplaced. After the culmination of orogeny, the area was exposed to erosion, and a mature topography developed.

During the Miocene, basaltic lavas flowed up through great fissures, and out over the erosional surface. Thick accumulations of lava finally covered the ancestral Wallowa Mountains.

The present mountains owe their grandeur to glacial erosion of areas uplifted by post-Miocene faulting. Most faults shown on the map were formed during this time. However, the association of the epidote zone with the Pine Creek fault may indicate that post-Miocéne movement merely followed the trace of an older fault.

Pleistocene glaciers moved down stream valleys from the high areas, gouging out immense quantities of rock as they moved. Long ridges and isolated gravel deposits were dumped when the ice melted.

In recent time most of the morainal deposits have been removed in the thesis area, leaving only deep valley fills and scattered glacial veneer. Land forms scoured from solid rock have been little altered by erosion since the Pleistocene.

APPENDIX

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