Igneous and Tectonic Structures of the Stillwater Complex Montana

By W. R. JONES, J. W. PEOPLES, *and* A. L. HOWLAND

CONTRIBUTIONS TO GENERAL GEOLOGY

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A study of the structures in a belt of upturned layered noritic and ultramafic Precambrian rocks on the northeast margin of the Beartooth Mountains

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IGNEOUS AND TECTONIC STRUCTURES OF THE STILLWATER COMPLEX, MONTANA

By W. R. JONES, J. W. PEOPLES, and A. L. HOWLAND

ABSTRACT

Igneous structures.—An upturned and previously beveled edge of the Stillwater complex, a Precambrian stratiform sheet about 18,000 feet thick and comprising a sequence of noritic and ultramafic rocks and chromite layers, crops out in a belt 30 miles long on the northeast margin of the Beartooth Mountains in Montana. According to the scheme of subdivision used in this paper, the complex consists of the following four zones from bottom to top: (a) the Basal zone, 200 feet thick, medium-grained noritic rocks; (b) the Ultramafic zone, 4,000 to 6,000 feet thick, a succession of layers of bronzitite, granular harzburgite, poikilitic harzburgite, and chromitite; (c) and (d) the Banded and Upper zones, in aggregate 14,000 feet thick, layers of norite, anorthosite, troctolite, and gabbro. The position of the contact between the Banded and Upper zones is in doubt because of uncertainty in lateral correlation of several troctolite layers. The rocks of the Ultramafic zone are easily distinguished from those of the Banded and Upper zones; however, the nature of the upper contact of the Ultramafic zone is uncertainly known in some places. Local discordances at that contact are probably the result of deformation after consolidation of the complex, but possibly they resulted from deformation during crystallization.

Layers within the major zones exhibit two types of primary structures: igneous lamination and rhythmic layering. Lamination, a function of the platy habit of the clinopyroxene, orthopyroxene, and plagioclase, is most frequently observed in the upper part of the Banded zone and in the Upper zone. Rhythmic layering, involving variations in mineral composition or mode and in texture, is more conspicuous in the Banded and Upper zones but is also common in the Ultramafic zone.

Rhythmic layers range greatly in thickness from a fraction of an inch to hundreds of feet. Many thin layers appear to branch and, farther on, to coalesce, forming primary lenses concave upward in the columnar section. All the layers are truly lenses, ranging from minute to large lenses thousands of feet long. Where the curvature of the lens is great, a primary basin or trough is formed. Such structures involving chromitite layers may be of economic significance, for detailed mapping will reveal trends in thickening and thinning. In primary basins, individual layers thicken toward the axis of the trough.

Irregularities in the trend of certain layers and groups of layers are believed to be due to movements before crystallization had been completed. Irregularities were observed in norite layers, and in the upper boundaries of some troctolite layers.

Tectonic structures and igneous activity.—Before Middle Cambrian time the metasedimentary rocks beneath the complex had been locally displaced by granite, and the complex may have been arched within an ancestral range. Diabase intruded the granite, the metasedimentary rocks, and the Stillwater complex, forming sills, dikes, and small irregular masses. Erosion, accelerated by the uplift, beveled the arched crustal block, exposing its core of granite, metasedimentary rocks, and an edge of the Stillwater complex. During Paleozoic and Mesozoic times, the Precambrian erosional surface was buried beneath 8,000 to 10,000 feet of sedimentary rocks, predominantly limestone deposited during the Paleozoic era, and sandstone, shale, and volcanic breccia deposited during the Mesozoic era.

Throughout the Paleozoic and most of the Mesozoic, the area was part of a structural shelf that underwent slow epeirogenic movements with little, if any, attendant igneous activity. The absence of rocks of Silurian, Late Pennsylvanian, and Permian age in this locality indicates intervals of uplift, and consequent erosion or nondeposition.

Forces of the Laramide orogeny greatly deformed the upturned edge of the complex and the overlying strata. During the early phase of the orogeny, deep-seated thrust and ramp faults dipping northeastward developed in the crystalline basement near the present mountain front. At the same time folds, overturned to the southwest, developed in the sedimentary strata, commonly as the near-surface expression of the northeast-dipping faults and of layering-plane adjustments. Movement on the ramp thrust increased the northeast tilt of the layers in the elevated blocks only 15° to 20°. Most of the deformation visible today is attributed to deformation in a later phase of the Laramide orogeny. The ends of the Stillwater complex, especially the eastern end, appear to have been twisted. The steep and overturned igneous layers, and major swings in their trend, are evidence of great rotational strain along segments of the mountain front where southwest-directed forces met massive resistance. In the eastern part of the complex, south-dipping thrusts eventually developed, breaking across the steepened layers and the related tight fold of the sedimentary blanket. Thrusts of the earlier phase, warped and steepened, are recognizable in the rotated sections of the complex. The attitudes of Precambrian diabase dikes in rotated blocks are also greatly changed from their original attitude. The Lake–Nye Creek fault developed along a diabase dike which probably dipped north originally, but which now stands vertical in one place and dips 60° S. in another.

Absence of Cenozoic strata in the Stillwater area precludes evaluating the extent of post-Laramide adjustments. Laramide structures may have been reactivated when the region underwent epeirogenic movements.

INTRODUCTION

The Stillwater complex, which comprises a series of noritic and ultramafic igneous rocks and associated mineral deposits, crops out in a belt 30 miles long on the northeast margin of the Beartooth Mountains in Montana (pl. 23). It is believed to be a concordant stratiform sheet or lopolith, from which erosion had removed the roof and an unknown amount of the complex itself before Middle Cambrian time.

Two of the authors of this report (Peoples and Howland) began work on the Stillwater complex in 1930 and 1931 as part of Princeton University's studies in the Beartooth–Bighorn–Yellowstone area. Prof. Edward Sampson, who directed the fieldwork, began a study of the chromite deposits. In 1935 Dr. H. H. Hess initiated a detailed study of the mineralogy of the complex. Before more than brief summaries of these studies were published (Peoples, 1933, 1936; Howland, Peoples, and Sampson, 1936; Hess, 1938a, 1938b, 1939, 1941; Hess and Phillips, 1938, 1940), Peoples, Jones, and Howland, with the help of many others, in the years 1939–1943 and 1949 mapped the chromite deposits in detail for the U.S. Geological Survey. Since 1949 the present authors have done some fieldwork to fill in details for reports. Maps and descriptions of the chromite deposits have been published covering the Boulder River area (Howland, Garrels, and Jones, 1949) and the central part of the complex (Howland, 1955). A preliminary report on the east end of the complex appeared in 1940 (Peoples and Howland). In 1951, E. D. Jackson of the Geological Survey began a detailed study of the chromite deposits, including petrology and geochemistry of the Ultramafic zone and mapping of the Banded and Upper zones. In the meantime, Hess (in press) has completed his mineralogical and petrological study.

The structures of the Stillwater complex are of two kinds: igneous or primary structures resulting from intrusion and crystallization, and tectonic or secondary structures created by later deformation of the region, chiefly in Laramide time. It is possible in most cases to determine whether the observed relations of the rocks are igneous or tectonic features; accordingly, the section "Igneous structures" largely the work of Peoples and Howland, is concerned with the age, form, and primary internal structures of the complex. The section "Tectonic structure and igneous activity," largely the work of Jones, considers the history of the complex subsequent to its solidification. The three authors, however, have collaborated on all parts of the report.

IGNEOUS STRUCTURES

CHARACTERISTICS OF LAYERED COMPLEXES

The Stillwater complex belongs to the great layered complexes of the world, which were recently defined by Wager (1953, p. 335) as follows: "A layered series of igneous rock may be defined as an igneous complex which can be separated by structural or mineralogical criteria into a succession of extensive sheets lying one above the other." In a previous paper on the Skaergaard complex, Wager and Deer (1939, p. 36) explicitly defined three types of layering:

1. Rhythmic layering caused by a variation in proportions of the component minerals in adjacent layers.
2. Igneous lamination resulting from the parallelism of platy minerals.
3. Cryptic layering due to the gradual change in composition of the various minerals.

The Stillwater complex belongs to the Skaergaard type of layered complex, for the detailed mineralogic and petrologic studies made by Hess (1940, p. 377; in press) have shown systematic variation in the composition of plagioclase, clinopyroxene, orthopyroxene and olivine with respect to height in the series.

GEOLOGIC SETTING AND AGE OF THE COMPLEX

The location and general setting of the complex are shown in plates 23 and 24. The complex is bordered on the north by Paleozoic sedimentary rocks, and on the south by the Precambrian core of the Beartooth Mountains, consisting dominantly of granite, granite gneiss, and schist.

The pre-Middle Cambrian age of the complex is established by the occurrence of boulders of gabbro, norite, and anorthosite in the basal Middle Cambrian strata. These rocks also contain boulders of diabase dikes showing chilled edges. Similar dikes cut the complex in a number of places and clearly were intruded after the complex had thoroughly cooled.

The Flathead sandstone is the basal Cambrian formation throughout the Beartooth Mountains except at the contact of the Cambrian with the complex, where, according to Vhay (1934[1]), the overlying Wolsey shale is the basal unit. The complex appears, therefore, to have formed a ridge standing slightly above its surroundings when Cambrian sedimentation began.

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[1] The following unpublished doctoral (and other) dissertations, prepared in partial requirement for advanced degrees from the universities indicated, may be obtained for reference in university libraries.

Hambleton, W. W., 1947, A petrofabric study of layering in the Stillwater complex, Montana: Northwestern University.

Peoples, J. W., 1932, The geology of the Stillwater igneous complex: Princeton University.

Richards, P. W., 1952, Structural geology of the Crazy Mountain syncline–Beartooth Mountains border east of Livingston, Montana: Cornell University.

Vail, P. R., 1955, The igneous and metamorphic complex of East Boulder River area, Montana: Northwestern University.

Vhay, J. S., 1934, Geology of part of the Beartooth Mountain front near Nye, Montana: Princeton University.

Wilson, J. T., 1936, Geology of the Mill Creek–Stillwater area, Montana: Princeton University.

The oldest Precambrian rocks are metasedimentary and include quartzite and various types of schist. Near the Stillwater complex the metasedimentary rocks have been altered to hornfels. The stratigraphy of the series has not been studied in detail, but banded rocks containing quartz, fayalite, iron-rich pyroxene, grunerite, and magnetite form a unit a few hundred feet thick near the base of the complex throughout most of its length. This unit is thought to be a metamorphosed sedimentary iron formation, and its distribution is strong evidence for the concordant nature of the complex.

Gray gneissic granite, cut by faintly foliated pink granite, is exposed in the canyon of the Stillwater River, south of the complex. These two granites may correspond to the Goose Creek and Cooke granites described by Lovering (1929, p. 16–17) in the Cooke City area, but most of the granitic rocks near the Stillwater complex do not closely resemble the descriptions of either, and some at least are quartz monzonite rather than granite (E. D. Jackson, written communication). No attempt at subdivision is made, but the authors believe that the granite adjacent to the Stillwater complex at the west end, and from the West Fork of the Stillwater River to the east end, is the equivalent of the Cooke granite. It has intruded the metasedimentary rocks and contains many large inclusions, as, for example, on the Nye–Flume Creeks divide. It also intricately intrudes hornfels formed by the Stillwater complex and cuts the lowermost zone of the complex in a few small dikes.

The age of the metasedimentary rocks is unknown, but they are considered pre-Belt in age because of their similarity in lithology and degree of metamorphism to other pre-Belt rocks of Montana. A series of schists, quartzites, marbles, and the iron silicate–magnetite rocks in the Tobacco Root Mountains were called the Cherry Creek series by Tansley, Schafer, and Hart (1933), and Seager (1944) has suggested a similar age for schists and quartzites in the Jardine district, Montana, on the southern side of the Beartooth Mountains. Parsons and Bryden (1952), however, consider the possibility of an older age, possibly the equivalent of the Pony series of Tansley, Schafer, and Hart (1933) in the Tobacco Root Mountains, for schists and gneisses intruded by granite and diabase dikes in Yankee Jim Canyon of the Yellowstone River, near Gardiner, Mont.

Helium age determinations on mafic rocks from the Beartooth Mountains near Red Lodge, Mont., were reported by Evans and others (1939, p. 63–64). A recalculation of age by Keevil (1943, p. 690) gave 450 million years for a diabase dike, and 2,875 million years for the gabbro mass of Quad Creek. The Quad Creek gabbro and similar masses of gabbroic rock on the Fishtail Plateau south of the east end of the Stillwater complex are intruded by granite, but their relation to the complex is not known. Unfortunately, the age determination on the Quad Creek gabbro has been cited for the Stillwater complex (Evans, and others, 1939, p. 946) and presumably the age of 2,000 million years cited by Horwood and Keevil (1943, p. 30) is based on the Quad Creek determination. The age of the granite intrusive into the Stillwater complex in the valley of the Stillwater River, based on lead-alpha age determination of zircon from the granite, is 1,530 to 1,580 million years. Diabase dikes that are known to cut granite and quartz monzonite as well as the Stillwater complex are the youngest Precambrian rocks recognized.

In summary, the history of the Stillwater complex seems to have been as follows:

1. Intrusion into metasedimentary beds early in Precambrian time.
2. Intrusion by granite.
3. Intrusion of diabase dikes after cooling of the granite.
4. Erosion until the rising Middle Cambrian seas covered the complex. The present outcrops of the complex were islands in the Flathead sea.
5. Later tectonic history of the complex as described under the heading "Tectonic structures and igneous activity."

STRATIGRAPHY OF THE COMPLEX

MAJOR SUBDIVISIONS

The rocks of the Stillwater complex exhibit many similarities to sedimentary rocks, and, indeed, if the concept of their origin as crystal accumulations in a chamber filled with basaltic magma is correct, the similarity should be expected. Attitudes of the rhythmic layering and igneous lamination are measured and used in the same way as analogous sedimentary structures, and some sedimentary terms are used for convenience. Two schemes of stratigraphic subdivision of the Stillwater complex are shown below for comparison. The terminology on the left represents only a slight modification of that first proposed by Peoples (1933; see also footnote p. 284). On the right is the more detailed subdivision of the noritic and anorthositic rocks based upon the study of the petrography and mineral variations by Hess. Although Hess' subdivisions may ultimately be preferred, the units have not yet been mapped in the field; inasmuch as our maps and sections were all prepared in accordance with the Peoples system, the latter system will be followed here, with some cross reference where appropriate.

Subdivisions of the Stillwater complex

<table>
<tr><th colspan="2">Terminology of this paper</th><th colspan="2">After H. H. Hess (in press)</th></tr>
<tr><th>Zones</th><th>Subzones</th><th>Zones</th><th>Subzones</th></tr>
<tr><td rowspan="5">Upper (6,700 feet)</td><td rowspan="5"></td><td>Hidden (1,000 feet)</td><td rowspan="2"></td></tr>
<tr><td>Upper Gabbro (2,200 feet)</td></tr>
<tr><td rowspan="5">Anorthosite (6,100 feet)</td><td>Anorthosite subzone 3 (2,000 feet)</td></tr>
<tr><td>Anorthosite subzone 2 (1,500 feet)</td></tr>
<tr><td rowspan="2"></td></tr>
<tr><td rowspan="4">Banded (7,400 feet)</td><td rowspan="4"></td></tr>
<tr><td>Anorthosite subzone 1 (1,200 feet)</td></tr>
<tr><td>Lower Gabbro (2,400 feet)</td><td></td></tr>
<tr><td>Norite (2,000 feet)</td><td></td></tr>
<tr><td rowspan="2">Ultramafic (4,000 feet)</td><td>Upper Bronzitite (1,000 feet)</td><td rowspan="2">Ultramafic (4,000 feet)</td><td rowspan="2"></td></tr>
<tr><td></td></tr>
<tr><td>Basal (200 feet)</td><td></td><td>Border (200 feet)</td><td></td></tr>
</table>

The Basal zone [2] is too thin to show separately in plate 24, where it is included with the Ultramafic zone. It consists of about 200 feet of medium-grained noritic rocks containing both ortho- and clinopyroxene and shows a faint rhythmic layering in places. The upper boundary of the Basal zone is taken as the top of the norite.

The Ultramafic zone consists of bronzitite, harzburgite, and chromitite in layered arrangement (see fig. 38). Minor amounts of olivine-rich harzburgite and dunite have an apparent intrusive relation to the layered rocks. The harzburgites are of two contrasting textures, granular and poikilitic. In the latter, large crystals of orthopyroxene include olivine crystals with various orientations. The upper part of the Ultramafic zone, a major Bronzitite subzone and prominent map unit, is shown separately in plate 24. The boundary between the Ultramafic and Banded zones is drawn at an abrupt change in the amount of plagioclase. Below this boundary, plagioclase is interstitial and rarely constitutes more than 15 percent of the rock. Above the boundary, plagioclase appears as euhedral crystals and in much greater quantity.

The Banded and Upper zones are shown together in plate 24, as the boundary between them has not been mapped throughout the

[2] Use of this term and other local informal terms follows previous usage in reports on this area. These informal terms are capitalized for clarity in the description of the subdivisions of the Stillwater complex.

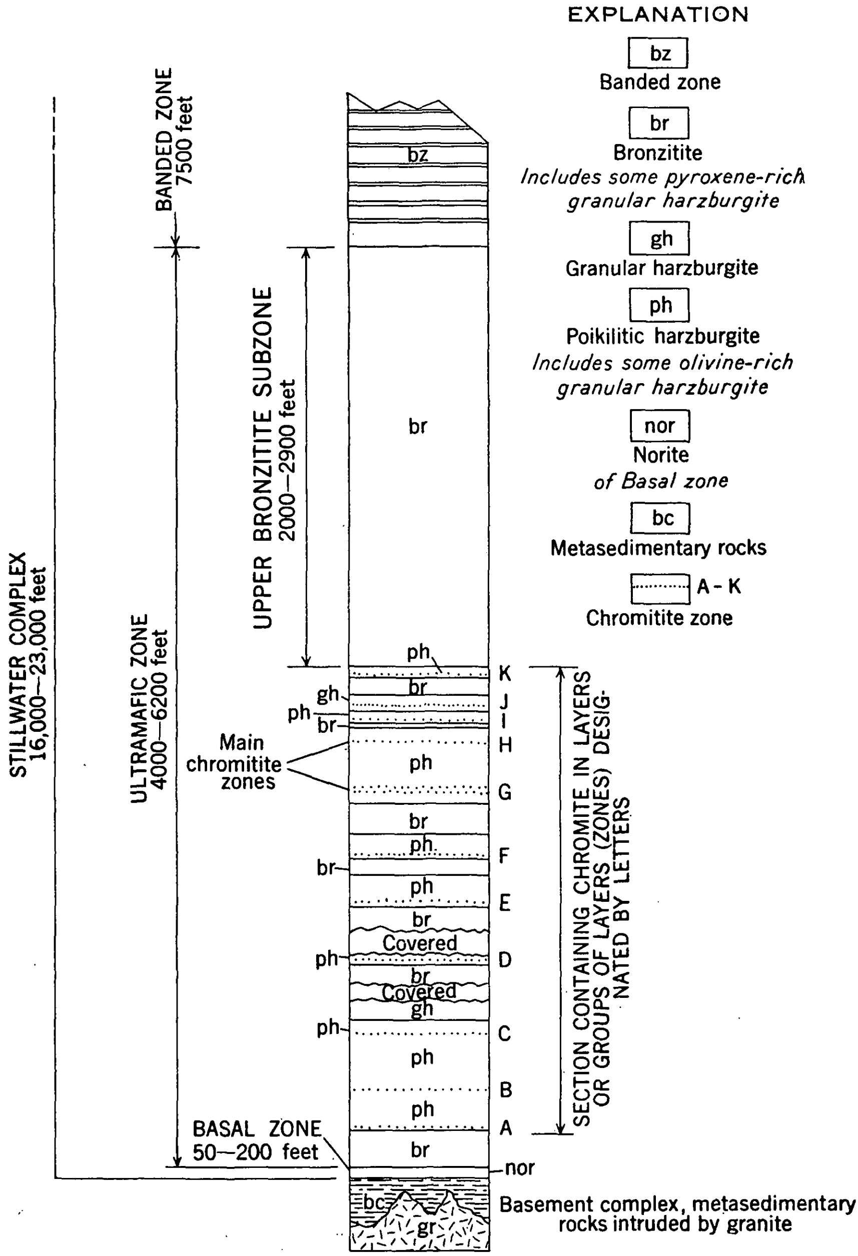


FIGURE 38.—Generalized columnar section of the Ultramafic zone, eastern part of the Stillwater complex, Montana.

complex. These zones consist of layers of norite, anorthosite, troctolite, and gabbro. The Upper zone was originally defined as comprising all of the complex above a prominent layer of troctolite noted in the canyon walls of the Stillwater and Boulder Rivers, but, after a number of troctolite layers were found in the much thicker section on the East Boulder Plateau, some doubt has arisen as to the correlation of the various troctolite layers.

Billings (1950, p. 440) has emphasized in the study of metamorphic rocks lacking fossils the necessity of working out the stratigraphy and structure together. Similarly, the detailed stratigraphy has been invaluable in working out the structure within the Stillwater complex. Unfortunately, the most complex cross section of the rocks above the Ultramafic zone (cross section *GG'*, pl. 25) is in one of the most inaccessible parts of the complex, the East Boulder Plateau. Hess, Doten, and Davis did reconnaissance work here in 1935 and collected specimens across the complex. Peoples and Howland did further reconnaissance work in 1936 and collected a more complete suite of specimens, but, because topographic maps and aerial photographs were not then available, no detailed mapping was done. The later detailed mapping (Howland, Garrels, and Jones, 1949; Howland, 1955) was confined to the Ultramafic zone. The thickness given on page 287 may be in appreciable error because of repetition or the cutting out of layers by faulting.

It is obvious from the cross sections in plate 25 that in the eastern part of the Stillwater complex, where there are a number of strike faults and where the layers are tilted on edge and in places overturned, the reconstruction of columnar sections is difficult. Nevertheless, an attempt has been made, and the results are shown in figure 39. A few significant facts should be noted. The Ultramafic zone is thicker at the east than at the west. In the eastern part of the complex, which is most accessible, only the lower 5,000 feet or so of the Banded zone is exposed. This corresponds to the Norite, Lower Gabbro, and part of the Anorthosite zones of Hess. (See page 287.)

DISTINCTIVE BOUNDARIES AND LAYERS

The most distinctive boundary within the complex is that between the Ultramafic and Banded zones, and its nature has considerable importance in understanding the plutonic and the tectonic history of the complex. It is well exposed in several places and is either a simple sharp contact betwen bronzitite and norite, or a series of alternating layers of the two over a distance of a few feet. In the latter case the base of the lowest norite layer is taken as the boundary between the zones. In the language of stratigraphy, the contact is conformable. Where the actual contact is not exposed its position is indicated fairly closely by float.

Several layers in which the mineral proportions, mineral composition, or texture is distinctive, can be recognized and traced for greater or less distances. In the Ultramafic zone the chromitite

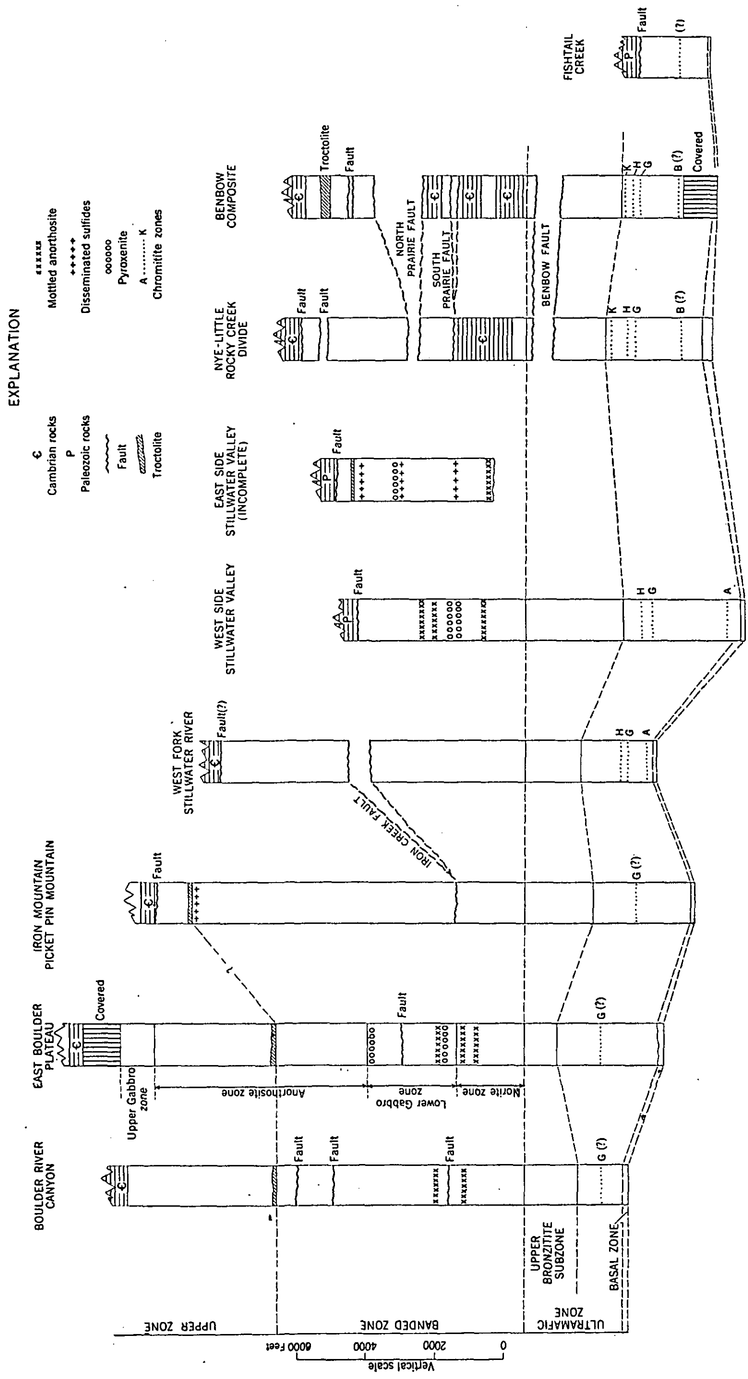


FIGURE 39.—Columnar sections of the Stillwater complex, Montana.

layers are useful for this purpose. Thin layers of bronzitite have also been used in both the Ultramafic and Banded zones, but they are less dependable. The same applies to the troctolite layers, a prominent one of which was used to separate the Banded and Upper zones. Concentrations of sulfides at certain horizons have been used as markers, but their validity as such has not been fully tested.

In the Ultramafic zone characteristic textures such as that of the poikilitic harzburgite have been important in distinguishing certain layers and determining their stratigraphic position. E. D. Jackson (written communication) reports that he finds textural variations the most valuable and persistent markers for mapping in the Banded zone.

SERPENTINIZED ROCK

Serpentinization is widespread in the Ultramafic zone. A detailed discussion of the origin of the serpentinization is beyond the scope of this paper, but it is pertinent to point out its general distribution. Serpentine is typically well developed along faults, but it is not restricted to their vicinity. It is most intense within a few hundred feet of the base of the Ultramafic zone and least intense in the Upper Bronzitite subzone. The fact that olivine is more readily serpentinized than bronzite may explain the distribution of serpentinized rock, but control in part by stratigraphic position may be inferred from Hess' suggestion (1938a, p. 334) that serpentinization may be caused by water taken up from the floor rocks by the magma. If so, it would be controlled in part by stratigraphic position. Serpentinization seems to have been least at the Mouat mine and in the western part of the valley of Nye Creek, perhaps because the total ultramafic section is thickest in this area.

CHARACTERISTICS OF LAYERS

The strikes and dips shown in plate 24 have been measured on two kinds of structure: (a) igneous lamination, best developed in the upper part of the Banded zone and in the Upper zone; and (b) rhythmic layering, best developed in the lower part of the Banded zone and in the middle of the Ultramafic zone. In a few places, both kinds of structure are found together, but in general they are not.

IGNEOUS LAMINATION

Lamination has been observed most frequently in three kinds of rock—gabbro, anorthosite, and pyroxenite—and is a function of the platy habit of the clinopyroxene, plagioclase, and orthopyroxene. Where the habit is nearly equidimensional, no lamination is possible. Examples of each will be briefly described.

In the thicker layers of bronzitite of the Ultramafic zone the bronzite crystals appear to have little preferred orientation. The Upper Bronzitite subzone is so notably lacking in both rhythmic layering and recognizable lamination that few reliable strikes and dips within its outcrop area have been obtained. But elsewhere in the Ultramafic zone the pyroxene of certain thin bronzitite layers, commonly a few inches to a foot or two thick, has a platy habit, and the rock has a marked lamination. A typical specimen on a face perpendicular to the layering shows bronzite crystals 5–30 mm long and a ratio of elongation of about 10:1. No linear structure was observed in the field. Some of the places and horizons where such laminated bronzitite occurs are:

1. Benbow mine area.—Four layers of laminated bronzitite occur interlayered with pegmatitic bronzitite about 120 feet below the E chromitite zone (fig. 38). Laminated bronzitite also occurs near the base of the Upper Bronzitite subzone.

2. Mouat mine area.—Thin laminated bronzitite occurs 400 feet stratigraphically below the G chromitite. Some thin layers of olivine bronzitite or harzburgite between the upper layers of both the G and H chromitite are laminated. Laminated bronzitite occurs in a layer 2 or 3 feet thick about 30 feet below the H chromitite, and more at a similar interval above it.

3. Iron Mountain.—The bronzitite lies above the main chromite horizon.

4. East Boulder Plateau.—The bronzitite lies near the main chromite horizon.

Many other examples could be cited and doubtless many specimens not showing lamination megascopically would show some preferred orientation if studied by petrofabric methods. Petrofabric diagrams of laminated bronzitite made by Hambleton (see footnote p. 284) all show a preferred orientation of the tabular (100) face, the (010) face of the orientation advocated by Hess and Phillips (1940, p. 271), in the plane of the layering. One specimen, from the H chromitite zone of the Mouat mine, also showed a lineation resulting from the alinement of bronzite crystals elongated parallel to their *c* axes in the plane of the layering.

Though igneous lamination is believed to have been formed largely by crystal settling, with or without convection currents, it is not clear why platy habit of crystals and consequent lamination are so well developed in some bronzitite layers and not in others. The laminated bronzitite commonly occurs in thin layers, from 1 inch to 10 feet thick, and are most common in the middle third of the Ultramafic zone. They contain little plagioclase.

The bronzite and hypersthene of the norites commonly form stubby crystals that show little obvious orientation. The augite of the lower part of the Banded zone is largely interstitial to plagioclase and orthopyroxene. The proportion of augite increases upward in the section as bronzite becomes less abundant, and there is an accompanying better development of the tabular habit of the augite crystals. The flat sides are commonly oriented in the plane of layering, giving the rock a lamination. Plate 26*A* shows a photograph of a specimen of laminated gabbro cut perpendicular to the foliation; the plagioclase as well as the pyroxene has preferred orientation. This structure occurs in the Banded zone as low as 2,500 feet above its base but is most common in the Upper zone. Laminated anorthosite is well developed in the same part of the section. Anorthosites in the lower part of the Banded zone do not show laminar structure. The variation in platy habit of the plagioclase is perhaps controlled by composition.

No obvious lineation has been observed in either the gabbros or the anorthosites.

RHYTHMIC LAYERING

The term rhythmic layering is used here to include variations in texture as well as mineral content (mode). Variations involving minerals of different color give the most striking examples of banding on outcrops. Plate 26*B* shows a 10-inch layer of anorthosite betwen much thicker layers of norite. Alternation of norite and anorthosite layers as shown in plate 27 is a conspicuous feature locally in the Banded zone. Detailed mapping of the chromite deposits has shown that layering is equally well developed in the ultramafic rocks, but, because bronzite and olivine are nearly the same color, the variations in abundance of each and texture are not as conspicuous.

VARIATIONS IN MODE

The mineral changes between layers may be sharp on both sides, as in plates 26*B* and 27, or sharp on one side and gradual on the other, as in plate 28. Plate 28 shows gravity-stratified layers in the position in which they are presumed to have been formed. At the bottom of the photograph a mafic layer is succeeded by an anorthosite layer containing a few bronzite crystals near its base. Above the anorthosite is a layer with bronzite concentrated at the base and gradually decreasing upward. The number of bronzite crystals per 2 square inches has been plotted in plate 28, against inches above the top of the anorthosite layer. The approximate mode of successive 1-inch layers has also been determined by a macroscopic Rosiwal analysis, and the volume percent bronzite has been plotted against height above the top of the anorthosite layer. The number of crystals per 2 square inches and the volume percent pyroxene plotted against inches above the base of the layer seem to show straight-line variation on a semilogarithmic plot, but in two cycles. The control is evidently differential settling. Many such gradations have been observed, with mafic crystals decreasing upward, followed by another cycle. Many layers, however, show no such gradation, and in a number of layers reverse gradation has been seen. The structure seems analogous to graded bedding. Peoples (1936, p. 357) described this gradation and pointed out its possible application in determining tops and bottoms of layers, and Cooper (1936, p. 29) described similar gradations in the Bay-of-Islands complex of Newfoundland. Wager and Deer (1939) described, in far greater detail, excellent examples of gravity-stratified layers in the Skaergaard complex. Since then a number of writers (Stewart, 1947; Stewart and Wager, 1947; Wager and Brown, 1951; Wells, 1954) have described such structures, and in one instance (Shackleton, 1948) this criterion, when used to determine the overturning of a layered gabbro, necessitated a considerable reinterpretation of the regional geology. Cornwall (1951, p. 165) has described graded layering due to size sorting in the lava flows of northern Michigan. It is possible that in addition to sorting of minerals of different density, size sorting also has taken place in the Stillwater complex, but the authors have not investigated this problem. The mechanism by which rhythmic layering such as shown in plates 27 and 28 is accomplished is beyond the scope of this report. However, it is interesting to note that Coats (1936, p. 416) has demonstrated that equal-sized grains of labradorite and pyroxene will settle in diluted bromoform to form successive layers, in which the proportion of each mineral varies so as to mimic natural rhythmic layering.

Many chromitite layers also show some evidence of gravity stratification, but many do not, and reverse gradations are also found. Chromitite layers quite commonly have a very sharp base with a heavy concentration of chromite, followed by gradation through disseminated chromite ore to harzburgite with accessory chromite. This is quite characteristic of the H chromitite zone at the Mouat mine. The G chromitite zone is far more complex and contains many individual chromitite layers; some show such gradation upward but others do not. In figure 40, by D. E. Flint, columnar sections of chromite in the valley of Nye Creek show the common gradation.

VARIATIONS IN TEXTURE

Some layers are characterized by textural differences as well as, or in addition to, compositional differences. The authors and their associates have distinguished between poikilitic and granular harzburgite in mapping the chromite deposits. The chromite deposits show a close association with the poikilitic harzburgite (Peoples and Howland, 1940; Howland, Garrels, and Jones, 1949; Howland, 1955).

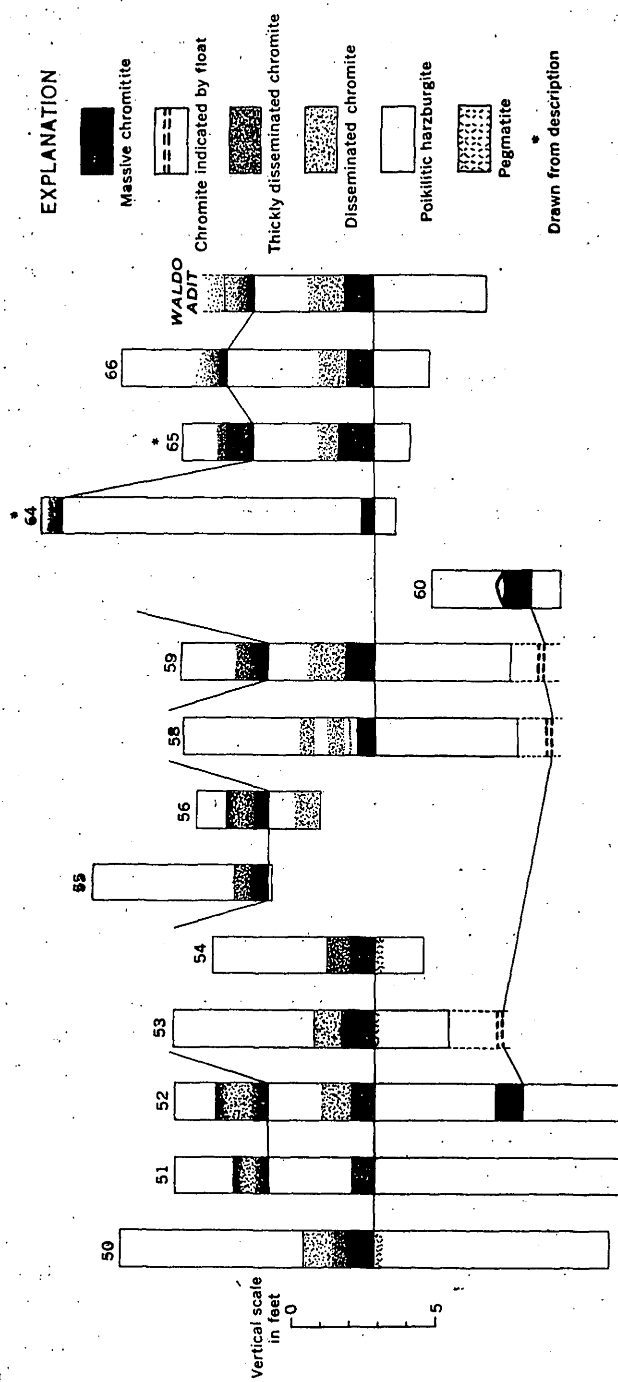


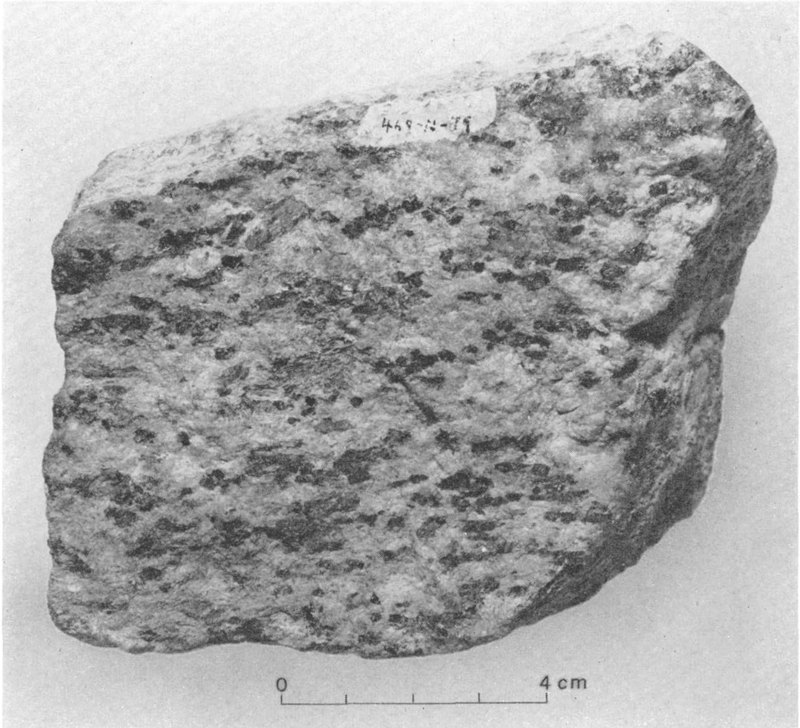
FIGURE 40.—Columnar sections of the B chromitite zone, lower valley of Nye Creek. Numbers refer to U.S. Bureau of Mines trenches. Sections by D. E. Flint, U.S. Geological Survey.

In some places the contact between poikilitic harzburgite and granular harzburgite is not at all sharp, but in the large boulder shown in plate 29*A* a sharp but irregular contact between granular harzburgite and poikilitic harzburgite is shown. The rhythmic layering of the granular harzburgite shows clearly. The poikilitic bronzite crystals show as rounded knobs 1 to 2 inches in diameter with a pseudocellular structure due to the differential weathering of the olivine inclusions in the large bronzite crystals. Poikilitic bronzite is more common in olivine-rich than in bronzite-rich harzburgite.

Green chrome augite is locally a distinctive constituent of the Ultramafic zone and occurs in two habits: (a) as interstitial grains between olivine or bronzite crystals, and (b) as anhedral to euhedral poikilitic crystals enclosing bronzite or chromite. On the divide between Little Rocky and Nye Creeks, a distinctive bronzitite layer with green chrome augite phenocrysts about 0.5 inch in length lies immediately above the Basal zone. Actually the chrome augite crystals, although in stout prisms, are poikilitic and enclose small crystals of olivine. A similar rock is found about 900 feet stratigraphically above the Basal zone on the west slope of the valley of the Stillwater River. Poikilitic chrome augite crystals from 0.5 to 1.0 inch across are also characteristic of the Upper Bronzitite subzone.

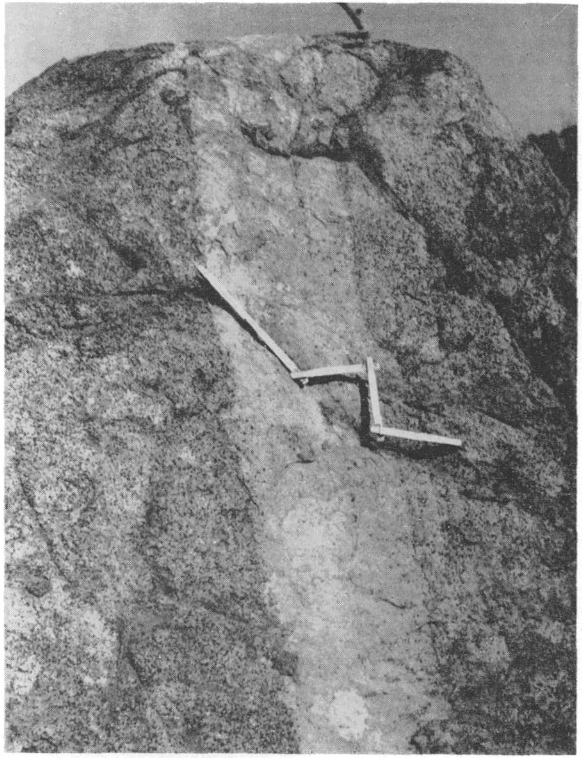
Mafic pegmatites represent another rock type that is distinguished on the basis of texture. In mineral composition, the pegmatites represent most of the lithologic varieties of the complex: bronzitite, anorthosite, dunite, troctolite, gabbro, and norite. Most occur in irregular crosscutting bodies, but in places pegmatites occur with remarkable continuity although with variable thickness and irregular boundaries with the overlying layer. The G chromitite zone is characterized at the Benbow, Mouat, and Gish mines by the occurrence of such a pegmatite immediately below the chromite, and in some places it projects into the base of the chromite ore. Where pegmatite is not present at the base of the G chromitite zone, the harzburgite at the base is coarser grained and more variable in grain size than normal. The pegmatites below some of the thin chromitite horizons, such as the I and J zones, are remarkably continuous in the Mouat mine and Benbow mine areas.

Within the noritic rocks above the Ultramafic zone the most distinctive textural type is the mottled anorthosite, characterized by scattered patches of interstitial poikilitic pyroxene. The size of the skeletal pyroxene crystals ranges from 0.5 inch to about 8 inches. The typical mottled anorthosite is very similar to that of the Bushveld described and illustrated by Wagner (1929, p. 126 and pl. XVI). This mottled texture is found at a number of horizons but is most common in the Anorthosite subzones (Hess' classification, p. 287). Exposures of it are found on the road to the Mouat mine.



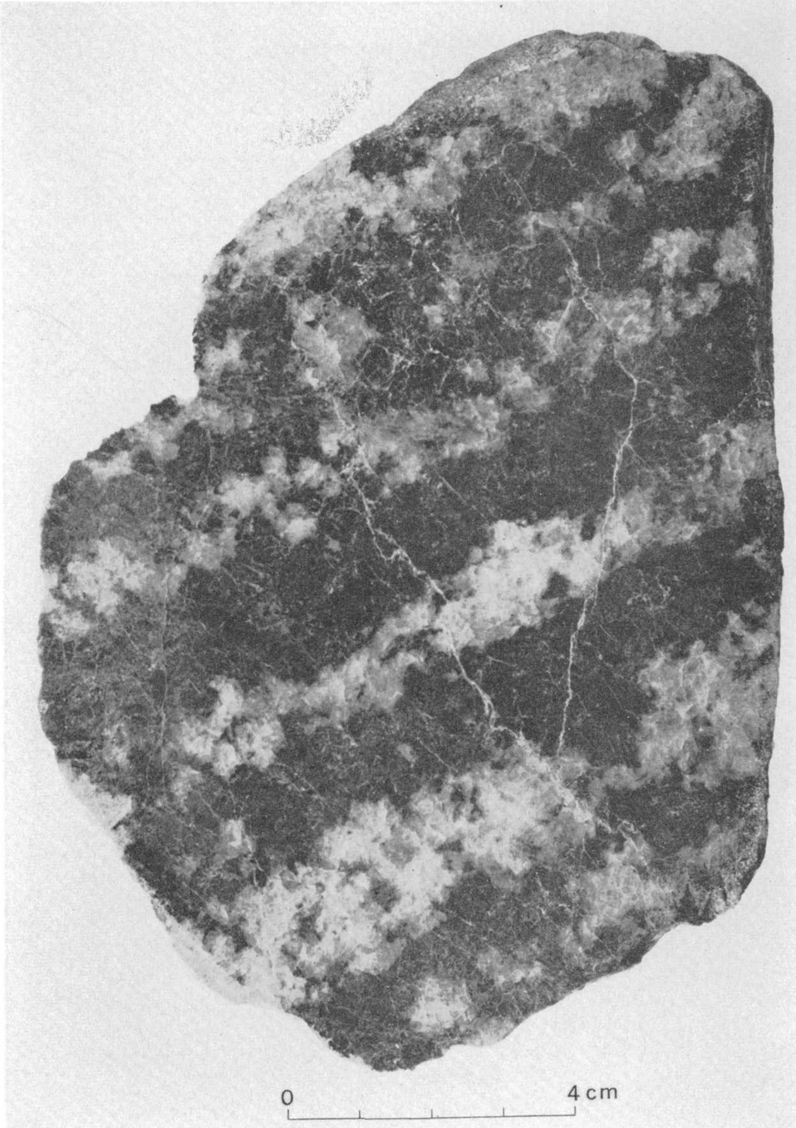
A. LAMINATED HYPERSTHENE GABBRO FROM UPPER PART OF BANDED ZONE

Both augite and plagioclase show dimensional orientation. Photograph by Fred Anderegg.



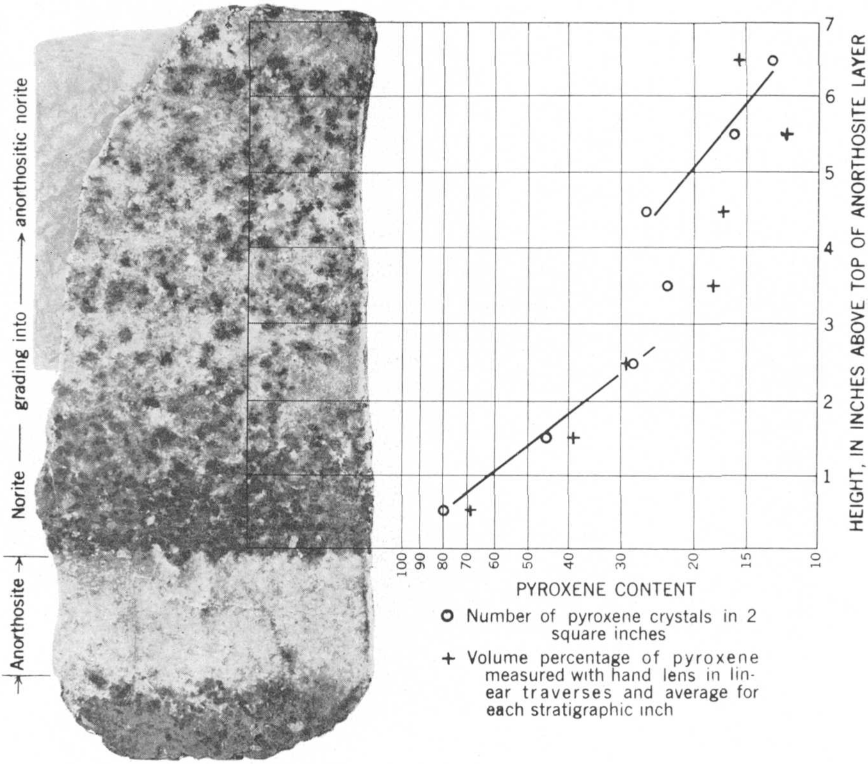
B. ANORTHOSITE LAYER BANDED WITH NORITE

Anorthosite layer is 10 inches thick.



ALTERNATION OF PYROXENE-RICH AND PLAGIOCLASE-RICH LAYERS (LIGHT-GRAY)

Photograph by Fred Anderegg.



GRAVITY STRATIFICATION OF NORITE LAYER ABOVE AN ANORTHOSITE LAYER

Three-fifths actual size.

A. CONTACT BETWEEN GRANULAR HARZBURGITE (TO LEFT) AND POIKILITIC HARZBURGITE (TO RIGHT). LARGE BOULDER, MOUAT CHROMITE MINE

B. "GRATING STRUCTURE"—THIN LAYERS OF AUGITE IN ANORTHOSITE. CANYON OF STILLWATER RIVER, ABOUT 2,500 to 3,000 FEET ABOVE BASE OF BANDED ZONE

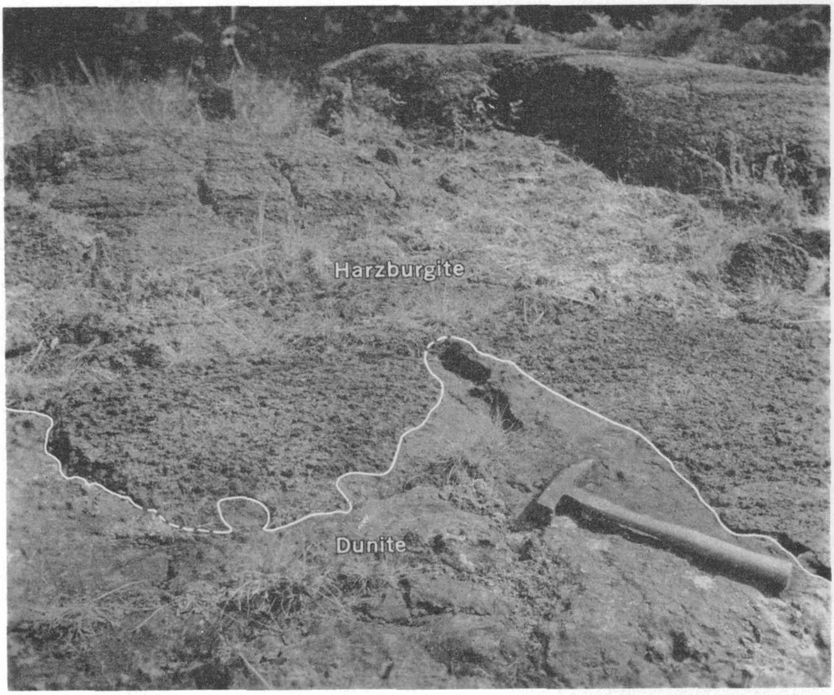
Photograph by Jack Satterly.

A. BRANCHING CHROMITITE LAYERS IN LARGE BOULDER

B. CLOSEUP OF BOULDER SHOWN IN *A*

Note pegmatitic crystals projecting into base of chromitite to left. In this exposure upper contact is sharper than lower contact, but reverse is true of chromitite layer to right.

BRANCHING CHROMITITE LAYERS ON SMALL SCALE



DUNITE "INTRUSIVE" INTO LAYERED HARZBURGITE, BOULDER RIVER AREA
Photograph by Paul MacClintock.

THICKNESS AND FORM

The layers of the complex have a great range in thickness. The Upper Bronzitite subzone, 1,000 to 3,000 feet thick, may be considered one layer. Some layers of chromitite are only a fraction of an inch thick. One very distinctive type of layering referred to in the field as "grating structure" is shown in plate 29*B*. The dark layers are pyroxene concentrations only a few crystals in width. In the lower part of the Banded zone, 1- or 2-inch anorthosite layers are separated by great thicknesses of average norite. In the upper part of the Banded zone anorthosite layers are hundreds of feet thick.

A number of stratigraphic sections of the rhythmic layering have been measured. In the lower part of the Banded zone on the west side of the canyon of the Stillwater River, 78 layers were measured over a stratigraphic interval of 233 feet. A summary of the rock types and average thicknesses, based on the field determinations, is given as follows:

Thickness of rock layers in Banded zone, west side of Stillwater River

Rock	Number of layers	Total thickness (feet)	Average thickness per layer (feet)
Anorthosite	35	51.6	1.5
Noritic anorthosite	8	21.0	2.6
Anorthositic norite or gabbro	23	76.9	3.3
Norite and gabbro	12	83.9	7.0

This section is exposed west of the Stillwater River beginning just back of the home of M. W. Mouat. Stratigraphically, it is about 1,000 to 1,200 feet above the base of the Banded zone (Norite zone of Hess). Hess (1938b) has also described the layering in the same part of the stratigraphic section.

The layered pattern of the Ultramafic zone is due to an alternation of bronzitite, granular harzburgite, and poikilitic harzburgite, the latter containing chromitite layers. (See figure 38.) Greater concentrations of chromite are found in the two thick layers of poikilitic harzburgite; the A, B, and C zones are in the lowest poikilitic harzburgite, and the G and H in a 500- to 600-foot poikilitic harzburgite layer near the middle of the Ultramafic zone. At the Benbow mine, the rock in the interval between the G and H chromitite zones is all poikilitic harzburgite, but at the Mouat mine the rock in the same interval contains a cyclic succession of several types of rock layers. Branching of the chromitite layers on a small scale is shown in plate 30.

The layers are truly lenses. They die out laterally or merge as shown by the chromitite layers in plate 30*A*. The lenslike shape of thicker layers is shown in some of the published detailed maps

(Howland, 1955, pls. 9 and 11). The branching of thin anorthosite layers is nowhere better illustrated than at the outcrop in the loop of the road just north of the Mouat chromite mill, where thin anorthosite layers branch and coalesce within a few feet.

Some chromitite layers branch and change strike (see figure 41). Two or more features of this kind are to be seen on the cliff east of the Cliff fault at the Mouat mine and at a number of places underground. This structure is evidently a primary basin or trough, probably analogous to the trough banding of Wager and Deer (1939), and may have an important bearing on the genesis of the ore deposits and their range in thickness.

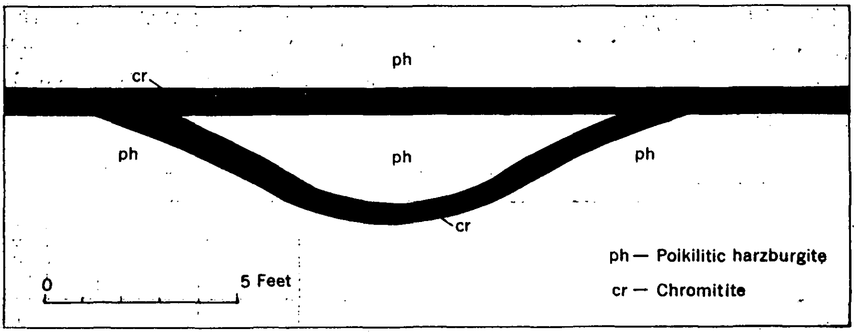


FIGURE 41.—Section showing chromitite layers in poikilitic harzburgite, Jupiter claim, West Fork of the Stillwater River, Mont.

The interval between the G and H chromitite zones does not vary significantly over a strike length of nearly 9,000 feet at the Benbow mine, but at the Mouat mine this interval changes rapidly as shown by the isopach map and vertical section in figure 42. This map is based on the mine maps available prior to 1949 and does not include the results of recent mining. Concomitant with the differences in the interval between the G and H chromitite zones, the G chromitite zone itself differs. Where first cut in the No. 5 adit, the G zone consists of separate layers of chromite concentrations separated by layers of harzburgite with accessory chromite. The total thickness is about 20 feet. Westward these layers coalesce and also thin to 2 or 3 feet of chromite.

A layer of chromitite about 40 feet stratigraphically above the G chromitite zone and 6 inches to 1 foot thick in surface outcrops is referred to as the hanging-wall G chromitite zone. As the G chromitite zone itself thickens and as the interval between the G and H thickens down dip and to the east (see figure 42), the hanging-wall G chromitite zone thickens to nearly 5 feet on level 5 and may be of minable thickness and grade.

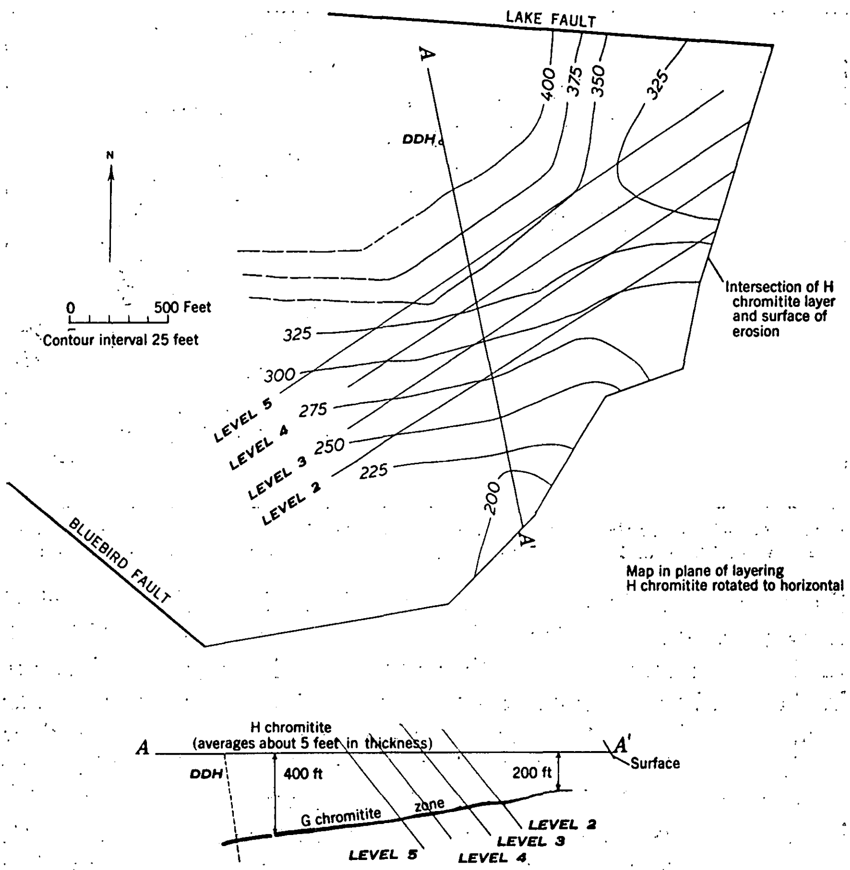


FIGURE 42.—Isopach map and vertical section showing interval between G and H chromitite zones, Mouat mine.

Some irregularities of layering are believed due to movements before crystallization had been completed. A sketch of a structure in norite considered to have developed by slumping before the overlying liquid had crystallized is shown in figure 43. The upper boundaries of a number of the troctolite layers are also irregular.

DISCORDANT MASSES

Locally in the lower part of the Ultramafic zone, layers of bronzitite and harzburgite are cut by irregular bodies of dunite, olivine-rich harzburgite, and coarse-grained pyroxenite. Gradations from dunite through harzburgite into layered bronzitite have also been seen, but it is only in favorable outcrops that the crosscutting dunite or harzburgite can be distinguished from the normal layered rocks. Excellent exposures occur above the lower adit at the Gish mine, Boulder River. One of these exposures is illustrated in plate 31, and this, as well as other localities in the western part of

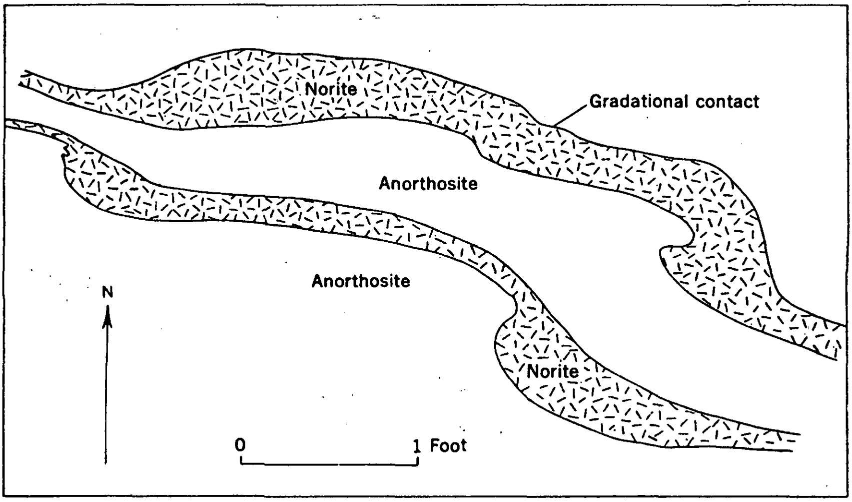


FIGURE 43.—Irregularities in norite layers, west side of valley of the Stillwater River, plan view. Strike of layering shown. Upper norite grades upward into anorthosite.

the complex, is shown on plates 35 and 38 of the U.S. Geological Survey Bulletin 948 (Howland, Garrels, and Jones, 1949). Although the best examples of crosscutting, apparently intrusive, relations are in the area between Boulder River and East Boulder River, similar relations are known to occur on the west side of the Stillwater River south of Verdigris Creek, and in the area of the Benbow mine near the eastern end of the complex. The latter have not been mapped—in part because many of the structures are too small to represent, even on a map scale of 1:2400, and in part because the crosscutting rocks could not everywhere be distinguished from the layered rocks.

Hess (1938a, p. 334–340, figs. 2–5) described the occurrences in the Boulder River area and discussed the question of whether the crosscutting dunite represented a magma or was a reaction effect. Experimental work in the system $MgO\text{-}SiO_2\text{-}H_2O$ led Bowen and Tuttle (1949) to conclude that the observed relations are best explained by hydrothermal reactions, and they have also shown how pyroxenite dikes or pseudodikes could be formed by a similar process. Hess (Davis and Hess, 1949, p. 857) accepts this suggestion as the probable explanation, as do the present authors.

The pseudointrusive olivine-rich rocks are found only in the lower part of the Uutramafic zone.[3] In addition to the gradations between "secondary" dunite and harzburgite described by Hess (1938a), gradations from bronzitite through "secondary" harzburgite to "secondary" dunite have been seen. In some of these cases, green clinopyroxene has formed in the bronzitite adjacent to the harzburgite.

[3] The exposures described by Hess (1938a, p. 335) as from near the middle of Ultramafic zone are actually only about 750 feet stratigraphically above the floor of the zone, which is here about 3,000 feet thick.

PRIMARY BASINS AND FOLDS IN ULTRAMAFIC ZONE

In the Insizwa type of intrusion, Scholtz (1936) has shown that accumulation of mafic minerals to form ultramafic rocks was not evenly distributed but localized in deeper parts of the sheet and, similarly, that some of the more felsic differentiates are locally concentrated beneath the roof at high points. The Bushveld complex shows what Hall (1932) called "intrusive transgressive overlap," resulting in contact of successively higher layers with the floor. Hess (1951, p. 159–167) has recently pictured the Great Dyke of Southern Rhodesia as merely the central axial remnant of a body which may have extended 60 miles on either side. In this case the greatest accumulation of ultramafic rocks is concentrated along the axis of the dike. No firm conclusions can be drawn concerning the original size and shape of the Stillwater complex, but it is to be expected that the Stillwater would, like the Bushveld and Insizwa types of intrusions, show variations in the thickness of the Ultramafic zone. There are some differences from west to east, with thickening to the east as shown in figure 39.

At three places on plate 24, marked changes in the trend of the base of the complex and of the layers of chromitite and ultramafic rocks are shown. From west to east these are (a) on Chrome Mountain, (b) on Iron Mountain, and (c) on the west valley slope of Stillwater River. Detailed maps of the first two have been published in the U. S. Geological Survey Bulletins 948–C and 1015–D and maps of the third have been placed on open file. Cross sections *F–F* and *G–G'* of plate 25 show lower dips to the south and increasingly steep dips to the north. Chrome Mountain and Iron Mountain are topographically the highest areas underlain by ultramafic rocks, and it is quite possible that elsewhere a comparable low-dipping portion of the Ultramafic zone has been removed. In any case, it seems probable that the differences in dip are in part primary or at least much earlier than the regional tilting. The rapid steepening of dip may be at the margin of a deeper portion of the magmatic chamber, and one might expect increasing thickness of ultramafic rock down dip. Great thickening is not apparent westward from Chrome Mountain to Boulder River, a drop of about 5,000 feet, but there are reasons to suspect that faulting may have modified the true thickness considerably. The Ultramafic zone is in general thicker east of the West Fork of the Stillwater River.

On Iron Mountain, as shown in plate 24, the strike of the chromitite zones diverges locally from east to almost north. Apparently the contact between the Upper Bronzitite subzone and Banded zone cuts across the layering of the ultramafic rocks. Absence of lamination and rhythmic layering in the Upper Bronzitite subzone and sparse outcrops have not permitted a final solution of the critical relations here. It seems quite possible that the ultramafic rocks were deformed before the noritic layers were deposited over them. In the block between the Bluebird and the Lake faults at the Mouat mine, however, another swing in the strike from the normal N. 60°–80° W. to N. 40° E., is apparent, and there the northeast trend is cut off by the Lake–Nye Creek fault. A similar fault is possible at Iron Mountain.

The thickening of the interval between G and H chromitite zones at the Mouat mine has been described and illustrated by an isopach map in the plane of layering and by a cross section (fig. 42). In the direction of greatest thickening the dip of the G chromitite zone would have been 7°–8° when the H chromitite zone was flat. If the chromite crystals of the H zone accumulated on an initial slope, the dip of the G zone was at that time 7°–8° steeper than any initial slope of the H zone. As has been pointed out, the thickening of the interval between the G and H zones is concomitant with increase in number of individual layers of the G zone and increase in the total amount of chromite. This thickening is of great importance economically.

Unfortunately, east of the Mouat mine, faults (see page 317) have cut out parts of the Ultramafic zone, and thus detailed variations of thickness cannot be followed. The Ultramafic zone as reconstructed from sections at the Benbow mine seems to be about 4,500–5,000 feet thick as compared to 5,300–6,800 feet for the maximum thickness at the Mouat mine. The interval between the G and H chromitite zones at the Benbow mine is nearly constant at about 220 feet, which is intermediate between the maximum and minimum thicknesses at the Mouat mine (fig. 39).

The ultramafic layers in the vicinity of Verdigris Creek, just south of the Mouat chromite mine, form a tight fold whose axis strikes and plunges westward (E. D. Jackson, 1953, written communication). Accordingly, the lens-shaped exposure of metasedimentary rocks within the Ultramafic zone, shown in plate 24 between section lines *G–G'* and *D–D'* is in the core of the fold and is not a large xenolith. The fold is broken by several faults and appears to be intruded in places along the axis by olivine-rich poikilitic harzburgite. To the west and south the fold is truncated and overridden by the upthrust block of the Bluebird thrust. Another fault may exist between the anticlinal fold and the contact of the Basal zone with the main mass of metasedimentary rocks on the south. The nature and attitude of that contact are in doubt. Jackson believes that the fold probably developed before complete consolidation of the Ultramafic zone, and prior to the introduction or formation of the olivine-rich harzburgite.

TECTONIC STRUCTURES AND IGNEOUS ACTIVITY

REGIONAL STRUCTURAL SETTING

The Stillwater complex is exposed along part of the northeast margin of the North Snowy block, one of three structural subunits of the Beartooth Mountains (see pl. 23). The Emigrant fault delineates the western boundary of the block; the Mill Creek–Stillwater fault delineates the southern boundary, and the mountain front is the northern boundary.

The Beartooth Mountains and the Crazy Mountain syncline (or basin) are structural units of the Bighorn-Beartooth structural province, a region characterized by structural basins encircled by elongate ranges.

PREVIOUS WORK

The structural features along the northern margin of the North Snowy block, from Boulder River to Livingston, Mont., have been described by Richards (1952, see footnote p. 284). The structural features from Boulder River to the east corner of the North Snowy block are described in this report. The earlier work in adjacent areas by Vhay (1934, see footnote p. 284), J. T. Wilson (1936, see footnote p. 284), Foote (*in* Rouse and others, 1937), Parsons (1942), and Vail (1955, see footnote p. 284), together with the discussions of the broader regional features of the Beartooth-Bighorn-Yellowstone region by Bucher, Thom, and Chamberlin (1934), and Chamberlin (1940, 1945) have been used in compiling the regional geologic map (pl. 23) and history of the Stillwater area.

OUTLINE OF IGNEOUS AND STRUCTURAL HISTORY

As very little is known about structures within the thick series of metamorphosed sedimentary rocks into which the Stillwater magma was intruded, a discussion of the structural and igneous history must begin with events following its intrusion.

Before Middle Cambrian time the metamorphosed sedimentary rocks, with the included Stillwater complex, were deformed and probably tilted northward. During or soon after their deformation the sedimentary rocks in the core of the present Beartooth Mountains were displaced in part by granite. Diabase dikes were intruded into fractures of all the older Precambrian rocks. Erosion accelerated by uplift stripped off Precambrian sedimentary rocks overlying the granite core and beveled one edge of the tilted lopolith. This ancient range was presumably not covered by seas until the Cambrian Flathead sandstone had been deposited in the surrounding area. During Paleozoic and Mesozoic times the eroded Precambrian surface was covered with several thousand feet of sediments, predominantly limestone during the Paleozoic, and sandstone and shale during the Mesozoic. Every period during these two eras except the Silurian, Late Pennsylvanian, Permian, and Triassic is represented by sedimentary rocks. Throughout most of this long interval from Middle Cambrian until Late Cretaceous times, crustal blocks, delineated by conjugate sets of faults inherited from the Precambrian, underwent slow epeirogenic movements with little if any attendant igneous activity.

In Late Cretaceous time explosive volcanic activity began in the area just north of the present site of the Beartooth Mountains. Magmas intruded the crust, forming sills, laccoliths, and stocks in the sedimentary cover. Later, in response to tangential stresses directed from the northeast and southwest, large crustal blocks rose and sank differentially, and folds and thrusts developed, trending normal to the compressive forces. During this episode, the areas at the extremities of the Stillwater complex were subjected to great rotational stresses. Longitudinal blocks in these areas were rotated, so that their northward tilt was increased or, in places, the layering was overturned. By Eocene time the stresses were largely relieved and the Laramide orogenic forces died out, or passed on to the northeast.

Throughout the Cenozoic era, the region underwent slow epeirogenic movements. Gradual uplift was countered by accelerated erosion, but the relative uplift of the ranges in early Pleistocene time has not yet been erased. Early in the Tertiary period, flows and pyroclastics aggregating about 11,000 feet in thickness covered a vast area in northern Wyoming and in the southwestern part of the Beartooth Mountains in Montana. Fault scarps in Pleistocene glacial debris show that adjustments in the crust have occurred in the Recent epoch.

PRE-MIDDLE CAMBRIAN IGNEOUS ACTIVITY AND DEFORMATION

IGNEOUS ACTIVITY

The broad core of the Beartooth Mountains consists largely of one or more Precambrian granitic bodies, but remnants of ancient sedimentary rocks underlie large areas of the North Snowy block. These metamorphosed sedimentary rocks are probably pre-Belt in age, and in part may be the source of the Belt sediments whose southern margin of deposition is considered by Sloss (1950, p. 430) to be an east-west line only a few miles north of the front of the Beartooth Mountains. A coarse-grained, gray to pink biotite granite replaced the metasedimentary rocks beneath the eastern part of the Stillwater complex, and, in places, granite dikes cut the basal chill zone. At the western tip of the complex, a similar granite is in contact with the Banded zone, but the contact is probably a fault. No metamorphism or deformation has been recognized in the rocks of the complex attributable to the emplacement of the granite.

The granite contact is smoothly undulating, and selvages of metasedimentary rock are left between the granite and the complex. In several places, inclusions of hornfels and norite are in the granite. When the granite was emplaced, the complex was probably nearly horizontal. As the complex was probably 23,000 feet thick and was probably overlain by a considerable thickness of roof rocks, the top of the granite was from 5 to 6 miles below the surface in Precambrian time. Inasmuch as the granite contact together with the eastern part of the complex was rotated to its present nearly vertical attitude in Laramide time, the isolated metasedimentary blocks that lie within the granite and are exposed a mile south of the contact near Flume Creek must have been nearly a mile below the top of the granite when the granite was emplaced. The bedding within the isolated blocks (pl. 24, near southern limit of sections *A–A'* and *B–B'*) strikes west and dips north. Such consistency in attitude is not expected in blocks stoped by a magma. Study of these inclusions by Howland indicates granitization in places.

Diabase dikes and sills cut the granite, the metasedimentary rocks, and the Stillwater complex, but none are known to cut Cambrian or younger beds. Furthermore, diabase fragments have been found in Middle Cambrian conglomerates that rest on the eroded surface of the complex. This evidence dates not only the diabase as pre-Middle Cambrian, but also the granite and other rocks cut by diabase.

It is quite possible that there are two Precambrian ages of basic dikes. Gabbroic rocks are cut by granite on the Fishtail Plateau (south of the Benbow mine area), and some of the basic dikes in the complex may be genetically related to these gabbroic bodies.

Diabase dikes and sills are found throughout the known 18,000-foot section of the complex, and many dikes intruded fractures that must have been nearly vertical in Precambrian time. Diabase intercalated in the upper layers of the complex may be flat offshoots from the vertical feeders.

DEFORMATION

Deformation was evidently mild in this area after the formation of the Stillwater complex and before Middle Cambrian time. With few exceptions, the exposed parts of the upper layers of the complex had a regional northward tilt of 25°–35° when the Cambrian beds were deposited. The northward tilt of the complex (by Middle Cambrian time) may be attributed to Precambrian arching of an ancestral Beartooth range, but it may just as readily be attributed to a primary inclination of the layering within the complex if it consolidated as a lopolith with an inherent basinlike structure. According to Thom (1952, p. 15) "the northwestern part of this area" (the Beartooth uplift) "was crossed by an early pre-Cambrian geosynclinical trough, which had a trend of about N. 55° E." The sediments in this trough and the included Stillwater complex according to Thom were "strongly compressed in pre-Huronian(?) time and were invaded by batholithic granites, which rose along lines trending N. 35° W." The predominance of northeast strikes and northwest dips in the Precambrian rocks in the Livingston Peak quadrangle, northwest of the Stillwater complex, as shown on plate 2 of Richards (see footnote p. 284) supports Thom's statement. As yet the prevailing attitude of the metamorphic rocks stratigraphically below the Stillwater complex is not known, although the impression is that they trend northwestward, generally concordant with the trend of the complex. Evidence of northwest-southeast compression of the Stillwater complex in Precambrian time has not been recognized by the writers.

Some of the offset noted along the Precambrian diabase dikes may have occurred before Cambrian time, but as most of these dikes were alined in the direction of compression during post-Cretaceous deformation, it is assumed that movement along the dikes was renewed, and that this later movement accounts for most of the offsets noted as well as for the sheared condition of the dikes.

Only a very small part of the complex can be seen in contact with Middle Cambrian or younger beds, hence it is not always possible to date deformational structures within the complex itself. Some of the flexures and faults, in the Ultramafic zone especially, may have developed in Precambrian time, when the layers of this zone were 4–6 miles below the surface prevailing in that era.

The basement complex of the province, comprising eroded Precambrian anticlinal ranges with massive cores of granite flanked by less competent Precambrian sedimentary rocks, was broken before Cambrian time into rectangular blocks by a conjugate system of nearly vertical faults—one set striking E. 5°–10° S. and the other striking about due north. These primary flaws in the crust are believed to have influenced major trends in subsequent deformation. (See Chamberlin, 1945.)

PALEOZOIC AND MESOZOIC INTERVAL

Following Precambrian igneous activity and deformation, erosion cut down through the roof rocks and beveled an edge of the gently inclined Stillwater complex. The beveled edge and surrounding rocks were then covered by about 8,000–10,000 feet of alternating marine and continental Paleozoic and Mesozoic sedimentary rocks. The shelf environment of deposition is reflected in the thinness of the total Paleozoic sedimentary section, about 2,800 feet; in the total Jurassic, about 800 feet; and in the Lower Cretaceous, about 3,200 feet. During Late Cretaceous time about 8,000–9,000 feet of dominantly volcanic debris accumulated near Livingston, Mont., but only a fraction of this thickness extended as far southeastward as the area of the Stillwater complex. A detailed description of the Paleozoic and Mesozoic formations is given by Vhay (1934; see footnote p. 284) and Richards (1952; see footnote p. 284).

From Cambrian to middle Cretaceous time deformation within the province was characterized by slow epeirogenic movements. The absence of Silurian rocks indicates nondeposition, or uplift and erosion before the Devonian. Demorest (1941, p. 174) cites evidence that the Bighorn Mountains were uplifted and deeply eroded at the close of the Paleozoic era, and the absence of Upper Pennsylvanian and Permian strata between Livingston and Nye, Mont., may be evidence of contemporaneous uplift. Thom (1952, p. 15) states that local vertical adjustment, warping, and tilting occurred along some of the basement faults during the Paleozoic, Triassic, Jurassic, and Early Cretaceous. Throughout the province there is no evidence of folding or thrust faulting during the long interval between Cambrian and Late Cretaceous times.

Thus, by the advent of the Laramide orogeny, a beveled edge of Stillwater lopolith and its enclosing Precambrian rocks lay beneath about 10,000 feet of flat-lying Paleozoic and Mesozoic sedimentary rocks. The layers of the Stillwater complex were evidently not greatly deformed, but in this area they were inclined 25°–35° northeastward and formed northwest-trending bands at the buried Precambrian erosional surface. Beneath the eastern half of the known segment of the complex, a granite batholith had penetrated in Precambrian time to the floor of the lopolith; the western half was underlain by a great thickness of metamorphosed sedimentary layers as well as granite. Dikes and sills of diabase had intruded in Precambrian time as high as the uppermost zone of the complex and had cut through the granite, though the total volume of diabase intruded was too small to influence the course of deformation.

LARAMIDE IGNEOUS ACTIVITY AND DEFORMATION

The Laramide orogeny, extending from mid-Cretaceous into early Tertiary time, began with differential uplift of the ranges of the region, including the Beartooth Mountains. The Precambrian erosional surface, 10,000 feet below the surface in Cretaceous time, eventually came to be 10,000 feet above sea level in certain areas. The sedimentary record shows that the uplifting was pulsatory. During a later episode of the Laramide orogeny, stresses within the region were relieved by thrusting and folding. The northwesterly trend of the thrust faults and fold axes shows that the major resultant of the Laramide forces during the later episode was northeast-southwest compression.

IGNEOUS ACTIVITY

Intrusive and extrusive igneous activity began during the early episode of uplifting and continued in some places through the later episode of thrusting and folding. Intrusions of intermediate composition preceded the thrusting and folding along the northeastern flank of the Beartooth Mountains, but it followed the thrusting and folding along the southwest flank (Rouse and others, 1937, p. 737). However, recent mapping by Howland and Vail (Vail, 1955, p. 62; see footnote p. 284) reveals intrusions of felsite along the Dry Fork thrust in the northern part of the area. Rouse dates the episode of thrusting and folding as early Eocene, (post–Fort Union but pre-Wasatch). Stocks, laccoliths, sills, and dikes intrude an area that lies between the northeast flank of the North Snowy block of the Beartooth Mountains and the Crazy Mountains syncline. This area is on the projected trend of the Nye-Bowler lineament (shown in plate 23 as Stillwater anticline), one of several belts of echelon structures within the province that are believed to mark major flaws (wrench faults) in the Precambrian basement complex (Wilson, C. W., Jr., 1936). Some of the intrusions are older than the basic pyroclastic rocks of the Livingston igneous series of Parsons (1942, p. 1175; see footnote p. 284), but some are younger.

A large sill-like body of quartz monzonite intrudes the upper zone of the Stillwater complex northeast of Contact Mountain, and sills of quartz keratophyre (Vhay, 1934, p. 35; see footnote p. 284) are in folded Cambrian beds which rest on the complex near the divide between the forks of the Stillwater River. Although these quartz monzonite and quartz keratophyre intrusions cannot be positively dated any closer than post-Cambrian, their similarity in composition to the intrusives in the area to the north suggests that they were intruded at the same time—during the Laramide orogeny, before and after the thrusting episode. According to Vail (1955, pl. 1; see footnote p. 284), the Laramide intrusions in the vicinity of East Boulder River are felsite, dacite, and rhyodacite—forming sills, dikes, and irregular masses in Paleozoic and Cretaceous formations and in the Precambrian metamorphic rocks as well. Most igneous activity ceased by Lance time; in the Stillwater–Boulder Rivers area, it was followed by Laramide thrusting and folding.

DEFORMATION

The structures described in the following pages are believed to have developed for the most part during the Laramide orogeny. However, as the area is within a region which has undergone epeirogenic movements throughout the Cenozoic era, even in the Recent epoch (Pardee, 1950), movement along some of the faults, especially the nearly vertical shear zones, may have been renewed. The lack of Cenozoic strata in the Stillwater area precludes dating many of the structures more closely than post-Cretaceous, and some of the faults ascribed to Laramide orogeny may have developed entirely in post-Laramide time.

In general the rocks of the complex, being competent, adjusted to the stresses of the Laramide orogeny chiefly by shearing, commonly along layering planes; by block faulting; and to a much lesser degree by folding, although large-scale warping or bending took place. However, it is not always possible to distinguish primary igneous structures from tectonic flexures, and adjustment by folding may be more prevalent than is supposed. The less competent overlying sedimentary rocks adjusted by folding, plastic flow, and faulting.

MAJOR STRUCTURAL FEATURES

TREND

Although slightly bowed to the northeast, the western two-thirds of the exposed segment of the Stillwater complex trends about S. 60° E. A gradual change in trend to about due east begins in the vicinity of the West Fork of the Stillwater River, near the boundary of the Mount Douglas and Mount Wood quadrangles. This trend continues for about 7 miles to the east before swinging rather abruptly back to S. 60° E. The outcrop pattern of the overlapping Paleozoic formations along the mountain front shows a parallel trend, but the changes in trend begin 1–2 miles farther east than like changes in the trend of the complex, and the final swing of the sediments is more pronounced, continuing until the formations strike S. 30° E., thus crossing the trend of the complex near Black Butte. Also at the western end, where the complex trends more to the west, the Paleozoic strata swing even more to the west and thus gradually cross the trend of the complex. The changes in trend are more apparent when one views plate 24, not from above as is normal, but from the northwest, in such a way that the line of sight just grazes the map surface. The northward bulge of the eastern part is noticeable from that viewpoint.

TILT

The western end of the complex, in the Boulder River area, dips steeply (60°–70°) north; the central part of the complex dips at a moderate angle to the northeast; the eastern third, on the other hand, is nearly vertical, or, in places, overturned. Corresponding variations in the attitude of the Paleozoic and Mesozoic sedimentary rocks along the mountain front imply that the attitude of the complex and of the sediments developed concomitantly in post-Cretaceous time.

From the West Fork Stillwater River eastward, the moderate northeast tilt of the complex steepens until at the Stillwater divide the layering is nearly vertical. There is little change from there eastward to the Stillwater River, but east of the river the layering in many longitudinal blocks is overturned and dips 70°–80° S. Great blocks of the complex bounded by longitudinal and transverse faults moved differentially during the deformation. In general, the longitudinal blocks close to the mountain front were rotated more than similar blocks farther back from the front. Vertical and overturned layering is found, however, at some distance back from the front in the eastern part of the Ultramafic zone, especially wherever the zone is underlain by a southward-dipping reverse or thrust fault—for example, above the Bluebird thrust, between the forks of the Stillwater River (west of section line *D–D′*, pl. 24).

The ends of the complex, especially the eastern end, appear to have been twisted clockwise (when viewed from the southeast) about a horizontal axis parallel to the strike of the complex. The twist in the eastern end of the complex is evident as far west as the canyon of the West Fork, where the trend of the complex swings gradually from due west to N. 60° W. A less prominent twist in the western end is evident only as far east as Contact Mountain, where the trend of the complex swings very gradually from about S. 75° E. to S. 60° E.

FOLDS

Although the present attitude of the layers of the complex resulted largely from rotation of longitudinal fault blocks, presumably during Laramide time, large-scale bending or arching of the complex also contributed to their present attitude.

Folding was a more common means of adjustment in the sedimentary blanket above the complex, but only the broader features of such folding are described here. Much of the second-order folding in the sediments is related to faulting and will be described with the major faults.

The attitude and arcuate trend of the Paleozoic and Mesozoic strata north of the southeastern extremity of the complex are evidence of a great upward and northward bulge in the sedimentary blanket. The southern limb of the broad syncline whose axis parallels the mountain front to the north is steep or overturned, and the limb swings northward where the crystalline rocks of the complex are strongly rotated and thrust northward. West of the Stillwater River, the tilt of the complex becomes progressively less steep for several miles and the southwestern limb of the syncline dips gently to the northeast. Obviously, the monoclinal fold in the sedimentary blanket weakened westward and eventually died out.

East of Little Rocky Creek, the mountain front, which is delineated by ridges of vertical Madison limestone, swings sharply to the south for about 2 miles before continuing to the east. This reentrant in the mountain front is similar to a reentrant in the eastern front of the Bighorn Mountains, where the West Billy anticline intersects the front at an acute angle. Evidence of a similar relation to explain the reentrant of the mountain front near Black Butte in the Stillwater area is not conclusive. Although what may be the north limb of an anticline is exposed, the south limb, if it ever existed, is buried under moraine and overridden by subsequent thrusts from the south. From Fishtail Creek to East Rosebud Creek (pl. 23), the Paleozoic section and the Stillwater complex are not exposed and presumably lie beneath the overthrust Precambrian rocks and, farther north, beneath Mesozoic rocks.

At the northwestern extremity of the exposed part of the complex in the vicinity of the Boulder River, the Paleozoic sedimentary rocks stand nearly vertical. West of the river their strike swings southward, so that the beds cross the trend of the banded zone at a progressively larger angle. With increasing altitude the beds dip more gently, bending so as to parallel the gently sloping surface of the plateau (plate 25, section *I–I′*). The Banded zone layers that form the core of this monoclinal fold dip steeply northeast but do not show bending comparable to that in the sedimentary rocks. Where exposed in Boulder River area, the over-all structure suggests a bulging out or incipient thrusting of the mountain mass northwards towards the Crazy Mountains syncline. The gradual flattening of the dip of the Paleozoic strata eastward along the mountain front is evidence that the fold dies out not more than 4 miles east of Boulder River. From there southeastward for about 12 miles to the canyon of the West Fork, the mountain front is not abrupt, and there is no evidence that a tight monoclinal fold ever existed along this segment of the mountain front south of the Dry Fork thrust. Westward, beyond Mount Rae, the monoclinal fold ends abruptly against the northward-striking Mount Rae fault. There are within the Livingston Peak and McLeod Basin quadrangles several northwest-trending anticlines and synclines that converge with the mountain front near the northwest extremity of the Stillwater complex. The largest and longest has been named the Livingston anticline by Andrews and others (1944) and is shown thus in plate 23. Richards (1952, p. 60; see footnote p. 284) later called this structure the Mission Creek anticline and syncline and noted that it is overturned southward except at the west end. The eastern parts of the axes of these folds swing southward around McLeod Basin and intersect the Dry Fork thrust at an acute angle east of Boulder River. A subparallel anticline to the northeast intersects the Dry Fork thrust farther east at such an acute angle that it follows the trace of the thrust for several miles. This structure has been named by Vail

(1955, pl. 3; see footnote p. 284) the Long Mountain anticline. Two to three miles beyond the western extremity of the Stillwater complex, Richards mapped the Lion Mountain anticline and syncline. He states that these folds are compressed against the Lost Creek fault and are overturned southward so that the south flank of the anticline dips as much as 80° S. "These folds die out a short distance east of West Boulder River, and both are cut off on the west by the Lost Creek fault," (Richards, 1952, p. 69; see footnote p. 284). Eastward, the folds end near the Mount Rae fault or the anticline may pass into this fault.

In the high plateau area between Chrome Peak and Iron Mountain (pl. 24) the Ultramafic zone is flat or dips gently northward, generally parallel to the slope of the plateau (see pl. 25, section *F–F'*). The ultramafic layers lie in faulted segments of shallow structural basins and domes, as shown by the quaquaversal dips of the chromite layers. Farther north, in a narrow longitudinal strip contiguous to the contact between the Ultramafic and Banded zones, the layers of both zones dip as much as 80° N. The attitude of the layering between Chrome Peak and Iron Mountain may be interpreted as a monoclinal bend within the complex.

Suggestion of a similar monoclinal bend within the Banded zone may be seen in the vicinity of Picket Pin Mountain (section *F–F'*). Here again, the flat south limb of the bend lies above the altitude of 9,000 feet, and possibly it is an erosional remnant of the flat limb of a much greater archlike structure. Because the structure is asymmetrical, with the steep limb on the north, it may be the eastern expression of the Lost Creek fault traced by Richards (1952; see footnote p. 284) to the western end of the complex, and by Peoples and Howland from there eastward for several miles. The south side of this fault is uplifted relative to the north side as may be seen in section *I–I'* of plate 25. A more thorough description of this fault is given on page 320.

The only other flat-lying segment of the complex, which is south of Chrome Peak in the Benbow mine area, is also above an altitude of 9,000 feet. This, too, may be a segment of a much more extensive longitudinal arch in the complex.

FAULTS

Four major sets of faults are recognized within the area of the Stillwater complex. These are classified as follows:

1. Longitudinal ramp and thrust faults, which strike N. 45°–75° W., and dip northeast, except where steepened and overturned by later deformation.

2. Longitudinal steep reverse, and (or) moderately flat thrusts, which strike nearly due west and dip south.

3. East-trending, vertical faults, along which the south side was raised and possibly moved eastward relative to the north side.

4. Steeply dipping transverse faults, which strike between N. 30° E. and N. 30° W.

Longitudinal ramp and thrust faults of northeast dip

Longitudinal ramp and thrust faults of northeast dip have been recognized along the northern flank of the North Snowy block from the West Fork of Fishtail Creak, northwestward to Livingston, Mont., (Vhay, 1934, and Richards, 1952; see footnote p. 284) (Lammers, 1937). The Iron Creek–Brownlee Creek, North Prairie, South Prairie, Castle Creek, and Dry Fork faults are examples of this type, cutting the Stillwater complex and the overlying sedimentary rocks. The Suce Creek, Dry Creek and Baldy Pass faults, mapped and described by Richards (1952; see footnote p. 284) northwest of Boulder River are of the same type. Similar faults are described by Blackstone (1940) in the Pryor Mountains, and by Demorest (1941) in the Bighorn Mountains. This type of fault is, in fact, characteristic of the Bighorn-Beartooth structural province, and may be classified as a cylindrical or ramp thrust (Hills, 1953, p. 121; Blackstone, 1940). Throughout the province, asymmetrical folds in the strata overlying the basement rocks are usually inclined toward the uplifted side of a mountain block, and these folds are commonly the surface expression of the cylindrical or ramp thrusts. Presumably, the hanging-wall blocks of these faults have been elevated and rotated by movement along surfaces that curve beneath the upthrust blocks. Alpha and Fanshawe (1954, p. 76) state, "it becomes mechanically impossible to tilt blocks such as the Pryor Mountains without a curved thrust plate which begins as a low-angle thrust movement within the basement, breaking upward at an ever increasing angle. At first the sedimentary cover is flexed over the basement fault, breaking as the displacement increases." Unless tilting in the uplifted block is obvious in the field, the upper parts of these faults are easily confused with steep normal faults. Either type may underlie sharp flexures in the sedimentary blanket. Where adjustment has been along layering planes, little if any displacement can be seen, and faults of this kind can rarely be recognized. For this reason, very few layering-plane faults appear on the geologic map (pl. 24). Where it can be deduced that the sedimentary strata were domed, and no faults can be seen, almost surely the adjustment in the crystalline core was accomplished by adjustment along closely spaced planes parallel, or nearly so, to the layering. (See section *H–H′*, pl. 25.)

Iron Creek–Brownlee Creek fault.—The Iron Creek and Brownlee Creek faults were originally mapped separately, but they are now considered parts of a single structure whose trace is clearly marked for several miles by the northern boundary of a large remnant of Cambrian strata in the central part of the Stillwater complex. Judging from its trace, the fault strikes N. 65° W. near Iron Mountain, but southeastward the strike changes to N. 80° W.; a similar change in trend of the complex in this locality suggests that the fault has been warped along with the complex. The fault dips about 50° NE., but presumably it flattens with depth. The igneous layering within the hanging-wall block on the northeast side of the fault dips 55°–65° NE., and is about 15° steeper than the layering in the footwall block, southwest of the fault. No Paleozoic rocks cap the north or hanging-wall block. These facts are best explained by assuming rotational movement of the hanging-wall block of the Iron Creek–Brownlee Creek fault about a horizontal axis.

The fault has not been recognized on the east slope of Boulder River canyon, and it may die out or be masked by later deformation.

The Iron Creek–Brownlee Creek fault cannot be traced east of the West Fork of the Stillwater River with any assurance. Possibly, the adjustment was taken up along a set of planes parallel, or nearly so, to the layering of the Banded zone. The igneous layering north of the limestone on the Stillwater divide dips 70°–85° NNE., whereas the layering exposed between patches of limestone farther south dips 40°–45° NNE. From section *D–D′*, plate 25, it is apparent that the basal Paleozoic strata were not disrupted by a single fault but were arched by adjustments in the underlying Banded zone, presumably by displacement along a set of layering planes. (See *B* in figure 44.) East of the Stillwater divide the Iron Creek–Brownlee Creek fault or fault zone cannot be positively identified. If earlier than the deformation that twisted and thrust the eastern half of the complex northward, the fault or fault zone has been steepened and possibly slightly overturned. One of the steep shear zones in the Stillwater valley may be its eastern continuation.

South Prairie and North Prairie faults.—The South Prairie and North Prairie faults crop out between the mountain front and the Benbow mine area. (See sections *A–A′* and *B–B′*, plate 25). Along most of their length they mark the northern boundary of long, narrow strips of Cambrian rocks, and the igneous layering on the north side of the faults is usually several degrees steeper than on the south side. Layers of the Banded and Upper zones show a progressive steepening and overturning upward in the section—from 45°–55° NE. at a point 1 mile north of the Benbow mine, to 60° SW. at the mountain front. This change in attitude, involving a net rotation of 70°–75°, is distributed among at least four members of this longitudinal set of faults. The present attitude of the layers is best explained by assuming that the layered blocks rotated while being upthrust along longitudinal faults concave to the northeast.

(See section *B–B'*). Although erosion has removed most of the evidence, it is clear that the faults were causally related to a parallel series of folds in the Paleozoic strata, overturned towards the southwest. Although the faults now are varied in attitude, both laterally and with depth, and in places even dip steeply south, it is reasoned that the faults originally developed with a moderate dip to the northeast, and that they have been rotated to their present steep attitude as the blocks containing them were upthrust and rotated during the later stage of deformation that twisted the eastern half of the Stillwater complex. These faults may be offset in depth by the Horseman thrust.

Castle Creek fault.—A northeast-dipping fault crops out at the head of Castle Creek about 2¼ miles northeast of the Iron Creek thrust, which it parallels. (See section *F–F'*.) Rocks belonging to the Upper zone of the complex are north of the fault and are thrust up on the lower part of the Cambrian formations. As yet no attempt has been made to trace this fault northwestward beyond the East Boulder River. It probably continues southeastward to connect with a set of minor thrusts noted by Vhay (1934; see footnote p. 284) in the Cambrian on the divide between Castle Creek and the north branch of Picket Pin Creek. East of this divide the minor thrusts pass beneath several folds in the Devonian and Mississippian beds. These folds are asymmetrical and locally overturned to the southwest, with their axes trending in a northwesterly direction.

Dry Fork thrust.—The Dry Fork thrust is exposed for about 4 miles west of the 110° meridian. It dips northeast and strikes N. 60°–70° W. To the southeast it apparently dies out or passes beneath folds in the sedimentary strata. Its course northwestward has not been followed, but it probably connects with a north-dipping thrust exposed in the Paleozoic formations east of the Boulder River.

Along the north side of East Boulder River, a sliver of Precambrian rock capped by lower Paleozoic strata rests against upturned Cretaceous (Kootenai) beds (Vail, 1955, pl. 1; see footnote p. 284 and section *G–G'*, pl. 25 of this report). Although only 1.5 miles north of the northern margin of the Stillwater complex, these Precambrian rocks are chloritic and amphibolitic schists resembling neither the rocks of the complex nor any of the metamorphic rocks south of and below the complex. Vail suggests that the amphibolitic schists may be metamorphosed facies of the Upper zone of the complex which, where unaltered, includes layers of gabbro, anorthosite, and troctolite. The possibility exists, however, that the Precambrian rocks north of the Dry Fork thrust may be flows, sills, and roof rocks of the complex.

The Dry Fork thrust was mapped by Iddings and Weed (1894) and later by Vail. Vhay traced it southeastward to where it may join the Nye-Bowler lineament, as suggested by C. W. Wilson, Jr. (1936; see footnote p. 284).

Suce Creek fault.—The Suce Creek fault (Richards, 1952, p. 56; see footnote p. 284) extends from a point 6 miles west of the Boulder River for 8 miles along the mountain front nearly to the Yellowstone River (pl. 23). It trends west-northwest and dips north—steeply in the western part and moderately in the eastern part. The fault is bordered on the north for most of its extent by Precambrian rocks and on the south by Paleozoic strata. Thus the relations are similar to those of the Dry Fork thrust.

The Lost Creek fault is located about 2 miles south of a line joining the ends of the Suce Creek and Dry Fork faults, which overlap the known trace of the Lost Creek fault. As is shown later, however, the north side of the Lost Creek fault is down dropped and the fault is assumed to be nearly vertical (section *I–I′*, pl. 25).

Longitudinal thrust and steep reverse faults of south dip

South-dipping steep reverse and thrust faults are well developed in the eastern half of the Stillwater area. It is reasonable to suppose that they are related to the change in trend of the complex and of the sedimentary rocks bordering the complex to the north, as well as to the vertical and overturned tilt characteristic of the southeastern part of the complex. The Horseman thrust is considered the sole of the imbricated eastern half of the complex. Successive slices of the lower part of the complex appear to be upthrust northward along a wide zone of south-dipping faults that extends from the canyon of the West Fork of the Stillwater River eastward to the most easterly exposure of the complex near Fishtail Creek. The Bluebird, Lake, and Nye Creek faults are economically important because they slice across the chromite deposits.

Horseman thrust.—In the course of an earlier study of the mountain front south of Nye, Mont., Vhay (1934; see footnote p. 284) mapped what is now termed the Horseman thrust. As shown on plate 24, the fault extends from a point west of the divide between Picket Pin Creek and West Fork of the Stillwater River eastward to near Little Rocky Creek, a distance of about 12 miles. The fault strikes N. 75°–80° W. and converges eastward toward the mountain front, crossing it at a small angle near the mouth of the Stillwater River canyon. Where exposed near the bottom of the canyon it dips about 30°–35° S. East of the canyon, splits of the main fault in the hanging wall steepen with increasing altitude.

The igneous layers in the hanging wall of the Horseman thrust, on the east side of the Stillwater canyon, dip 70°–80° S., whereas on the west side of the canyon they dip 80°–90° N. The nature of the transition from north to south dip cannot be seen. Presumably, differential rotation occurred across a north-trending tear fault.

The drag effect due to thrusting is apparent in the sedimentary beds for several hundred feet below the Horseman thrust. (See pl. 25, sections *C–C′* and *D–D′*.) This is best seen at the mouth of the Stillwater canyon, where erosion has removed part of the overriding block, exposing the underlying sedimentary beds. The latter dip south—that is, are overturned—and are cut by many faults into several overlapping slices (Vhay, 1934; see footnote p. 284). Northward from the trace of the fault the drag effect diminishes. Within several hundred feet the dip changes to vertical; farther north it gradually flattens to form the rather gently dipping southern limb of the broad synclinal structure of northwest trend that lies between the Horseman thrust and the town of Nye (section *C–C′*, pl. 25). East of the Stillwater River, however, this limb of the syncline stands almost vertical and has an arcuate trend, concave to the southwest. Westward from the river, the northeast dip of the beds becomes progressively less, and the formation boundaries have an arcuate trend, concave to the northeast.

The stratigraphic throw of the Horseman thrust, about 1,500 feet at maximum, is not great compared with other thrusts in the Big Horn–Beartooth region. The base of the Cambrian in the overthrust block rests upon the Mississippian limestone of the footwall block, but the direction of net slip is not known. The movement may be analogous to "scissor" action, with the pivot located southeast of Picket Pin Mountain.

Lake–Nye Creek fault.—Economically, the Lake–Nye Creek fault is the most important structure of the area. As shown on plate 24, the fault extends from a point near the head of Initial Creek eastward 5 to 6 miles to where it ends on the Big 7 fault, in the west Benbow mine area. From surface and underground exposures, it is clear that west of the Stillwater River the Lake fault coincides with a thick Precambrian diabase dike that trends east and dips 55°–60° S., except at its westernmost exposure where it strikes N. 75° E. and is nearly vertical. The dike is sheared along both margins as well as internally, and it is broadly warped, so that its trace on deep levels must be gently winding.

At least 3,000 feet of the Ultramafic zone is missing east of the Stillwater River in the lower part of Nye Creek valley. In an isolated exposure of ultramafic rock at the west end of the valley, three south-dipping faults are recognized (E. D. Jackson, 1952, written communication). It is assumed that these faults represent the eastward continuation of the Lake fault. The northern tip of the exposure consists of rocks belonging to the Upper Bronzitite subzone. As the projected base of the Banded zone lies not more than 600 feet to the north, the apparent thickness of the Upper Bronzitite subzone must be 1,400 feet thinner than it is known to be 1 mile to the east. A wide shear zone in a diamond-drill hole located at the northern end of the isolated ultramafic exposure is probably the footwall fracture or sole of the imbricated block.

The progressive westward thinning of that part of the Ultramafic zone stratigraphically below the Upper Bronzitite in the valley of Nye Creek west of the Big 7 fault can be explained by a fault down the middle of the valley. This interpretation is shown on the geologic map (pl. 24), and in section *B–B′* (pl. 25), where the fault is called the Nye Creek fault. Its continuance westward to its probable connection with one of the splits of the Lake fault is masked by a thick cover of moraine and by a landslide.

The direction of net slip along the Lake–Nye Creek fault is not known. Vertical cross sections show the hanging wall as elevated relative to the footwall. When the bearing and plunge of the axes of broad corrugations of the fault and dike are known, the direction of net slip will be better understood. Speculation on the development of the fault is given on pages 326 and 327.

Bluebird thrust.—The Bluebird thrust fault extends across the divide between the forks of the Stillwater River along the southern margin of the complex. Except for a few hundred feet of its trace, which is clearly defined by a shear zone 100 feet wide near Cathedral Creek, the position of the fault's trace is based on geologic inference. Where exposed, the shear zone strikes east and dips approximately 40° S. From the trace of the fault as it crosses the Stillwater divide, it is deduced that there the fault strikes N. 65°–70° W. and dips 55°–60° SW. (pl. 25, section *D–D′*).

South of the fault, in the hanging-wall block, ultramafic layers including chromitite strike N. 85° W., dip 55° S. (overturned) and are broken by cross faults into numerous short blocks. Between Cathedral Creek and the west fork of Initial Creek the fault is not well exposed, but farther east its trace is fixed by the contact between the overturned or vertical ultramafic layers to the south and the Cambrian rocks to the north.

Farther east the trace swings gradually southeastward, forming the contact between the Banded and Ultramafic zones on the northeast, and the Ultramafic zone and metamorphic rocks on the southwest. All the ultramafic layers, including the G and H chromitite zones of the Mouat chromite mine, disappear beneath the Bluebird thrust block, and, according to the present interpretation, the Lake fault and dike have been truncated by the Bluebird thrust. Where next exposed on the west side of the canyon of the West Fork Stillwater River, the ultramafic and chromitite layers are considerably changed in character, and the Ultramafic zone itself is apparently 2,700 feet thinner. The eastern position of the Bluebird thrust is not well known, and it may end against the Mill Creek–Stillwater fault zone, which, according to J. T. Wilson (1936; see footnote p. 284), strikes across the Stillwater River near the Beartooth ranch and extends eastward up Flume Creek.

The western extremity of the Bluebird fault also is obscure. Just west of Cathedral Creek the thrust is apparently offset to the south by a cross fault. Beyond this cross fault the projected trace of the Bluebird fault follows the West Fork Stillwater River and may join the Mill Creek–Stillwater fault zone.

Although the actual movement along the Bluebird fault is not known, the hanging-wall block has been thrust up in a northerly direction for several thousand feet.

Thrust east of Fishtail Creek.—An isolated exposure of the complex east of Fishtail Creek (southeast corner pl. 24) reveals a relatively thin wedge of the Ultramafic zone thrust northward over lower Paleozoic formations. North of the fault the Paleozoic beds are overturned and dip 70° S., essentially parallel to the ultramafic layers south of the fault. At the western end of the exposure the Ultramafic zone rests on the Ordovician and Devonian beds, whereas near the eastern end it rests on vertical Mississippian limestone. This thrust may be a branch of the Mill Creek–Stillwater fault zone, and presumably continues westward beneath the moraine south of the Benbow mine area.

Graham Creek fault.—In the vicinity of Boulder River, in the Gish mine, a south-dipping fault was encountered in two development adits. At the surface it is covered with glacial and alluvial debris in the valley of Graham Creek. The fault strikes about N. 60° W., dips 60°–70° S., and has a dip-slip of about 300 feet (see fig. 40*B*). The chromitite-bearing part of the Ultramafic zone is apparently upthrust on the Upper Bronzitite subzone. This fault is the only south-dipping fault known in the western part of the complex.

East-trending vertical faults

Only two vertical east-trending faults of any consequence are recognized in the area: the Lost Creek fault, which cuts into the western end of the complex near Boulder River; and the Mill Creek–Stillwater fault, which, when projected, slices across the trend of the complex east of the West Fork Stillwater River.

Mill Creek–Stillwater fault zone.—J. T. Wilson (1936, see footnote p. 284) traced this fault across the northwestern corner of the Beartooth Mountains, from Mill Creek (a tributary of Yellowstone River) on the west to the West Fork of the Stillwater River on the east. According to Wilson, the fault splits into two branches near the latter stream. Although detailed mapping shows that the north split cannot go where Wilson postulated it, it may be represented by the Bluebird, Lake–Nye Creek, and other faults. The south split presumably passes south of the complex and may be represented at the mountain front east of Fishtail Creek by a south-dipping thrust. This is the interpretation of Thom, Jones, and Chamberlin in their structure contour maps (Thom and others, 1937).

The Mill Creek–Stillwater fault, according to J. T. Wilson (1936; see footnote p. 284), is nearly vertical and movement on it was pivotal; west of the pivot, the north block was uplifted relative to the south block; east of the pivot, the south block was uplifted. Wilson also postulated that the south block moved east relative to the north block. It is possible that the Mill Creek–Stillwater fault zone is a major wrench fault of the region, marking the northern limit of the Beartooth thrust block (see pl. 23).

Lost Creek fault.—This fault was mappd by Richards (1952; see footnote p. 284) from a point near the western end of the complex, westward for about 7 miles to Davis Creek. It apparently dies out farther west. Along this segment of the fault the south block is raised relative to the north block, and Precambrian metamorphic rocks of the south block are in contact with Paleozoic strata of the north block. Earlier, Peoples and Howland had concluded that the contact between the Banded zone of the complex and the metamorphic rocks and granite on the west slope of Boulder canyon was probably a fault contact. It now appears that the Lost Creek fault extends as far east as Boulder River, and that it coincides with the fault postulated by Peoples and Howland. Its course west of Boulder River has not been recognized, but the Graham Creek fault, a steep south-dipping fault, may be a split of the Lost Creek fault. The monoclinal bend in the complex farther to the east may be the eastward expression of the Lost Creek fault, as mentioned above (p. 312).

The fact that the Banded zone rests on the metamorphic rocks on the west slope of the Boulder River canyon suggests that the south block of the fault moved eastward as well as upward. An alternative possibility is discussed in the speculative section on Laramide deformation.

Transverse or cross faults

The Stillwater complex, as we see it, is presumably little more than a segment of an upturned edge of a large lopolith. Structurally, the exposure of the complex is limited to the northwest by the Mount Rae fault, and to the southeast by an unnamed fault which is presumed to underlie the moraine-filled canyon of Fishtail Creek. These bounding faults are major transverse structures. Other transverse or cross faults, generally of steep dip, are abundant from one end of the complex to the other, and displace known horizons for distances of a few feet to 1,000 feet or more. Not all cross faults which displace the base of the complex displace the base of the Banded zone an equivalent amount. This anomaly may be explained by the fact that the cross faults, which are steep and caused a vertical or nearly vertical displacement, produced larger offsets in the gently dipping base of the complex than in the steeper base of the Banded zone. In other places—for example, in the Gish mine area—movement along faults bounding transverse blocks was rotational, and the amount of movement decreased toward the axis of rotation.

Throughout the complex, the east side of cross faults is generally offset to the south, though there are a few exceptions.

Most of the cross faults strike between N. 30° E. and north, although a few strike between north and N. 30° W. Commonly, cross faults follow Precambrian diabase dikes.

East of the West Fork of the Stillwater River most of the cross faults mapped are within the hanging-wall blocks of south-dipping thrusts. The apparently greater abundance of cross faults in the Ultramafic zone compared to the Banded zone may be due to the lack of comparable detailed mapping in the Banded zone.

Cross faults, other than superficial faults related to landslides, are rare in the wedge between the Bluebird and Lake faults. The only cross fault worthy of note offsets the base of the complex several hundred feet to the left, just west of section *C–C′*. East of the Stillwater River, cross faults are abundant and deserve special mention. From upper part of Nye Creek valley near the Big 7 fault, eastward to Fishtail Creek, the Ultramafic layers are progressively offset to the south (right) along a prominent set of north-striking faults. Within this part of the complex the total apparent offset of the G (main) chromitite zone aggregates about 4,000 feet. The Big 7 fault accounts for 1,000 feet of this total, and the Central Benbow shift zone (crosses section *A–A′* in Ultramatic zone) accounts for about 2,000 feet; the remaining 1,000 feet are distributed among other similar cross faults, many of which follow diabase dikes.

In the Benbow mine area the major cross faults strike between N. 15° E. and N. 15° W., and dip steeply to the east or west except in the west Benbow area, where most of the major cross faults dip 30°–60° E. Abundant minor faults and joints strike between N. 30° E. and N. 30° W. and dip east or west at low to high angles. Several of the major offsets have taken place along north-striking mafic dikes, with consequent brecciation and shearing of the dike material. Some of the blocks bounded by these dikes and faults have been differentially rotated, so that in some the chromitite and related layers dip south, and in others, north.

Similar relations have been described in the Gish mine area, east of Boulder River (Howland, Garrels, and Jones, 1949).

DEVELOPMENT OF LARAMIDE STRUCTURAL FEATURES

REGIONAL DEVELOPMENT

Because the mechanics and history of Laramide deformation in the Stillwater area are an integral part of the story of deformation of the region, and because the relations as here interpreted gain credibility when viewed with the broader picture in mind, a summary of regional deformation here precedes the discussion of the local structural development. Fortunately many excellent summaries of the regional tectonic development are available, some of which are listed under "References cited." The most recent of these, by Alpha and Fanshawe (1954), incorporates slightly earlier summaries by Thom (1952, p. 15–17) and Fanshawe (1952, p. 19), and still earlier accounts by R. T. Chamberlin (1940, 1945) and Bucher and others (1934). Excerpts from these reports will suffice to reveal the development of regional features.

Thom has divided the tectonic history of the Yellowstone-Bighorn-Beartooth region into seven main phases (see Fanshawe, 1952, p. 19). In this section of the report, we are concerned with phase 4—the Nevadan-Laramide phase—during which

> repeated pulses of explosive volcanism, compressional deformation, and batholithic intrusion began to be felt near the Pacific Coast in Triassic time. Throughout Jurassic and Cretaceous time the zone of maximum Laramide compression and thrusting shifted eastward, step by step, until it reached culmination in the eastern Front Ranges of the Rockies at the end of the Paleocene (Thom, *in* Fanshawe, 1952, p. 19).
>
> The influence of the eastward advancing disturbance is evident during Meeteetse, Claggett, Judith River, and Bearpaw time. . . . With the advance of the tectogene towards the foreland area, basement forces found release upward in relative elevation of the various fractured segments of the foreland. Some blocks rose relative to others; all were bounded by the fracture system inherent from the pre-Cambrian. (Alpha and Fanshawe, 1954, p. 74).

First-order forces were alined in western United States in a general east-northeastward direction. These forces produced varied tectonic effects according to the yield characteristics of crustal segments. Within the various structural provinces thus formed, tectonic features of a lesser order developed. In the region surrounding the Stillwater complex, three main types of tectonic features are recognized: (a) positive blocks, elevated either by massive intrusions or by compression; (b) local downward- or upward-pointing crustal wedges "which were respectively elevated or depressed by orogenic thrust"; and (c) "the larger, sub-basinal, crustal plates which were forcibly flexed downward into basin form by regionally applied compression." (Quoted matter from Thom, *in* Fanshawe, 1952, p. 19.) The Bighorn and Crazy Mountains basins are examples of subbasinal crustal plates. Tectonic features of a lesser order developed around the margins and within the three major types of tectonic units as they competed for space in the ever-shortening crustal block. These marginal tectonic features show a closer relationship to the regional tectonic units, such as the basins, than they do to the first-order forces. The principal structures developed around basin rims are listed by Fanshawe

(1952, p. 20–21) as: (a) low-angle overthrusts; (b) high-angle thrusts, which are called ramp or cylindrical faults in this report; (c) abrupt flexures; (d) tear faults or nearly vertical transcurrent faults with large horizontal component of movement. Major ramp faults in the basement complex gave rise to tilted mountain blocks, such as those in the Pryor Mountains. Chamberlin (1940) from a regional study noted that the margins of the tilted mountain blocks were deformed in one of two ways: (a) Along margins where the surface of the basement complex was gently inclined towards the adjoining basin, the sedimentary beds were forced up the gentle slope of the block or crumpled into a series of parallel folds, overturned towards the uplifted edge of the block, and split by thrusts dipping toward the basin. (b) Along margins where the steep side of the mountain block faced the basin, the basin margin was forced under the uplifted block. Thrusts, dipping beneath the mountain mass, developed in the zone of shear between the overthrust and underthrust blocks. These "bordering thrust faults vary from ordinary reverse faults, with moderate slip where bulging above was not great, to low-angle overthrusts, with notable horizontal displacement where greater rotational strain developed." (Chamberlin, 1940, p. 690.)

DEVELOPMENT OF DEFORMATION IN VICINITY OF STILLWATER COMPLEX

The structural features described in an earlier section of this report and those described by Vail (1955; see footnote, p. 284), Richards (1952), Lammers (1937), C. W. Wilson, Jr. (1936), and Vhay (1934), developed along the indefinite northeast margin of the North Snowy block of the Beartooth Mountains. From another viewpoint, these structures developed along the southern rim of the Crazy Mountains basin or syncline, and the North Snowy block, which is inclined gently northeastward, was an integral part of the basin rim.

It is obvious that rotational strain developed along certain parts of the indefinite margin of the North Snowy block but not along other parts. Along the western part and along the block margin between the West Fork of the Stillwater River and East Boulder River, the observed structures indicate that little if any rotational strain developed. In the vicinity of Boulder River and at the eastern part of the block margin, moderate to intense rotational strain developed. From Chamberlin's regional study of the structural deformation along the margins of mountain blocks it can thus be inferred that the surface of the basement complex in the North Snowy block was gently inclined northeastward towards the Crazy Mountains basin, except along the eastern and central parts of the block, where presumably steep walls of basement complex faced the adjoining basin.

As suggested earlier by Richards (1952; see footnote, p. 284) the movement along the Lost Creek fault in the Boulder River area was such that a steep wall of Precambrian granite faced the adjoining basin to the north. The sedimentary beds on the north side of the fault were downthrown and later were compressed against the massive wall of Precambrian rocks on the uplifted south side of the fault. Evidently the forces involved were not adequate or were too short lived to cause great rotational strain at this place, for there is little evidence that the mountain mass bulged over the adjoining basin.

Evidence that a similar steep wall of Precambrian rocks faced the basin along the eastern part of the block margin is less certain in spite of the obviously much greater development of rotational strain there than in the Boulder River area. The Mill Creek–Stillwater fault is shown on plates 23 and 24 as passing south of the complex and intersecting the mountain front east of Fishtail Creek. According to J. T. Wilson (1936; see footnote, p. 284) and Thom (1952, p. 15), the movement along this segment of the fault was such that a steep wall of massive Precambrian granite faced the basin when tangential pressures began. However, field evidence for the continuation of this fault beyond the valley of the West Fork of the Stillwater River is not conclusive. In any case, it is apparent that a buttress of some sort existed in this area.

Longitudinal arching of the Stillwater complex is indicated by a few relatively flat segments of the complex above an altitude of 9,000 feet, and the generally steeper attitude along the mountain front. This arching could be in part Precambrian in age, or even a primary feature, but also it conforms to the buckling which would be expected under the compressive forces that existed during the Laramide orogeny.

Laramide deformation in the area of the Stillwater complex can be considered as developing in an early and late phase. Structures of the late phase apparently deformed those of the early phase, which is characterized by—

1. Development of sheeting along layering planes, ramp and low-angle thrusts dipping northeast, and asymmetrical folds overturned to the southwest, along the southern rim of the Crazy Mountains basin in a belt which in part includes the present mountain front;
2. Possibly by development of the vertical Lost Creek and Mill Creek-Stillwater faults along Precambrian flaws.

Early phase

At the beginning of the Laramide orogeny, when the area was under compression by forces from the northeast and southwest, the layering of the Stillwater complex presumably determined the grain of the basement rocks underlying the present mountain front. The layers were inclined about 25°–35° NE. It is reasonable to suppose that deep-seated adjustments were made by movement along certain favorable layering planes; where movement was concentrated on a single plane or on a closely spaced group of planes, a low-angle thrust developed, and where movement was distributed over a thick section of layers, a sheeted zone developed. Close to the surface the low-angle thrusts and fractures of the sheeted zone left the layering planes and broke upward at an ever-increasing angle. Continued movement on the curved faults increased the tilt of the layering in the upthrust block. All but the major faults probably died out within the 8,000 feet of sedimentary strata overlying the complex. Arching of the sedimentary rocks overlying the Banded and Upper zones of the complex, as indicated in several sections of plate 25, was probably accomplished largely by movement along numerous layering-plane faults before these planes were steepened by the rotational forces that eventually developed.

The northeast tilt of the igneous layers was increased about 15° by movement on the Iron Creek fault in the central part of the complex. Similar increases were noted across other ramp faults. The South Prairie, North Prairie, and related faults formed an imbricated block in which the tilt was greater in successively higher slices. The actual dips of the layering in each slice at the time of imbrication are not known, for the imbricated block has subsequently been rotated. However, the relative increase in tilt between successive slices is probably not greatly changed. Similar imbricated blocks probably underlie the sets of folds southeast of Squaw Pass and the Castle Creek fault.

During the early phase, the complex and its layers probably had a general northwestward trend, as measured on the Precambrian erosional surface—which, of course, was buried by about 8,000 feet of strata. A pronounced arcuate bend, concave to the northeast, probably existed in the Stillwater River area, where a primary basin or trough existed in the Ultramafic zone. The degree of curvature was probably greatest at the base of the complex, and decreased in successively higher layers, dying out below the Banded zone. A similar but less pronounced primary basin existed in the Ultramafic zone near the present site of Iron Mountain, and the trend of the layers was irregular, as it is today in that sector.

In general, the changes in trend effected during the early phase of the orogeny were probably slight and are masked by changes attributed to the later phase.

Late phase

The late phase in the development of Laramide deformation is characterized by (a) warping and twisting of layered rocks as reflected in changes in trend of outcrop pattern, (b) steepening of the northward tilt and overturning of the layers where rotational strain developed, and (c) thrusting from the south.

The changes in tilt and trend attributed to the Laramide orogeny and described above (p. 309) represent deformation largely of the late phase. The major changes in trend are related directly to the steepening on rotation of the complex. In the Boulder River area, and especially in the Stillwater River area, the southwestward-directed force was deflected downward and the opposing northward force was deflected upward, resulting in rotation about a horizontal axis trending west-northwest. The greatest changes in trend coincide with great steepening or overturning of the layers.

Stillwater River area.—According to the present interpretation, the late phase of the orogeny—especially its rotational effects—deformed the earlier structural features in the Boulder River and Stillwater River sectors. In the Stillwater area, the faults and related flexures of the earlier phase—for example, the Iron Creek, South Prairie, and North Prairie faults—were involved in the rotation and northward bulge of the eastern part of the complex and enclosing rocks. This is deduced from the fact that in this twisted part of the complex, the traces of these faults indicate that they are very steep or are overturned and warped. Earlier observers assumed they were vertical faults along which the south block had dropped. (See J. T. Wilson, 1936; see footnote, p. 284.) Recognition of the progressive steepening and overturning of igneous layers across each fault towards the mountain front suggested the present interpretation. With this possibility in mind, it is not difficult or unreasonable to suppose that the South Prairie and Iron Creek faults were essentially one structure and that the near-vertical to overturned shears and layering-plane slips crossing the Stillwater valley represent the connecting link. As is to be expected where adjustment has been almost parallel to the layering planes, displacements in the Banded zone are difficult to detect. West of the West Fork of the Stillwater River, near section *E–E′*, plate 25, the Iron Creek fault dips 55° N., and at that place the original tilt of the entire complex has been steepened only 15° or 20°.

The effect of rotation on the Lake–Nye Creek fault and the dike that it follows is especially interesting. Heretofore the Lake fault has been considered as a rather steep reverse fault along which the south block was uplifted, and it is so classified in this report.

Although the latest movement on it may have been reverse, it can be reasoned that the original movement, in Precambrian time, was normal, with the north block down along a north-dipping fault and dike. This interpretation is shown in figure 44.

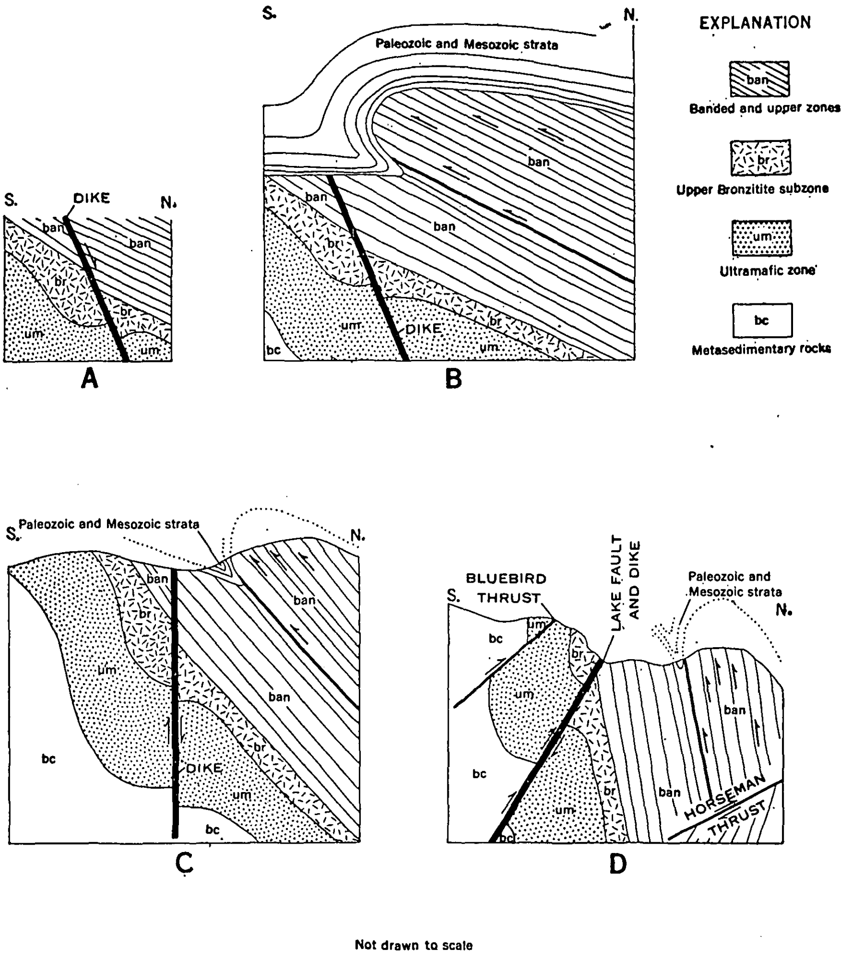


FIGURE 44.—Sections showing possible development of Lake-Nye Creek fault and dike. Not drawn to scale.

A. Pre-Middle Cambrian time: Normal fault developed in inclined layers of Stillwater complex and fault intruded by diabase dike.

B. Early phase of Laramide orogeny: In response to northeast-southwest compression, overturned fold developed in overlying Paleozoic and Mesozoic strata as the result of shearing in Banded and Upper zones.

C. Continued compression results in rotation of dike to vertical and steepening of layers.

D. Further rotation results in overturning of dike and fault, and steepening of layers. Apparent movement on Lake-Nye Creek fault now reverse. When fault assumed south dip, hanging wall probably rose relative to footwall. Continued compression resulted in northward directed thrusting along Bluebird and Horseman thrusts. Erosion shown so sketch depicts present-day relations in vicinity of Mouat mine.

In section *A* of figure 44, the diabase dike is assumed to be of Precambrian age, as no younger diabase is known in the region. A small normal-type displacement is assumed to have preceded the introduction of the dike, although this is not essential to the new interpretation. The inferred angular relations between the dip of the layering in the Banded zone on both sides of the dike and the attitude of the dike are based on observations near the Stillwater divide. These relations are maintained in sketches *B*, *C*, and *D*, depicting subsequent stages in the history of the fault.

Section *B* shows conditions during the early phase of the Laramide orogeny, when a northward-dipping thrust formed in or at a very small angle to the layering of the Banded zone. This might be the eastward extension of the Iron Creek fault. Numerous layering-plane faults probably formed in the hanging wall of the thrust, causing the sedimentary blanket to bulge upward to the south. The gentle north dip shown for the igneous layering is based on the consistent angular relations (25°–35°) between the Cambrian strata and the igneous layers.

Section *C* of figure 44 depicts conditions after the eastern part of the Stillwater complex had been moderately rotated—that is, after the start of the later phase of the Laramide orogeny. The dike is now vertical and the tilt of the layering and the Iron Creek thrust has been increased. It is presumed that the Bluebird and Horseman thrusts had not as yet formed. Much of the sedimentary cover is shown as eroded, so that the sketch would serve to show the present-day relations at the Stillwater divide, where rotation of the Banded zone was moderate, and the dike, judging from its surface trace, is vertical.

Section *D* shows the generalized relations about 4,000 feet east of section *C*, in the vicinity of the Mouat chromite mine. The dike and fault in the mine are known to dip about 55°–60° S., and the Banded zone layering north of the mine dips 80°–85° N. The increased apparent movement along the Lake fault in vertical section, shown in section *D*, is meant to imply reverse movement in the late phase of compression. The Iron Creek fault is now nearly vertical and may be represented by the sheared zones noted in the Banded zone north of Mountain View Lake. The interpretation shown in section *D* explains the occurrence of the tightly folded syncline of Cambrian limestone, which, in the field, appears to be infolded into the Banded zone on the west slope of the Stillwater canyon, above Mountain View Lake (pl. 24, just east of section *D–D′*). It is difficult to depict satisfactorily the attitude of the ultramafic layers in the sections because in this segment of the complex they form a deep primary basin or trough and intersect the Lake fault and dike at an ever-increasing angle eastward along the fault. The eastern margin of the basin, which must have contained a sharp primary flexure where the layers flattened to a more normal attitude, was truncated by the original dike and fracture. The original fracture may have cut across the sharp flexure in such a way that the metasedimentary rocks and the Precambrian granite formed the south side of the fault for a limited distance. The Nye Creek fault, which is apparently a continuation of the Lake fault east of the Stillwater River, may have originated as a normal fault also, but the latest movement probably involved upthrusting of the south side.

Boulder River area.—The effects of rotation on preexisting structures in the Boulder River area are less obvious. For one thing, early northeast-dipping thrusts are less evident, probably because the Cambrian and younger rocks have been eroded from most of the area east of Boulder River, and adjustments within the complex evidently took place largely along layering-plane faults. The trace of the Brownlee Creek fault down the east slope of the Boulder River canyon has not been recognized, but presumably it would be nearly parallel to the trace of the layers which dip 55°–65° N. North of the Graham Creek fault, along section *H–H′*, it is evident from the steepening of the dip of the igneous layering that rotational stresses were active. Layering-plane faults and low-angle thrusts have not been mapped in this sector of the complex, but if any formed in the early phase of the Laramide orogeny they have been steepened. The apparent steepness of the Dry Fork thrust may in part be explained by rotational movement along that part of the mountain flank. If the Lost Creek fault developed during the early deformation of the area as suggested by Richards (1952, p. 72; see footnote, p. 284), that fault was involved in the rotation and must originally have been inclined to the north at a moderate angle. If the Lost Creek fault developed initially in Precambrian time, the lower part of the complex and some of the metasedimentary floor rocks may have been eroded before Cambrian time from the south or relatively uplifted side. The sharp northwest swing in the trace of the Lost Creek fault beyond West Boulder River may be related to late-phase rotational deformation which only affected the eastern extremity of the fault.

The Graham Creek fault is nearly parallel to the strike of the layering and dips 60°–70° S. The dip slip is estimated to be about 300 feet. Where penetrated in exploratory drifts, the fault zone consisted of several feet of rubbery gouge, which had to be cut through with axes. The possible original development of the Graham Creek fault as a normal fault is shown in figure 45*A*, in which the igneous layers are shown rotated back to their assumed attitude at Precambrian time or just prior to the Laramide orogeny. The present gougy character of the fault zone indicates intense grinding along the fault and is more typical of reverse faults than of normal faults. For this reason much of the displacement is assumed to have occurred

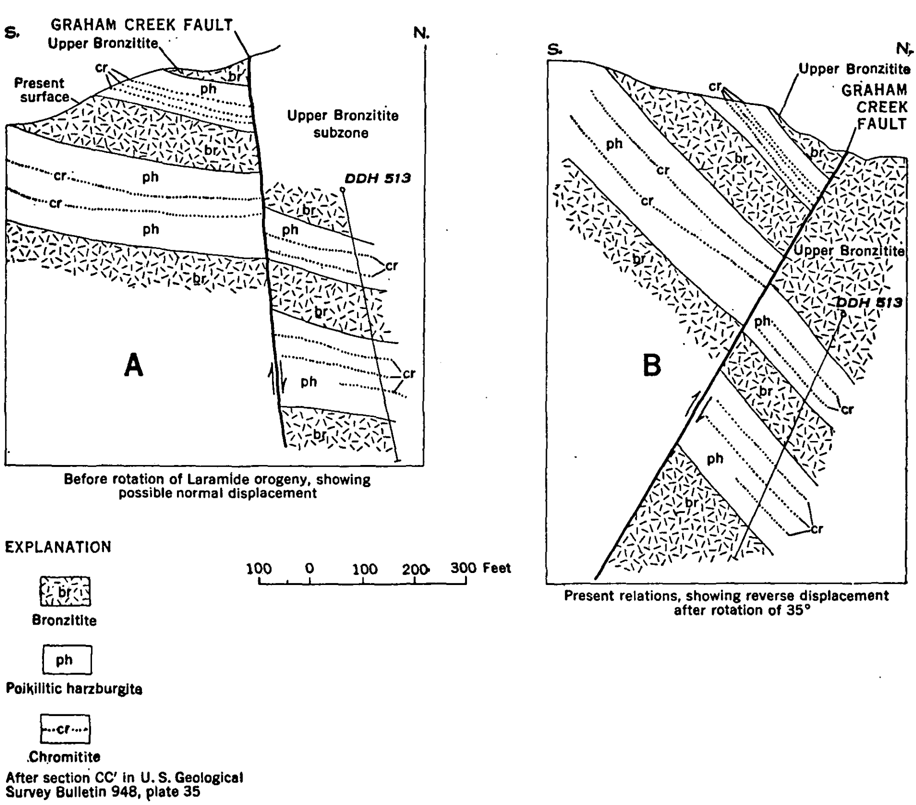


FIGURE 45.—Sections showing possible development of Graham Creek fault, Gish mine, Montana.

after rotation, when the fault plane dipped south. The strike slip cannot be deduced; if considerable, it may account in part for the thick gouge.

If, on the other hand, the Graham Creek fault developed initially during the early phase of the Laramide orogeny, rotation would have reduced its southward dip from nearly vertical to its present 60°–70° S. dip. Section *A* in figure 45 will serve to show this possibility as well as that of possible Precambrian age of initial movement. In either case the north block dropped relative to the south block. It thus could have had the same type of displacement as the Lost Creek fault and may be a continuation of it, although the dip-slip component along the Graham Creek fault seems inadequate.

A third interpretation can be made in which the fault developed as a steep reverse fault after the igneous layers had been tilted northward by rotational forces. No evidence favors one interpretation over the other two.

Summary

Earlier interpretations of the development of Laramide deformation in the Stillwater region depicted simultaneous thrusting towards the southwest and northeast along adjoining sectors of the mountain front. The zone of transition between these opposed movements was supposed to coincide roughly with the northeast-trending canyon of the West Fork of the Stillwater River. The present interpretation agrees that the resultant of Laramide forces in the Stillwater region was northeast-southwest compression. Northwest-trending anticlines overturned to the southwest and northeast-dipping thrusts or ramp faults are considered early manifestations of that compression. These structures developed along the present mountain front, from Livingston southeastward at least as far as Fishtail Creek, east of the Benbow mine area. These structures are not confined to the area northwest of the West Fork of the Stillwater River as earlier workers maintained. With time, resistance to the southward-directed force built up, so that, in the words of R. T. Chamberlin (1940), "rotational strain developed" along the mountain front in the Boulder River and, more notably, in the Stillwater River area. Northward bulging and thrusting is evident only in these two sectors of the mountain front.

POST-LARAMIDE IGNEOUS AND DEFORMATIONAL HISTORY

The lack of Cenozoic strata in the Stillwater area precludes dating many of the structural features more closely than post-Cretaceous. However, broader regional studies suggest that most of those features developed during the Laramide revolution, but that some may postdate the revolution or Laramide structures may have been reactivated later in the Cenozoic. In order to emphasize the fact that the Stillwater area lies within a region that has been undergoing epeirogenic movement since Laramide time, a brief summary of Cenozoic deformation is appended.

REGIONAL EVENTS

Topographic irregularities resulting from Laramide deformation were largely erased by Oligocene time, for the surface then was of moderate relief (Pardee, 1950).

From late Eocene to early Pliocene, slow crustal movements and intensified volcanic activity prevailed throughout the Middle Rockies. Many basins were filled with lake beds of Miocene and Pliocene age. South of Livingston, the Yellowstone Valley was partly filled by upper Miocene and lower Pliocene sediments derived from erosion of slowly rising ranges (Horberg, 1940). By late Miocene or early Pliocene, the region was again characterized by a surface of moderate relief—the late Tertiary peneplain. From Pliocene to middle Pleistocene, intermittent uplift of the region took place, with the ranges rising relatively higher than adjoining basins. The uplift was caused by arching of the region along an axis trending northwest from Yellowstone Park. Late Cenozoic normal faults that developed along the flanks of the arch dip southwest and northeast, away from its axis.

EVENTS IN THE STILLWATER AREA

Although the major displacement occurred along the Emigrant fault, which delineates the west side of the North Snowy block, during the Laramide uplift, intermittent movements took place alng it throughout the Cenozoic up to Recent time (Horberg, 1940, p. 282).

An erosional surface of probable Pliocene age, remnants of which are represented today by the East Boulder and West Boulder Plateaus, has the same elevation south of the Mill Creek–Stillwater fault, where the surface is on Eocene volcanic rocks capping the South Snowy block, and north of the fault, where the surface is on Cretaceous and older rocks. These relations suggest that movement along this major fault was not renewed during the late Cenozoic faulting episode.

A set of east-trending trenches on the south slope of Contact Mountain, north of the Gish mine (Howland, Garrels, and Jones, 1949, pl. 34, section *A–A′*) may mark recent faults, probably postglacial. The topographically high south sides of the trenches indicate that the south sides were uplifted relative to the north sides. The trenches lie slightly north of the eastward projection of the Lost Creek fault, along which, early in Laramide time, the south block was uplifted relative to the north block.

Pleistocene glaciers scoured out deep U-shaped valleys in the Beartooth Mountains. After the ice was gone, the oversteepened walls in many places slid into the valleys along low-angle gravity faults. Landslides are common in the Little Rocky and Stillwater drainage basins. In some of the slides, large blocks have moved considerable distances downslope without much internal deformation.

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