

## PETROLOGY OF THE HORN AREA, BIGHORN MOUNTAINS, WYOMING

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**ABSTRACT.** — Laramide block-like uplift of the Precambrian basement produced a faulted mountain mass, approximately 27 square miles in area, extending southward from the central Bighorn unit. The core of this uplift contains complexly folded, foliated high-grade metamorphic rocks.

Precambrian rock types include pegmatite, amphibolite, marble, calc-silicate rock, feldspathic rock, biotite schist, and amphibole rocks in addition to the predominant gneiss. Schistosity, mineralogical and lithological layering are conformable throughout the complex with cross-cutting pegmatites being the only exception. These rocks are believed to have originated from regional metamorphism and later alkali metasomatism of supracrustal rocks. Alkali metasomatism, apparently a post-tectonic event and perhaps a late stage of the regional metamorphism, culminated in pegmatitization. Mineral assemblages indicate the staurolite-quartz subfacies, and almandine-amphibolite facies of regional metamorphism.

The Bighorn Mountains (Fig. 1) are a broad, asymmetric, anticlinal uplift between the Powder River Basin on the east and the Bighorn Basin on the west. The north end of the range rises in southern Montana, southeast of the Pryor Range from which it is structurally distinct (Blackstone, 1940). This northern unit is asymmetrical with the steeper flank to the west, and locally is overthrust to the west as in the Five Springs Creek area (Wilson, 1934). Two subsidiary anticlines with the same asymmetry and trend as the northern unit modify the gently dipping east flank. An ill-defined fault zone

(Tongue River fault zone) serves as a boundary between the northern and central sectors.

In the central unit, where uplift was greatest, the sedimentary rocks have been extensively removed and much more Precambrian basement is exposed than in the combined northern and southern units. Moreover, the structural asymmetry of the central unit is opposed to that of the northern and southern units. Steep dips with local overthrusts bounded by tear faults mark the east flank whereas the west side is characterized by a gentle monoclinal dip. Asymmetry of subsidiary folded structures at the northern and southern ends of the central unit's east flank conforms to that of adjacent units. For example, Walker Mountain anticline at the north end of the central unit and West Billy Creek, Beaver Creek and Horn anticlinal structures at the south end have their steeper flanks to the west, whereas the central unit proper has its steep flank to the east.

The southern unit is separated from the central unit by the Ten-sleep fault. This southern unit trends north to north-northeast and is asymmetrical, with the steep flank toward the west; there are several subsidiary anticlines with similar asymmetry which trend north-northwest. A north-northeast trending high angle fault is related to

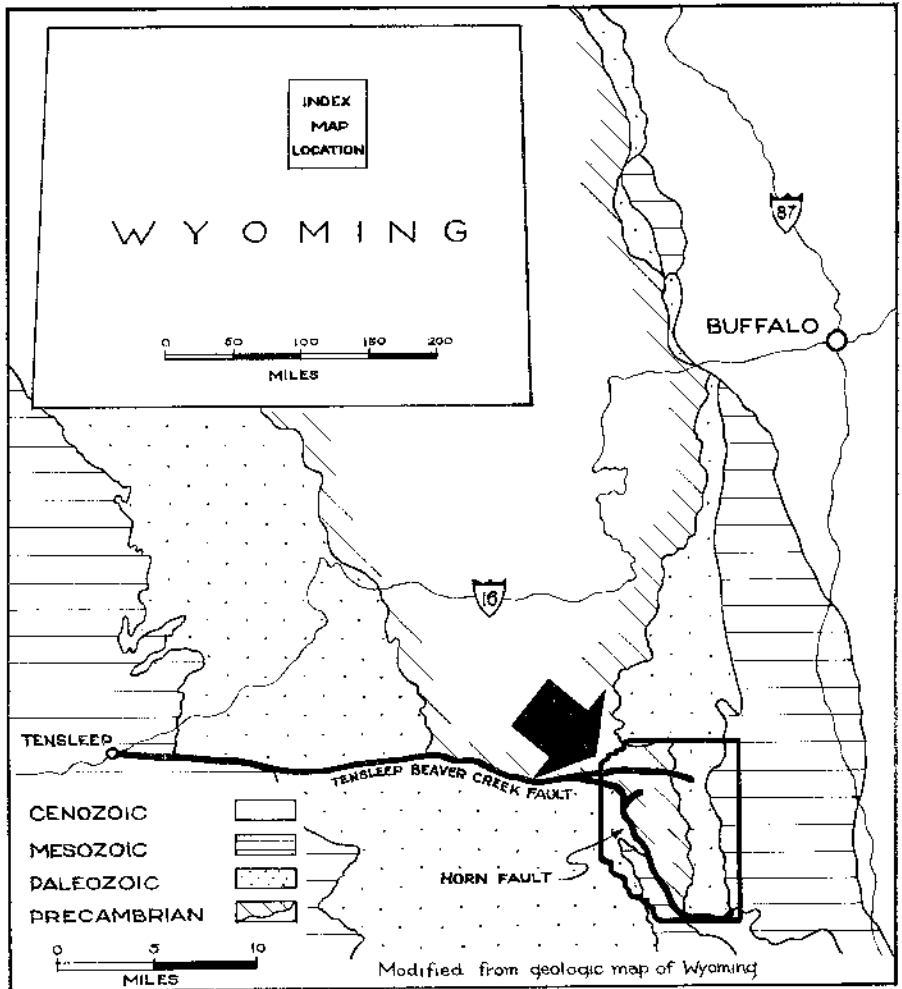
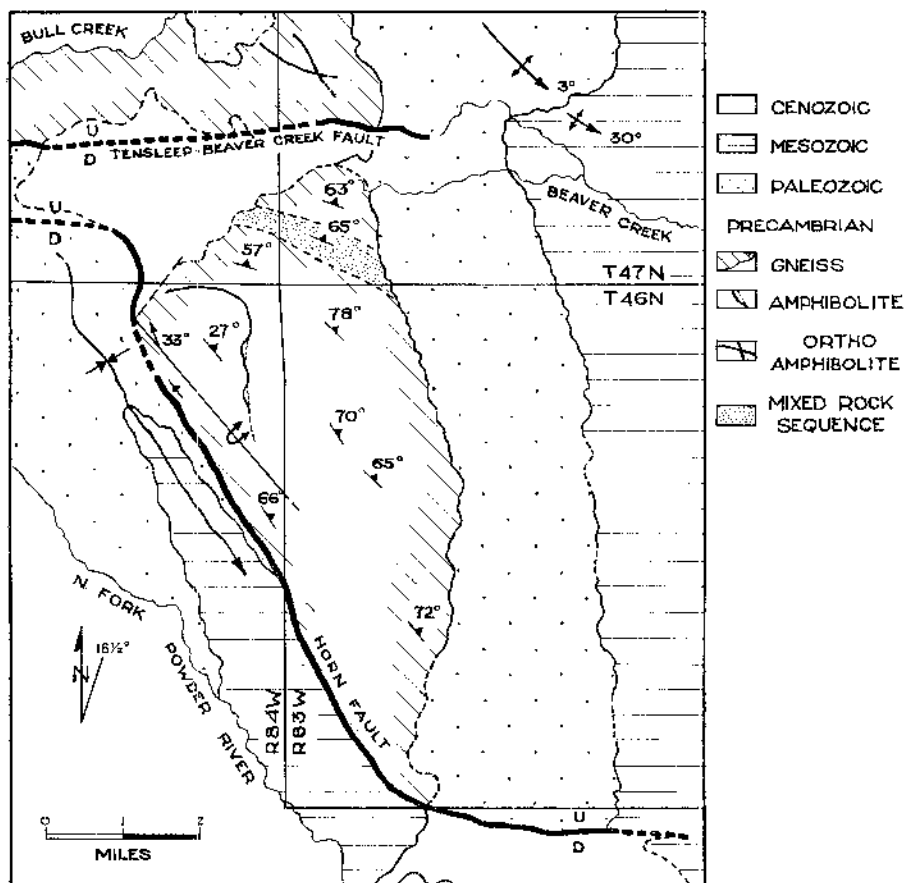


FIGURE 1.—Index map of the central Bighorn unit showing location of the Horn area (large arrow).

uplift of the southern unit. This fault divides into subsidiary ones at the southern terminus of the range where the Bighorns join the westward trending Bridger-Owl Creek Uplift.

The Horn area (Fig. 2) which is of primary concern herein, lies along a portion of the east flank and includes parts of both the central and

southern units. A feature identified as the Horn is a relatively small mountain mass which extends as a horn-shaped prominence southward from the central unit. The Horn itself is a block-like uplift of the Precambrian basement with its western and southern boundaries sharply delineated by the Horn fault. This is a high angle, reverse fault along



- |       |                                 |     |  |
|-------|---------------------------------|-----|--|
| 53°   | attitude of foliation           | 3°  | anticline, showing trace of axial plane and bearing and plunge of axis                         |
| 12°   | bearing and plunge of lineation |     | syncline, showing trace of axial plane   |
| —     | definite contact                | 33° | overturned anticline showing trace of axial plane direction of dip of limbs and plunge of axis |
| - - - | approximate contact             | U   | high angle fault, movement - U, up and D, down   |
| ↖     | strike of vertical foliation    | D   |  |

FIGURE 2.—Geologic map of the Horn area.

the western boundary but becomes a transverse fault along the southern boundary. On the east side of the uplift superjacent sedimentary rocks dip moderately eastward in continuity with the east flank of the

central unit of the range. On the west, the sedimentary rocks have been dragged into an overturned syncline by movement on the Horn fault. The over-turned eastern limb of this syncline becomes the western

margin of the Horn, whereas its normal limb constitutes the east flank of the southern Bighorn unit.

#### GENERAL DESCRIPTION OF PRECAMBRIAN ROCKS

A wide variety of Precambrian metamorphic rock types are exposed in what is referred to herein as the Horn gneiss complex, although granitic gneiss overwhelmingly dominates. Cross-cutting and conformable planar pegmatite bodies, irregular pegmatite masses and conformable lenses or pods of amphibolite commonly are associated with gneiss. Amphibolite characteristically occurs as small pods less than one or two meters thick; rarely is it found in planar units of mappable size. Pegmatites, too, are generally small scale features. Consequently, only a small proportion of the amphibolite and none of the pegmatite bodies are large enough to be shown on the geologic map and sections. Locally, biotite schist occurs and is gradational into biotite gneiss. The three rock types, granitic gneiss, pegmatite and amphibolite are well exposed. Other rare and poorly exposed rock types, include biotite schist, calc-silicate rock, marble, quartzite, quartz-hematite schist and garnetiferous rock. Some of these types would probably not have been discovered were it not for numerous test pits in the area.

Perhaps the most striking structural feature of these rocks is the conformability of their foliation or schistosity with lithologic contacts. With the exception of cross-cutting planar and irregular massive pegmatite, all rock types occur as in-

terlayered, parallel or sub-parallel units. This conformability is disturbed locally, by complex minor folding, lensing, or boundinage effects. In some occurrences foliation may be obliterated by cataclasis, but the over-all parallelism of foliation and the various rock units remains a dominant characteristic.

#### GRANITIC GNEISS

*Megascopic features.* The granitic gneisses are fine- to medium-grained rocks, the color of which ranges from light gray, to pink or tau, to dark gray. Several varieties were distinguished in the field on the basis of texture and structure, irrespective of mineralogical composition. The most common variety is "normal" granitic gneiss having indistinct to well-developed foliation. Other varieties, listed in the order of estimated abundance, are: permeation gneiss, porphyroblastic gneiss, banded gneiss, augen gneiss, migmatitic gneiss and veined gneiss.

Mineralogical varieties include quartz-feldspathic gneiss, quartz-plagioclase gneiss and feldspathic gneiss; each of these may contain biotite or hornblende or both as the mafic varietal(s). (In this paper, the term "quartz-feldspathic" means that quartz, plagioclase, and potassium feldspar are present in significant amounts.) Biotite quartz-feldspathic gneiss constitutes the most abundant variety. As the percentage of microcline decreases this variety becomes biotite quartz-plagioclase gneiss. Feldspathic gneiss (in which quartz is absent or minor) was found only in the vicinity of marbles and calc-silicate rocks. Contacts between mineralogical varieties are generally gradational, but some are sharp and parallel to foliation.

Banding in the gneisses is defined by alternating felsic and mafic layers and is accentuated by grains of biotite and hornblende lying with flakes or long axes in the plane of layering. The felsic layers generally consist of xenoblastic quartz, oligoclase, and microcline with minor amounts of either biotite or hornblende, depending upon which is the dominant mineral in the associated mafic-rich layers. Similarly, the mafic layers are biotite-rich, or more rarely, hornblende-rich, but some quartz and

foldspar usually are present. Some thin layers (less than 3 mm thick) may consist exclusively of hornblende, which tends to be more strongly segregated than biotite. Gneisses in which biotite is the dominant mafic varietal mineral tend to be less distinctly banded. Hornblende gneisses, on the other hand, show a stronger development of compositional layering; in the hornblende-rich layers the hornblende prisms often are aligned so as to define alinement in the plane of foliation. Within the felsic layers further segregation is sometimes present; quartz stringers and lenses and plagioclase-rich layers alternate with quartz-plagioclase-microcline layers. This type of segregation is developed commonly only in the leucocratic varieties of granitic gneiss.

Granitic gneisses show widespread mineral lineation which is marked by elongate aggregates of biotite or hornblende (streaks), or by the sub-parallel alignment of hornblende prisms or ellipsoidal biotite plates. The fact that hornblende prism alignment is more common than biotite lineation has been alluded to; the latter is seen only in areas of intense folding. Streaking and lineation involving hornblende alignment lie within the foliation plane and are developed commonly even where strong folding is not apparent. Foliation generally is more pronounced than lineation except in the axial zone of a major fold.

*Mineralogy and textures.* — The predominant gneisses show a wide variety of textural features and mineralogical types in thin section. Gneiss generally consists of approximately 90 percent quartz, plagioclase and microcline, with the remainder being biotite and/or hornblende plus accessories.

Quartz occurs characteristically as xenoblastic grains. Lenses and layers of quartz aggregates elongated parallel to foliation are common. Individual crystals of quartz embay plagioclase, but boundaries with other quartz grains are sutured. Strain effects are invariably present in the form of undulatory extinction and, less commonly, as deformation lamellae. Commonly, very fine (usually less than 0.1 mm), round quartz grains are enclosed by plagioclase and microcline.

Plagioclase feldspar is abundant in the granitic gneisses, having an antipathetic relation to potassium feldspar. Individual crystals are fine- to medium-grained,

hypidioblastic, usually polysynthetically twinned and slightly altered. They appear cloudy or dusty as a result of the characteristic alteration to sericite, kaolinite and epidote. Sericite alteration often is preferentially developed along cleavage planes. Effects of stress in plagioclase are wavy, bent, or rarely, faulted cleavage and twin planes. Plagioclase composition ranges from  $An_2$  to  $An_{30}$ , the mean composition from determinations made in 21 thin sections being  $An_{14}$ . Oligoclase may show albitic rims that are free of alteration. Myrmekite commonly occurs along contacts with microcline.

Potassium feldspar, ranging widely in percentage from sample to sample, is a constituent of nearly all samples. It exhibits a variety of textural relationships and unlike plagioclase and quartz shows no strain effects. Where present in minor amounts, it occurs interstitially and as fine-grained patch replacements in plagioclase (incipient replacement stage). In more advanced stages of replacement, potassium feldspar occurs either as disseminated medium-grained crystals or as microcline-rich layers. Coarse grained subhedral grains of microcline characteristically form the porphyroblasts in porphyroblastic gneiss. Most potassium feldspar shows well-developed grid twinning and is micropertitic, the strings or lenses of albite being in positions crystallographically controlled by the microcline host. Crystals of microcline are clear in contrast to the cloudy plagioclase. A thin section showing a pygmatically folded microcline-quartz "vein" revealed that microcline is much more abundant in the gneiss adjacent to the "vein" than elsewhere in the gneiss.

Biotite is the usual mafic varietal, occurring as fine-grained, ragged plates or as fresh appearing lepidoblastic crystals. It cuts across plagioclase, is interstitial in quartz-feldspathic material and has crystallized as flakes along shear planes. A thin section at right angles to the axial plane of a microfold shows that biotite flakes are oriented with their {001} cleavage parallel to the axial plane of the microfold. More commonly biotite is crystallized along shears parallel to the foliation. Absorption is strong (pleochroism X = straw yellow, Y = Z = dark brown) and pleochroic haloes often are well developed.

The alteration of biotite in the gneisses is far from simple. One thin section showed three distinct altera-

tions: (1) chlorite and magnetite, (2) bleached biotite and rutile needles, and (3) muscovite. The rutile needles are of interest because they may signify the release of  $TiO_2$  upon retrograde transformation from a higher temperature assemblage (DeVore, 1955).

Hornblende is less abundant than biotite. It occurs characteristically as ragged prismatic to subhedral grains that are strongly pleochroic ( $X$  = pale greenish-yellow,  $Y$  = light green,  $Z$  = bluish-green or dark green). Some of the larger grains may contain quartz blebs and, less often, subhedral apatite. The characteristic alteration is to epidote, although biotite, chlorite and magnetite are not unusual.

Muscovite (including sericite), epidote, allanite, apatite, sphene and zircon are fairly common accessory minerals whereas magnetite, hematite, leucoxene, chlorite and garnet are less common. Muscovite occurs in sufficient amounts in some of the more sheared rocks to warrant the designation "two mica" gneiss. Such muscovite, having crystallized late, developed in part by replacement of biotite (it is often inter-layered with biotite) and, in part, by forming lepidoblastic crystals oblique to foliation and cross-cutting quartz, feldspar and biotite. Sericite, epidote-group minerals, hematite, leucoxene and chlorite are alteration products whereas magnetite, apatite and sphene are associated with mafic varieties. In particular, sphene and especially apatite are associated with hornblende. Leucoxene alteration is observed only on sphene; hematite most commonly is on the margins of magnetite or in fractures emanating from magnetite. Expansion cracks usually are developed in plagioclase enclosing metamict allanite grains.

#### PEGMATITE

*Megascopic features.* — Quartz-feldspar pegmatites are widespread. Most pegmatites contain both potassium feldspar and plagioclase; potassium feldspar is more abundant although a few pegmatites contain plagioclase to the exclusion of potassium feldspar. The ratio of feldspar to quartz is approximately 1:1 but often is higher, especially in pegmatites that are dominantly composed of microcline perthite and quartz. Biotite, magnetite and muscovite are coarse enough to be recognized in the field but other minor constituents were

identified in thin section. A pegmatite may display a pink color owing to disseminated hematite but pinkish-gray, light gray or white colors are more common.

The pegmatites occur either as planar bodies or irregularly-shaped masses. Planar pegmatites may cut across or trend parallel to foliation. Conformable planar pegmatites often are quite thin, their thickness being measured in inches whereas, cross-cutting pegmatites generally are thicker, sometimes exceeding 10 feet although most are less than 1 foot thick. Irregular, massive pegmatites appear to have engulfed the country rock inasmuch as they contain gneissic remnants. Planar pegmatites tend to have sharp contacts with the country rock whereas in irregular pegmatites boundaries are gradational. Cross-cutting planar pegmatites commonly exhibit very sharp contacts, fine-grained borders and coarse-grained central zones. Grain size is more uniform in the irregularly shaped pegmatite masses.

*Mineralogy and Textures.* — Coarse granoblastic texture predominates but locally graphic textures have developed. Some microcline perthitic crystals are several inches long, and these often contain discrete quartz grains in conical shapes or as blebs. In some cases quartz and feldspar form regular intergrowths of rods or plates. Generally, however, quartz and feldspar are xenoblastic. Cataclastic features are characteristic in quartz and plagioclase; in two examples mortar structure was observed.

Quartz is generally anhedral, presenting serrate or sutured borders to feldspar or itself forming a quartz mosaic. Cataclastic features, invariably shown by quartz, occur most commonly as undulatory extinction but deformation lamellae were noted also.

Plagioclase generally is dusty with sericite alteration. In many pegmatites bent plagioclase lamellae testify to pre-tectonic crystallization. Pegmatite plagioclase is generally more sodic than plagioclase of the gneisses (albite is characteristic of the pegmatites, oligoclase of the gneisses). Rims of clear, more sodic albite may be developed and myrmekite is observed on the border of potassium feldspar. In contrast to most plagioclase, microcline is clear and unstrained and usually perthitic.

Minor constituents may include biotite, magnetite, hematite, allanite, epi-

dote, clinozoisite, muscovite, hornblende, diopside, apatite, sphene, leucocene, zircon, garnet, calcite, chlorite. Such constituents locally may reflect the mineralogy of the country rock: pegmatites in biotite gneiss contain biotite, pegmatites in hornblende gneiss contain hornblende, pegmatites in diopside gneiss contain diopside, pegmatites crossing amphibolites rich in sphene contain hornblende and sphene, etc.

#### AMPHIBOLITE

*Megascopic features.* — Amphibolites in the Horn area are black to dark gray or black and white, fine- to medium-grained rocks consisting principally of hornblende and plagioclase. Locally, coarse-grained patches consisting exclusively of hornblende have developed. In some occurrences a "salt-and-pepper" appearance is imparted because of scattered plagioclase. In a few exposures quartzofeldspathic material forms conformable layers, lenses or streaks; in others it forms cross-cutting veins in the amphibolite. At one locality, amphibolite and quartz-feldspar veins are highly deformed. The over-all appearance suggests that the amphibolite was passively rolled in the surrounding, more plastic gneiss by the action of tectonic transport.

Amphibolite generally occurs in bodies too small to be mapped but with three principal habits: (1) as conformable planar layers; (2) as conformable pods or lenses; and (3) as cross-cutting planar bodies. Conformable planar amphibolite is abundant in the mixed rock sequence (Fig. 2). Only one conformable planar amphibolite was mapped but it has significance because it serves as a key horizon for structural determinations. Amphibolite lenses are widespread throughout the gneiss complex although they are more abundant in certain zones. These zones are parallel to foliation in the surrounding rocks, suggesting that the lenses once were connected. Only two cross-cutting planar amphibolite bodies were observed, both north of the Tensleep-Beaver Creek fault in the northeast part of Precambrian exposure.

Foliation and lineation are conspicuous. The former is marked by the arrangement of hornblende crystals in layers, or by the segregation of the minerals into light and dark layers, whereas lineation is often evidenced by aligned crystals of hornblende. Many of the massive appearing amphibolites

show foliation, lineation, or both when examined in thin section.

*Mineralogy and textures.* — Typical amphibolite in thin section has fine- to medium-grained crystalloblastic texture. Hornblende is nematoblastic, either lineated or decussate. Plagioclase is usually xenoblastic, ranging in composition from  $Al_{10}$  to  $An_{40}$  but sodic andesine is most common. Hornblende generally is altered to epidote or chlorite (usually penninite) or both, whereas plagioclase generally is altered to sericite. The hornblende to plagioclase ratio varies widely, but in most specimens it is slightly greater than one. Coarse hornblende commonly is poikiloblastic. Pleochroism of hornblende is commonly X — pale greenish-yellow, Y — light green, Z — bluish-green or dark green.

Minor constituents include quartz, biotite, sphene, apatite, diopside, magnetite, microcline, allanite, and garnet.

*Garnetiferous and related rocks associated with amphibolite.* — Exposed near the center of the mapped, conformable amphibolite in Secs. 1 and 12, T. 46 N., R. 84 W. are some garnetiferous and related rocks, which indicate the composition of the rocks prior to metamorphism. Despite poor exposure, garnetiferous gneiss was traced discontinuously for over one-half mile as an apparently conformable zone (or zones) within the amphibolite body. Related rocks were observed in a more restricted area (SW $\frac{1}{4}$  SE $\frac{1}{4}$ , Sec. 1, T. 46 N., R. 84 W.). Associated with garnetiferous gneiss, but in much smaller amounts, are garnetiferous amphibolite, garnet-quartz-cummingtonite rock, tremolite schist and gedrite rock.

The garnetiferous gneiss has a rather complex mineral composition including quartz, calcic oligoclase, red-brown biotite, almandine, cordierite, sillimanite, magnetite, hematite and epidote and is similar to kinzigite of European petrologists. Foliation is defined both by subparallel orientation of lepidoblastic biotite flakes and by a tendency for the light and dark constituents to be segregated. This foliation is modified by large almandine garnet porphyroblasts (diameters range from a few millimeters to over two centimeters). Biotite foliae were thrust apart forcibly by the growing garnet, and quartz recrystallized in the pressure shadows. The garnet porphyroblasts are more noticeably poikiloblastic at their centers whereas their margins are relatively free of inclusions, suggesting that at a late stage of growth

the garnet was able to rid itself of foreign material. Both biotite and cordierite show pleochroic haloes. Some of the cordierite is altered to "pinite."

In sharp contact with garnetiferous biotite gneiss is a reddish-brown, hematite-stained garnet-quartz rock the texture of which superficially resembles that of a grit. Under the microscope a slightly strained, fractured, coarse-grained quartz mosaic is seen to surround and include xenoblastic, poikiloblastic, and fractured medium-grained almandine and lesser amounts of nematoblastic, fine-grained cummingtonite. Sub-parallel orientation, in discrete planes, of the prismatic cummingtonite gives the massive appearing rock a poorly developed lineation and schistosity.

Pale green and red mottled tremolite schist was collected in the locality of the garnet rocks. Schistosity results from planar arrangement of fine-grained, nematoblastic tremolite and poorly developed lineation is imparted by sub-parallel alignment of amphiboles. The green and red colors are due, respectively, to partial alterations of tremolite to chlorite plus talc and of magnetite to hematite.

Purplish-red gedrite rock also is associated with the garnetiferous biotite gneiss. The gedrite, an aluminous variety of anthophyllite, is asbestiform and largely altered to talc and lesser chlorite. Prisms of gedrite are oriented perpendicular to schistosity.

Amphibolites adjacent to the garnetiferous biotite gneiss also are garnetiferous. Foliation in these amphibolites is expressed as alternating layers of very fine- and fine- to medium-grained hornblende, quartz and andesine. The finer grained layers are  $\frac{1}{8}$  -  $\frac{1}{4}$  inches thick whereas the coarser grained layers may exceed  $\frac{1}{2}$  inch. Such layers show a tendency to be hornblende-rich or hornblende-poor. Hornblende-rich layers are modified by almandine porphyroblasts which are rimmed by alteration to a complex of sericite, penninite, and epidote.

#### MARBLE AND CALC-SILICATE ROCK

Carbonate rocks are exposed in a relatively narrow conformable zone (Fig. 2). Except for the northernmost exposure shown in Figure 2 they were investigated by Sargent (1969) and much of the following is taken from his report.

*Foliated calcite marble.* — This rock is generally dark blue to white, having fine- to coarse-grained granoblastic texture. The only consistent major constituent is calcite, although magnetite-ilmenite, diopside, apatite, garnet (andradite) and phlogopite occur locally in considerable amounts. Minor constituents include magnetite-ilmenite, diopside, apatite, garnet, phlogopite, epidote, tremolite, rutile, pyrite, chondrodite, allanite, zircon, quartz, chlorite, brucite and antigorite. Foliation is imparted by lepidoblastic phlogopite, nematoblastic tremolite or flaser structure in calcite. Deformation in the marble is evidenced by cataclastic effects in calcite, diopside and garnet.

Quartzo-feldspathic gneiss and pegmatite, calc-silicate rock, amphibolite, feldspathic rock and magnetite-ilmenite all form thin (usually less than a foot) interlayers, lenses or pods in the calcite marble. Commonly, the interlayers and lenses are gently warped. Contacts between foliated calcite marble and calc-silicate rocks are irregular and gradational, whereas contacts of calcite marble with the other rock types mentioned are usually sharp and regular.

*Calc-silicate rock.* — The calc-silicate rocks are best developed adjacent to or enclosed in marble. Major constituents are diopside and garnet (andradite); minor constituents include allanite, calcite, epidote-clinozoisite, hornblende, actinolite, magnetite, microcline, plagioclase (albite-oligoclase), sphene, chlorite, quartz and zircon.

#### MIXED ROCK SEQUENCE

An interlayered sequence of banded amphibolites, migmatitic quartzo-feldspathic schists and gneisses and impure quartzites was distinguished from its contiguous gneisses for the following reasons: (1) rocks in the sequence are much more highly differentiated than elsewhere in the gneiss complex, (2) banded amphibolites are much more abundant than elsewhere, and (3) cataclastic effects are more pronounced and better developed within the sequence than elsewhere.

These rocks were mapped as a unit and their distribution is shown in Figure 2. Table 1 gives the succession and thickness of the exposed rock units within the sequence. Youngest (?) rocks are at the top.

*Amphibolite.* — Banded amphibolite comprises nearly half of the exposed sequence. Amphibolite from the mixed rock sequence, in general possesses a better developed foliation than does amphibolite from other portions of the complex. The constituent minerals are variously proportioned in distinct layers. Typically, fine-grained, cataclastically granulated, andesine-quartz-hornblende layers alternate with medium-grained, hornblende-rich layers. Thin magnetite layers commonly are associated with hornblende-rich layers. Quartz and plagioclase are granoblastic, whereas hornblende is nonatoblastic and may be aligned to yield a lineation. Some specimens, namely, the "feather amphibolites," contain aggregates of porphyroblastic hornblende which poikiloblastically includes quartz, plagioclase and hornblende, and which are flattened in decussate arrangement on foliation planes. Epidote-clinozoisite, zoisite and chlorite are alteration products of hornblende, and plagioclase is often altered to sericite or sericite and epidote; however, the alteration is not uniform. Some samples are fresh throughout, whereas others appear severely altered. Even within a single thin section, altered layers may alternate with relatively fresh layers.

Overall mineralogy generally is like that of the previously described amphibolite elsewhere in the complex, although one specimen departs from the usual in that it contains abundant biotite and quartz; it might better be termed biotite-hornblende-quartz gneiss. Coarse, euhedral, black tourmaline was found within a quartz-feldspar segregation contained in an amphibolite from this mixed rock sequence.

*Quartzo-feldspathic schist and gneiss.* — These rocks are similar to the leptytes of Scandinavian petrologists. Principal minerals are quartz, plagioclase, microcline and biotite but there is considerable variation in the proportions. At one extreme is quartz-biotite schist or biotite quartzite. With more plagioclase the rock is called quartz-plagioclase schist. The name, quartzo-feldspathic biotite schist, is applied when microcline becomes a more important constituent. With increasing grain size, muscovite becomes prominent and the rocks may be called quartzo-feldspathic "two-mica" gneiss. Quartzo-feldspathic veins and lenses are abundant enough in some quartz-feldspar-biotite schists to

warrant use of the term migmatite. Pygmatic folding is well shown in some migmatites.

Textural relations of the constituent minerals are similar to those in the gneisses described previously. Microcline replaces plagioclase and muscovite replaces biotite, usually post-tectonically; however, in some examples from the mixed rock sequence, both microcline and muscovite are cataclastically deformed and fractured. In other cases the usual situation prevails, that is, clear, undeformed microcline replaces cloudy, deformed plagioclase.

Cataclastic features are abundant in these rocks. Undulatory extinction, bent plagioclase cleavage and twin units are nearly always present. In an extreme case, coarser quartz and feldspar grains form lenses around which granulated quartz and feldspar and micaceous material appears to flow in anastomosing streams. Such rocks are termed augen gneisses. In two locations phyllonites were observed. The massive appearing, resistant quartzo-feldspathic unit at the base of the sequence was called a "granite sill" in the field, but in thin section this rock shows a well-developed mortar structure. Thus cataclastic features are varied and abundant in the mixed rock sequence. *Banded quartz-hematite schist and impure quartzite.* — These rocks were found at two localities within the mixed rock sequence. The localities are stratigraphically separated by more than 300 feet, and only a few feet of quartz-hematite rock is poorly exposed in test pits at each place.

Banded quartz-amphibole rocks are associated with the ferruginous quartzites. The quartz-hematite schist consists of alternating  $\frac{1}{8}$  -  $\frac{1}{16}$  inch bands of quartz and hematite. Flakes of hematite are dispersed throughout the quartz bands, and small amounts of fine quartz (chalcodony?) occur within the hematite bands, but the segregation is marked. Granerite is a minor constituent. Magnetite also occurs within the hematite bands.

A thin section of hematite-stained quartzite consisted of a fine-to medium-grained quartz mosaic in which very fine-grained, accessory hornblende, cumingtonite, garnet, biotite and magnetite are arranged in planes. The quartz grains have sutured boundaries, and their long dimension tends to parallel the planes of accessory minerals which are preserved to denote relict stratification.

FACIES CLASSIFICATION AND  
CONDITIONS OF METAMORPHISM

According to Read (1952, p. 7), traces of regional metamorphism may be preserved in resister rocks which may be used to reconstruct the metamorphic facies before granitization. Resister rocks are those extreme chemical types which require a great expenditure of energy and metasomatic action to convert them to granite. In the Horn area, resister rocks include amphibolite, marble, calc-silicate rock and quartzite. Because of the wide stability range of quartz, the quartzites are of little use in determining metamorphic facies; however, the mineral assemblages of amphibolite and carbonate rocks allow an accurate interpretation of metamorphic facies. The critical assemblages are as follows:

*Amphibolite*

Hornblende-plagioclase-epidote  
(quartz-biotite)

Hornblende-plagioclase-almandine-  
epidote (quartz-biotite)

Hornblende-plagioclase-epidote  
(diopside-quartz)

*Calcite marble (after Sargent, 1960)*

Calcite-diopside-phlogopite

Calcite-diopside-tremolite  
(chondrodite-olivine)

Calcite-tremolite-phlogopite (epidote-  
chondrodite-olivine)

*Calc-silicate rock (after Sargent, 1960)*

Calcite-diopside-garnet-epidote  
(-tremolite-plagioclase)

Calcite-diopside-epidote-plagioclase

Diopside-hornblende-epidote-tremolite

These are believed to be equilibrium assemblages of the staurolite-quartz subspecies of the almandine amphibolite facies (Fyfe, Turner and Verhoogen, 1958, p. 229). Metamorphism in almandine-amphibolite facies covers a tempera-

ture range of perhaps 550° to 750° C., and pressures normally between 4,000 and 8,000 bars (Turner and Verhoogen, 1960, p. 553). The prevalence of amphiboles and micas indicates high water pressures.

Disequilibrium assemblages were also observed in the Horn area. High-grade metamorphic assemblages commonly show local or partial replacement by low-grade assemblages.

The following reactions have occurred:

plagioclase → epidote, sericite, kaolinite and more sodic plagioclase  
diopside → amphibole  
amphibole → chlorite, epidote, biotite  
cummingtonite → talc, chlorite  
gedrite → talc, chlorite  
grunerite → hematite, silica

Such reactions are believed to occur during cooling following the main high-temperature phase of metamorphism. The modern interpretation holds that these reactions are limited by the lack of water, which was driven away during the high-temperature phase. The necessary water could only become available by diffusion inward from some external source (Turner and Verhoogen, 1960, p. 505). In the Horn area minerals characteristic of a lower facies commonly occur in rocks strongly affected by cataclasis. This suggests that reaction rates were faster in cataclastically granulated materials and that, perhaps, the influx of the necessary water was guided by the granulated zones.

PETROGENESIS

The occurrence of thin, conformable rock layers of undoubted sedimentary parentage (e.g., marble,

quartzite and banded quartz-hematite schist) intimately associated and intercalated with gneiss and amphibolite strongly suggests that the entire gneiss complex was initially of supracrustal origin. Schistosity, as well as mineralogical and lithological layering are conformable throughout the complex; cross-cutting pegmatites are the only exception. Furthermore, on the scale of the whole area, these features form a tightly folded, complex anticline. The ghost stratigraphy, revealed by resister rocks, and the large-scale lithologic architecture are difficult to explain unless these rocks represent transformed and partially granitized supracrustal rocks. A discussion of the origin of specific rock types follows:

*Granitic gneiss.* — Additional criteria favoring an origin by regional metamorphism and granitization of supracrustal rocks for the gneisses, in particular, include: (1) the occurrence of accessory rounded zircons in the gneiss, and (2) the banded nature of much of the gneiss.

Although detailed zircon studies were not attempted, observation of thin sections suggests that the rounded zircons are sedimentary relics. Beklemann and Poldervaart (1957, p. 1242-1244) made detailed zircon studies of metamorphic rocks of the Beartooth Mountains which are similar in many respects to the rocks of the Horn area. They concluded (1957, p. 1250): "The high percentages of rounded zircons in all the rocks favor their sedimentary origin."

In regard to the genetic significance of banded gneisses, the follow-

ing conclusions of Dietrich (1960, p. 99) are important:

"The banding of nearly all banded gneisses reflects directly or reflects formation controlled by supracrustal layering.

"... presently observable banding of many banded gneisses is probably hybrid in that after it was formed originally it was subsequently modified (commonly accentuated) as the result of differential anatexis, permeation, metamorphic differentiation, differential cataclasis, or some combination of such processes."

It is possible that the sedimentary parent of the quartz-feldspathic gneiss was an argillaceous or pelitic rock. The chemical compositions of argillites and granites are not vastly different and, according to Misch (1949, p. 226) the addition of alkali and some silica will transform argillite into a rock of granitic composition. Evidence will be introduced later which supports this suggestion.

*Pegmatite.* — Ramberg (1952, p. 248) considers pegmatitization to be a phase of granitization; pegmatites observed in the Horn area conform to his genetic classification.

Most of the Horn area pegmatites are the replacement (non-dilation) pegmatites of Ramberg (1952). Criteria for recognition of replacement dikes were discussed by Goodspeed (1940). Evidence of a replacement origin for many of the Horn pegmatites includes: (1) lack of offset of the gneissic layers on either side of cross-cutting pegmatites (Fig. 3.), (2) relation of pegmatite-country rock mineralogy (p. 246), (3) external rim of ferromagnesian minerals (Fig. 4.), (4) undisturbed inclusions and relics of wall rock structure, and (5) variations in



FIGURE 3. — Non-dilation pegmatite cutting across banded gneiss. Note the lack of offset in the gneiss bands.



FIGURE 4. — Pegmatite with basic rim of dark minerals that presumably represents Fe, Mg and Ca originally distributed in the space occupied by the pegmatite but now displaced by Si, K and Na.



FIGURE 5. — Pegmatite exhibiting variation in width, fine-grained boundaries, a coarse quartz-rich core, and reaction zone in the country rock.

width (Fig. 5.) The fact that several cross-cutting pegmatites have sharp, fine-grained borders and coarse-grained quartz-rich cores sug-

gests that these characteristics are not exclusively those of magmatic dikes or else that these represent an extreme case where pegmatite fluids were evolved.

*Amphibolite.* — Ortho-amphibolite occurs only north of the Tensleep-Beaver Creek fault where two cross-cutting, intersecting amphibolite bodies were mapped. In addition to field relations, thin section study revealed blastophytic texture to further indicate a magmatic origin for these bodies. Thus, diabase(?) dikes were intruded prior to the regional metamorphism in the Precambrian rocks now exposed north of the Tensleep-Beaver Creek fault.

In the remainder of the area, conformability and foliation suggest para-amphibolite. From the available data the writer is unable to discern whether the amphibolite was derived from thoroughly recrystallized metatuffs or metasediments. It is possible that conformable amphibolite represents former sills or flows of mafic composition.

The absence of cross-cutting quartz-dabase, and quartz-gabbro dikes in the area south of the Tensleep-Beaver Creek fault is in sharp contrast to the situation further north in the Bighorns where these are prominent (Hoppin, 1961, L. O. Williams, personal communication).

*Carbonate rock.* — Sargent (1960, p. 111) suggests that the parent rock of calcite marble was a somewhat impure dolomitic limestone, and upon metamorphism the magnesium became fixed in phlogopite, diopside, chondrodite and forsterite. Misch (1949, p. 236-237) reports a similar occurrence of thin marble layers in

a regionally metamorphosed terrain of the northwest Himalayas.

The calc-silicate rocks include types intermediate in composition between marble and quartzo-feldspathic gneiss. Sargent (1960, p. 108) suggests that they may represent calcareous argillites or argillaceous limestones (dolomites).

*Garnetiferous rock.* — The garnetiferous rocks, being conformably enclosed in an amphibolite "resister", were well shielded from alkali metasomatism. Thus the garnetiferous gneiss may reveal the chemical composition of the sedimentary rock prior to granitization. The pelitic mineral assemblage described for the garnetiferous gneiss (kinzigitite) is strong evidence supporting the notion that the quartzo-feldspathic gneisses were derived from argillaceous rocks. Alkali metasomatism of argillites will form potash and soda feldspars with pure aluminum silicates becoming an unstable phase.

The gedrite and cummingtonite rocks associated with the garnetiferous rocks probably resulted from local Mg-Al metasomatism.

*Banded quartz-hematite schist.* — Accessory hornblende, cummingtonite, garnet and magnetite (arranged in planes) have been described previously and interpreted as marking relict stratification planes in quartzite. These accessories are believed to represent, not relict heavy minerals, but ferruginous, calcareous, aluminous impurities in a very fine-grained siliceous sediment (chert or siliceous lutite). The quartzite and associated quartz-

hematite schists are believed to have originated in the following way.

High-grade regional metamorphism of chert-siderite, chert-greenalite or intercalated Fe, Mg-rich clay and siliceous lutite yielded a quartz-magnetite-grunerite layered rock. Later oxidation by hydrothermal(?) solutions caused magnetite to go to hematite and grunerite to go to hematite plus silica. The occurrence of a chalcedony vein with combstructure in a hematite-rich band is further indication of late hydrothermal(?) action. The effects of the oxidizing, hydrothermal(?) solutions were very minor, being recognized only in these rocks. The age of this event can only be given as post-metamorphism.

*Summary of petrogenesis.* --- (1.) Supracrustal rocks, dominantly argillaceous but locally siliceous, calcareous, magnesian or ferruginous, were deposited. Volcanic layers probably were intercalated with sedimentary layers. (2.) Regional metamorphism with synkinematic neocrystallization and recrystallization in amphibolite facies formed complexly folded high-grade metamorphic rocks. (3.) Alkali metasomatism was a late phase of the regional metamorphism and culminated in pegmatitization. Such rocks as amphibolite, marble, calc-silicate rock and quartzite were relatively unaffected by this metasomatism. (4.) The last phase of regional metamorphism selectively formed rocks of greenschist facies. The reactions are believed to have been influenced by such factors as  $p\text{H}_2\text{O}$  and  $p\text{CO}_2$  which in turn were controlled by cataclastic features

TABLE 2. — Succession and thickness of rock units in the mixed rock sequence.

ROCK TYPE	THICKNESS (feet)
Banded amphibolite .....	35
Banded "feather amphibolite" ...	12
Biotitic quartzite .....	12
Conformable quartz-plagioclase pegmatite .....	3
Micaceous quartzite with lenses of pegmatitic quartz, albite and muscovite .....	14
Garnetiferous quartz-plagioclase- biotite schist .....	6
Banded amphibolite .....	17
Quartzo-feldspathic biotite schist.	42
"Feather amphibolite" .....	10
Quartz-plagioclase-biotite schist..	15
Covered .....	6
Quartzo-feldspathic biotite schist.	5
Covered .....	36
Banded amphibolite interlayered with chlorite schist .....	300
Coarse biotite-oligoclase rock with minor almandite, quartz plagio- clase biotite schist and banded quartz-hematite schist (poorly exposed) .....	30
Micaceous quartzo-feldspathic gneiss with minor interlayers of banded amphibolite .....	120
Quartz-biotite amphibolite .....	18
Micaceous quartzo-feldspathic gneiss interlayered with quartz- biotite schist .....	76
Covered .....	126
Quartzitic rocks including banded quartz-hematite schist, and banded quartz-amphibole, horn- blende, cummingtonite-gruner- ite, actinolite (?) rock .....	8
Covered .....	116
Quartzo-feldspathic rock with mor- lar structure .....	1
	1,018

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