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GEOLOGY OF THE PRECAMBRIAN ROCKS OF THE KEYSTONE PEGMATITE DISTRICT, SOUTHERN BLACK HILLS, SOUTH DAKOTA

by

James Jennings Norton

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CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGY OF THE PRECAMBRIAN ROCKS OF THE KEYSTONE PEGMATITE DISTRICT, SOUTHERN BLACK HILLS, SOUTH DAKOTA

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ABSTRACT

The Keystone pegmatite district is on the northeast flank of the mountainous area around Harney Peak in the southern part of the Precambrian core of the Black Hills, South Dakota. The chief mineral products have been potash feldspar, spodumene, amblygonite, lepidolite, beryl, scrap mica, and gold. Gold mining was important from 1891 to 1903. Pegmatite mining began in 1898, and has been a major activity since about 1929. Approximately 18 square miles have been mapped geologically at a scale of 1:10,000 in and near the pegmatite-bearing area of the Keystone district.

The Keystone district contains an estimated thickness of 11,000 feet of metasedimentary rocks. These are mostly quartzose and micaceous schists; other rocks include amphibole schist, quartzite, and mica-graphite schist. Ortho-amphibolite intrudes the metasedimentary rocks.

All metamorphic rocks of the southern Black Hills increase in grade toward the area of abundant pegmatitic intrusives near Harney Peak. The southern and southwestern part of the Keystone district is in the sillimanite zone; staurolite is the highest grade mineral elsewhere.

The metamorphic rocks were deformed first by isoclinal folds, then by intense cross folds, and finally by gentle flexures associated with pegmatite intrusives. The plunges of isoclinal folds are generally more than 70° in the north and northeast parts of the district, but are ordinarily between 0° and 50° elsewhere.

A large transcurrent fault strikes northwest across the district. Smaller high angle faults have been recognized both in the vicinity of the main fault and also in the northwest part of the district. The abundance of faults in the Keystone district, at the edge of the pegmatite-bearing area of the southern Black Hills, suggests that faulting was caused by forces associated with intrusive activity. Faults cut the isoclinal and cross folds, but they preceded the climax of the progressive metamorphism that affected the rocks surrounding Harney Peak.

Pegmatites of the Keystone district and other parts of the southern Black Hills are here classified as layered, homogeneous, and zoned pegmatites. Layered pegmatites consist of relatively fine-grained plagioclase, quartz, and muscovite with layers and lenses of coarser-grained pegmatite made up of perthite, quartz, and plagioclase. Homogeneous pegmatites are composed virtually entirely of unsegregated plagioclase, quartz, perthite, and muscovite. Zoned pegmatites are the least common variety, though they have been widely described in the literature.

An isopleth map showing the abundance of pegmatites throughout the southern Black Hills indicates that the pegmatites are concentrated around the Harney Peak dome and many satellitic domes. Layered pegmatites are most abundant within these domes, and homogeneous pegmatites are most abundant on the flanks. Zoned pegmatites are in a belt at the outer edge of the pegmatite-bearing area. The Keystone district, on the northeast side of the Harney Peak dome, contains all three types of pegmatites. The belt of zoned pegmatites goes northwest through the Keystone district, where it is 1 to 2 miles wide.

Structural, mineralogic, and petrographic evidence suggest that these pegmatites formed from a magma-like liquid. The internal structure indicates that zoned pegmatites formed in an essentially closed system, but layered pegmatites may have crystallized in a more open system. All varieties of pegmatite have approximately the same content of SiO_2, Al_2O_3, Na_2O, and K_2O. The fluid from which the zoned pegmatites formed may, however, have been enriched in H_2O, B, F, and such "rare" constituents as Li and Be. Hydrothermal or pneumatolytic fluids given off during crystallization of zoned pegmatites formed replacement bodies that cross-cut the zonal structure.

Nearly all pegmatite mining in the Keystone district has been in zoned pegmatites. Units in these pegmatites contain minable concentrations of potash feldspar, lithium minerals, scrap mica, beryl, and small quantities of other industrial minerals.

INTRODUCTION

The Keystone pegmatite mining district is in the south central part of Pennington County, in the southern Black Hills, South Dakota. The district is on the northeast side of the mountainous area around Harney Peak in the southern part of the Precambrian core of the Black Hills. All of the pegmatite mines are in a northwesterly trending belt 1 to 2 miles wide that is southwest of Keystone. Several small gold mines, where the first mining in this district was done, are clustered around the village of Keystone.

The total area mapped geologically (fig. 3) is about 18 square miles. This area includes all or large parts of 22 sections in four townships, T. 1 and 2 S., R. 5 and 6 E. Wherever localities are described in the text [redacted] the section number will be given without the township and range numbers. No section number occurs more than once within the mapped area (fig. 2).

The Keystone district is in a maturely dissected region that consists almost entirely of forested slopes. Valley bottoms are narrow; the widest is about 500 feet where Battle Creek passes through Keystone.

The highest altitude is 5,856 feet at the top of a peak in the SE 1/4 sec. 26, 4 miles northwest of Keystone. The lowest is about 4,150 feet where Iron Creek leaves the area in sec. 14.

The largest stream is Battle Creek, which flows S. 75° E. across the area (fig. 3). It is joined by Grizzly Bear Creek at Keystone. The southern part of the district is drained by Iron Creek. Iron Creek enters Battle Creek southeast of the mapped area, and Battle Creek ultimately enters the Cheyenne River.

The forests consist predominantly of Ponderosa pine. Scrub oak grows on many slopes. Aspen and birch are common along valley floors.

The total permanent population of the Keystone district is about 400 persons, nearly all in Keystone itself. The chief industries are mining, lumbering, and tourist trade. Mining is mostly for pegmatite minerals, but gold mining and tin prospecting have been important in the past. The lumbering industry depends entirely on Ponderosa pine. The major tourist attraction in the area is the Mt. Rushmore National Memorial, 2 miles west-southwest of Keystone, where the heads of Washington, Jefferson, Lincoln, and Theodore Roosevelt have been sculptured on the mountainside.

Visitors to Keystone come by automobile on U. S. Highways 16 and 16A. A spur line of the Chicago, Burlington, and Quincy Railroad carries only freight.

Rapid City, 25 miles by highway to the northeast of Keystone, is the economic center of western South Dakota. The population is about 35,000. Rapid City is served by the Chicago and Northwestern Railway, the Chicago, Milwaukee, and St. Paul Railroad, and Western Air Lines.

History

The earliest recorded entry of white men into the central part of the Black Hills was an expedition led by Lt. Col. George A. Custer in 1874. Gold was discovered near the site of the present city of Custer (fig. 1) by Horatio N. Ross, one of the members of the Custer expedition, and a rush to the Black Hills began shortly thereafter. The first major settlement, established in 1875, was named Custer. Gold was discovered in Deadwood Gulch late in 1875, and the area around Lead and Deadwood in the northern Black Hills became the center of greatest interest.

The history of mining in the southern Black Hills has been described in many publications. Connolly and O'Harra 1/ wrote the principal general reference. Page and others 2/ summarized the history of pegmatite mining in the Black Hills through 1945. Newton and Jenney 3/ presented an account of the original gold discovery and the first prospecting and mining. Allsman 4/ summarized the history of gold mining throughout the Black Hills. Sterrett 5/ described the early mica mining, especially for the years 1906-1911.

Gold prospecting in the Keystone area doubtless began in the late 1870's, but the first significant mining was at the Keystone mine, which was not discovered until 1891. Gold mining continued until 1903, but little work has been done since then. The Bullion gold mine was operated for a short time in the early 1920's, but the chief product was arsenic. The combined Keystone and Holy Terror mines were worked for a while prior to World War II. The only work since World War II was at the Juniper mine.

1/ Connolly, J. P., and O'Harra, C. C., 1929, The mineral wealth of the Black Hills: S. D. School Mines, Bull. 16.

2/ Page, L. R., and others, 1953, Pegmatite investigations 1942-1945, Black Hills, S. D.: U. S. Geol. Survey Prof. Paper 247, especially p. 4-6.

3/ Newton, Henry, and Jenney, W. P., 1880, Geology and resources of the Black Hills of Dakota: U. S. Geog. and Geol. Survey of the Rocky Mtn. Region.

4/ Allsman, P. T., 1940, Reconnaissance of gold-mining districts in the Black Hills, S. D.: U. S. Bur. Mines Bull. 427.

5/ Sterrett, D. B., 1923, Mica deposits of the United States: U. S. Geol. Survey Bull. 740, p. 289-302.

The original discovery of lode tin in the Black Hills was made in 1883 at the Etta pegmatite 1/ in the NW 1/4 sec. 16 (fig. 3). From 1884 to 1894 there was a great tin prospecting boom in which the major company was the Harney Peak Tin Mining, Milling, and Manufacturing Company. This company spent more than $3,000,000 in the southern Black Hills, yet produced less than 5 tons of metallic tin 2/. The Etta pegmatite was one of the chief deposits, but other pegmatites in the Keystone district doubtless were prospected for tin. Since 1894 there has been virtually no exploration for tin near Keystone.

The first major pegmatite mining in the Black Hills was for sheet mica between 1879 and 1884. Most of the mining was in the area around Custer, and production from the Keystone district was meager.

Spodumene was first mined from the Etta pegmatite in 1898; this date is ordinarily taken as the beginning of lithium mining in the United States. The Etta mine has been operated on a small scale during nearly every year since it was first opened.

Amblygonite, especially from the Hugo mine, was the chief lithium mineral produced between 1908 and 1916. The Hugo mine was also a source of tantalite.

The first potash feldspar mined in the Black Hills was obtained in 1923 from the Hugo pegmatite by the Keystone Feldspar and Chemical Company. The same company began mining the Peerless pegmatite for scrap mica and potash feldspar in 1924. This company's Peerless operation has continued to the present day; the most important products have been scrap mica, beryl, and potash feldspar.

1/ Headden, W. P., 1906, Mineralogical Notes, No. III: Colo. Sci. Soc., v. 8, p. 169.

2/ Hess, F. L., 1908, Tin, tungsten, and tantalum deposits of South Dakota, in Contributions to Economic Geology, 1908: U. S. Geol. Survey Bull. 380, p. 134-135.

The Hugo pegmatite was leased to the Consolidated Feldspar Corporation in 1929. In subsequent years this company, now a department of the International Minerals and Chemical Corporation, became the largest pegmatite mine operator in the Black Hills. It built a feldspar grinding plant at Keystone that was operated from 1929 until it was destroyed by fire in February 1957. The largest sources of potash feldspar have been the Hugo, Dan Patch, and Hesnard pegmatites mined by the Consolidated Feldspar Corporation, the Big Chief pegmatite mined by the Consolidated Feldspar Corporation and by other operators, the Bob Ingersoll mine operated by the Black Hills Keystone Corporation, the White Cap pegmatite mined by the Lithium Corporation of America and others, and the Etta mine operated by the Maywood Chemical Company. Many smaller deposits have also been worked.

World War II marked the start of a very active period of pegmatite mining in the southern Black Hills. The principal products between 1942 and 1955 were potash feldspar, lithium minerals, beryl, sheet mica, and scrap mica. Sheet mica was of greatest importance in the Custer district, especially between 1942 and 1945; scarcely any sheet mica has been mined in the Keystone district.

The principal change in the pegmatite mining industry at Keystone since 1942 has been the great increase in lithium and beryl mining. Scrap mica has continued to be produced, especially from the Peerless mine. Potash feldspar was mined from many pegmatites. The large deposits at the Hugo, White Cap, and Dan Patch mines have been virtually exhausted.

The Edison mine, like the Etta, became a major source of spodumene. The Lithium Corporation of America built a sink-float mill at the Edison and vigorously mined the deposit from 1948 to 1950, when all the spodumene that could be obtained by mechanized open pit methods had been mined. The Black

Hills Keystone Corporation mined lepidolite from the Bob Ingersoll No. 1 pegmatite, especially between 1938 and 1945. Spodumene has been mined at the Bob Ingersoll No. 2 pegmatite, and also at the Dyke Lode and Hugo mines.

The largest sources of beryl have been the Bob Ingersoll and Peerless mines, each of which has produced more than 500 tons. Other sources have been the Hugo, Dyke, Dan Patch, White Cap, Big Chief, and many smaller pegmatites.

Production figures for the Keystone district have never been reported separately from the rest of the Black Hills. Nevertheless production data and estimates from many sources, especially Page and others 1/, have been used to compile the figures shown below.

Estimated production of pegmatite minerals through 1955, Keystone district

Mineral	Tons
Potash feldspar	300,000
Scrap mica	13,000
Beryl	1,700
Spodumene	60,000
Lepidolite	8,000
Amblygonite	6,000

The total value of these minerals probably has been between 6 and 7 million dollars. In addition, the gold production probably has been between 1.5 and 2 million dollars, mostly from the Holy Terror-Keystone group of claims 2/. Through 1955 this district has probably produced about one-fifth of the world's lithium and 2 percent of the world's beryl.

1/ Page, L. R., and others, 1953, Pegmatite investigations 1942-1945, Black Hills, S. D.: U. S. Geol. Survey Prof. Paper 247.

2/ Allsman, P. T., 1940, Reconnaissance of gold-mining districts in the Black Hills, S. D.: U. S. Bur. Mines Bull. 427, p. 92-93.

Geologic Investigations

The earliest geologic investigation of the Precambrian core of the Black Hills was in 1875 by Newton and Jenney 1/. Their report contains the first description of a zoned pegmatite in the Black Hills 2/.

During the succeeding years a large body of geologic literature has been assembled on the Black Hills. Only the principal articles concerning metamorphic rocks and pegmatites will be mentioned here.

Van Hise 3/ visited the Black Hills in 1889 and wrote a report that was chiefly on the petrographic characteristics and metamorphism of Precambrian rocks.

N. H. Darton and Sidney Paige 4/ between 1900 and 1915 made a geologic map of four 30-minute quadrangles that include the entire central Black Hills. Their report is still the principal reference on the general geology of the Black Hills. The geology of the metamorphic rocks in the southern Black Hills was mapped with less precision than in the northern Black Hills, and the structure was worked out only in a generalized fashion. Nevertheless, the distribution of the metamorphic and igneous rock types was shown with considerable accuracy. Paige 5/ described the pegmatitic character of the

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1/ Newton, Henry, and Jenny, W. P., 1880, Geology and resources of the Black Hills of Dakota: U. S. Geog. and Geol. Survey of the Rocky Mtn. Region.

2/ Idem, p. 71.

3/ Van Hise, C. R., 1890, The Precambrian rocks of the Black Hills: Geol. Soc. America Bull., v. 1, p. 203-244.

4/ Darton, N. H., and Paige, Sidney, 1925, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219.

5/ Paige, Sidney, 1925, Precambrian rocks: in Darton, N. H., and Paige, Sidney, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219, p. 4.

so-called granite around Harney Peak, and was the first to emphasize the layering of this rock. He stated that the granitic rocks came into their present position by distention of the older rocks under great pressure 1/, and this conclusion has been generally accepted by later workers.

J. J. Runner and his associates wrote a series of reports from 1921 to 1946 on the Precambrian geology of various parts of the Black Hills. Part of this work was southeast of Lead in the northern Black Hills 2/. Runner 3/ and also Balk 4/, who was with Runner in the field, wrote brief descriptions of the rocks around Harney Peak. Hamilton 5/ wrote an unpublished doctorate thesis on the geology of the metamorphic rocks in the Keystone district, but his map showed stratigraphic and structural relations in only a generalized fashion.

1/ Paige, op. cit., p. 5.

2/ Runner, J. J., 1921, Evidences of an unconformity within the Precambrian of the Black Hills of South Dakota (abstract): Geol. Soc. America Bull., v. 32, p. 37-38; and 1934, Precambrian geology of the Nemo district, Black Hills, S. D.: Am. Jour. Sci., 5th ser., v. 28, p. 353-378.

Berg, J. R., 1946, Precambrian geology of the Galena-Roubaix district, Black Hills, S. D.: S. D. Geol. Survey, Rept. Inv. 52.

3/ Runner, J. J., 1928, Intrusion mechanics of the Harney Peak batholitic granite (abstract): Geol. Soc. America Bull., v. 39, p. 186; and 1943, Structure and origin of Black Hills Precambrian granite domes: Jour. Geology, v. 51, p. 431-457.

4/ Balk, Robert, 1931, Inclusions and foliation of the Harney Peak granite, Black Hills, S. D.: Jour. Geology, v. 39, p. 736-748.

5/ Hamilton, R. G., 1935, Precambrian geology of the Keystone district, Black Hills, South Dakota: Univ. of Iowa Ph. D. thesis.

J. A. Noble and his colleagues in the Homestake Mining Company made detailed studies of the geology of the Lead area in the northern Black Hills 1/. Harder 2/ mapped similar rocks in the Rochford district, 16 miles south of Lead.

Higazy 3/ undertook a regional study of the pegmatites in the Keystone district. He did not, however, make maps of any kind to show the relations between pegmatite and country rock, and his work on pegmatites was limited almost entirely to a mineralogic study of perthite.

Many geologists have made detailed studies of pegmatites in the Keystone area. Pegmatites of the Keystone district were described by Hess in one of three papers published by geologists of the United States in 1925 proposing that pegmatites were formed largely by replacement 4/. In the same year a

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1/ Noble, J. A., 1948, High-potash dikes in the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 59, p. 927-939; and 1950, Ore mineralization in the Homestake gold mine, Lead, S. D.: Geol. Soc. America Bull., v. 61, p. 221-252.

Noble, J. A., and Harder, J. O., 1948, Stratigraphy and metamorphism in a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 59, p. 941-975.

Noble, J. A., Harder, J. O., and Slaughter, A. L., 1949, Structure of a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 60, p. 321-352.

2/ Harder, J. O., 1934, Geology of a Precambrian area at Rochford and its relation to the regional structure of the northern Black Hills: S. D. School Mines E. M. thesis.

3/ Higazy, R. A., 1949, Petrogenesis of perthite pegmatites in the Black Hills, S. D.: Jour. Geology, v. 57, p. 555-581.

4/ Hess, F. L., 1925, The natural history of the pegmatites: Eng. and Min. Jour. - Press, v. 120, p. 289-298.

Landes, K. K., 1925, The paragenesis of the granite pegmatites of central Maine: Am. Mineralogist, v. 10, p. 353-411.

Schaller, W. T., 1925, The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., v. 10, p. 269-279.

description of the Etta pegmatite was published by Schwartz 1/. Shortly thereafter Landes 2/ published an article on the petrology and mineralogy of the Bob Ingersoll, Peerless, Etta, and Hugo pegmatites. Many less significant articles published between 1884 and 1944 described various aspects of the geology of Keystone pegmatites.

In the years since 1942 most of the geologic work done in the Keystone district has been by the U. S. Geological Survey. Several mineralogic studies, however, have been made by other organizations. Keith and Tuttle 3/ of the Geophysical Laboratory, Carnegie Institution at Washington, measured the inversion temperature of quartz from various types of pegmatites and from various units of zoned pegmatites. P. L. Weis 4/, working under the auspices of the University of Wisconsin, made fluid inclusion studies of specimens from zoned pegmatites. Still more recently Grootemaat and Holland 5/ of Princeton University determined the potassium and sodium content of samples of muscovite from all zones of the Peerless pegmatite, and discussed the genetic significance of their results. Norton participated in the field work of each of these investigations in order to designate the structural position of the specimens within the various pegmatites.

1/ Schwartz, G. M., 1925, Geology of the Etta spodumene mine: Econ. Geology, v. 20, p. 646-659.

2/ Landes, K. K., 1928, Sequence of mineralization in the Keystone, S. D., pegmatites: Am. Mineralogist, v. 13, p. 519-530, 537-558.

3/ Keith, M. L., and Tuttle, O. F., 1952, Significance of variation in the high-low inversion of quartz: Am. Jour. Sci., Bowen volume, p. 233-238.

4/ Weis, P. L., 1953, Fluid inclusions in minerals from zoned pegmatites of the Black Hills, S. D.: Am. Mineralogist, v. 38, p. 671-697.

5/ Grootemaat, T. B., and Holland, H. D., 1955, Sodium and potassium content of muscovites from the Peerless pegmatite, Black Hills, S. D. (abstract): Geol. Soc. America Bull., v. 66, p. 1569.

A program of detailed structural study of pegmatites in the southern Black Hills was carried out in 1942-1945 when L. R. Page and other geologists of the U. S. Geological Survey, including the present author, mapped pegmatite mines and prospects at scales of 1:600 and larger 1/. Additional detailed studies were completed in later years. [redacted]

In 1945 the Geological Survey began mapping the general geology of the principal pegmatite mining districts at scales of 1:10,000 and 1:12,000. By 1955 approximately 110 square miles underlain by Precambrian rocks had been mapped in the Custer, Hill City, and Keystone districts. Ultimately the entire area around Harney Peak will be mapped at scales of 1:10,000 to 1:24,000.

The work throughout the southern Black Hills was supervised by Norton in 1949 and 1950, and again from 1954 to 1957. J. A. Redden was the project supervisor during Norton's absence in 1951 and 1952. L. R. Page was supervisor from 1943 through 1948 and again in 1953.

This report [redacted] is chiefly an account of some of the more significant results of field work by Norton in the Keystone district. It is based largely on areal geologic mapping. In addition, some of the more important data acquired during detailed study of individual pegmatites have been used. Metamorphic rocks and pegmatites elsewhere in the southern Black Hills have also been studied by Norton and his associates, and areas to the north have been examined in reconnaissance fashion. The information thus obtained has been used as part of the background of this report [redacted].

1/ Page, L. R., and others, 1953, Pegmatite investigations 1942-1945, Black Hills, S. D.: U. S. Geol. Survey Prof. Paper 247.

The geologic map of the Keystone district (fig. 3) covers 18 square miles at a scale of 1:10,000. Most of the field work was done in the summers of 1947 through 1949 and 1953 through 1955. Norton mapped about 10 square miles without assistance. He was assisted by J. A. Redden, P. M. Orville, P. L. Weis, and J. B. Hanley in mapping 4 square miles in secs. 9, 10, 15 to 17, and 20 to 22; by R. E. Langen, R. E. Roedifer, and R. E. Burns in mapping 1 square mile in secs. 5, 7, 8, and 9; and by R. G. Wayland and P. M. Orville in mapping 2 square miles in secs. 1, 2, 35, and 36. L. R. Page mapped 1-1/3 square miles in secs. 29 to 32. Certain unsolved stratigraphic and structural problems require that additional work be done in parts of the mapped area, and thus the geologic map (fig. 3) has not been entirely completed.

The U. S. Bureau of Mines and the U. S. Geological Survey obtained diamond drill records from 7 pegmatites in the Keystone district and 12 pegmatites elsewhere in the southern Black Hills between 1943 and 1953. The drilling was done by private contractors. Norton did the greater part of the geologic work during drilling at 5 of these pegmatites, and participated in the geologic work at 8 others. Part of the data obtained from drilling at the Big Chief, Diamond Mica, and Peerless pegmatites have been incorporated in this thesis. Specific data obtained by drilling other pegmatites will not be presented here, except insofar as these data have been used with a large body of other information that aids in interpreting the geology of zoned pegmatites.

Acknowledgments

L. R. Page has been the most valuable source of advice during the work in the Keystone district and elsewhere in the Black Hills. J. A. Redden, who not only did part of the Keystone work but also mapped the Custer pegmatite district, has been a continual source of ideas on areal geologic problems. The work of P. M. Orville, J. B. Hanley, R. E. Roadifer, R. G. Wayland, P. L. Weis, R. E. Langen, and R. E. Burns is gratefully acknowledged.

The detailed nature of D. M. Sheridan's logs of diamond drill core from the Peerless pegmatite in the Keystone district made possible the determination of the sequence of layers in the wall zone of this pegmatite.

D. H. Kupfer, as an associate on the Black Hills project in 1948 and 1949, was assigned to map the Calamity Peak area in the Custer district, where he obtained data that have helped in understanding the geology of layered pegmatites elsewhere in the southern Black Hills.

U. S. Bureau of Mines engineers who supervised diamond drilling projects were E. O. Binyon, D. H. Mullen, Glen Walker, Fremont Clarke, and Stuart Ferguson. Their cooperation has made it possible to determine the geology in three dimensions of several economically important pegmatites.

From July 1, 1947, to June 30, 1950, the Black Hills pegmatite project was a part of the Geological Survey's beryllium program carried out in behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

The assistance and extraordinary cooperation of mine operators and prospectors throughout this work is greatly appreciated. These include the Consolidated Feldspar Corporation, Keystone Feldspar and Chemical Company, Maywood Chemical Company, Lithium Corporation of America, Black Hills Keystone Corporation, and many others. A. I. Johnson, a consulting engineer at Keystone, has always been very helpful.

This report has been reviewed by Professors C. H. Behre, Jr., W. H. Bucher, Arie Poldervaart, and Brian Mason of Columbia University. Their comments are greatly appreciated.

REGIONAL GEOLOGY

The Black Hills is an elongate, asymmetric dome in which the Paleozoic and Mesozoic rocks dip more steeply on the east flank than on the west flank. The Precambrian core is exposed in an oval area that is 60 miles long in a N. 15° W. direction and has a maximum width of 26 miles. The schists throughout this area are highly deformed. They range in metamorphism from the chlorite to the sillimanite zones.

The geology of the Black Hills metamorphic rocks is understood in detail in only a very few areas. Elsewhere only enough data have been acquired to explain the overall geologic relations in a very generalized fashion, and the necessary detailed data are not likely to be assembled for many years to come. Nevertheless, in order to obtain information that may apply to structural, stratigraphic, and metamorphic problems in the southern Black Hills, areas of metamorphic rocks elsewhere in the region have been examined, and all available published and unpublished geologic maps have been studied. During the time that the Keystone work has been underway, geologic mapping has also been done by J. A. Redden and others near Custer and by R. G. Wayland near Hill City. Continual efforts have been made to correlate the geology of these three areas.

Precambrian Rocks of the Northern Black Hills

The most thoroughly studied Precambrian area for which there is a published geologic map is in the vicinity of Lead in the northern Black Hills. The rocks at Lead are in isoclinal folds that plunge 10° to 45° SE.[1] The

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1/ Noble, J. A., Harder, J. O., and Slaughter, A. L., 1949, Structure of a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 60, p. 325.

isoclinal folds are deformed by cross folds and a few small faults. The stratigraphic sequence consists of six formations described as follows by Noble and Harder 1/, in order from oldest to youngest: 1) Poorman formation (possibly 2,000 feet or more), 2) Homestake formation (200 to 300 feet), 3) Ellison formation (3,000 to 5,000 feet), 4) Northwestern formation (0 to possibly 4,000 feet), 5) Flag Rock formation (possibly 5,000 feet), and 6) Grizzly formation (possibly 3,000 feet or more). The age order is based partly on superposition and partly on a supposed unconformity at the base of the Flag Rock formation, but the evidence is inadequate 2/.

The thicknesses given for these units are based "on the assumption that the present shapes of the folds in the rocks are a result of shear folding rather than flexure folding" 3/. Consequently the thickness of each formation is measured on the noses of folds parallel to the axial plane. This method is objectionable because it fails to take into account the possibility of flowage of material into the noses of folds and because the shear planes along which the folds developed were not necessarily perpendicular to bedding. Even Noble and Harder must have had difficulty in selecting places to measure thickness. They give the thickness of the Homestake formation as 200 to 300 feet, yet in many places on their map the Homestake formation forms a long thin nose in an isoclinal fold, and a thickness of many hundreds of feet could be measured parallel to the axial plane. Noble and Harder fail to give the

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1/ Noble, J. A., and Harder, J. O., 1948, Stratigraphy and metamorphism in a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 59, p. 941-975.

2/ Noble, J. A., personal communication, 1954.

3/ Noble and Harder, op. cit., p. 944.

thickness of these units on the limbs of folds, and it is difficult to estimate the figures because they also fail to provide geologic sections. Calculations based on their geologic map [1/] suggest that the thickness on the limbs is about one-fourth the thickness stated in their text. Furthermore, the limbs of the major folds contain many small drag folds that may cause the thickness as measured on the map to be several times as much as the actual thickness. Thus the thickness of the Lead sections, given by Noble and Harder [2/] as at least 17,000 feet, may be only 1,000 to 3,000 feet on the limbs of folds. Other workers in the Black Hills, including the present author, have measured thicknesses on the limbs of folds, and thus the figures for the Lead section must be converted in this way before they can be compared with thicknesses in other areas. Regardless of how the calculations are made, the present thicknesses cannot be converted to thicknesses prior to deformation, and the most that can be asked is that the method of making the calculation be uniform.

The Homestake formation is the most distinctive unit in the Lead area, and it is also the key to solving many of the structural and stratigraphic problems. In the biotite zone of metamorphism, the Homestake formation is a carbonate-quartz schist containing many pods and seams of recrystallized quartz that probably was originally chert [3/]. The carbonate is sideroplesite, $FeCO_3$, $MgCO_3$. Noble and Harder [4/] describe this formation as being similar to the iron formations of the Lake Superior region. Mineralogically

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1/ Noble and Harder, op. cit., plate 1.

2/ Idem, p. 944.

3/ Idem, p. 946

4/ Idem, p. 947.

it corresponds to the carbonate facies described by James 1/. In the garnet zone of metamorphism this formation consists predominantly of cummingtonite schist. In this zone it is very similar to a unit consisting predominantly of amphibole schist in the Keystone area, just east of the northwesterly trending fault zone that passes through Keystone (fig. 3). In the Keystone district, as at Lead, this unit contains pods and seams of quartzite that probably was derived from chert. The rocks on either side of this unit at Keystone are similar to the rocks on either side of the Homestake formation at Lead, and a tentative correlation based on lithology is suggested in table 1.

Noble and Harder's descriptions of the Lead stratigraphic units give the characteristics of these rocks in the biotite zone of metamorphism and then show how the rocks were changed at higher grades of metamorphism 2/. In the biotite zone the Poorman formation, beneath the Homestake formation, is a gray phyllite consisting chiefly of quartz, muscovite, and ankerite. The Ellison formation overlies the Homestake formation, and is succeeded by the Northwestern, Flag Rock, and Grizzly formations. In the biotite zone the Ellison formation consists mostly of phyllite and schist containing quartz and muscovite, but quartzite is abundant in many places. The Northwestern formation consists of phyllite and schist containing quartz, muscovite, and commonly biotite. The most evident difference between the Northwestern and Ellison formations is the absence of quartzite in the Northwestern. Where

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1/ James, H. L., 1951, Iron formation and associated rocks in the Iron River district, Michigan: Geol. Soc. America Bull., v. 62, p. 251-266; and 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geol. Soc. America Bull., v. 66, p. 1455-1488, especially p. 1475.

2/ Noble and Harder, Op. cit.

quartzite is found adjacent to the Flag Rock formation, the Northwestern formation is considered to be absent along a presumed unconformity at the base of the Flag Rock. The Flag Rock consists largely of sericitic phyllite, but also contains graphitic schist, quartzite, and sideroplesite schist. The Grizzly formation has phyllite consisting dominantly of quartz and muscovite.

The biotite zone is in the southwestern part of the Lead district. Metamorphism increases to the northeast through the garnet zone and into the staurolite zone. The rocks that were originally argillaceous become garnet and staurolite schists. The sideroplesite rocks become cummingtonite schists. The ankerite-bearing rocks may contain hornblende in the higher grades of metamorphism, but the evidence is meager, largely because these rocks rarely occur in the higher grade parts of the district 1/.

The Lead area also contains many amphibolite masses that have been described by Dodge 2/ as metamorphosed intrusive rocks, probably gabbroic.

Precambrian Rocks of the Middle Part of the Black Hills

The Lead area is separated from the rest of the Black Hills Precambrian rocks by Paleozoic and later rocks 3/. Nevertheless, rocks to the south and southeast have been correlated with the Lead section. At Rochford, 16 miles south of Lead and 15 miles north-northwest of Hill City (fig. 1 shows the

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1/ Noble and Harder, op. cit., table 1 and p. 962.

2/ Dodge, T. A., 1942, Amphibolites of the Lead area, northern Black Hills, S. D.: Geol. Soc. America Bull., v. 53, p. 561-584.

3/ Darton, N. H., and Paige, Sidney, 1925, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219, geologic map.

location of Hill City), Harder [1] mapped rocks that he correlated with part of the Lead section. East of Rochford and southeast of Lead, Runner [2] and Berg [3] mapped what they called the Lead system as the youngest part of a sequence of rocks that is several tens of thousands of feet thick. Noble and Harder [4] question the validity of this correlation, but they too have recognized rocks in this area that they think correspond to the Lead section [5]. In addition, they have found a rock unit of thin-bedded chlorite schist above the Grizzly formation that they call the Uncle Sam formation [6].

The geologic relations elsewhere in the central part of the Black Hills Precambrian core are known only from the map by Darton and Paige [7] and from reconnaissance. Strikes throughout most of this area are north-northwest, and dips are steep. Darton and Paige [8] show four large anticlines and three large synclines in geologic sections extending across the widest area of Precambrian rocks. These geologic sections, though correct in a broad and generalized sense, do not adequately portray the structural complexity of these rocks. The rocks are isoclinally folded wherever the structure can be

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1/ Harder, J. O., 1934, Geology of a Precambrian area at Rochford and its relation to the regional structure of the northern Black Hills: S. D. School Mines E. M. thesis.

2/ Runner, J. J., 1934, Precambrian geology of the Nemo district, Black Hills, S. D.: Am. Jour. Sci., 5th ser., v. 28, p. 353-378.

3/ Berg, J. R., 1946, Precambrian geology of the Galena-Roubaix district, Black Hills, S. D.: S. D. Geol. Survey, Rept. Inv. 52.

4/ Op. cit., p. 955.

5/ Noble, J. A., and Harder, J. O., personal communication, 1954.

6/ Harder, J. O., personal communication, 1954.

7/ Op. cit.

8/ Idem.

recognized, as in the outcrops of the McVey Burn extending from 3 to 8 miles north of Hill City. Large faults may also exist. The structural grain of the rocks in the McVey Burn, for example, is northerly, yet just to the northeast a lithologically different group of rocks has a northwesterly trend; either faults, an unconformity, or very intricate folding are required to explain the observed relations.

Precambrian Metamorphic Rocks of the Southern Black Hills

The metamorphic rocks of the southern Black Hills are in many ways like the rocks to the north that have already been described. They have additional complexities, however, associated with the pegmatitic and granitic intrusives around Harney Peak (fig. 1). The isoclinally folded rocks have been deflected around and domed over the larger intrusives, and many faults have been recognized.

Metamorphism and Stratigraphy

The most conspicuous change in the metamorphic rocks from north to south is the great increase in grade. This increase is from the chlorite and biotite zones in the central part of the Precambrian core to the garnet, staurolite, and sillimanite zones in the southern part of the Black Hills. The garnet isograd is about 12 miles north of Harney Peak. Toward the west it curves first to the southwest and then to the northwest before passing beneath the Paleozoic rocks. The change to a northwesterly trend carries this isograd around a small granite body 9 miles west-southwest of Hill City.

The staurolite and sillimanite isograds form roughly concentric curves that pass, respectively, 6 and 3 miles north of Harney Peak; the sillimanite isograd is shown on fig. 1. The highest grade rocks are sillimanite-mica schists containing sillimanite aggregates as much as 1-1/2 inches long. All of the Precambrian rocks south of Harney Peak are in the sillimanite zone. The area containing sillimanite is 26 miles long and as much as 16 miles wide. The shape of the isograd indicates that if it could be extended beneath the Paleozoic cover, the total area of the sillimanite zone probably would be at least twice as great as shown on figure 1.

The close areal association between the high grade metamorphic rocks and the Harney Peak granitic and pegmatitic rocks leaves little doubt that the metamorphism to garnet, staurolite, and sillimanite grades was genetically related to the intrusions. It is possible that the lower grade rocks to the north, containing chlorite and biotite, were the product of an earlier and perhaps more widespread metamorphism, but neither the data in the scanty literature nor observation of the rocks themselves indicate the existence of any compelling evidence for two kinds or two periods of metamorphism.

Quartz- and mica-bearing schists derived from thick clastic and argillaceous rocks are by far the most abundant metamorphic rocks in the southern Black Hills. These range in composition from micaceous schists to impure granular quartzites. Over many large areas these rocks cannot be separated into readily distinguishable stratigraphic units that are small enough to show the geology on a map in a complete fashion. The quartz-mica schists contain lime-silicate nodules, which Runner and Hamilton 1/ show are metamorphosed calcareous concretions, but even these cannot be used as horizon markers. Runner and Hamilton 2/ thought that the lime-silicate nodules

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1/ Runner, J. J., and Hamilton, R. G., 1934, Metamorphosed calcareous concretions and their genetic and structural significance: Am. Jour. Sci., 5th ser., v. 28, p. 51-64.

2/ Idem, p. 53.

occur through several thousand feet of beds, and Redden 1/ found them distributed through a thickness of 40,000 feet of schists in a single large syncline near Custer. Similarly, at Keystone, lime-silicate nodules are at many horizons in quartz-mica schists.

In a few areas, as in secs. 2 and 35 of the northwest part of the Keystone district (fig. 3), the quartz-mica schists can be subdivided into small units. Interbedded units consisting of alternating quartzose and micaceous beds can be separated from more homogeneous rocks on either side. Units rich in mica and other aluminous minerals, especially staurolite, can be separated from adjacent units rich in quartz. In a few places, especially southwest of Custer 2/, metamorphosed grit and conglomerate beds can be recognized and mapped.

Fortunately the southern Black Hills also contain several highly distinctive units, ordinarily less than 700 feet thick, that have been recognized in many places. These units have lithologies that suggest they were originally chemical sediments or fine-grained muds. Largely on the basis of these units, enough progress has been made to suggest the tentative stratigraphic sequence shown in table 1.

The lower part of this sequence is based largely on the geology east of the northwesterly trending fault zone that passes through Keystone (block VI A of fig. 2; also see figs. 3 and 4). The geology of this area will be discussed in detail in a later section [redacted]. The structure here is dominated by isoclinal folds (fig. 4), in which the older rocks are generally

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1/ Redden, J. A., 1955, Geology of the Fourmile pegmatite area, Custer County, S. D.: U. S. Geol. Survey open file report [redacted]

2/ Idem.

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Table 1. Tentative correlation of metasedimentary rocks in the Keystone, Custer, Hill City, and Lead districts, S. Dak.

	Keystone (see table 2)	Custer	Hill City	Lead [1/]
12		Mayo formation		
11		Crow formation		
10		Bugtown formation --- Fault contact ---	Quartz schist, quartz-mica schist, and micaceous quartzite	
9	Micaceous schists and quartzites --- Fault contact ---	Mica schists	Mica schists	
8	Biotite-garnet schist	Oreville formation	Oreville formation	Uncle Sam formation
7	Quartz schist and quartzite --- Fault contact ---			
6	Quartz-mica schist and quartz-mica-staurolite schist	Quartz-mica schists	Quartz-mica schist and quartz schist	Grizzly formation
5	Mica schist, mica-graphite schist, and quartzite			
4	Quartz-mica schist and quartz-mica-staurolite schist	--- Fault contact ? ---		
3	Mica-garnet schist, pseudoconglomerate, quartzite, quartz-mica schist, and amphibole schist	Mica-garnet schist, pseudoconglomerate, quartzite, quartz-mica schist, and amphibole schist		Flagrock formation Northwestern formation (cut out south of Lead by unconformity) Ellison formation
2	Amphibole schist, quartzite, and mica-graphite schist	Amphibole schist and quartzite		Homestake formation
1	Quartz-mica schist, quartz-mica-staurolite schist, and quartz-mica-andalusite schist	Sillimanite schist		Poorman formation

1/ Based on Noble, J. A., and Harder, J. O., 1948, Stratigraphy and metamorphism in a part of the northern Black Hills and the Homestake mine, Lead, South Dakota: Geol. Soc. America Bull., vol. 59, p. 941-975. No description of the Uncle Sam formation, found southeast of Lead, has been published. The correlation is based on oral communications with J. O. Harder and R. G. Wayland, 1955.

to the southwest, in the cores of anticlines, and the younger rocks are to the northeast. The southwesternmost unit consists of quartz- and mica-bearing schists shown in tables 1 and 2 as the oldest unit in the Keystone district. The next unit consists mainly of amphibole schist with pods and seams of quartzite, but also contains mica-graphite schist. Lithologically this unit is similar to the Homestake formation at Lead, and the two are correlated in table 1. The most abundant minerals are cummingtonite and quartz, as in the Homestake formation at Lead. The highest grade parts of the Homestake formation are in the garnet zone 1/, and the Keystone rocks are in the staurolite and sillimanite zones. H. L. James 2/ describes similar rocks from northern Michigan as consisting dominantly of grunerite (iron-rich cummingtonite) and quartz in the garnet, staurolite, and sillimanite zones. He shows that these rocks are metamorphosed iron formation of his carbonate or non-clastic silicate facies.

The succeeding unit at Keystone (number 3 on table 1) is exposed in block V as well as block VI (figs. 2 and 3). The older part of this unit has quartz-mica schist and quartzite similar to the Ellison formation, and the upper part has mica-garnet schist and metamorphosed iron formation similar to rocks in the Flag Rock formation 3/.

This unit is followed at Keystone by quartz-mica schist and quartz-mica-staurolite schist (number 4 of table 1) that extend over a wide area in blocks V and VI. Lithologically this rock is very similar to staurolite-bearing schists of the Grizzly formation that R. G. Wayland has shown the

1/ Noble and Harder, op. cit., p. 964-965.

2/ James, 1955, op. cit., p. 1474-1478.

3/ Noble and Harder, op. cit., p. 947-952 and 959-960.

author near the railroad station in Deadwood, at the northeast edge of the map published by Noble and Harder 1/.

At Keystone there is at least one unit containing abundant graphitic schist with quartz-mica and quartz-mica-staurolite schist on each side (numbers 4, 5, and 6 of table 1). Similar graphitic schist has not been mapped elsewhere in the Black Hills. Noble and Harder 2/ note that some parts of the Grizzly formation are extremely graphitic.

The area southeast of Custer also contains rocks having similarities to the Lead section. Here the older rocks are to the east and the younger are to the west. The rocks are truncated above unit 3 (table 1) by a probable fault.

The key to the sequence from units 6 to 9 of table 1 is the Oreville formation. The type section was described by Redden 3/ at the Oreville railroad siding, 7 miles north of Custer. This unit consists predominantly of thin-bedded biotite-garnet and biotite schists, but also contains beds of quartzite and beds of schist rick in microcline, graphite, or amphibole. The biotite-garnet schist of the Keystone district (fig. 3) probably belongs to this formation.

The Oreville formation has also been recognized in various parts of the Hill City area. North of Hill City the metamorphic grade decreases until the garnet crystals are less than 1 mm. across and the groundmass consists of very fine-grained quartz, mica, and chlorite. Noble and Harder

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1/ Op. cit.

2/ Idem, p. 952.

3/ Op. cit.

and their colleagues [1] have mapped similar rocks as a unit they call the Uncle Sam formation, overlying the Grizzly formation near Roubaix, 6 miles southeast of Lead. Specimens collected by R. G. Wayland from this unit are lithologically the same as the Oreville formation.

The Oreville formation is in contact with very quartzose schists in many places. One such place is in sec. 1 of the Keystone district (fig. 3), where biotite-garnet schist is in contact with a unit consisting of quartz schist and quartzite. The other side of the Oreville formation is in contact with more micaceous schists in both the Custer and Hill City areas. Evidence for the age order from truncated cross-bedding and a few imperfect examples of graded bedding suggests that the quartzose schists are older and the micaceous schists younger than the Oreville. Furthermore, the quartzose schists resemble units 4 and 6 at Keystone, which may correspond to the Grizzly formation, and thus would be older than the Uncle Sam and Oreville formations. For these reasons the age order for units 6-9 of table 1 is the best that can now be suggested.

The upper three units of table 1 are the Bugtown, Crow, and Mayo formations described by Redden [2] in the area west of Custer. The Bugtown formation has been traced into the area west of Hill City, but its relations to other quartz- and mica-rich rocks there are not known.

In the Custer district these three formations are exposed in a syncline that plunges 40° S. 5° E. Most of the exposures are on the east limb of this syncline; all but a small part of the west limb is covered by Paleozoic rocks. The structure of this syncline is brought out graphically on Redden's

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1/ Harder, J. O., personal communication, 1948.

2/ Op. cit.

map 1/ by the trace of the Crow formation on the limbs of the syncline. The Crow formation, though only about 200 feet thick, contains a great variety of rocks: amphibole schists of various kinds, impure marble, cordierite-biotite schist, microcline-biotite schist, quartz-mica-feldspar schist, and quartzite. The other two formations--the Mayo above and the Bugtown below the Crow--consist mostly of quartz-mica schists. The Mayo formation also contains many beds rich in staurolite and garnet and a few beds derived from grit and conglomerate. The estimated thickness of this series of three units is 40,000 feet; neither the top nor bottom are exposed.

A major thrust fault passing through Custer truncates the Bugtown, Crow, and Mayo formations on the east limb of this syncline. These three formations have not been definitely recognized in any other part of the Black Hills, and thus their age with respect to units 1-9 in table 1 cannot be known precisely. Reconnaissance to the north, however, suggests that some of the units 2-8 of table 1 may occur beneath the Bugtown formation, and thus the age order shown in table 1 is suggested.

Structural Geology of the Metamorphic Rocks

The rocks throughout the southern Black Hills are isoclinally folded. In addition, the isoclinal folds were deformed by later cross folds, similar to the cross folds at Lead 2/. The strike of bedding is north to northwest and dips are more than 50° in most of the southern Black Hills. The Keystone district, as discussion on later pages will show, contains many isoclinal

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1/ Op. cit.

2/ Noble, J. A., Harder, J. O., and Slaughter, A. L., 1949, Structure of a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 60, p. 321-352.

folds that have plunges ranging from nearly vertical, in the area northeast of the large northwesterly trending fault, to relatively low angles in the west and southwest (fig. 4).

The large syncline west of Custer has many small isoclinal folds on the limbs of the main fold. The isoclinal fold pattern is shown best on Redden's map 1/ by the distribution of the Crow formation.

Elsewhere in the Custer area and in the Hill City area isoclinal folds have been mapped in many places. Plunges are generally between 30° and 70° to the south near Custer. Plunges of isoclinal folds are at low angles, either north or south, in much of the Hill City area.

The isoclinal folds are deflected around many of the larger masses of pegmatite and granite. In places domal structures have been formed in which the isoclinal folds are recumbent. The largest dome is in the area surrounding Harney Peak, where the strikes of bedding and schistosity are approximately parallel to the border of the main mass of granite and pegmatite, and the dips are outward at moderate to low angles. Both Balk 2/ and Runner 3/ recognized these relations, and ascribed the doming to force of intrusion of the granitic rocks. These relations are most apparent along the north edge of the Harney dome. Strikes are northerly and dips are steep only about 5 miles north of the granite contact, as shown on the map and structure sections by Darton and Paige 4/. As the area of granitic rocks is approached, however, the average strike changes to westerly and the dip assumes a low angle.

1/ Op. cit.

2/ Balk, Robert, 1931, Inclusions and foliation of the Harney Peak granite, Black Hills, S. D.: Jour. Geology, v. 39, p. 736-748, especially fig. 1 and p. 737.

3/ Runner, J. J., 1943, Structure and origin of Black Hills Precambrian granite domes: Jour. Geology, v. 51, p. 431-457, especially fig. 1 and p. 440-441.

4/ Op. cit.

In detail, this change in the attitude of isoclinally folded rocks is much more complex than the necessarily generalized mapping by Balk and Runner could show. The change may have been in large part doming caused by force of intrusion, but it was associated with faulting, which may also have been caused by force of intrusion. Faults have been mapped in the Keystone district (figs. 3 and 4) on the northeast flank of the Harney dome, and also in the areas mapped by J. A. Redden and R. G. Wayland on the northwest and southwest flanks of the Harney dome. However likely it may be that there are also faults to the north in the central part of the Black Hills Precambrian core, the fact remains that they have not been recognized. Thus it may be supposed that faults are more abundant in the area around the Harney dome, and that the process of faulting was a part of the mechanism of emplacement of the large intrusives. The northwest part of the Keystone district (figs. 1, 3, and 4) illustrates, in detail, the structure of part of the north flank of the Harney dome. It is true that the dips in much of this area are at a low angle and the strikes are diverse, in contrast to the steep dips and north to northwest strikes that are common elsewhere in Black Hills Precambrian rocks. On the other hand, this area is intensely faulted, and it seems likely that these and similar faults must be an important structural element on the flanks of the Harney dome.

Smaller domes elsewhere are either known to be associated with intrusives, or it may be suspected that unexposed intrusives lie at depth. Near the large pegmatites in the S. 1/2 sec. 17 and in sec. 20 of the Keystone district, bedding is warped and partially domed (figs. 3 and 4). Further east, in secs. 15 and 22, the schists have a domal structure that may reflect underlying intrusives larger than the pegmatites that reach the surface.

Similarly, south of Custer, bedding is deflected around large intrusives 1/. A dome 3 miles northwest of Custer has a folded thrust fault mapped by Redden; any associated intrusive, if present, is unexposed.

The structure near Bear Mountain, 9 miles west-southwest of Hill City, is described by Runner 2/ as a similar dome around an intrusive.

Pegmatites of the Southern Black Hills

The pegmatites and the so-called granite around Harney Peak are the most prominent geologic feature of the southern Black Hills. The concentration of these rocks is greatest near Harney Peak (fig. 1). The concentration decreases sharply to the northeast toward Keystone and to the northwest toward Hill City. These intrusives are abundant, however, in much of the area south of Harney Peak, extending as far as the Paleozoic contact.

Nomenclature

Rock names.--The granitic rocks of the southern Black Hills have been divided into pegmatite and Harney Peak granite in the published literature but no attempt has been made to define a distinction between the two 3/. Several authors have stated that the so-called granite has many of the

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1/ Redden, op. cit.

2/ Runner, 1943, op. cit., especially fig. 1 and p. 441.

3/ Paige, Sidney, 1925, Precambrian rocks, in Darton, N. H., and Paige, Sidney, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219, p. 3-5.

Runner, 1943, op. cit.

Page, L. R., and others, 1953, Pegmatite investigations 1942-1945 Black Hills, S. D.: U. S. Geol. Survey Prof. Paper 247.

characteristics of pegmatite 1/. Paige, for example, said 2/, "Much of the granite is so very coarse grained that it may be called pegmatite."

There are all gradations from intrusives that consist virtually entirely of pegmatite to intrusives in which true, coarse-grained pegmatite is a minor constituent. Or, stated another way, there are all gradations from intrusives that consist predominantly of leucocratic soda granite, or less commonly aplite, to those containing almost no rock that can compositionally or texturally be called either granite or aplite. The contacts between these varieties of rock are gradational; commonly the gradation is over a distance of several feet, but in other places it is over a distance of only a fraction of an inch. Contacts may be planar or highly irregular. In many places a contact could be drawn, if one were so inclined, between a "granite" groundmass and "pegmatite" consisting of a single large crystal of perthite. Furthermore, the groundmass could be subdivided into "granite" and "aplite" with gradational and highly debatable boundaries. Many Black Hills pegmatites that have been widely described in geologic literature--including the Etta and Peerless, which have never been called anything but pegmatite--contain units of "granite" or "aplite".

Thus, this problem of nomenclature can be resolved into the simple question of whether to use one rock name or as many as three names for what, in any practical sense, is a single rock. Henceforth in this thesis the

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1/ Paige, op. cit., p. 4.

Schwartz, G. M., 1925, Geology of the Etta spodumene mine: Econ. Geology, v. 20, p. 648.

Runner, 1943, op. cit., p. 447.

Page and others, op. cit., p. 6-7.

2/ Paige, op. cit., p. 4.

name pegmatite will ordinarily be used. All of these rocks, considered in outcrop rather than hand specimen size, have the great range in grain size that is characteristic of pegmatite 1/. Plagioclase is more abundant than potassic feldspar; this is true of most of the pegmatites the author has seen in South Dakota, Colorado, New Mexico, North Carolina, Virginia, and Ontario, yet the converse is true of normal granite 2/. Tourmaline and garnet are the dominant dark minerals. Biotite is the only dark mineral in these rocks that is typical of granite; biotite is not only uncommon, but where it occurs at all, it is ordinarily in crystals more than 1 inch across, and in some places more than 1 foot across. As a matter of semantics, it seems doubtful if any name but pegmatite means a rock of this sort to most geologists.

"Pegmatite" as a structural term.--An additional difficulty in nomenclature is introduced by the widespread practice of using "pegmatite" not only as a rock name, in the petrographic sense, but also in reference to a body of rock, in the structural sense. The usage is essentially structural when authors describe "homogeneous" and "heterogeneous" pegmatites 3/, "zoned and unzoned pegmatites" 4/, "the internal structure of granitic

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1/ Stokes, W. L., and Varnes, D. J., 1955, Glossary of selected geologic terms: Colo. Sci. Soc. Proc., v. 16, p. 104.

2/ Turner, F. J., and Verhoogen, Jean, 1951, Igneous and metamorphic petrology: New York, McGraw-Hill Book Co., Inc., p. 65.

Johannsen, Albert, 1932, A descriptive petrography of the igneous rocks, v. 2, The quartz-bearing rocks: Chicago, Univ. Chicago Press, p. 124.

3/ Johnston, W. D., Jr., 1945, Beryl-tantalite pegmatites of northeastern Brazil: Geol. Soc. America Bull., v. 56, p. 1025.

4/ Cameron, E. N., Larrabee, D. M., McNair, A. H., Page, J. J., Shainin, V. E., and Stewart, G. W., 1945, Structural and economic characteristics of New England mica deposits: Econ. Geology, v. 40, p. 373.

pegmatites" 1/, "the Etta pegmatite" 2/ or "Pegmatite 537" 3/. These rock bodies occur as dikes, sills, lenticular masses, tear-drop shaped bodies, pipes, or in many more irregular forms. The only available all-inclusive structural term is "pegmatite", unless one wishes to use the frequently awkward terms "pegmatite body" or "pegmatite mass" 4/. Inasmuch as the context can show clearly whether the petrographic or structural sense is intended, the word "pegmatite" will be used with both meanings in this report. [redacted]

Pegmatite units.—A well-defined terminology has been established in recent years for the units within "zoned pegmatites" 5/ or "heterogeneous pegmatites" 6/. The definitions are as follows, from Cameron and others 7/:

> "The lithologic and structural units found within pegmatite bodies differ in mineralogy or texture, or both. Three basic types of units are distinguished and are defined as follows:
>
> 1. Fracture fillings are units, generally tabular, that fill fractures in previously consolidated pegmatite.
>
> 2. Replacement bodies are units formed primarily by replacement of pre-existing pegmatite, with or without obvious structural control.

1/ Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., 1949, Internal structure of granitic pegmatites: Econ. Geology Mon. 2.

2/ Schwartz, op. cit., p. 651.

3/ Staatz, M. H., and Trites, A. F., 1955, Geology of the Quartz Creek pegmatite district, Gunnison County, Colorado: U. S. Geol. Survey Prof. Paper 265, p. 54.

4/ Jahns, R. H., 1955, The study of pegmatites: Econ. Geology, Fiftieth Anniversary Volume, p. 1030.

5/ Cameron and others, 1945, op. cit., p. 372-373.

6/ Johnston, op. cit., p. 1024-1025.

7/ Cameron and others, 1949, op. cit., p. 14.

3. Zones are successive shells, complete or incomplete, that reflect to varying degrees the shape or structure of the pegmatite body. Where ideally developed, they are concentric about an innermost zone or core. Some concentric units, however, are not zones but belong in the categories above".

Zones have been further classified into border zone, wall zone, intermediate zones, and core according to their position within a single pegmatite 1/.

These terms will be used in this thesis wherever they are applicable. Examples of fracture fillings, replacement bodies, and zones are illustrated in figures 6 and 7.

Grain-size classification.--Pegmatites have such variable grain size and so many large crystals that it has been found desirable to establish a special grain size classification for use in these rocks. The word "pegmatitic" is not sufficiently specific for use in describing textures. The size classification that will be used here is the same as suggested by Cameron and others 2/ except that the very fine-grained (or aplitic) category has been added.

Very fine-grained (or aplitic)	Less than 0.1 inch (0.25 cm.)
Fine-grained	0.1 to 1 inch (0.25 to 2.5 cm.)
Medium-grained	1 to 4 inches (2.5 to 10.2 cm.)
Coarse-grained	4 to 12 inches (10.2 to 30.5 cm.)
Very coarse-grained	More than 12 inches (30.5 cm.)

1/ Cameron and others, 1949, op. cit., p. 20-59.

2/ Idem, p. 16.

Types of Pegmatites

The pegmatites of the southern Black Hills can be conveniently classified in three categories: (1) zoned pegmatites, (2) homogeneous pegmatites, and (3) layered pegmatites. All gradations between these categories can be recognized. Nevertheless, this classification aids in understanding the geologic relations, distribution, petrology, and genesis of the various types of pegmatite.

Ultimately a fourth category, perhaps called "leucocratic soda granite", may be necessary for rocks that contain only a small quantity of coarse-grained material. These rocks occur chiefly on the southeast flank of the Harney dome. They have yet to be adequately mapped and described, and until they are, they are best regarded as an extreme phase of what will here be called layered pegmatite.

Zoned pegmatites.--The zoned pegmatites are the ones for which the three varieties of pegmatite units--zones, replacement bodies, and fracture fillings--were originally defined. Zones are the dominant units, as in figures 6 and 7 and in many maps and sections published by Page and others 1/. Fracture-filling units are best illustrated in the Big Chief pegmatite (fig. 6); in most other pegmatites fracture-filling units are smaller and less abundant than in the Big Chief pegmatite. The best example of a replacement unit in the southern Black Hills is in the Hugo pegmatite (fig. 7), which will be discussed in more detail on later pages. A similar replacement unit has also been mapped in the Peerless pegmatite 2/. Elsewhere in the southern Black

1/ Op. cit.

2/ Sheridan, D. M., Stephens, H. G., Staatz, M. H., and Norton, J. J., Geology and beryl deposits of the Peerless pegmatite, Pennington County, S. D.: U. S. Geol. Survey Prof. Paper 297A, in press.

Hills the only replacement units consist of irregular aggregates of quartz and muscovite that in part cut across the zonal structure; even the largest of these contain only a few hundred tons of rock, and adequate evidence for a replacement origin is difficult to find.

Mining has been mostly in the zoned pegmatites, and nearly all previous studies have been on pegmatites of this type. Nevertheless, the homogeneous and layered pegmatites are far more numerous.

Homogeneous pegmatites.--The distinguishing characteristic of the homogeneous pegmatites is their lack of any conspicuous zoning, layering, or other internal structure, although the grain size ordinarily increases inward from the contact and very thin, fine-grained border and wall zones may be recognizable. Most of these pegmatites consist almost entirely of plagioclase-quartz-perthite pegmatite in which the perthite occurs as coarse crystals in a fine- to medium-grained groundmass that is chiefly quartz and plagioclase. A few of these pegmatites are made up of quartz-plagioclase-muscovite pegmatite. Fracture-filling units containing quartz, perthite, plagioclase, and muscovite are no less common than in layered and zoned pegmatites; and segregations of coarse-grained pegmatite or even poorly defined layering can be found in places. Nevertheless, all of these structures are relatively insignificant in homogeneous pegmatites.

Layered pegmatites.--The distinctive feature of layered pegmatites is the presence of layers differing in composition, texture, or both. Ordinarily these layers are approximately parallel to the contact. The most common variety of layering is formed by coarser-grained lenses and layers, consisting chiefly of perthite, quartz, and plagioclase, surrounded by finer-grained rock in which plagioclase and quartz are the dominant minerals. Quantitatively, the proportion of these two types of rock ranges greatly from one intrusive to another and from one place to another in a single intrusive; the average is about one-third of the coarser-grained material to two-thirds of the finer-grained pegmatite.

In the coarser layers, crystals of perthite or graphic granite 4 inches to 5 feet long are in a groundmass of quartz and albite-oligoclase in which the grain size is ordinarily between 1/2 and 2 inches. In places, there are very coarse- or coarse-grained lenticular to pod-like segregations of quartz-perthite pegmatite or even quartz pegmatite.

Contacts of coarse layers are ordinarily gradational. Many are so vaguely defined that only by standing at a distance can one see that the perthite-rich parts of the rock are in layers or in parallel elongate aggregates. On the other hand, a few contacts are so sharp as to suggest that the coarse layers are actually fracture-filling units concordant with the layered structure, and that is what they may well be. In the outer parts of many of these, tourmaline and perthite crystals are oriented normal to the contact with the adjacent finer-grained layer; the same orientation is common at the edge of fracture-filling units and at the outer contacts of many pegmatites.

The finer-grained layers consist chiefly of quartz and albite-oligoclase, but may have 5 percent or more microcline, muscovite, or tourmaline. The average grain size is ordinarily between 1/4 and 1-1/2 inches. Some of the layers, however, have an average grain size of less than 1/4 inch, commonly even aplitic.

Many of the fine-grained layers are divided into still smaller layers differing from each other in the content of quartz, plagioclase, muscovite, tourmaline, or garnet. The average thickness of such layers is about 0.1 inch. Some of these thin layers contain as much as 90 percent quartz, plagioclase, or muscovite; others have as much as 50 percent tourmaline or garnet.

Layers of this kind have ordinarily been called "line rock" in other pegmatite districts 1/.

Many coarse-grained layers have offshoots that cut across adjacent fine-grained rock. This evidence for age relations cannot, however, be used to show that all of the coarse-grained rock is necessarily younger than all of the fine-grained rock. Fine-grained layers near the center of a pegmatite may well be younger than coarse-grained layers near the outer edge of the same pegmatite.

Layered pegmatites also contain cross-cutting fracture-filling units as much as 5 feet thick consisting of perthite-quartz-plagioclase, quartz-perthite, or quartz pegmatite. Many of these fracture-filling units have wall zones rich in muscovite and plagioclase. These are, in effect, zoned pegmatites within layered pegmatites.

Size of Pegmatites

The pegmatites of the southern Black Hills range greatly in size and have a wide variety of structural forms. The smallest pegmatites are lenticular aggregates, as little as 2 inches in length, that are concordant with the schistosity of the wall rock. These very small pegmatites, however, are generally very near much larger intrusives, to which they may be tributary. Pegmatites that are far enough from any other intrusives to be considered

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1/ Schaller, W. T., 1925, The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., v. 10, p. 273.

Jahns, R. H., and Wright, L. A., 1951, Gem- and lithium-bearing pegmatites of the Pala district, San Diego County, California: Calif. Div. Mines Special Rept. 7-A, p. 22.

Staatz, M. H., and Trites, A. F., 1955, Geology of the Quartz Creek pegmatite district, Gunnison County, Colorado: U. S. Geol. Survey Prof. Paper 265, p. 23-24.

essentially independent are rarely less than 30 feet long or 2 feet thick. Pegmatites as small as this may be layered, homogeneous, or zoned.

The largest pegmatites are layered. Probably the largest is the pegmatite that forms Harney Peak; it may be several hundred feet thick and cover several square miles. Many other layered pegmatites are thousands of feet long and more than 100 feet thick. Most of these are near Harney Peak, but the area containing large intrusives extends into the southwestern part of the Keystone district (fig. 3).

At least 90 percent of the homogeneous and zoned pegmatites are between 30 and 400 feet long and less than 50 feet thick. The three largest zoned pegmatites for which the dimensions beneath the surface are well known are the Hugo and Peerless in the Keystone district and the Helen Beryl in the Custer district. Each of these contains at least 500,000 tons of rock, and the largest may have contained nearly 2,000,000 tons before erosion. Few other zoned pegmatites are as large as these, and it is clear that any zoned pegmatite containing 1,000,000 tons of rock is unusual.

The largest homogeneous pegmatite is about the same size as the largest zoned pegmatite. The Diamond Mica North pegmatite in the NE 1/4 sec. 17 in the Keystone district (fig. 3) has been found by drilling to contain approximately 500,000 tons of rock to a depth of 150 feet. The pegmatite is tear-drop shaped and pinches in depth. The tonnage beneath the drill holes probably is not great enough to make the total quantity of rock more than 1,000,000 tons. No homogeneous pegmatite elsewhere in the southern Black Hills is known to be larger than this.

Thus, it may be concluded that in the southern Black Hills the largest layered pegmatites are far larger than any of the homogeneous or zoned pegmatites.

Shape and Structural Relations to Adjacent Rocks

Pegmatites of the southern Black Hills occur as sills and dikes, and in many irregular forms. In a gross sense, most of the intrusives have a tabular to lenticular form, but in many places they are sinuous, branching, or arcuate. The smaller intrusives are commonly thickly lenticular, tear-drop shaped, or pipe-like. Typical forms are shown by Page and others 1/ and the Keystone geologic map (fig. 3). Geologic maps of the Custer and Keystone district show that approximately 70 percent of the homogeneous and layered pegmatites are essentially concordant, 85 percent of minable zoned pegmatites are concordant, and 90 percent of the 33 major mines shown on figure 1 are in concordant pegmatites.

Most of the zoned pegmatites are thickly lenticular to tear-drop shaped. The upper end of a pegmatite is commonly blunt, and the lower part is thinly tapering. One of the prominent characteristics of these pegmatites is their great thickness in relation to other dimensions. The plane defined by the intermediate and long axes of nearly all zoned pegmatites is approximately parallel to the schistosity of the country rock. Locally, however, contacts are cross-cutting. The plunge, or longest axis of each pegmatite, is most commonly parallel to the plunge of nearby isoclinal folds.

1/ Op cit., fig. 1.

Some of the pegmatites that intrude competent rocks, especially amphibolite, have branching forms. An example is the Bull Con in the SE 1/4 sec. 9, in the Keystone district (fig. 3).

Irregular multiple intrusives are uncommon among the zoned pegmatites. The Edison, SE 1/4 sec. 9, is the only good example illustrated on the Keystone map (fig. 3). Page and others 1/ describe this pegmatite as consisting of at least six separate intrusives. Boundaries between the separate intrusives can be recognized by the presence of schist septa and by wall zones of adjacent intrusives in contact with each other.

Multiple intrusives are common among the large layered pegmatites of the Harney region. Runner 2/ called this a "multiple sill structure", and was the first to describe it clearly as a structure that is separate, though similar in general appearance, to what is here called the layering of these pegmatites. The complex outlines of these multiple intrusives are illustrated in secs. 20 and 21 in the southern part of the Keystone district (fig. 3). In sec. 21, for example, the map shows many parallel dikes coming together to form a single mass consisting almost entirely of pegmatite. Discontinuous thin schist septa surrounded entirely by pegmatite can be found, but except in a few places, as in the pegmatite in the E. 1/2 sec. 21 (fig. 3), they are not large enough to be mapped. These schist septa have the same attitude as the surrounding country rock; none have been found that were clearly inclusions in a liquid and have attitudes bearing no apparent relation to the attitudes of structural features in the wall rock.

1/ Op. cit., p. 111.

2/ Op. cit., 1943, p. 442-443.

Multiple intrusive structures are common throughout the Harney dome. In places the age relations are so complex among contiguous intrusives, one intruding another, that only by very large scale planetable mapping will the structure ever be worked out in detail. These multiple intrusives are very similar to those described by Noble 1/ in the northern Black Hills and in the Sierra Nevada batholith. They indicate, as Noble concludes, that large intrusives may grow by accretion through successive injection of many smaller bodies.

Distribution

The pattern of the distribution of pegmatites in the southern Black Hills is shown in figure 1. This map was compiled from geologic maps of the Custer and Keystone districts and from aerial photographs. The area around Harney Peak containing 50 percent or more pegmatite and granite is in large part the same as the area shown as granite on the map by Darton and Paige 2/. The rocks of this area may conveniently be called the "main intrusive", remembering, of course, that it actually consists of many small intrusives.

Surrounding this central area there are approximately 15,000 pegmatites. Isopleths on figure 1 show the distribution of these pegmatites in terms of the number of pegmatites per square mile; the number of intrusives is also approximately proportional to the size of the intrusives, and thus the isopleths show in a general way the quantity of pegmatite at any place on the map.

1/ Noble, J. A., 1952, Evaluation of criteria for the forcible intrusion of magma: Jour. Geology, v. 60, p. 34-57.

2/ Op. cit.

The abundance of pegmatites decreases sharply north of Harney Peak. To the south, however, pegmatites are widely distributed. The greatest concentration of pegmatites is along a line that goes south-southwest from Harney Peak. It may be that the main intrusive plunges south-southwest--that is, that it was intruded upward from a point to the south-southwest of Harney Peak. If this is so, the reason for the concentration of pegmatites at the surface along a south-southwesterly trending line becomes apparent; these pegmatites would be in the roof above the deeply buried, plunging main intrusive.

The metamorphism of the country rock associated with these intrusives supports this interpretation of plunge. The sillimanite isograd is near the north border of the Harney dome, and metamorphism drops off sharply to the north. The narrowness of the sillimanite zone north of the main intrusive suggests that it is dipping steeply. South of the main intrusive, however, a broad area contains sillimanite (fig. 1). Thus, in this region the border of the sillimanite zone probably has a gentle dip, and the top of the main intrusive would have a correspondingly gentle inclination.

Layered pegmatite is characteristic of the areas on figure 1 containing more than 50 percent pegmatite. Among the estimated 15,000 pegmatites outside of these areas, however, homogeneous pegmatites predominate, though the layered variety is common. Approximately 150, or 1 percent, of the total number of pegmatites are zoned pegmatites. Thirty-three of these are large minable deposits, each of which has been or could certainly be the source of industrial minerals having a total value of more than $100,000 at 1955 prices. The locations of these pegmatites are shown in figure 1 under four categories, according to their principal mineral products: (1) potash feldspar mines, (2) sheet mica mines, (3) beryl-scrap mica mines, and

(4) lithium mines. These large zoned pegmatites, and many smaller ones as well, are chiefly in the outer parts of the pegmatite-bearing region. Thus, in a general way, it may be said that there is a regional zonation in the distribution of the pegmatites: layered pegmatites tend to be in the center, followed by homogeneous pegmatites, and then by zoned pegmatites in the outer parts of the region.

Generalizations of this sort appear widely in the pegmatite literature 1/. The concept, as ordinarily expressed, is that a large granitic intrusive in the center is surrounded by zones containing various types of pegmatites. In such a simple form, this concept can be supported only in a generalized way by any published map known to the author, just as it is supported only in a generalized way by figure 1. Cameron and others 2/ state:

> "....regional zoning, if it indeed exists, is far from clearcut. There must be much overlapping of zones, for in many districts several types of pegmatites occur side by side."
>
> "The concept of zonal distribution is appealing in its simplicity, but it may be that factors other than distance are of equal or greater importance in controlling the distribution of types of pegmatites."

The complications may be caused in part by chemical and structural factors that influence the crystallization history of any single pegmatite. These will be discussed in later pages, where the geology of the Keystone pegmatites will be considered in sufficient detail to explain, in some degree at least, why layered, homogeneous, and various kinds of zoned pegmatites can occur together.

The complications may also be caused in part by elements of the regional geology that can be clarified by consideration of figure 1.

1/ Heinrich, E. W., 1953, Zoning in pegmatite districts: Am. Mineralogist, v. 38, p. 68-87.

2/ Op. cit., 1949, p. 8.

Zoned pegmatites occur chiefly between the isopleths for 0 and 100 pegmatites per square mile. Many of the zoned pegmatites are in a belt that extends from Keystone west to Hill City, then goes south-southwest, and finally passes beneath Paleozoic rocks southwest of Custer. Zoned pegmatites also occur in a belt east of the long area of abundant pegmatites that trends south from Custer. This belt has a generally northerly trend, but near Custer it turns to the northeast along the south flank of the Harney dome. The map suggests that zoned pegmatites should be found along the southeast side of the Harney dome and also near the pegmatite-rich area in the southeastern part of the Precambrian rocks. These areas, however, are in Custer State Park where mining and prospecting have not been permitted for many years and the absence of zoned pegmatites may be more apparent than real.

If the isopleths of figure 1 are pictured as contours describing an imaginary surface, then it can be seen that this surface contains many domes. In effect, these domes are either cupolas in the top of the main intrusive or they are satellitic intrusives.

The distribution of most of these domes is unexplainable in terms of anything known about the pre-intrusion geology of the metamorphic rocks. The only important exception is a thrust fault mapped by Redden along the east side of the elongate dome south of Custer. This thrust fault coincides so closely with the east side of this dome that it must be related to the distribution of pegmatites. Either the intrusive process was in part controlled by the fault or the rock units west of the fault were more readily penetrated by pegmatite fluids than those to the east.

Zoned pegmatites are most abundant on the lower parts of the flanks of these domes, both around the main Harney dome and the many smaller ones in outlying areas. The 0, 50, and 100 isopleths indicate that in many places the imaginary surface formed by the isopleths has a low angle of slope and a gently undulating shape. In these places zoned pegmatites are found over broad areas. Southeast of Keystone, for example, there are many zoned pegmatites in a broad depression in the isopleth "surface". Similar, but larger, areas are southeast and southwest of Custer. The area southwest of Custer is in a large syncline. Part of the reason for distribution of pegmatites over this broad area may be that the ascending pegmatite solutions were dispersed outward as they passed through the limbs of this syncline.

On the other hand, where the isopleths are closely spaced and the "surface" is very steep, zoned pegmatites are concentrated in a correspondingly narrow belt. This is true south-southeast of Custer and also southwest of Keystone. The isopleths are very closely spaced on the north flank of the Harney dome, and it may be expected, in a statistical sense, that very few zoned pegmatites will be exposed. Actually only two zoned pegmatites large enough for mining have been found in this area.

Figure 1 also suggests a pattern in the distribution of the various economic varieties of zoned pegmatites, which for this purpose have been classified according to their predominant mineral products, either potash feldspar, lithium minerals, sheet mica, or scrap mica and beryl. Potash feldspar, scrap mica-beryl, and lithium mines are mostly between the 0 and 50 isopleths. All but one of the nine lithium mines shown on figure 1 are adjacent to steep gradients in the isopleths. This may mean that lithium-rich fluids are more commonly ejected from the sides of the source magma than from the top.

On the other hand, all of the sheet mica mines large enough to show on figure 1 are southwest of the Harney area, and thus are presumably in the roof of the main intrusive. Some of these are in areas containing more than 150 pegmatites per square mile. These relations suggest that pegmatite fluids that form zoned pegmatites containing sheet mica are more likely to be ejected from the top of a source magma than from the sides. Water would be likely to concentrate in the top of the magma, and sheet mica pegmatites probably are generally richer in OH than other zoned pegmatites. Furthermore, the abundance of pegmatites near Custer suggests a high temperature environment, which would favor slow cooling and the development of the large well-formed muscovite crystals that are characteristic of sheet mica pegmatites, but are rare in the areas containing lithium pegmatites.

It is interesting to note that similar relations have been observed near Shelby and Kings Mountain, N. Car., in the only other area in the United States that contains both sheet mica and lithium pegmatites. The pegmatites in that region are near the Cherryville quartz monzonite batholith, which strikes northeast and has a moderate dip to the northwest 1/. The spodumene pegmatites of the Kings Mountain district are on the footwall side of this batholith, and the sheet-mica pegmatites near Shelby are on the hanging-wall side of the batholith.

METAMORPHIC ROCKS OF THE KEYSTONE DISTRICT

The Keystone district consists of intricately folded metamorphic rocks cut by many faults and intruded by ortho-amphibolite and pegmatite. In order to simplify discussion of the structure and stratigraphy, the Keystone district has been divided into the seven structural blocks designated by Roman numerals in figure 2; three of these blocks have been subdivided into smaller blocks designated by letters. The borders of all of these

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1/ Griffitts, W. R., personal communication, 1956.

blocks are faults. Probably the largest of these faults is a great transcurrent fault along the boundary between blocks V and VI (figs. 2, 3, and 4), but many of the others are large enough to cause difficulty in correlating stratigraphic units from one part of the district to another.

The Keystone district contains many tight folds, and in discussing stratigraphic and structural relations it will be convenient to use the terms "left-hand folds" and "right-hand folds", corresponding to the "sinistral" and "dextral" folds of White and Jahns 1/. This terminology is based on the common practice of using the shapes of drag folds to determine the relative movement of adjacent beds. If an observer looks across such a fold in a direction normal to the axial plane and notes that the beds at a distance moved to the left with respect to the beds on which he is standing, the fold is left-hand. Conversely, if the movement was to the right, the fold is right-hand. This terminology is useful only in plan; the corresponding terminology that will be used in section is "east-over-west" and "west-over east". Figure 4 has examples of left-hand folds near the center of sec. 9, and right-hand folds in the SW 1/4 sec. 31. This terminology is similar to that suggested by Anderson 2/ for transcurrent faults.

Stratigraphic Sequence

The most satisfactory information that can be used to establish a stratigraphic sequence in the Keystone district is to be found in block VI A. Figure 4 shows that the structural pattern of this block is dominated by

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1/ White, W. S., and Jahns, R. H., 1950, Structure of central and east-central Vermont: Jour. Geology, v. 58, p. 197.

2/ Anderson, E. M., 1942, The dynamics of faulting: Edinburgh, Oliver and Boyd, p. 55.

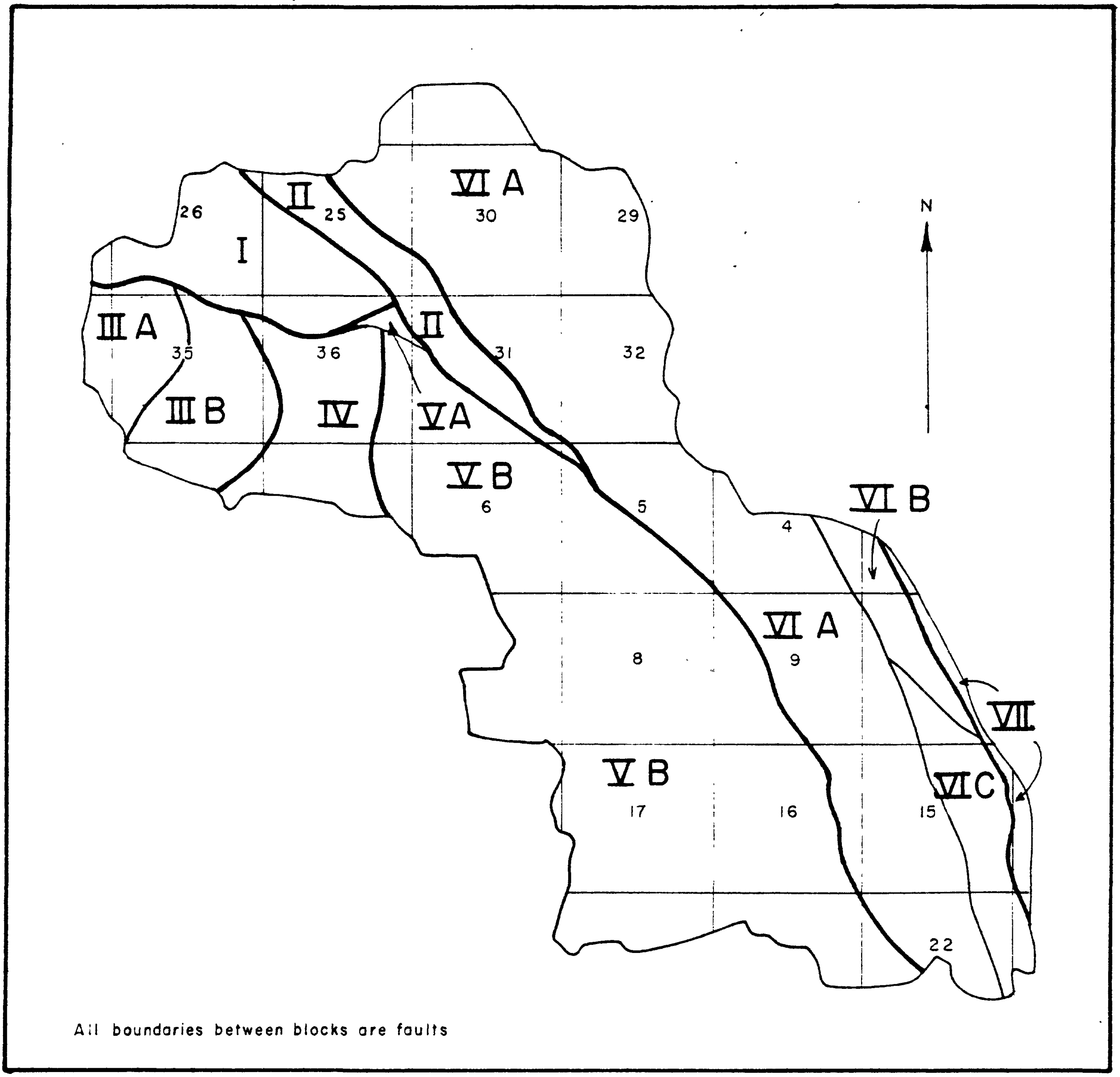

FIGURE 2.-STRUCTURAL BLOCKS, KEYSTONE DISTRICT

left-hand isoclinal folds on the west limb of a major syncline. The axial planes strike in a northerly direction; they are cut off on the south by the major transcurrent fault that separates blocks V and VI (figs. 2, 3, and 4).

The older rocks of block VI A lie generally to the south and southwest in the cores of anticlines, and the younger rocks are to the north and northeast. The age relations have been established by truncated cross-bedding near the contact between the unit consisting of quartz-mica schist and quartz-mica-staurolite schist (unit 4 of table 2) and the unit consisting of mica-garnet schist, pseudoconglomerate, and other rocks (unit 3 of table 2). The best examples are on the ridge in the NE 1/4 SE 1/4 sec. 5 (fig. 3).

Along most of the southwestern boundary of block VI A the oldest rock unit exposed consists of amphibole schist, quartzite, and a few beds of mica-graphite schist (unit 2 of table 2). An older unit consisting of quartz-mica schist, quartz-mica staurolite schist, and quartz-mica-andalusite schist is exposed in two places. One is in the northwest part of block VI A in secs. 25, 30, and 31. The other is in block VI C, where it and the amphibole schist-bearing unit are the only rocks exposed. A thin discontinuous quartzite between these two units is best exposed in sec. 31; it is shown separately on the map (fig. 3), but it is essentially a part of the amphibole schist-bearing unit (unit 3 of table 2). A similar quartzite on the other side of the amphibole schist-bearing unit is well exposed in two areas: near the Edison mine (sec. 9) and northwest of Keystone in sec. 32.

The next major stratigraphic subdivision (unit 3 of table 2) consists of mica-garnet schist, pseudoconglomerate, quartzite, quartz-mica schist, and amphibole schist. This unit is exposed in a belt through block VI A

Table 2. **Distribution and tentative stratigraphy of metasedimentary rocks, Keystone district, S. Dak.**

Unit	Rock	Structural blocks (see fig. 2) I	II	III A	III B	IV	V A	V B	VI A	VI B	VI C	VII	Estimated thickness (in feet)	
9	Micaceous schists and quartzites: **Mica schist**				X								700+	2000+
	Quartz-mica schist and quartz schist				X								100-200	
	Quartz-mica-staurolite schist				X								200	
	Quartz-mica schist, quartz schist, and micaceous quartzite				X								100	
	Quartz-mica schist				X								100	
	Quartz-mica schist, quartz schist, and quartzite			X	X								600	
	Quartz-mica-staurolite schist			X									200+	
	--- Fault contact ---													
8	Biotite-garnet schist					X						X	500+	
7	Quartz schist and quartzite (also quartz-mica schist in block I)	X 1/				X							700+	
	--- Fault contact ---													
6	Quartz-mica schist and quartz-mica-staurolite schist (also quartz schist in block II)		X 1/					X 1/					1000+	
5	Mica schist, mica-graphite schist, and quartzite (in block II the predominant rocks are mica-graphite schist, amphibole schist, and microcline schist)		X 2/					X					700	
4	Quartz-mica schist and quartz-mica-staurolite schist (in block II the predominant rocks are quartz-mica schist and quartz schist)		X 1/				X	X 1/	X	X			3000	
3	Mica-garnet schist, pseudoconglomerate, quartzite, quartz-mica schist, and amphibole schist						X	X	X	X			200-900	
2	Amphibole schist, quartzite, and mica-graphite schist (including discontinuous quartzite units at either contact)								X	X	X		400	
1	Quartz-mica schist, quartz-mica-staurolite schist, and quartz-mica-andalusite schist								X		X		2000+	

1/ Correlations uncertain. These five units may in part correlate with each other. They are shown in separate patterns on the geologic map (fig. 3).

2/ Correlation uncertain. Shown in separate pattern on geologic map (fig. 3).

that extends from the north edge of the mapped area in sec. 19 southeast to Keystone and then south-southeast to sec. 22. In detailed mapping in sec. 9, southeast of Keystone, it was found that seven subdivisions of this unit can be recognized. The isoclinally folded traces of two horizons shown passing through the center of sec. 9 in figure 4 are based on this mapping; the subdivisions have not, however, been plotted on figure 3. The seven subdivision, in order from youngest to oldest, or from east to west, are:

	Estimated average thickness (Feet)
Mica-garnet schist, quartz-mica schist, pseudoconglomerate, and quartzite	300
Amphibole schist and quartzite	50
Quartz-mica schist and pseudoconglomerate	100
Amphibole schist and quartzite	50
Quartz-mica schist and pseudoconglomerate	100
Amphibole schist and quartzite	50
Quartz-mica schist	100
Total	750

The youngest unit in block VI A (unit 4 of table 2) consists of quartz-mica schist and quartz-mica-staurolite schist exposed through most of the eastern part of this block (figs. 2 and 3).

Units 2, 3, and 4 of table 2 are also exposed in block VI B, especially in sec. 10 (fig. 3). The structural pattern (fig. 4) indicates that they are on the east limb of a major syncline.

Units 3 and 4 are the predominant rocks of block V (table 2 and fig. 3). Though the structural geology of this block is complex, as later discussion will show, the distribution of rock types gives evidence of what the stratigraphic sequence may be. The two oldest units recognized in block VI (units 1 and 2 of table 2) are not exposed in block V. On the other hand, new and thus younger rocks consisting of mica schist, mica-graphite schist, and quartzite (unit 5 of table 2) are exposed in two places: (1) near the intersection of secs. 8, 9, 16 and 17; and (2) near the intersection of secs. 15, 16, 21 and 22.

The first of these extends for 0.4 mile east-northeast of the Hugo mine. This may be the core of a syncline that is faulted on the east side (figs. 3 and 4).

Unit 5, where exposed to the south in sec. 21 and adjacent areas, is succeeded on the southeast by quartz-mica schist and quartz-mica-staurolite schist designated unit 6 in table 2. Units 4, 5, and 6 may correlate with the three units in block II (figs. 2 and 3). If so, the lateral displacement along the transcurrent fault between blocks II and V is about 5-1/2 miles. The central unit in block II consists chiefly of mica-graphite schist, but also contains amphibole schist and microcline schist. In both blocks II and V, the rocks to the south of unit 5 contain more mica and staurolite than do those to the north.

The relationship between the rocks in block V and the rocks to the northwest presents troublesome stratigraphic problems. The southeastern part of block IV (figs. 2 and 3) contains biotite-garnet schist that can be correlated lithologically with the Oreville formation. It has already been shown that geologic relations elsewhere in the Black Hills suggest that the Oreville formation is younger than the sequence of rocks described in the immediate vicinity of Keystone (table 1).

The quartzose schists that extend throughout block I and most of block IV are so similar to each other lithologically that they probably are stratigraphically equivalent. More mapping is needed, however, in areas to the north and south to demonstrate the geologic relations between these two blocks. The beds of block I have easterly strikes and high angle dips; the beds in block IV have northerly strikes and low dips. Some of the schist in block I is lithologically similar to quartz-mica schist in block V, indicating that it may be transitional between units 6 and 7.

The suggestion that these quartzose schists are older than the biotite-garnet schist is supported by the only good example of truncated cross-bedding found in block IV (plate 1). The quartzose schists in block IV lie above the biotite-garnet schist (section AA, fig. 3). The truncated cross-bedding of plate 1 indicates that the quartz schist is upside down near the center of sec. 36. This is far from the contact with biotite-garnet schist, however, and there may be many small unrecognized folds in the area in between. Thus, the evidence from truncated cross-bedding is by no means conclusive.

Block III contains micaceous schists similar to schists that have been found in the Hill City area on the opposite side of the Oreville formation from the quartzose schists (table 1). Thus, these schists are probably younger than the biotite-garnet schist of block IV. The rocks of block III constitute unit 9 of table 2. These rocks have been intensely folded and faulted and they were subdivided into seven units (see table 2 and fig. 3) for the purpose of working out the structure and stratigraphy. Ultimately all of these units probably will be classified as members of a single formation. Imperfect examples of truncated cross-bedding suggest that the order of superposition is probably also the age order of these units, but conclusive evidence has not been obtained.

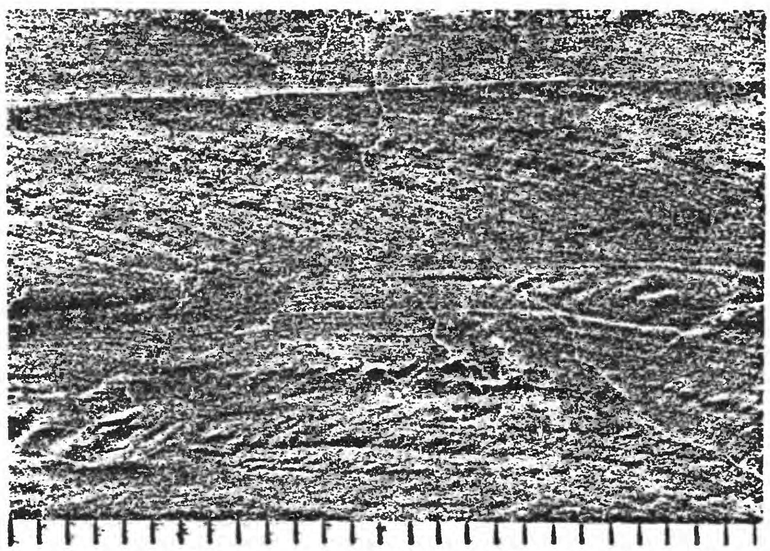

Plate 1. Truncated cross-bedding in quartz schist, near center of sec. 36, T. 1 S., R. 5 E. 1.5 times natural size.

Description of Rock Types

The most abundant metasedimentary rocks of the Keystone district are quartz- and mica-rich schists. These occur in all of the units shown in table 2, though they are relatively uncommon in units 2, 5, and 8. Quartzites occur in units 2, 3, 5, 7, and 9. Amphibole schist is the predominant rock of unit 2, and also occurs in unit 3. Pseudoconglomerate is a characteristic rock of unit 3. Thin-bedded biotite-garnet schist is the chief rock of unit 7. Graphitic schists are characteristic of unit 5.

The only metamorphosed igneous rock recognized in the district consists of amphibolite. The largest body of ortho-amphibolite is in secs. 29, 30, and 32. Many smaller ones lie to the south and southeast.

The rock descriptions that follow will be grouped according to rock types rather than arranged in stratigraphic sequence. The stratigraphy is still not well enough known to justify formal stratigraphic names and descriptions.

The rock descriptions are based chiefly on megascopic examination. Enough petrographic study has been done to be certain that the major minerals have been correctly identified. Some minerals, especially feldspar, may be more common than the rock descriptions indicate. The microscopic work has been done by P. M. Orville and J. A. Redden, as well as the present author. More complete and detailed petrographic work to increase understanding of metamorphism in this area will be done at a later time.

Quartz- and Mica-rich Schists

The quartz- and mica-rich schists consist chiefly of quartz-mica and quartz-mica-staurolite schist. Other varieties include quartz schist, mica schist, mica-garnet schist, and quartz-mica-andalusite schist. The composition ranges from rocks that grade into quartzite to rocks that have 20 percent quartz, 40 percent muscovite, 25 percent biotite, and 15 percent other minerals. Most of these schists, however, are in the range: quartz - 40 to 65 percent; muscovite - 10 to 25 percent; biotite - 10 to 30 percent; feldspar - 5 to 20 percent; and staurolite - 0 to 5 percent. Other minerals include andalusite (0-5 percent), sillimanite (0-1 percent), garnet (0 to 10 percent), chlorite, tourmaline, graphite, sphene, zircon, and iron oxides. The quartz and micas form a very fine- to medium-grained groundmass containing porphyroblasts of staurolite, garnet, andalusite, or sillimanite. Schistosity is caused chiefly by the planar orientation of mica, and thus is much better developed in the more micaceous phases of the rock than in the very quartzose schists.

Bedding is commonly massive, but in many places thin laminae, 1 to 3 mm. thick, can be recognized by differences in the abundance of dark minerals, especially biotite and graphite. These thin laminae may be cross-bedding (pl. 1) or true bedding. Three of the subdivisions of unit 9 (table 2) in block III (fig. 2) consist of interbedded quartz-mica schist and quartz schist or quartzite. The micaceous beds have an average thickness of 1 foot, and the quartzose beds have an average thickness of 1.5 feet.

Garnet is the most widely distributed porphyroblastic mineral of these rocks. Virtually everywhere euhedral crystals of red-brown garnet can be found. The size is most commonly between 1 and 3 mm.

Staurolite is more abundant than garnet, but not so ubiquitous. It occurs as porphyroblastic euhedra, either single crystals or twins, that are as much as 1-1/2 inches long, though the average length is about 3/8 inch. The larger staurolite crystals are in the more quartzose rocks. Much of the staurolite contains few inclusions of quartz, mica, and other minerals.

In the southern part of the area, especially near pegmatites, staurolite has been pseudomorphically replaced by muscovite, quartz, chlorite, and biotite. Where the pseudomorphism is complete, chlorite is concentrated in the interior, muscovite is richest in a zone outside the chlorite-rich core, and biotite forms a dark brown to black rim at the outer edge of the pseudomorphs.

Andalusite is most common in the upper part of unit 1 (table 2), where it occurs in lenticular aggregates as much as 4 inches across containing abundant inclusions of quartz and mica. The schistosity curves around these inclusions. Andalusite crystals as much as 1 foot long have been found in unit 3 (table 2) 1,000 feet southeast of the Bob Ingersoll mine (sec. 6).

Sillimanite occurs only in aggregates 1 to 2 mm. across in the southern part of the area. These aggregates also contain quartz and muscovite.

Lime-silicate nodules having the shapes of triaxial ellipsoids are sparsely distributed throughout much of these schists. They are most common in quartz-rich beds, especially in units 4 and 7 (table 2). These nodules have been described by Runner and Hamilton 1/, who show that they are metamorphosed concretions. Runner and Hamilton 2/ and Redden 3/ have found that they occur through a wide stratigraphic range. In the Keystone district, such nodules may be concentrated at a relatively few stratigraphic horizons. They are not abundant enough to determine how many horizons there are, and they have not proved useful in mapping.

1/ Runner, J. J., and Hamilton, R. G., 1934, Metamorphosed calcareous concretions and their genetic and structural significance: Am. Jour. Sci., 5th ser., v. 28, p. 51-64.

2/ Idem, p. 53.

3/ Redden, J. A., 1955, Geology of the Fourmile pegmatite area, Custer County, S. D.: U. S. Geol. Survey open file report, [redacted]

The maximum length of the long axis of the ellipsoids is 2 feet, the intermediate axis 1 foot, and the short axis 6 inches. The ratio of the lengths of the various axes ordinarily falls in the range 1.5 to 5:1 to 3:1. The long and intermediate axes are parallel to schistosity. The long axis is most commonly parallel to the plunge of nearby isoclinal folds, and thus is in b. Others may be in a or in directions with less readily apparent affinities. Presumably these concretions originally were more nearly equidimensional than they now are, and their present shapes reflect rolling and plastic deformation during folding.

The minerals of these nodules show an imperfect zoning. The outer part ordinarily contains biotite, quartz, and actinolite. The predominant minerals in an intermediate zone are actinolite, epidote, quartz, and garnet. The core consists chiefly of garnet, diopside, quartz, calcite, calcic plagioclase, and clinozoisite.

The quartz- and mica-rich schists are the most abundant rocks of units 1, 3, 4, 6, 7, and 9 (table 2). The lithologic similarities among these rocks are far more evident than the differences. Nevertheless, some differences can be recognized.

Unit 1 is generally more schistose and contains more andalusite than other units. Bedding is very difficult to recognize.

In unit 3 quartz- and mica-rich schists are associated with pseudoconglomerate, quartzite, and amphibole schist. In the upper part of this unit garnet is an abundant mineral. It occurs as clear euhedral crystals having an average diameter of 2 mm. The groundmass is very fine-grained and has a dark color caused by biotite and accessory graphite. Thin beds, 1 to 3 mm. thick, can be recognized by differences in the abundance of biotite and graphite.

Unit 4 contains many lithologic varieties ranging from very quartzose to mica- and staurolite-rich schists. The most abundant minerals are quartz (40 to 70 percent), muscovite (10 to 25 percent), biotite (5 to 25 percent), feldspar (5 to 20 percent), garnet (0 to 3 percent), and staurolite (0 to 5 percent). The quartz content tends to increase from older to younger parts of the unit, and the content of mica, staurolite and garnet correspondingly decreases. In the quartz-rich rocks schistosity is poorly developed. Lime-silicate nodules are more abundant in unit 4 than in other units.

In many places the quartz-mica schist of unit 4 contains rounded quartz aggregates 1 to 3 mm. in diameter. The quartz in these aggregates is granoblastic and fine-grained. The aggregates have a white color that contrasts with the normal gray quartz of the groundmass. They are most common near the contact with unit 3, especially in the SE 1/4 sec. 6, SE 1/4 sec. 7, NW 1/4 sec. 8, SW 1/4 sec. 31, near the center of sec. 32, and in the W 1/2 sec. 15. These aggregates form as much as 25 percent of beds that are as much as 2 inches thick. They probably are detrital fragments derived from older rock units.

Unit 6 is very similar to unit 4. It contains somewhat more mica and staurolite and few, if any lime-silicate nodules. Beds containing rounded quartz aggregates have not been found.

Unit 7 consists chiefly of quartzose schists and quartzite. Beds that are sufficiently aluminous to contain staurolite are rare. The most abundant minerals are quartz (40 to 80 percent), feldspar (10 to 30 percent), muscovite (5 to 20 percent), and biotite (5 to 25 percent). Beds of the more quartzose rocks have an average thickness of 3 feet and a maximum thickness of 15 feet. Beds of the more micaceous rocks are ordinarily 3 to 12 inches thick. Lime-silicate nodules are common in the quartzose varieties of this rock unit.

Unit 9 has been separated into seven subdivisions (table 2). The most striking characteristic of all of these units is the presence of fine-grained aggregates of biotite, muscovite, and quartz that are 2 to 6 mm. long and 1 to 3 mm. wide. The largest of these are zoned; biotite is concentrated at the outer edge of the aggregates, and quartz and muscovite are concentrated in the core. The aggregates tend to be more abundant and larger in the upper units of the sequence.

The lowest of these seven subdivisions is a relatively uniform rock consisting of quartz-mica-staurolite schist. This is succeeded by a subdivision consisting of alternating beds of quartzose and micaceous rocks. Next is quartz-mica schist with only rare staurolite. It is followed by a thin unit of alternating quartzose and micaceous rocks, and then by more quartz-mica-staurolite schist. The next unit consists of still more alternating quartzose and mica-rich beds, but these are more micaceous than previously described interbedded units. The uppermost of these seven subdivisions consists of schist very rich in mica (50 to 70 percent) and having an extraordinarily well-developed schistosity.

Quartzites

The Keystone district contains two types of quartzite: (1) glassy quartzite and (2) granular quartzite.

Glassy quartzite occurs chiefly as thin discontinuous beds on either side of unit 2 (table 2). The largest outcrops are in secs. 31 and 32, and near the intersection of secs. 9, 10, 15, and 16. Thin dark layers containing graphite, biotite, and tourmaline give the rock a streaked appearance. Other accessory minerals include chlorite and garnet. Abundant tight folds give this unit a false appearance of great thickness in many places on the map. In the NE 1/4 sec. 16 (fig. 3) this quartzite has been folded on itself so many times that it has an apparent thickness of 500 feet, but the actual thickness is less than 50 feet.

Fine-grained, glassy quartzite also occurs in association with amphibole schist in units 2 and 3. The quartzite is in pod-like to lenticular masses that have an average thickness of 1/4 inch and length of 3 inches. The most common accessory minerals are graphite, garnet, and iron oxides.

Granular quartzite occurs in units 3, 5, 7, and 9. The quartzites of units 7 and 9 are quartzose varieties of the schists previously described in these units. In units 3 and 5, however, most of the quartzite consists of fine-grained granoblastic quartz (90 to 100 percent) and accessory muscovite, biotite, tourmaline, garnet, and rare light-colored amphibole. The best exposure of this rock is a bed 1,200 feet long and as much as 10 feet thick near the center of the N 1/2 SW 1/4 sec. 6. A somewhat different variety of quartzite occurs just north of the intersection of U. S. Highways 16 and 16A, in the NE 1/4 sec. 31 and SE 1/4 sec. 30. These quartzite beds have quartz grains with a maximum size of 2 mm. and contain as much as 15 percent mica and 5 percent microcline.

Pseudoconglomerate

Pseudoconglomerate is common in the central part of unit 3 (table 2). Excellent exposures extend over broad areas in the SW 1/4 sec. 19, the center of sec. 6, the center of sec. 5, and a belt extending 1 mile southeast from Keystone.

This rock consists of rounded fragments of quartzite (30 percent) in a matrix of very fine- to fine-grained quartz-mica schist (70 percent). The matrix contains quartz (40 percent), muscovite (30 percent), biotite

(25 percent), garnet (0 to 10 percent), chlorite, staurolite, graphite, iron oxides, and tourmaline. The garnet crystals are free of inclusions and have an average diameter of 2 mm.

The quartzite fragments or "pebbles" are ordinarily in the form of triaxial ellipsoids. The ratio of the three axes of most fragments is in the range 5 to 10: 1.5 to 2:1. The intermediate axis is rarely greater than 10 inches, but at least 5 quartzite ellipsoids have intermediate axes that are between 10 and 15 feet. The quartzite contains granoblastic quartz (90 to 100 percent) having an average grain size of 0.2 mm. Accessory minerals include muscovite, biotite, tourmaline, and garnet. The edges of many of the fragments are very vaguely defined. There are all gradations between sharply bounded fragments and lenticular aggregates that in their outer parts have nearly the same composition as the matrix.

The only other variety of "pebble" consists of micaceous schist that must have been derived from a sedimentary rock rich in clay. No convincing examples of vein quartz pebbles have been found, despite thorough search.

The peculiar composition of this rock indicates that it is not a true conglomerate. It is also unlikely that it is an intraformational conglomerate. The pebbles of intraformational conglomerates are shale and the matrix is sand 1/; the converse is so in this pseudoconglomerate.

F. S. McNeil 2/ has observed balls of sand in a matrix of clay in northeastern Mississippi. His description indicates that this rock, if metamorphosed, would resemble the pseudoconglomerate of the Keystone district.

1/ Pettijohn, F. J., 1949, Sedimentary rocks: New York, Harper and Brothers p. 210-211.

2/ Personal communication, 1956.

Sediments of this sort are so very uncommon, however, that it seems inadvisable to call on them in explaining the origin of the pseudoconglomerate of Keystone.

Still another possibility is a tectonic conglomerate. The plunge of the pseudopebbles is parallel to the plunge of isoclinal folds. Cloos [1] points out that the plunge of extremely elongate stretched pebbles in a true conglomerate should be a lineation in a, inasmuch as that is the direction of greatest tectonic transport. Fragments like these that are very elongate in the b direction are more likely to have formed by fracturing of competent beds and subsequent rolling and rounding of the fragments. This would be an extreme form of boudinage structure. The "pebbles" in this rock are not lined up in such a way that the original beds can be traced, nor can fractures associated with the formation of the boudins ordinarily be recognized. A few specimens found near the Bob Ingersoll mine suggest that the rounded fragments may have developed in four successive stages, each grading into the next: (1) quartzite beds or lenses; (2) fractured quartzite; (3) fragments with rounded corners and straight sides; and (4) rounded fragments. These, however, are rare and unconvincing. If the rock formed in this way, deformation has carried it far beyond the point where boudinage structure can be readily demonstrated.

It may be concluded that pseudoconglomerate is the best name for this rock, and that it probably formed by deformation of interbedded quartzite and micaceous schist.

1/ Cloos, Ernst, 1946, Lineation: Geol. Soc. America, Mem. 18, p. 17, 30, and 42.

Amphibole Schist

Amphibole schist is the predominant rock of unit 2; it occurs at three levels in unit 3; and it has been found in unit 5. Typical exposures are in the vicinity of the Edison mine, SE 1/4 sec. 9, and throughout much of the E 1/2 sec. 31, and W 1/2 sec. 32. All outcrops are heavily iron-stained; no fresh exposures of this unit have been seen. The amphibole schist contains many pod-like to lenticular masses of fine-grained quartzite having an average length of 3 inches and thickness of 1/4 inch. The average ratio of amphibole schist to quartzite is about 7:3, but the range in the ratio is very great; each of these rock types forms from 10 to 90 percent of outcrops that are as much as 10 feet wide.

The amphibole schist contains amphibole (60 percent), quartz (25 percent), iron oxides (5 percent), garnet (5 percent), and small quantities of graphite, chlorite, biotite, plagioclase, pyrite, arsenopyrite, sphene, tourmaline, clinozoisite, hedenbergite, and zircon. The grain size is fine to very fine.

Amphibole occurs as radial aggregates of colorless to green needles. The most abundant amphibole is cummingtonite, but tremolite-actinolite is plentiful, and hornblende has been recognized. Cummingtonite is distinguished from tremolite-actinolite by its higher index and from common hornblende by its lighter color. Hornblende has a higher index and a deeper green color than tremolite-actinolite. The cummingtonite may contain enough iron to be more properly called grunerite, but conclusive evidence for this has not been obtained. The iron- and aluminum-bearing amphiboles, actinolite and hornblende, may increase at the expense of cummingtonite and tremolite in the high-grade rocks in the southern part of the district. Even if this is so, however, the distribution of the various amphiboles is locally irregular and probably in part reflects variations in the composition of the original sediment. Hornblende has been found at the tips of radiating cummingtonite needles in a specimen from north of U. S. Highway 16 in sec. 30. Glaucophane has been found near the Edison pegmatite.

In mineralized areas, as at the Bismark mine near the center of sec. 5 this rock contains such minerals as talc, serpentine, chlorite, dolomite, and perhaps clay minerals. The most common metallic minerals are pyrite and arsenopyrite. These presumably are abundant in the gold ore bodies, but inasmuch as none of the mines have been open in recent years, little information on this score could be obtained.

The amphibole schist and associated quartzites are very similar to iron formation in this same grade of metamorphism described by James 1/ in northern Michigan. James describes rocks in the staurolite and sillimanite zones that consist predominantly of grunerite and quartz, and shows that they are metamorphosed equivalents of his carbonate and non-clastic silicate facies of iron formation. Similarly, Noble and Harder 2/ show that the Homestake formation is similar to Lake Superior iron formations. The Homestake formation fits rather well in the carbonate facies described by James 3/.

1/ James, H. L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geol. Soc. America Bull., v. 66, p. 1474-1478.

2/ Noble, J. A., and Harder, J. O., 1948, Stratigraphy and metamorphism in a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 59, p. 947.

3/ Idem, p. 967.

James, 1955, op. cit., p. 1475.

It may be concluded that the amphibole schist and associated quartzite are metamorphosed iron formation. The quartzite is thus equivalent to the chert that is characteristic of these rocks in the Lake Superior region 1/.

Biotite-garnet Schist

Biotite-garnet schist of unit 8 is exposed along the railroad east of the center of sec. 1, and also along Iron Creek near the west edge of sec. 14. This schist is thinly bedded and has a well-developed schistosity. The chief minerals are biotite (45 percent), quartz (40 percent), garnet (10 percent), graphite (2 to 5 percent), tourmaline, muscovite, and microcline (?). Most of the garnet is less than 1 mm. in diameter. Microcline (?) occurs as porphyroblasts 0.5 to 1 mm. long. Other minerals are very fine- to fine-grained.

Mica-graphite Schist and Microcline Schist

Mica-graphite schist is the predominant rock of unit 5. The best exposures of mica-graphite schist are along the highway in the NW 1/4 sec. 31. Table 2 shows that the rocks in this exposure may correlate with rocks in block V B near the intersection of secs. 8, 9, 16, and 17 and near the intersection of secs. 15, 16, 21, and 22 (figs. 2 and 3).

The mica-graphite schist consists of muscovite (15 to 35 percent), biotite (10 to 40 percent), graphite (3 to 10 percent), quartz (20 to 50 percent), and chlorite (5 to 10 percent). The rock is very fine-grained. Much of the muscovite is sericitic.

1/ James, H. L., 1954, Sedimentary facies of iron-formation: Econ. Geology, v. 49, p. 239-240.

Unit 5 also has microcline schist that includes a variety of rocks containing as much as 40 percent microcline together with muscovite, biotite, quartz, chlorite, cordierite (?), oligoclase, and sphene. Other rocks contain plagioclase, carbonate minerals, and zircon, as well as minerals already listed. Such facies, however, are rare, and have received virtually no study. All of these rocks are very fine- to fine-grained.

Ortho-amphibolite

Amphibolite bodies with structure and mineralogy that suggest intrusive origin occupy a large part of block VI A, but are small and rare in other parts of the mapped area.

The large body in and near secs. 29, 30, and 32 is most certainly a metamorphosed intrusive. Contacts are cross-cutting in many places, especially in the SE 1/4 sec. 30. Isolated quartzite in which pre-intrusive folds are preserved form an especially striking map pattern in sec. 32.

The rock in most of this intrusive is coarse-grained. Fine-grained and very fine-grained amphibolite are most common near contacts. Needles of hornblende (55 percent) are surrounded by finer grained oligoclase-andesine (40 percent). Conclusive evidence of the preservation of original pyroxene has not been observed.

The amphibolite of the large intrusive is virtually structureless. No lineation or schistosity has been recognized. Rarely there is a tendency for segregation of minerals into bands that may be an incipient gneissic structure.

The smaller amphibolite bodies are very similar to the large intrusive. The chief difference is that many of these bodies are parallel to bedding and have an imperfect compositional layering that may be either bedding or gneissic structure. The mineralogy, however, is so similar to the mineralogy of the large amphibolite mass that these rocks probably are chiefly of igneous origin. Some, however, may be metamorphosed extrusive rocks. Small parts of the area mapped as amphibolite may have been metamorphosed calcareous shale.

The minerals include hornblende (50 to 75 percent), oligoclase-andesine (20 to 45 percent), quartz (0 to 15 percent), chlorite (0 to 5 percent), biotite, magnetite (0 to 10 percent), ilmenite, sphene, zircon, tourmaline, pyrite, and arsenopyrite. Small quantities of altered material in the amphibolite also contain calcite, zoisite, and serpentine.

Structural Geology of the Metamorphic Rocks

The structural geology of the Keystone district is complex. Previous workers have treated the structure only in a generalized fashion 1/. The map made by Hamilton 2/ shows details in many places, but it also contains many unexplained features: thick stratigraphic units lens out without reason; stratigraphic correlations are made that require great unexplained lithologic changes; and conversely, rocks that are lithologically identical with each other are placed in different stratigraphic units without apparent necessity. For these reasons, Hamilton also had to treat the structure only

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1/ Paige, Sidney, 1925, Structure of Algonkian rocks, in Darton, N. H., and Paige, Sidney, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219, p. 17.

Balk, Robert, 1931, Inclusions and foliation of the Harney Peak granite, Black Hills, S. D.: Jour. Geology, v. 39, p. 736-748.

Hamilton, R. G., written communication [redacted]

Runner, J. J., 1943, Structure and origin of Black Hills Precambrian granite domes: Jour. Geology, v. 51, p. 431-457.

2/ Op. cit.

in a very general way. The principal difficulty is that faults have never before been recognized in this district, and they are a significant element of the structure. Furthermore, previous work has not been sufficiently detailed to show that there is more than one set of folds. The Keystone district contains at least three sets of folds, and the complexity thus introduced is an important cause of confusion in the geologic maps of this area.

The oldest folds are isoclinal folds; these were later tightly cross-folded; still later these intensely deformed rocks were warped into broad flexures, evidently by intrusion of pegmatites.

Many high angle faults cut the district. These faults are younger than the isoclinal and cross folds, but older than the pegmatites. The largest of the faults is the transcurrent fault going in a northwesterly direction across the district. Other faults are approximately parallel to this fault. Still other faults strike north, northeast, and east.

Folds

The patterns of the various types of folds in the Keystone district are shown by form lines on the map of structural trends (fig. 4). Each thin solid line on this map shows the trace of a single horizon. Most of these are at the contacts of units shown on the geologic map. A few are displaced slightly from the nearest contact, but are drawn parallel to that contact. The two form lines passing through the center of sec. 9 are drawn on amphibole schist beds that are not shown separately on the geologic map (fig. 3). A few of the form lines have been restored across faults, where they are shown as a dotted line, to indicate how the structure is interpreted.

Isoclinal folds.--In the area northeast of the main fault, isoclinal folds are best shown by the form lines in secs. 9 and 32 (fig. 4). From sec. 9 to the north border of the map the isoclinal folds have a left-hand movement pattern. Anticlines close to the north and synclines to the south. The younger beds lie generally to the northeast. All but a few dips are between vertical and 80°, either to the east or the west. Nearly all plunges are between 70° and 85° south; thus the isoclinal folds are inverted, and anticlines close downward and synclines upward.

These folds are on the west limb of a major syncline. The axis of this syncline is shown going northwest through secs. 9 and 4 (fig. 4) in a position that, though approximately correct, is based on imperfect examples of truncated cross-bedding. On the east limb of this fold the form line passing through the center of section 10 has a right-hand movement pattern.

This relatively simple pattern dominated by isoclinal folds is complicated by later folds south of sec. 9. A large cross fold is near the southeast corner of sec. 9. The isoclinal folds maintain their left-hand pattern as they go around the nose of this cross fold (fig. 4). The cross fold itself has a right-hand pattern.

Farther south the dip of the bedding and of the axial planes of isoclinal folds becomes gentle on the flanks of the late dome-shaped structure in the W 1/2 sec. 15 (fig. 4). Plunges of isoclinal folds are to the northwest on the north flank of this dome. Farther south, as the dips change from northwest to southwest in going over the top of the dome, the isoclinal folds also pass over the dome and reappear to the south with a right-hand movement pattern (fig. 4). Similarly, the plunge changes from northwesterly on the north flank of the dome to southerly on the southwest flank.

The predominant folds of block VI C, in the E 1/2 sec. 15 and adjacent areas (fig. 2, 3, and 4), consist of an isoclinal syncline with smaller isoclinal folds on each limb. Further mapping to the south is needed to show how this syncline is related to the structure to the west in block VI A.

The pattern of the isoclinal folds in block V is more difficult to work out because small stratigraphic subdivisions can be mapped in only a few parts of this block. The interpretation shown in figure 4 is that this block consists of isoclinal folds that have been severely cross-folded. An isoclinal anticline, which has stratigraphic unit 3 in its core, goes south across secs. 6 and 7, then north into sec. 5, and finally southeast into secs. 8 and 9. The axis of cross-folding that goes through the SW 1/4 sec. 5 is the main axis around which isoclinal folds are cross-folded in secs. 8, 9, 16, and 17. Anticlines close to the east and synclines to the west.

Plunges of isoclinal folds go around the noses of the large cross folds of figure 4 in a way that shows there are two separate types of folds, and that the isoclinal folds are not drag folds on the limbs of the larger folds. Figure 4 shows plunges of 40° and 48° SE. in the SW 1/4 sec. 31 and the central part of sec. 6. Plunges are northeasterly on the east side of the cross fold that passes through sec. 7; figure 4 shows plunges of 20°, 38°, 40°, and 55° NE. in sec. 17. The plunge is about 55° NE. near the crest of the cross fold in the NW 1/4 sec. 16 and NE 1/4 sec. 17. On the east side of the axis of this same cross fold, a plunge of 30° SE. is shown in the N 1/2 sec. 8.

This structural interpretation is part of the basis for the stratigraphic sequence of units 4, 5, and 6 in table 2. Unit 3, which is known from truncated cross-bedding in block VI to be older than unit 4, forms the core of the isoclinal anticline in secs. 5, 6, 7, and 8. It follows from this that the exposures of mica schist, mica-graphite schist, and quartzite (unit 5) near the intersection of secs. 8, 9, 16, and 17 (fig. 3) are younger than unit 4. In figure 4, this unit is shown as the core of an isoclinal syncline. Similar rocks, also here included in unit 5, reappear farther south (fig. 3) in the NE 1/4 sec. 21, on the west side of the main fault. Rocks that are lithologically very similar have been mapped east of the fault in sec. 25, thus indicating a horizontal displacement of 5-1/2 miles. Both east and west of the fault, the graphitic schist (unit 5) has small folds with a left-hand movement pattern, and consequently is on the north limb of a syncline that closes to the west. This relationship confirms the lithologic evidence that the quartz-mica schist (unit 6) south of the graphitic schist (unit 5) is different from and younger than the quartz-mica to the north.

In the northwest part of the mapped area, isoclinal folds are best demonstrated in sec. 35 and adjacent areas of block III (figs. 2, 3, and 4), where the plunge is gentle to the south. Block III A has a series of faulted anticlines and synclines. Block III B has one large syncline that plunges generally to the south. In the northeast part of sec. 35, however, the axis is cross-folded, and the plunge is to the north for a short distance (fig. 4). The limbs of this syncline have many small folds.

Isoclinal folds have also been recognized in blocks I and IV (fig. 2), but they cannot be shown on fig. 4 because of the lack of traceable horizons. In block IV the isoclinal folds are recumbent and plunge at low angles, mostly between 0° and 15° north or south. In block I the dips are steep, and plunges are 55° - 65° west.

Cross folds.--Cross-folding is a major element of the structural interpretation in figure 4. These folds have similarities to cross folds that deform isoclinal folds at Lead 1/ and in the Galena-Roubaix area of the northern Black Hills 2/.

The form line going through the intersection of secs. 9, 10, 15, and 16 (fig. 4) indicates that the isoclinal folds are deformed by a larger cross fold. The isoclinal folds in this area have a consistent left-hand pattern. The form lines and strike and dip symbols on figure 4 indicate that in sec. 9 the axial planes of these folds strike slightly west of north and have an average dip between 85° W. and vertical. In the northwest part of sec. 15, however, the axial planes have turned to an east-northeast strike and a dip of about 60° N. In sec. 16 they turn back to a northerly strike and a nearly vertical dip. These attitudes of the axial planes of the isoclinal folds describe a cross fold in which the axial plane strikes northwest and the plunge is about 60° to the north-northwest. This cross fold has a right-hand movement pattern, in contrast to the left-hand movement pattern of the isoclinal folds.

Similar right-hand cross-folding explains the structural pattern in the north central part of sec. 31. A form line on figure 4, following the contact between the oldest two rock units, trends north-northwest through sec. 30. To the south in sec. 31, however, it turns west and goes into a fault.

The description of isoclinal folds in block V has suggested that the northwesterly trending fold extending from sec. 21 to sec. 5 and a corresponding fold to the west are cross folds. This interpretation is unavoidable

1/ Noble, J. A., Harder, J. O., and Slaughter, A. L., 1949, Structure of a part of the northern Black Hills and the Homestake mine, Lead, S. D.: Geol. Soc. America Bull., v. 60, p. 326-330.

2/ Berg, J. R., 1946, Precambrian geology of the Galena-Roubaix district, Black Hills, S. D.: S. D. Geol. Survey, Rept. Inv. 52, p. 48.

if the rocks of unit 3 (table 2 in blocks V and VI are all considered to be the same stratigraphic unit. Rocks characteristic of units 1 and 2 and the older part of unit 3 appear only in block VI. Their absence in block V is explained in figure 4 by making unit 3 the core of a cross-folded anticline.

A somewhat simpler structural interpretation can be devised if the rocks of unit 3 in block V are not in the same stratigraphic unit as the lithologically similar rocks in block VI. If this is so, then the fold axis that goes northwest from sec. 21 to sec. 6 (fig. 4) may be the axis of a syncline in which the rocks are progressively older to the northwest. The crescent-shaped area of rocks belonging to unit 3 just west of Keystone (fig. 3) would be different from and younger than the northerly trending belt of similar rocks that lie farther west. The fact that this crescent-shaped unit lenses out at its two ends would have to be explained either by deformation or as an original sedimentary feature.

The axis of the large syncline of block III B, in the east part of sec. 35, has a pattern that indicates cross-folding. In the north part of this block the axis goes slightly east of north. To the south, it turns to a northwesterly direction, and the axes of nearby minor folds adopt the same trend. As the axis continues to the southeast, it turns again to a trend that is slightly east of north. This pattern indicates a cross fold that has a left-hand movement pattern.

Late flexures.--The rocks have also been deformed by broad flexures that are associated with large masses of pegmatite.

Figure 4 shows that the bedding has been significantly warped in the area of abundant pegmatites in the S 1/2 sec. 17 and in adjacent areas to the east and south. An isoclinal fold axis drawn parallel to the strike of bedding in sec. 17 is bent so as to change its trend from south to southeast. The dip of bedding becomes much more gentle than it is to the east and north. Thus the rocks form part of a dome, apparently in response to intrusive forces of pegmatite.

To the east there is another area of abundant pegmatites in the north part of sec. 22. These pegmatites, and perhaps larger intrusives at depth, may have caused the domal structure in secs. 15 and 22. Strike and dip symbols on figure 4 show that the top of this dome is near the center of the S 1/2 sec. 15. The form line on the west flank of this dome shows that the isoclinal folds have a left-hand pattern in secs. 15 and 16, and that after the folds go over the top of the dome they necessarily change to the right-hand folds shown in sec. 22.

The cross fold that has been described near the intersection of secs. 9, 10, 15, and 16 should also pass over the top of this dome, and should reappear in sec. 22 south of the mapped area. The main fault passes through this area, however, and evidence for the reappearance of the cross fold will not necessarily be found. Even in the absence of this evidence, it still seems likely that the cross fold and the dome are two separate structures formed at different times. No apparent geometry can explain how the cross fold and the dome can form from the same set of forces.

The strikes and dips on figure 4 suggest that the east flank of the dome extends across the fault in sec. 15, and that the doming was later than the fault. This possibility cannot be proved or disproved without more data.

Faults

The Keystone district is divided into two parts by the transcurrent fault that goes northwesterly across the district. This fault accounts for the lack of any apparent structural relation between the northerly trending, steeply plunging isoclinal folds in block VI A and the folds of block V (figs. 2 and 4). Southeast of Keystone this fault forms the boundary between quartz-mica and quartz-mica-staurolite schist to the west and the various rock units to the east. The relation between the trace of this fault and topography indicates a steep dip.

In the NW 1/4 sec. 5 this fault splits into two faults that continue on either side of block II to the northwest boundary of the mapped area. It has already been shown that the micaceous and graphitic schists of block II can probably be correlated with the schists in the southeast corner of block V. If so, the horizontal displacement measured along the west side of block II and the east side of block V is 5-1/2 miles. The displacement between block II and the rocks to the east cannot be determined. It is clear, however, that the graphitic schist in block II is in discordant contact with rocks to the east that are lithologically very different, and that the fault must be large (figs. 3 and 4).

The distribution of rock units in the region extending for 1-1/2 miles northwest of Keystone indicates that there are several smaller faults both parallel to and normal to the main faults (fig. 3). Most of the Keystone gold mines are in this area, and it is probable that these fractures in part controlled the mineralization.

Other faults of blocks V and VI trend northwest to north-northeast. These faults are based on discordant contacts between rocks of unlike lithology. In the NE 1/4 SE 1/4 sec. 9 (fig. 3), the northerly trending fault divides highly garnetiferous schists on the west and very quartzose schists on the east. The rocks on either side strike directly toward the fault. The fault plane, though not actually exposed, can be located within 20 feet for a distance of 600 feet. It is impossible that anything but a fault can account for the observed relations.

Very similar relations are observable along parts of each fault in secs. 10 and 15. The northwesterly trending fault near the Edison mine displaces amphibolite in the NW 1/4 SE 1/4 sec. 9 (fig. 3). The northwesterly trending faults in block V B are based on similar, though less satisfactory, evidence; they are imperfectly known because they are chiefly in quartzose and micaceous schists that contain no beds sufficiently distinctive to be traced.

The faults of block III in sec. 35 and adjacent areas are mappable only by virtue of the feasibility of subdividing unit 9 into seven smaller units. This procedure was possible because of the great abundance of outcrops throughout this part of the mapped area. Faults are actually exposed in five outcrops: three of these are in the SW 1/4 NW 1/4 sec. 35; one is in the NW 1/4 SW 1/4 sec. 35; and one is in the NE 1/4 NW 1/4 sec. 2 (fig. 3). The dips in these five places range from 63° W. to 85° E.

The faults forming the east and north boundaries of block III are where the subdivisions of unit 9 abut against the quartzose schists and quartzite of blocks I and IV. The fault at the east side of block III has a low dip, and thus is presumed to be a thrust fault. The fault along the north boundary of block III evidently extends east to form the boundary between blocks I and IV. Block I has steep dips, westerly strikes, and moderate to steep plunges; in contrast, block IV has gentle dips, northerly strikes, and low plunges.

A few of the pegmatites are cut by very small faults not shown on the geologic map.

Schistosity

The dominant schistosity throughout the Keystone district is generally nearly parallel to bedding. This schistosity is formed by the tabular orientation of mica, and is much more readily apparent in micaceous beds than in highly quartzose beds.

In many places the divergence between bedding and schistosity, though small, is large enough to be measured and shown on the geologic map (fig. 3). The schistosity may be in part an axial plane schistosity in the isoclinal folds. Rarely, in the noses of small isoclinal folds, large angles of divergence have been observed. On the other hand, attempts to use the angular relationship between bedding and schistosity to interpret the structure of isoclinal folds have been unsuccessful.

It seems likely the schistosity was modified by movements along bedding planes during later folding and during metamorphism. Thus, it is not surprising that the divergence between schistosity and bedding does not bear a consistent relation to the folds.

A second schistosity has been developed in the quartzose beds in block III. In this schistosity micas are oriented such that the dip is south to west at angles of 15° to 35° (fig. 3). There is no apparent relation between this schistosity and folds.

Age Sequence of Structural Features

Isoclinal folds and cross folds have been found in many parts of the Black Hills. They are the only structures of the Keystone district that have no readily apparent relation to the pegmatitic intrusives. The faults, high-grade metamorphism, and late flexures are known only in the pegmatite-bearing areas of the southern Black Hills, and thus are probably related to the intrusive activity. The pegmatites themselves, however, are undeformed; any tectonic events associated with the intrusion of pegmatites were either just before or during intrusion.

Isoclinal folding is the oldest recognizable structural event. The isoclinal folds were deformed by the cross folds formed during the second stage in the structural history of the region. The isoclinal folds were also disrupted by intrusion of the ortho-amphibolite, especially in the SE 1/4 sec. 30 (fig. 3). The relation between the amphibolites and cross-folding, however, is not clear.

The isoclinal folds, cross folds, and amphibolite are cut by faults. Faulting was in large part prior to the peak of metamorphism, but it may have been partly contemporaneous with metamorphism. Where faults are exposed, the fractures are so thoroughly healed that they cannot be seen readily even in outcrop. None of the observed porphyroblasts of staurolite and garnet adjacent to fault planes are deformed, and thus they must have crystallized after the last fault movement. A possible fault breccia has been seen only where the southwest branch of the main fault crosses U. S. Highway 16 1.3 miles northwest of Keystone. The fragments have shadowy outlines and are difficult to recognize. They could well belong to a metamorphosed conglomerate were it not that they are in a fault and have the same composition as the adjacent schist.

Elsewhere in the southern Black Hills faults have been found that may have had some movement during metamorphism. An example is a fault about 8 miles north of Custer. Here the regional schistosity is approximately normal to the fault plane. For a distance of 100 feet outward from the fault, however, a second schistosity parallel to the fault plane completely masks the regional schistosity.

The very small faults that cut pegmatites are the only faults that are definitely later than the metamorphism.

If the metamorphism was later than faulting, the micas and other minerals that cause the schistosity of the Keystone rocks must have crystallized in their present form after the faulting. The faults are undeformed by the isoclinal folds and cross folds. It is probable, of course, that the rocks had a schistosity before the faulting; lower grade metamorphic rocks in the central and northern Black Hills have a schistosity. The opportunity for dating provided by the faults, however, suggests that the schistosity as it is now seen in the Keystone district is a product of the growth of micas along the earlier schistosity, along bedding planes, and in other directions. This accounts for the fact that in the Keystone district, the angular relations between bedding and schistosity have not been useful in interpreting the structure of isoclinal folds.

The flexures associated with pegmatites are the latest stage of folding. These may have deformed the faults, but no conclusive evidence, one way or the other, has been found. Both the flexures and high-grade metamorphism are characteristic of pegmatite-bearing areas, and thus were probably essentially contemporaneous with each other.

Metamorphism

The Keystone district is in the region between the sillimanite-rich rocks of the Harney Peak area and the chloritic and micaceous rocks of the central part of the Black Hills Precambrian core. Sillimanite occurs only in the south and southwest parts of the Keystone district (fig. 3), and even in this area it is an uncommon mineral. Garnet and staurolite, however, are abundant in all rocks of appropriate composition throughout the district.

Garnet occurs in idioblastic crystals that ordinarily have a diameter of 1 to 2 mm.; crystals larger than 5 mm. are rare. Inclusions in garnet are scarce. Staurolite can be found in aluminous phases of all rocks of the district. It is idioblastic and porphyroblastic in habit. Inclusions of virtually all other minerals of these rocks have been recognized in staurolite. Sillimanite occurs with quartz and muscovite in small aggregates in aluminous schists. Rarely are these aggregates more than 2 mm. in diameter.

Cummingtonite, tremolite-actinolite, and hornblende are the predominant minerals of metamorphosed iron formation. Cummingtonite and tremolite may decrease in abundance, and actinolite and hornblende may increase toward the south, but not enough petrographic work has been done to substantiate this conclusively. It is certain, however, that there are only minor changes in the amphibole with increasing metamorphism. Any changes are gradual and irregular, and doubtless in part reflect composition of the original sediments.

In areas containing many pegmatites, staurolite and sillimanite have been replaced by quartz and micaceous minerals. The best material found for study consists of altered staurolite in several drill cores from the Peerless mine, near the center of the E 1/2 sec. 8. Idioblastic staurolite with relatively few inclusions is common in much of the area near the Peerless mine, especially to the northwest along U. S. Highway 16A going north from Keystone. Diamond drill cores at the Peerless mine, however, contain many well-formed six-sided pseudomorphs consisting chiefly of muscovite, quartz, chlorite, and biotite. Some of the pseudomorphs contain remnants of staurolite, but in others no staurolite has been found. Pseudomorphs that are only partially replaced contain muscovite, quartz, chlorite, and biotite in a haphazardly distributed fashion. The best developed pseudomorph examined was 1.5 cm. by 2.5 cm. in cross-section and had a euhedral six-sided form (pl.2). The minerals of this pseudomorph are muscovite (50 percent), quartz (20 percent), chlorite (20 percent), and biotite (10 percent). All of these minerals except quartz have a conspicuous zonal distribution. Biotite is chiefly at the rim of the pseudomorph in a zone 0.8 mm. wide. Muscovite is concentrated in an intermediate zone that has an average width of 5 mm. Nearly all of the chlorite is in the core of the pseudomorph.

As Yoder indicates 1/, metamorphism of argillaceous sediments ordinarily requires the removal of water from the rock. The breakdown of staurolite to mica and chlorite, however, requires the addition of water from a new source, presumably by the escape of water into the country rock during crystallization of the pegmatites 2/. Potassium may also have been obtained from pegmatite or from some other outside source, but this is not necessarily so. Doubtless the Fe:Mg ratio in the biotite of the groundmass increased as iron was obtained by destruction of staurolite, and at the same time potassium would be released to enter minerals in the pseudomorphs. Thus extensive sampling and analytical work are necessary to show whether or not potassium was added to this rock.

The introduction of this water and the emplacement of the pegmatites must have followed the peak of metamorphism to the staurolite and sillimanite grades. Similarly, Redden 3/ has found that in an area southeast of Custer

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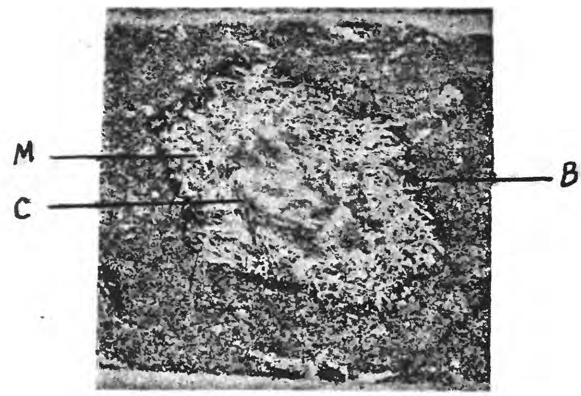
1/ Yoder, H. S., 1955, Role of water in metamorphism, in Poldervaart, Arie, and others, The crust of the earth: Geol. Soc. America, Special Paper 62, p. 508-509.

2/ Idem, p. 518-520.

Yoder, H. S., 1952, The MgO-Al_2O_3-SiO_2-H_2O system and the related metamorphic facies: Am. Jour. Science, Bowen volume, p. 619.

3/ Redden, J. A., Written communication.



Quartz-mica-chlorite schist at depth of 34.8 feet in drill hole 5, and 35.5 feet from the pegmatite contact. The groundmass contains quartz (50 percent), biotite (25 percent), muscovite (20 percent), chlorite (3 percent), and titanite (trace). Pseudomorphs of euhedral staurolite crystals forming 5 to 10 percent of the schist are composed of muscovite (50 percent), quartz (20 percent), chlorite (20 percent), and biotite (10 percent). In the pseudomorph shown in the thin section, biotite (B) forms the outer rim, muscovite (M) forms the next layer, and chlorite (C) is concentrated near the center of the pseudomorph.

PLATE 2. PSEUDOMORPH OF A STAUROLITE CRYSTAL (photomicrograph 2-1/3 times natural size)

sillimanite crystals are deformed by folds that controlled the emplacement of pegmatites; the pegmatites, therefore, were intruded after the peak of metamorphism.

PEGMATITES

Approximately 650 pegmatites have been mapped in the Keystone district. Of these, 40 are zoned. The remainder are about evenly divided between homogeneous and layered pegmatites. The very large pegmatites extending over broad areas in secs. 7, 16, 17, 20, and 21 are layered, and the quantity of rock in these large intrusives greatly surpasses the quantity of rock in all the other pegmatites of the district.

All but about 30 of the pegmatites are essentially concordant with the country rock. Figure 5 is a stereographic projection of 160 strike and dip readings along contacts of these 30 pegmatites. The dominant attitude is a northeasterly strike and a nearly vertical dip. Pegmatites having this attitude are most abundant in secs. 7, 8, and 17. They have an average thickness of about 10 feet, but their lengths are commonly very great; three of them are more than 0.5 mile long. These pegmatites are normal to the main northwesterly trending fault, and parallel to small faults that go outward from the northwesterly trending faults. It seems likely, therefore, that these pegmatites were controlled by fractures formed during faulting.

Most of the zoned pegmatites are more or less imperfectly concordant with the schistosity of the country rock and plunge parallel to isoclinal fold axes. Of the zoned pegmatites listed in tables 3 and 4, only the Peerless, one segment of the Monte Carlo, and the King Lode pegmatites are conspicuously discordant. Homogeneous and layered pegmatites tend to be somewhat longer and thinner than zoned pegmatites. Many of them are tabular intrusives, either concordant or discordant with the schist.

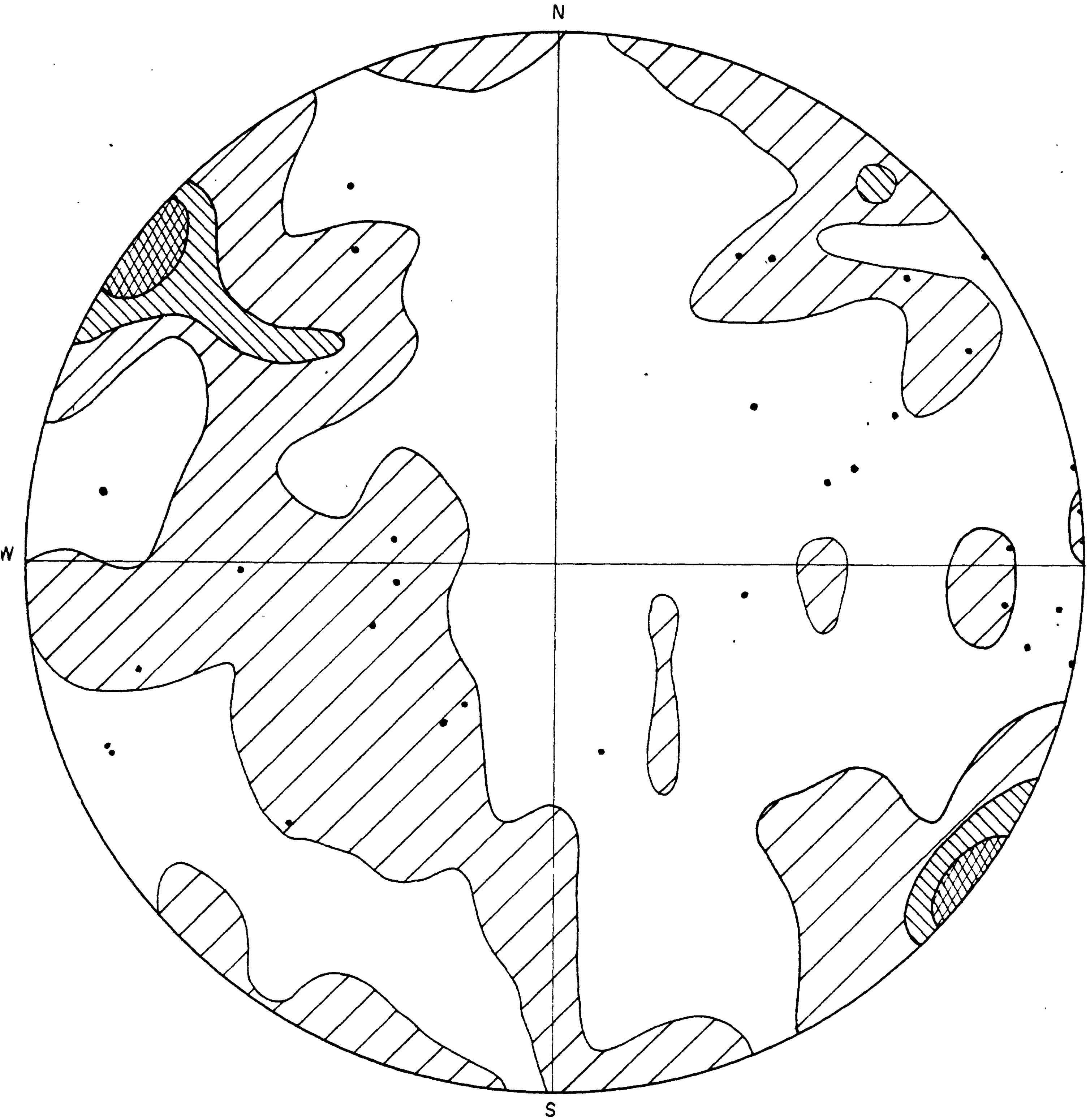


Figure 5.--Orientation of 160 poles to discordant contacts of 80 pegmatites. Contours at 5-3-1 percent. Dots are poles to 32 discordant quartz veins. Plotted on lower hemisphere of Schmidt net.

Layered pegmatites predominate along the southern and southwestern borders of the mapped area (fig. 3). All of the very large pegmatites on the map are layered pegmatites. Homogeneous pegmatites have been recognized from the south edge of the mapped area as far north as Keystone. Zoned pegmatites are concentrated in a belt 1 to 2 miles wide that goes from the southeast corner of the mapped area to the SW 1/4 sec. 31 (fig. 3), and then west toward Hill City (fig. 1).

Age determinations of samples from the Bob Ingersoll No. 1 and Peerless pegmatites have been made during recent years at the Lamont Geological Observatory and the Carnegie Geophysical Laboratory. The results shown below have been recalculated using the latest determinations of the physical constants 1/.

Apparent age (millions of years)

Pegmatite	Mineral	Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}	Th/Pb^{208}	K/A	Rb/Sr
Bob Ingersoll No. 1	Uraninite (C)	1580	1600	1630	1440		
	Uraninite (L)	1615	1615	1620	1370		
	Muscovite (C)					1550	1740
	Lepidolite (C)					1360	1665
	Microcline (C)					1080	1625
Peerless	Muscovite (wall zone)(L)					1615	
	Muscovite (replacement unit) (L)					1430	
	Lithia mica (replacement Unit) (L)					1270	

C - Carnegie Geophysical Laboratory
L - Lamont Geological Observatory

The age may be taken as 1,630 million years with a probable uncertainty of ± 20 million years 2/. This age is indicated by concordance of the

1/ Kulp, J. L., Written communication, 1957.

2/ Idem.

uranium-lead ratios with the potassium-argon date of coarse wall zone muscovite and also with the rubidium-strontium dates. The experimental error for uranium-lead ages is ± 2 percent and for potassium-argon and rubidium-strontium it is ± 3 to 5 percent, though the rubidium-strontium age of muscovite may have a slightly greater error (perhaps ± 100 million years). The low potassium-argon ages are probably caused by the loss of A^{40} in minerals that are in small or poorly ordered crystals. The time of pegmatite formation in the Black Hills is one of the best established points of the geologic time scale 1/. Measurements are in progress at the Lamont Observatory to show whether or not 1,630 million years is also the age of metamorphism.

Layered Pegmatites

The chief layered pegmatites are the very large intrusives in the SW 1/4 sec. 7 and in the southern part of the mapped area in secs. 16, 17, 20, 21, and 22. Many of the smaller pegmatites, however, are also layered. Most of the larger intrusives and many of the smaller ones are sills; some of the small ones are dikes.

The distinguishing characteristic of this rock is a layering, ordinarily vaguely defined, consisting most commonly of alternating coarse-grained perthite-quartz-plagioclase pegmatite and finer-grained plagioclase-quartz pegmatite. The layering generally is parallel to the pegmatite contacts. The average thickness of layers is about 1 foot, but the maximum thickness is at least 10 feet.

1/ Kulp, J. L., Written communication, 1957.

The overall composition of layered pegmatites ordinarily is in the range: plagioclase (albite and oligoclase) - 30 to 45 percent; quartz - 25 to 40 percent; perthite - 15 to 25 percent; and muscovite - 2 to 10 percent.

Coarse-grained perthite-quartz-plagioclase pegmatite is rarely found in contact with the wall of a pegmatite; almost invariably there is an intervening layer of finer-grained pegmatite. An exception is in a road cut in the SE 1/4 SW 1/4 SW 1/4 sec. 17, where a fracture-filling extends outward across fine-grained pegmatite to the schist contact and then follows the schist contact for several feet before dying out. Near many contacts the fine-grained plagioclase-quartz pegmatite becomes coarser in texture and more quartzose within 1 inch or less from the contact.

The finer-grained layers consist of very fine-grained to medium-grained plagioclase-quartz or plagioclase-quartz-muscovite pegmatite. Where the rock is very fine-grained and has an aplitic texture, it consists dominantly of plagioclase (55 to 80 percent), but also contains quartz (15 to 30 percent), muscovite (1 to 10 percent), microcline (0 to 15 percent), tourmaline (0 to 5 percent), reddish brown garnet (0 to 2 percent), and very small quantities of other minerals. Where the grain size is fine to medium, the rock contains less plagioclase (25 to 60 percent), more quartz (25 to 40 percent), and rare garnet (0 to 1 percent); the other minerals are not significantly different. Most of the plagioclase is albite and the rest is oligoclase. Many of the fine-grained layers contain "line rock", which is in all respects the same as described on previous pages in the general description of Black Hills pegmatites. One of the best examples of line-rock is shown on plate 3. Ordinarily "line-rock" is parallel to the pegmatite contact, but locally it may be at a strong angle to the contact.

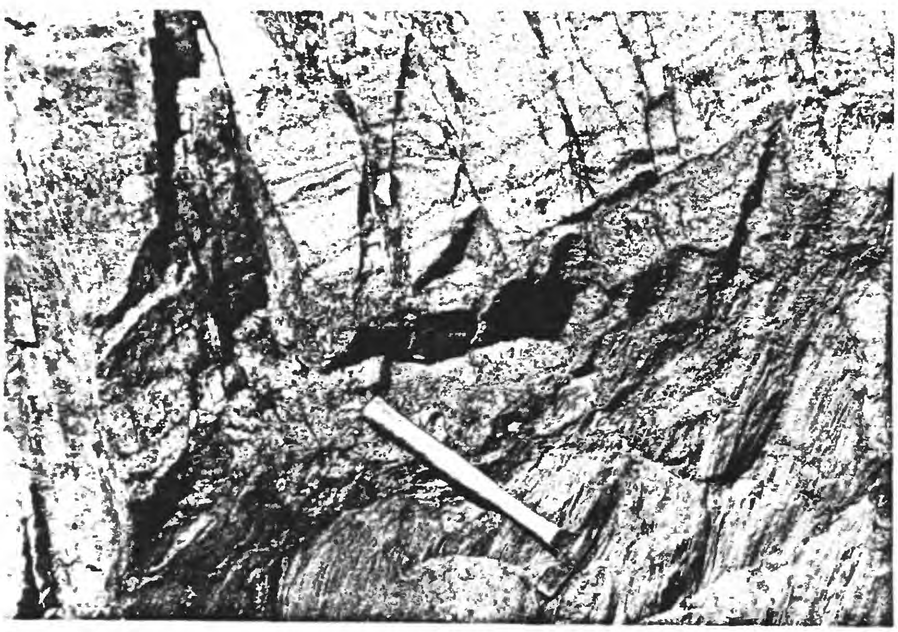


Plate 3. Line rock oriented parallel to pegmatite contact and at an angle to schistosity, S 1/2 SW 1/4 sec. 17, T. 2 S., R. 6 E.

The chief constituents of the coarser layers are perthite, plagioclase (albite and perhaps oligoclase), and quartz. The most common form is perthite-quartz-plagioclase pegmatite consisting of coarse to very coarse perthite or graphic granite crystals in a medium-grained groundmass of quartz and plagioclase. The composition ordinarily is in the range: perthite - 25 to 50 percent; quartz - 25 to 40 percent; plagioclase - 20 to 30 percent; muscovite - 1 to 5 percent; and tourmaline - 0 to 2 percent. Less commonly, coarse-grained layers consist only of quartz or of quartz and perthite in lenticular to pod-like aggregates.

The coarse-grained layers are evidently segregations that formed shortly after the crystallization of the adjacent fine-grained layers. They have gradational contacts, and so far as can be determined they are entirely surrounded by finer-grained pegmatite. Layering is parallel to the pegmatite contact and ordinarily is not associated with fractures. Coarse layers are fairly evenly distributed throughout layered pegmatites; they do not have the irregular distribution that would be expected if they formed by intrusion after the finer-grained pegmatite had crystallized. On the other hand, there is evidence that they crystallized later than the adjacent finer-grained layers; they ordinarily embay and vein finer-grained layers and tourmaline crystals in the outer parts of coarse-grained layers are oriented perpendicular to the contact. Contradictory relations can be found indicating that there may have been some overlap in time between the crystallization of coarse- and fine-grained layers that are in contact with each other. In general, however, coarse-grained layers are younger than adjacent fine-grained layers.

Within coarse-grained layers the perthite crystals are commonly corroded by the groundmass of quartz and plagioclase. This quartz and plagioclase is very similar, and in many places grades into, the finer-grained quartz and plagioclase of the adjacent layers. Thus there is considerable overlap in the time of crystallization of these minerals. Furthermore these relations have only local paragenetic significance; they do not mean that a coarse layer in one part of a pegmatite is necessarily younger than the fine layers that are some distance away. Fine-grained layers in the outer part of a pegmatite, where crystallization ordinarily would begin, may well be older than coarse-grained layers near the center of the pegmatite.

Fracture-filling units in layered pegmatites of the Keystone district consist of perthite-quartz-plagioclase, quartz-perthite, or quartz pegmatite. Ordinarily they are enriched in muscovite at their outer edges. Muscovite-rich pegmatite of this sort at the Hesnard mine, SE 1/4 sec. 17, contains about 1 percent beryl. A few fracture-filling units are parallel to the layering structure, and where these consist of perthite-quartz-plagioclase pegmatite they may be virtually indistinguishable from coarse-grained layers. The large pegmatite southwest of the Big Chief mine, in the NE 1/4 sec. 22, has units of this sort that are considered to be fracture-fillings rather than layers because of the extreme sharpness of their contacts. One quartzose fracture-filling in this pegmatite contains spodumene. Elsewhere in layered pegmatites lithium minerals have not been recognized.

The best examples of layered pegmatites within the mapped area are the very large pegmatites in sec. 20 and adjacent areas to the east and north. In addition to the normal layering, some of these pegmatites have a layering caused by multiple intrusion. In the central part of the N 1/2 sec. 20, the geologic map (fig. 3) shows many places where small pegmatites coalesce to form larger ones. The outer parts of these small pegmatites are finer-grained than the inner parts, and where several of these pegmatites coalesce, an alternating sequence of fine- and coarse-grained layers is formed.

In the long narrow dikes of secs. 7, 8, and 17, layering is less well defined than in the larger intrusives to the south and west. The layering of these dikes is distinguishable chiefly by the elongation of aggregates consisting of perthite crystals in a groundmass of quartz and plagioclase that are more coarse-grained than the quartz and plagioclase of the fine-grained layers. Layering is better developed along the contacts than in the center of these pegmatites.

Homogeneous Pegmatites

Homogeneous pegmatites consist of the same material virtually throughout the intrusive. Thin border and wall zones can be recognized in some pegmatites regarded here as homogeneous, but they are at most an inconspicuous element of the structure. Fracture-filling units consisting of quartz or of quartz and perthite occur in many homogeneous pegmatites, but other types of segregations enriched in quartz and perthite are rare.

Most of the homogeneous pegmatites are small tabular to lenticular intrusives, usually concordant with the enclosing schist. A few are large and thickly lenticular. The largest is the Diamond Mica north pegmatite in the NE 1/4 sec. 17. This pegmatite has a tear-drop shape, and is very similar in outward form to the nearby Etta pegmatite.

Homogeneous pegmatites ordinarily consist of quartz (25 to 40 percent), plagioclase (20 to 35 percent), perthite (15 to 40 percent), muscovite (4 to 15 percent), and tourmaline (1 to 3 percent). Most of the plagioclase is albite, but some is oligoclase. All the minerals except perthite are fine- to medium-grained. Perthite crystals are coarse- to very coarse-grained; the largest are as much as 15 feet across. The large crystals of perthite are intergrown with quartz to form graphic granite. Perthite crystals are embayed and corroded by intergrown groundmass minerals consisting largely of quartz and plagioclase. As in the layered pegmatites, these paragenetic relations are significant only locally: they indicate that quartz and plagioclase in contact with a perthite crystal are younger than that perthite crystal, not that they are younger than all the perthite in the pegmatite.

Some of the homogeneous intrusives consist of quartz-plagioclase-muscovite pegmatite. Few, if any, of these pegmatites are more than 10 feet thick and 150 feet long.

The average composition of the Diamond Mica north pegmatite (NE 1/4 sec. 17) has been estimated from diamond drill core and surface exposures to be: quartz - 30 percent; albite - 27 percent; perthite - 27 percent; muscovite - 15 percent; and tourmaline - 1 percent. This is close to the average composition of all homogeneous pegmatites except that the muscovite content is somewhat high, and the quartz and plagioclase may be low.

The very small border and wall zones of homogeneous pegmatites consist of fine- to medium-grained albite-oligoclase (25 to 50 percent), quartz (25 to 45 percent), muscovite (10 to 25 percent), and tourmaline (1 to 5 percent).

Zoned Pegmatites

Many of the zoned pegmatites of the Keystone district have been mapped at scales of 1:240 and 1:480. The data to be presented here will consist chiefly of material that is significant with regard to genesis and to the relations of the zoned pegmatites among themselves and with other types of pegmatites.

Data for the 19 most important zoned pegmatites in the mapped area are presented in tables 3 and 4. An additional 21 zoned pegmatites are known within the limits of the geologic map.

Zoned pegmatites range in size from bodies a few inches long to very large pegmatites like the Hugo, Peerless, and Monte Carlo, each of which contains more than half a million tons of rock. Even the largest of these, however, are far smaller than the largest layered pegmatites.

Most of the zoned pegmatites are lenticular (table 3); the thick part of the lens, however, is ordinarily nearer the top than the center of the pegmatite. Some are teardrop-shaped to pipelike. Two discordant pegmatites, the Peerless and the King Lode, are crescent-shaped. The Edison is a multiple intrusive consisting of several tabular to lenticular pegmatites, which, taken together, give the entire body an irregular form.

All but three of the pegmatites in table 3 have generally concordant relations, though locally all of them have cross-cutting relations to the

Table 3. Important zoned pegmatites of the Keystone district

Name	Location	Shape
* Big Chief	NE ¼ sec. 22	Lenticular
* Bob Ingersoll No. 1	SE ¼ SW ¼ sec. 31, and NE ¼ NW ¼ sec. 6	Teardrop
* Bob Ingersoll No. 2		Thickly lenticular
Bob Ingersoll No. 3		Lenticular
Bob Ingersoll No. 4		Lenticular
* Dan Patch	NE ¼ NE ¼ sec. 7	Teardrop
Dan Patch No. 2	NW ¼ NE ¼ sec. 7	Lenticular
Diamond Mica, south pegmatite	SE ¼ NE ¼ sec. 17	Thickly lenticular
* Dyke Lode	NE ¼ sec. 21	Teardrop
* Edison	SE ¼ sec. 9	Multiple intrusive consisting of several tabular to lenticular pegmatites.
* Etta	NW ¼ NW ¼ sec. 16	Teardrop
Eureka	SW ¼ SE ¼ sec. 15	Pipelike
Hardestey	SE ¼ NE ¼ sec. 36	Thickly lenticular
* Hugo	NE ¼ sec. 17	Multiple intrusive consisting of two thickly lenticular pegmatites.
King Lode	SW ¼ SW ¼ sec. 15	Crescent-shaped, concave upward.
Monte Carlo	NE ¼ NE ¼ sec. 17	Multiple intrusive, consisting of a thinly lenticular pegmatite and a thickly lenticular pegmatite.
* Peerless	SE ¼ NE ¼ sec. 8	Thickly crescent-shaped, concave downward.
Sitting Bull	SW ¼ sec. 5	Thickly lenticular
* White cap	NW ¼ NE ¼ sec. 16	Lenticular

* Pegmatites of major economic importance.

country rock. The plunge is parallel to the plunge of isoclinal folds. Inasmuch as the isoclinal folds have been deformed by later folds and faults, the attitudes of concordant zoned pegmatites differ greatly throughout the district.

The discordant pegmatites are the Peerless, Monte Carlo, and King Lode. The Peerless pegmatite in section has the form of a crescent that is concave downward; the attitudes of the two limbs suggest control by fractures that strike N. 30° W. and dip 45° NE and SW. The Monte Carlo pegmatite is a multiple intrusive in which the largest of the two component bodies is thinly lenticular and discordant. The King Lode is intrusive into massive amphibolite.

Sequence of Zones

Table 4 shows the sequence of mineral assemblages in zoned pegmatites of the Keystone district in the form originally used by Cameron and others 1/ and by Page and others 2/. The Keystone pegmatites contain all of the mineral assemblages in the general sequence recognized in other pegmatite districts of the United States. In particular, assemblages 5 through 11 of table 4 are unusually well represented. Figures 6 and 7 show the internal structure of two zoned pegmatites: (1) the Big Chief, which consists almost entirely of perthite-quartz-albite and quartz pegmatite, and (2) the Hugo, which contains many units.

The outermost unit of nearly all of these pegmatites consists of fine- to medium-grained quartz, plagioclase, and muscovite. The content of muscovite

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1/ Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., 1949, Internal structure of granitic pegmatites: Econ. Geology Mon. 2, p. 59-70.

2/ Page and others, op. cit., p. 15-16.

decreases greatly inward from the contact, but perthite becomes an abundant mineral. All but two of the pegmatites of table 4 contain perthite-rich zones of assemblage 3 or 4, in which the perthite is very coarse-grained and the other minerals are medium- to coarse-grained. The perthite-rich units occur as hoods in the upper part of the pegmatite. At the Hugo a zone consisting of assemblage 3 has been subdivided into three smaller units, each of which is shown on the right-hand side of figure 7. The outer and upper parts of this unit consist of perthite-quartz-albite pegmatite containing more than 50 percent perthite. The perthite is very coarse-grained; one crystal was 35 feet long and 10 feet by 10 feet in cross-section, and much larger crystals have been mined 1/. Downward and inward this is succeeded by quartz-albite-perthite pegmatite containing 5 to 50 percent perthite. Finally, in the lower parts of the pegmatite, this unit consists of medium-grained quartz-albite pegmatite containing 0 to 5 percent perthite.

These perthite-rich units are ordinarily followed by very coarse-grained units increasingly rich in quartz. Other common minerals in assemblages 5-8 are plagioclase, spodumene, amblygonite, and perthite. The final unit in nine of the pegmatites on table 4 is a quartz core.

Three of the pegmatites in table 4, however, have cores with a relatively low content of quartz and a high content of minerals with alkalies, water, and fluorine. The Bob Ingersoll No. 1 pegmatite has a core consisting of quartz-cleavelandite-lepidolite pegmatite (assemblage 9). The Hugo and Peerless pegmatites each have a core rich in a gray "lithia mica" (assemblage 11), and a zone adjacent to the core that consists of quartz and non-perthitic microcline (assemblage 10).

1/ Schwartz, G. M., personal communication, 1948.

"Lithia mica" is a field name used for a fine-grained gray mica in assemblage 11 that is very similar to lepidolite except that it is gray in color and has a much lower lithium content. Optical data and partial chemical analyses suggest that it is a lithium-rich muscovite, but more data are needed.

Replacement Features

The Hugo and Peerless pegmatites also contain replacement units that extend outward from the core and cut across the zonal structure. The introduced minerals are dominantly fine-grained lithia mica and cleavelandite, indicating that the pneumatolytic or hydrothermal fluids that caused the replacement bodies contained alkalies, water, and probably fluorine. Figure 7 shows that two replacement units were mapped at the Hugo: (1) cleavelandite-microcline-lithia mica pegmatite, which replaces inner zones, and (2) cleavelandite-quartz-lithia mica pegmatite, which replaces outer zones. The differences between these two units may have been caused by differences in the composition of rock that was replaced and by changes in the composition of the fluid as it advanced through the rock.

The replacement units contain isolated remnants of unreplaced parts of the zones, one of which is shown in the left-hand part of figure 7. In many places minerals and textures of the pre-existing zones are sufficiently well preserved so that zonal contacts can be traced through the replacement body. Thus, in the Hugo pegmatite, the quartz-cleavelandite-microcline-amblygonite zone characteristically has blade-shaped aggregates of minerals. These blades can also be recognized in the replacement unit, though lithia mica and cleavelandite have been added to the blades and to the surrounding rock. In replaced parts of the quartz-microcline-spodumene zone the outlines of spodumene crystals can be recognized even where the rock consists almost entirely of cleavelandite, lithia mica, and small rubbly masses of microcline.

The replacement units also contain many examples of embaying, veining, and pseudomorphic replacement of some minerals by other minerals. These textures, however, also occur in zones. They can be used to determine age relations among the minerals, but they are not direct evidence for the massive replacement of an entire rock that characterizes the replacement units. Davidson, Grout, and Schwartz 1/ have discussed a similar problem regarding ilmenite in a gabbroic dike in Virginia. Petrographic evidence indicates that part of the ilmenite formed after minerals with which it is associated. Davidson and his coauthors point out, however, that this does not justify liberal use of the words "replacement" and "secondary". They consider that "replacement" should not include "late magmatic or deuteric changes" caused by "reactions with magma." They also believe that "secondary" should be restricted to minerals that are "later than magmatic minerals", and should not be based only "on the observation that a mineral is later than some other mineral" 2/.

Textures indicating corrosion are more common in inner zones than outer zones. These textures are least common in assemblages 1 and 2. Perthite of assemblages 3 and 4 is characteristically embayed and veined by quartz and albite of the groundmass. In the Hugo pegmatite the quartz-cleavelandite-microcline-amblygonite zone (assemblage 5) contains many pseudomorphs after

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1/ Davidson, D. M., Grout, F. F., and Schwartz, G. M., 1946, Notes on the ilmenite deposit at Piney River, Virginia: Econ. Geology, v. 41, p. 738-748, especially p. 746-748.

2/ Idem, p. 747-748.

spodumene that can be recognized as such by their bladed shape and by cleavelandite sheaths that ordinarily surround spodumene crystals in this and other pegmatites. Assemblages 9 and 11 characteristically have a great variety of corrosion textures. At the Hugo, for example, aggregates of cleavelandite form many veinlets that cut across all other minerals. Lithia mica, however, though in part earlier than cleavelandite, also occurs in many vein-like masses that cut cleavelandite, and thus the age relations are overlapping.

A criterion for replacement that has been used by many authors, though not used here, is the presence of minerals that occur in radiating masses, "rosettes", or "bursts". Cleavelandite is the principal mineral that forms in this fashion. Hess 1/ was the first to use this criterion when he applied it to the radiating disposition of spodumene crystals and stated that such mineral forms are evidence for replacement because they must have been supported to develop in this fashion. He cites pyrite balls in sediments as an analogous example. Landes 2/ expressed the same view in his discussion of Keystone pegmatites.

Jahns 3/ has recently stated that spodumene rosettes may have been supported by "the crystal-bearing liquid or by the crystal mesh." At an earlier time, however, Jahns 4/ considered that "bursts" and "rosettes" are generally formed by replacement processes." His view seemed to be that

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1/ Hess, F. L., 1925. The natural history of the pegmatites: Eng. and Min. Jour. - Press, v. 120, p. 295.

2/ Landes, K. K., 1928, Sequence of mineralization in the Keystone, S. D. pegmatites: Am. Mineralogist, v. 13, p. 543-549.

3/ Jahns, R. H., 1953, The genesis of pegmatites: Am. Mineralogist, v. 38, p. 594.

4/ Jahns, R. H., 1946, Mica deposits of the Petaca district, Rio Arriba County, New Mexico: N. Mex. Bur. Mines and Mineral Resources, Bull. 25, p. 69 and 233.

radiating cleavelandite is in many replacement bodies, and that it occurs less commonly, and perhaps never, as a primary mineral.

In the Keystone pegmatites, minerals with radiating structure are primary zonal minerals. Radiating cleavelandite occurs in many inner zones, but the cleavelandite in bodies definitely of replacement origin does not as a rule show the "rosette" or radiating structure. It is possible that the only inference one can draw from cleavelandite crystallized in a radiating fashion is that this is the natural form for these masses to take if allowed to develop without interference. Spodumene in the Etta pegmatite and elsewhere forms an interlocking network of crystals; the radiating characteristic described by Hess is at junctions in this network. Minerals of the groundmass embay and vein the spodumene, and thus are at least in part younger than the spodumene. As Jahns has suggested 1/, it seems probable that the only support radiating masses ever had or needed, was from other crystals of the partially solidified pegmatite.

The large size of some crystals has also been cited as an example of unsupported structures that require a replacement origin 2/. Large crystals occur in nearly all zones of every zoned pegmatite, and if they formed by replacement, it is difficult to understand how the different mineral species forming large crystals were distributed among the zones in such a fashion as to form a consistent zonal sequence. Furthermore, the largest crystals are usually potassium feldspar, used by many writers as the primary host of cleavelandite and lithium minerals. It is more likely that the large crystals,

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1/ Jahns, 1953, op. cit., p. 594.

2/ Hess, 1925, op. cit., p. 291.

Connolly, J. P., and O'Harra, C. C., 1929, The mineral wealth of the Black Hills: S. D. School Mines, Bull. 16, p. 238-239.

like the rosettes, obtained their support chiefly from other crystals during primary crystallization of the pegmatite.

Mineral Variations

The minerals of zoned pegmatites show consistent changes from the wall zone to the core. Table 5 shows that in the Hugo and Peerless pegmatites the An content of plagioclase and the BeO content of beryl decrease from the wall zone inward. Plagioclase in the Hugo pegmatite is An_{3-14} in the border zone, An_{4-14} in the wall zone, An_{4-11} in intermediate zones, and An_{4-6} in the core. The fine-grained introduced cleavelandite in the Hugo replacement units contains as little as 2 percent An. One specimen collected from the contact between the wall zone and the cleavelandite-quartz-lithia mine replacement body had oligoclase from the wall zone adjacent to the very sodic albite of the replacement unit.

Muscovite decreases in the content of soda, and thus of paragonite from the wall zone inward. Spectrochemical analyses of Hugo micas were made by Charles E. Harvey, Univ. of Michigan Engineering Research Project M-[illegible], supported by the U. S. Army Signal Corps, and directed by E. W. Heinrich. One specimen from the wall zone contained 1.6 percent Na_2O; four specimens from the first two intermediate zones contained 1.4 to 1.5 percent Na_2O; and one specimen from the core contained 0.37 percent Na_2O. Grootemaat and Holland 1/ found similar changes in mica from the Peerless pegmatite.

1/ Grootemaat, T. B., and Holland, M. D., 1955, Sodium and potassium content of muscovites from the Peerless pegmatite, Black Hills, S. D. (abstract): Geol. Soc. America Bull., v. 66, p. 1569.

57-84

Table 5. Indices of refraction of plagioclase and beryl, Hugo and Peerless pegmatites

Mineral assemblage (from table 4)	Pegmatite units	Hugo pegmatite, south segment				Peerless pegmatite			
		Plagioclase		Beryl		Plagioclase		Beryl	
		Minimum index of cleavage fragments	An content (percent)	N_o	BeO content (percent) 1/	Minimum index of cleavage fragments	An content (percent)	N_o	BeO content (percent) 1/
1	Border zone	1.530-1.534	8-14			1.528-1.533	4-13	1.577-1.581	13.0-13.3
	Wall zone	1.528-1.534	-14	1.583-1.588	12.2-12.8	1.528-1.531	4-9	1.574-1.587	12.3-13.5
1		---	---	---	---	1.528-1.530	4-8	1.575-1.584	12.6-13.4
3	Intermediate	1.529-1.532	6-11	1.577-1.590	11.8-13.3	---	---	---	---
5	zones	1.528-1.531	4-9	1.585-1.591	11.7-12.6	1.528	4	1.584-1.587	12.3-12.6
10		1.528-1.529	4-6	---	---	---	---	---	---
	Core	1.528-1.529	4-6	---	---	---	---	---	---
11	Relict minerals of replacement units	1.523(?)-1.531	6-9	1.586-1.589	12.0-12.4	---	---	---	---
	Introduced minerals of replacement units	1.527-1.529(?)	2-6	---	---	---	---	---	---

1/ Based on written communication from W. T. Schaller.

Keith and Tuttle [1] found that the variations in the temperature of the high-low inversion of quartz also shows a regular sequence of changes. The inversion temperature in the Hugo, New York, and Helen Beryl pegmatites of the Black Hills generally decreases from the wall zone through intermediate zones, and then increases as the core is approached.

Comparison of Zoned Pegmatites with Homogeneous and Layered Pegmatites

Table 4 shows that one of the most evident characteristics of zoned pegmatites is that many of them contain units belonging to mineral assemblages 4 through 12; in contrast, the layered and homogeneous pegmatites consist chiefly of rock types that belong to assemblages 1 through 3. Most of the so-called rare minerals of pegmatites are in assemblages 4 through 11; the most important exceptions are sheet mica in assemblage 1 and beryl in assemblages 1 and 3.

Actually, however, the differences in mineral composition between zoned pegmatites and other pegmatites is commonly overemphasized. Quantitatively, outer units belonging to assemblages 1 through 3 form a much greater part of zoned pegmatites than inner units belonging to assemblages 4 through 12. The only exceptions shown on table 4 are the Etta pegmatite, and perhaps the Edison pegmatite, in which assemblages 7 through 12 form more than half of the total quantity of pegmatite. Generally quartz and plagioclase are the dominant minerals, and perthite and muscovite are the only other abundant minerals, just as in the layered and homogeneous pegmatites. The zoned pegmatites may contain somewhat more perthite and muscovite than other pegmatites, but if so, the difference is not great. Such minerals as beryl, amblygonite,

1/ Keith, M. L., and Tuttle, O. F., 1952, Significance of variation in the high-low inversion of quartz: Am. Jour. Sci., Bowen volume, p. 234-237.

lepidolite, and columbium-tantalum minerals form only a very small part of any zoned pegmatite. The greatest difference between zoned pegmatites and other types of pegmatites is that the minerals are concentrated in certain zones, and thus there are units that are very rich in perthite (as much as 90 percent), muscovite (as much as 30 percent), spodumene (as much as 30 percent), lepidolite (as much as 25 percent), beryl (as much as 3 percent), and other minerals.

The border and wall zones of the Peerless pegmatite have a possibly significant resemblance to layered pegmatites. Figure 8 shows a sequence of 15 layers numbered from 1 at the contact inward to 15. They are based chiefly on seven diamond drill holes, but in part on a study by L. R. Page and J. A. Redden of one surface exposure of the wall zone. The layers are discontinuous, and in any one place only a few of the layers shown in figure 8 can be recognized.

A sequence of 15 layers has been built up by correlation from one place to another. Though some of the correlations may be debatable, the general relations shown in figure 8 must be essentially correct. From layers 1 to 8, the quartz content shows a general decrease and the albite content an increase; the muscovite content reaches a peak in layer 3 and then decreases in abundance. Layer 6 has the only break in this sequence: the albite content is less and the quartz and muscovite contents are greater than in adjacent layers. The contacts of this layer cut the layers on either side, and thus indicate that this may be a fracture-filling unit that crystallized later than the surrounding rock. The composition suggests that this fracture-filling unit corresponds with the cleavelandite-quartz-muscovite pegmatite of the first intermediate zone. Layer 9 is a perthite-rich segregation ordinarily surrounded by albite-quartz-muscovite pegmatite of layers 8 and 10.

An abrupt change takes place between layers 10 and 11. The quartz and muscovite content increase and the albite content decreases. The sequence from layer 11 to 14 is a telescoped series that is very similar to the sequence from layer 3 to 10. The quartz-albite pegmatite of layer 15 suggests the start of still another series that extends into the inner zones of the pegmatite.

Comparison with table 4 shows that the sequence of layers has a striking similarity to the normal sequence of mineral assemblages in zoned pegmatites. If the probable fracture-filling unit forming layer 6 is disregarded, layers 1 through 8 are in the same sequence as the subdivisions of assemblage 1. The perthite-bearing layers 9 and 13 correspond to assemblage 3, and are equivalent to intermediate zones and cores of many Black Hills pegmatites.

Similarly, in layered pegmatites there is evidence previously cited that layers consisting of assemblage 3 are generally younger than adjacent layers consisting of assemblage 1. The contacts between layers have the same changes in perthite and plagioclase content shown at the contacts of layers 9 and 13 in the Peerless pegmatite. Homogeneous pegmatites also have this sequence; the outer parts of homogeneous pegmatites have narrow border and wall zones of assemblage 1, and the remainder of the pegmatite ordinarily consists of assemblage 3.

Chemical Composition of Pegmatite

Table 6 shows the estimated chemical composition of (1) average layered pegmatite, (2) a typical homogeneous pegmatite, the Diamond Mica north pegmatite, and (3) the Hugo and Peerless zoned pegmatites, including the composition of units within these two pegmatites. In calculating the overall composition of the Hugo and Peerless pegmatites, the tonnage of

57-84

Table 7. Mineral compositions used in computing chemical composition of pegmatite.

Composition (in percent)

Mineral	SiO_2	Al_2O_3	Fe_2O_3, FeO	MgO	CaO	Na_2O	K_2O	Li_2O	H_2O	P_2O_5	BeO	Other constituents
Quartz	100.0	—	—	—	—	—	—	—	—	—	—	—
Plagioclase (An_5) 1/	67.1	20.3	—	—	1.0	11.2	0.4	—	—	—	—	—
Perthite and microcline	64.4	19.8	—	—	0.4	2.7	12.7	—	—	—	—	—
Muscovite	45.2	36.5	1.5	0.5	0.2	1.0	9.0	—	5.0	—	—	1.1
Lithia mica	47.0	35.0	0.5	—	—	0.7	10.5	0.4	4.0	—	—	1.9
Beryl	66.8	18.9	—	—	—	0.2	—	0.1	—	—	12.8	1.2
Tourmaline	37.0	32.0	14.0	2.0	—	2.0	—	—	3.0	—	—	10.0
Iron-lithium-manganese phosphates	—	—	35.0	—	—	—	—	9.0	—	45.0	—	11.0
Amblygonite	—	34.0	—	—	—	3.0	—	9.5	5.0	47.5	—	1.0
Apatite	—	—	—	—	51.0	—	—	—	2.0	42.0	—	5.0

1/ Slightly different figures used for plagioclase in which the An content is known to be other than An_5.

P. 110 IS BIG SIZE

each unit was determined by making successive geologic sections. Most of these chemical data were calculated from modes, using chemical compositions for the various minerals shown in table 7.

The composition of the Diamond Mica north pegmatite was also calculated from 10 chemical analyses of drill core. The chemical analyses show more Na_2O and less K_2O than do the modes. The chief cause of this difference is that blocky albite was mistaken for microcline in the mode. Furthermore, muscovite was probably overestimated in the mode. It is unlikely that errors of this magnitude were made in the modes of the other pegmatites.

The most evident conclusion from table 6 is that the overall compositions of the Hugo, Peerless, Diamond Mica north, and average layered pegmatite are very similar. The table suggests that homogeneous pegmatite, represented by the north pegmatite on the Diamond Mica claim, has somewhat more K_2O than average layered pegmatite, but this may be explained by the fact that the Diamond Mica pegmatite has more muscovite than most other homogeneous pegmatites.

The layered rock in the border and wall zones of the Peerless pegmatite (table 6) is very similar in composition to homogeneous and layered pegmatite; the greatest difference is that it has less K_2O, but the Peerless pegmatite as a whole has an unusually small quantity of K_2O.

The two zoned pegmatites in table 6 have somewhat more SiO_2 and less Al_2O_3 than layered and homogeneous pegmatites. Similar calculations for other zoned pegmatites might show, however, that these differences are not significant. Many zoned pegmatites in the Black Hills consist almost entirely of mineral assemblages 1 through 3, and table 6 shows that these mineral assemblages in the Hugo and Peerless pegmatites have aggregate SiO_2 and Al_2O_3 contents that are about the same as layered and homogeneous pegmatites.

The Hugo pegmatite contains less Na_2O and perhaps less K_2O than layered and homogeneous pegmatites. The Peerless pegmatite contains extraordinarily little K_2O, but it has about as much Na_2O as layered and homogeneous pegmatites. K_2O of zoned pegmatites is ordinarily concentrated in perthite- or mica-rich zones that form only a relatively small part of the entire pegmatite.

Such elements as Li, Be, Cb, Ta, and Sn form such a small part of any of these pegmatites that they do not show in table 6. In spite of this, the Peerless pegmatite has a beryl-rich unit that has been the source of more than 500 tons of beryl, or about 1 percent of the total world production prior to 1952 1/. The tonnage of beryl reserves in this pegmatite is several times the total tonnage of production to date. The Hugo also has been a major source of beryl and has reserves comparable to the Peerless reserves. In addition, the Hugo has been a major source of amblygonite and was at one time mined for tantalite. The units containing these minerals form such a small part of the pegmatite that although they contain several hundred tons of Li_2O and a few tons of tantalite, the total quantity of these materials is very small in relation to the size of the pegmatite.

The principal changes indicated by the chemical composition of the various subdivisions of the Hugo and Peerless pegmatites (table 6) are an increase in SiO_2 and a decrease in Al_2O_3 inward toward the center of each pegmatite. The very small quantity of pegmatite forming assemblage 11, however, is low in SiO_2 and rich in Al_2O_3, Na_2O, and K_2O.

The layered rock in the Peerless border and wall zones is higher in SiO_2 and lower in Al_2O_3 than the adjacent intermediate zone. Na_2O is rather evenly distributed through these two pegmatites, though each of them does

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1/ Staff of U. S. Bur. Mines and Geol. Survey, 1953, Beryllium: National Security Resources Board, Materials Survey, P. IV-9.

contain units that have very little Na_2O. K_2O is concentrated only in the few units rich in muscovite or potassium feldspar.

The enrichment of inner units in SiO_2 suggests a relation between pegmatites and certain quartz veins in the Keystone district. Some of the quartz veins have thin border and wall zones containing plagioclase, muscovite, and rare microcline crystals. These may be essentially zoned pegmatites consisting almost entirely of a quartz core, and thus they are much richer in SiO_2 than any of the pegmatites in table 6.

Genesis

In past discussions of the genesis of Black Hills pegmatites, no attempt has been made to coordinate evidence from layered, homogeneous, and zoned pegmatites. Investigators of the layered pegmatites or "granite" have agreed that these are intrusive rocks of magmatic origin 1/. As for the homogeneous pegmatites, it seems to have been generally assumed that these too are of intrusive magmatic origin, though it is difficult to make any definite statement to this effect in the absence of any specific discussion of these pegmatites, or even of recognition of their existence as a separate category.

On the other hand, investigators of what are here called zoned pegmatites have brought forth a great variety of conclusions regarding genesis. Prior

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1/ Paige, Sidney, 1925, Precambrian rocks, in Darton, N. H., and Paige, Sidney, Central Black Hills, S. D.: U. S. Geol. Survey Geol. Atlas, folio 219, p. 4-5.

Balk, Robert, 1931, Inclusions and foliation of the Harney Peak granite, Black Hills, S. D.: Jour. Geology, v. 39, p. 736-748.

Runner, J. J., 1943, Structure and origin of Black Hills Precambrian domes: Jour. Geology, v. 51, p. 431-457.

to 1925 these pegmatites were generally considered to be of intrusive magmatic origin; indeed, early writers seemed to think the subject scarcely warranted discussion 1/. In the years since 1925, those who have studied Keystone pegmatites have arrived at conclusions regarding genesis that can be divided into three categories:

(1) Crystallization of an essentially magmatic fluid in a restricted system. This fluid may give rise to hydrothermal or pneumatolytic solutions that cause a relatively minor amount of replacement of previously crystallized pegmatite 2/.

(2) Crystallization in two or more stages, of which the first was magmatic and the others hydrothermal. Replacement is considered to be of major quantitative importance. The hydrothermal fluids were from a source, or sources, outside the pegmatite 3/ or within the pegmatite 4/.

(3) Metasomatic replacement of metamorphic rocks 5/.

The Keystone pegmatites that have been the principal sources of data for genetic theories are the Etta, Hugo, Peerless, Bob Ingersoll Nos. 1 and 2,

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1/ Paige, op. cit., p. 4-5.

2/ Page and others, op. cit., p. 17-24.
Sheridan and others, op. cit.

3/ Hess, op. cit.

4/ Landes, K. K., 1928, Sequence of mineralization in the Keystone, S. D., pegmatites: Am. Mineralogist, v. 13, p. 519-530, 537-558.

5/ Higazy, R. A., 1949, Petrogenesis of perthite pegmatites in the Black Hills, S. D.: Jour. Geology, v. 57, p. 555-581.

Edison, and Dyke Lode. Higazy's work 1/ was largely on 15 pegmatites in the southern part of the Keystone district. Most of the pegmatites studied by Higazy are zoned, but some are layered and some probably homogeneous, though his index map is not entirely adequate for determining exact locations.

Pegmatites elsewhere in the world have ordinarily been interpreted in one of these three ways. Most of the literature is on zoned pegmatites; the monograph by Cameron and others 2/ contains scarcely a hint that there are any pegmatites except zoned pegmatites. The relations between zoned and unzoned pegmatites in any single region have rarely, if ever, been fully described, nor indeed, has the difference between the two always been fully recognized.

Magmatic Intrusion

The chief evidence for intrusion of a large quantity of magmatic material in the southern Black Hills lies in the structural relations between the pegmatite and country rock, both the gross relations recognizable over broad areas and the smaller scale relations recognizable in a single pegmatite. The close areal association among the pegmatites, the high grade metamorphic rocks, and the latest deformation of the country rock suggests that all of these were associated genetically.

Many authors 3/ have shown that the schists are domed in the southern Black Hills, and have attitudes quite different from the attitudes to the

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1/ Op. cit., p. 555-556.

2/ Op. cit., 1949.

3/ Paige, op. cit., p. 4-5.

Balk, op. cit.

Runner, 1943, op. cit.

north. The present work shows that these structural changes were caused in part by faulting and in part by folding that took place after the isoclinal folding characteristic of all Black Hills Precambrian rocks. Locally, near large pegmatites or groups of pegmatites, the country rock has been deformed, as in secs. 16, 17, 20, and 21 of the Keystone district (fig. 4).

Many features of individual pegmatites that have been studied in detail suggest an essentially magmatic origin:

(1) Contacts are ordinarily sharp. Altered wall rock consisting of a granulitic aggregate of plagioclase, muscovite, and quartz with lesser quantities of tourmaline, biotite, and other minerals occurs chiefly where the contact is cross-cutting and fluids from the pegmatite could most readily escape into the schist. Altered rock of this kind is less than 2 inches thick along more than 90 percent of exposed pegmatite contacts. The maximum thickness is only a few feet, in contrast to the much greater thickness of many pegmatites. At the Hugo pegmatite (fig. 7), for example, this rock has been found at several places, but a thickness of more than 1 foot is uncommon. This alteration is best explained as caused by material contributed by the pegmatitic fluid to the schist, not as a gradational contact between metasomatic pegmatite and unaltered schist.

(2) Within zoned pegmatites, structural relations of fracture-filling and replacement units (figs. 6 and 7) indicate that outer zones formed before inner zones, suggesting crystallication of a fluid inward from the contact. Solidified outer zones were fractured, and rest liquid was injected to form fracture-filling units that are similar in composition to

inner zones (fig. 6). Replacement units extend outward from central units, as if formed by hydrothermal or pneumatolytic fluids that escaped from the rest liquid at a late stage of crystallization (fig. 7). Thus these replacement units came from the interior of the pegmatite, not from an exterior source.

(3) Plagioclase of inner zones is more sodic than plagioclase of outer zones, and the outer part of plagioclase grains is more sodic than the inner part. In the Hugo pegmatite, replacement units extending outward from the core (fig. 7) have very sodic albite that contrasts with less sodic albite and oligoclase of the replaced zones. Thus, the plagioclase developes in the normal sequence, from less sodic to more sodic, that has been recognized in many igneous rocks. Ramberg [1] dismisses similar changes in New England pegmatites [2] by saying that they are too small to be significant, but this view hardly seems justified.

(4) Tapered crystals are oriented normal to pegmatite contacts; the small end is nearest the contact, and the broad end is toward the center of the pegmatite. Among the many examples are beryl in the Peerless and Bob Ingersoll pegmatites and muscovite at the contacts of many pegmatites in the NW 1/4 sec. 21. This suggests that the crystals grew inward from a seed near the contact of the pegmatite, and the tapered

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1/ Ramberg, Hans, 1956, Pegmatites in west Greenland: Geol. Soc. America Bull., v. 67, p. 208.

2/ Cameron, E. N., and others, 1954, Pegmatite investigations, 1942-45, New England: U. S. Geol. Survey Prof. Paper 255, p. 31.

form developed as new material was added to the sides and to the inner end of previously crystallized material. Jahns [1] has an illustration of a tapered perthite crystal of this sort with phantoms showing the outline of the crystal at various stages of its development.

(5) Near discordant contacts of many pegmatites, the schistosity of the country rock is exactly parallel to the pegmatite contact. The Peerless pegmatite is discordant to the regional schistosity, but within a few inches of the pegmatite the only schistosity recognizable is parallel to the contact. A similar schistosity observed in underground workings at the Victory pegmatite, near Custer, follows the contact around the end of the pegmatite without once showing any discordance. The outer part of these pegmatites is not significantly deformed, and thus the induced schistosity must have formed before crystallization of the pegmatite. It seems explainable only as recrystallization of the schist under pressure during injection of the pegmatitic fluid.

(6) In a few places [2] beds of the wall rock are dragged upward within a few inches of pegmatite contacts, thus suggesting forcible intrusion. Unfortunately, exposures nowhere are adequate to show whether a single bed several feet from a pegmatite has been forced outward far enough

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1/ Jahns, R. H., 1955, The study of pegmatites: Econ. Geology, Fiftieth Anniversary Volume, fig. 16.

2/ Page and others, op. cit., p. 18.

to account for the expansion required to make room for the pegmatite. Though no such traceable horizon has been found, the distortion of the country rock near the large intrusives of secs. 17 and 20 is strong evidence for forcible intrusion (figs. 3 and 4). If the pegmatites formed by metasomatism of the country rock, however, it is difficult to explain why phantom contacts of rocks of contrasting composition--for example, amphibole-rich and mica-rich rocks at the Edison mine--cannot be traced through any of the pegmatites.

(7) Nowhere have schist fragments in pegmatite been found to have an "island-mainland" relation to the wall rock that would suggest that the pegmatite formed by metasomatism of schist. The only schist fragments within the pegmatites have an arrangement that indicates they are schist screens along contacts between adjacent pegmatites in a multiple intrusive. This conclusion is further substantiated where zoned pegmatites form multiple intrusives; in these, schist screens separate the wall zone of one pegmatite from the wall zone of the next pegmatite.

Black Hills pegmatites lack inclusions of foreign rocks and diversely oriented inclusions of nearby rocks that can be used as evidence that the pegmatite was derived from a magmatic fluid. Pegmatites that the writer has seen elsewhere in the United States are similar in this respect. It seems porbable, however, that the country rock--mostly quartz and mica schists--was deformed only by plastic means in the immediate vicinity of pegmatites during intrusion, and thus only very rarely could inclusions break loose and sink into the fluid. It also seems likely that the inclusions would go into solution, and that ordinarily undissolved material would not be found. The Eureka pegmatite and other pegmatites in the SE 1/4 sec. 15 have disseminated graphite that may have been obtained in this fashion; if so, the graphite probably came from a source at depth because there is very little graphite in the rocks near these pegmatites.

The Harding mine, near Dixon, N. Mex., which R. H. Jahns showed the author in 1949, has randomly oriented spodumene fragments that probably fell to the floor of the pegmatite chamber after crystallization of the outer zones but during crystallization of the spodumene-bearing zone. In the upper part of the spodumene-bearing zone, the spodumene forms a network having the same appearance as in other pegmatites. Only the spodumene at the bottom of the unit has the appearance of a heap of fragments.

In the Black Hills room was made for the intrusive fluid by deformation of the country rock. The deformation could proceed slowly as the many separate pegmatites were injected. The largest bodies are multiple intrusives that grew by accretion from successive injections of pegmatitic fluid. Thus the process by which the large quantity of pegmatite accumulated in the southern Black Hills is very similar to the process described by Noble 1/ both for the rhyolite dikes of the northern Black Hills and also for the Sierra Nevada batholith, where work by Mayo 2/ shows that there are many separate intrusions.

Evidence from metamorphism and distribution of pegmatites (fig. 1) has previously been cited to show that the intrusives as a group plunge at a

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1/ Noble, J. A., 1952, Evaluation of criteria for the forcible intrusion of magma: Jour. Geology, v. 60, p. 34-57.

2/ Mayo, E. B., 1941, Deformation in the interval Mt. Lyell-Mt. Whitney, California: Geol. Soc. America Bull., v. 52, p. 1001-1084.

moderate angle to the southwest. Thus, it may be inferred that the route of travel of the fluids was upward from the southwest.

Evidence that Black Hills pegmatites are in any part magmatic has been disputed only by Higazy 1/, who argued for origin by metasomatism of schist. Higazy's work consisted chiefly of making chemical analyses and petrographic studies of 16 specimens of perthite, 1 of microcline, 1 of cleavelandite, 1 of "albitite" (probably aplite), and 2 of schist.

Higazy made the assumption that the composition of perthite from a pegmatite is equivalent to the composition of the pegmatite itself. He cites the Glendale pegmatite, 3 miles southeast of Keystone, as an example of a pegmatite that "consists of perthite only" 2/. Actually, the Glendale pegmatite has more of both quartz and plagioclase than perthite. There may be pegmatites in the Black Hills in which perthite is the most abundant mineral, but none are known that do not contain almost as much quartz and plagioclase as perthite.

Higazy shows that the composition of his perthite specimens falls on the orthoclase side of the cotectic line in the albite-anorthite-orthoclase system. He assumes that the perthite is equivalent to the rock as a whole, and that no other minerals were crystallizing at the same time. He states that if magmatic pegmatites are residual solutions derived from a magma having an original composition on the other side of this line, then it would be impossible to produce a rock having the composition of perthite. Higazy concludes that magmatic crystallization is impossible, and metasomatism is the only alternative. If, however, all of the plagioclase as well as the perthite

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1/ Op. cit.

2/ Idem, p. 557.

of the pegmatites had been taken into account, the composition would fall very close to the eotectic line, and the basis for Higazy's argument disappears.

Higazy 1/ goes so far as to say that "Whenever perthite forms pegmatitic pockets or forms a zone in a pegmatite body, its chemical composition should closely approximate the mother-liquor from which it crystallized." As Jahns 2/ points out, Higazy discounts "the very real possibilities of fractional crystallization, resurgent boiling, and liquid immiscibility."

Higazy 3/ also discusses the textural relations between albite and microcline in perthite. He shows that the albite is later than the microcline, but this proves only the age relation between these two minerals; it does not prove, as Higazy 4/ seems to think, that both of these minerals necessarily formed by metasomatism of schist.

Some of the Black Hills schists contain porphyroblasts of perthite that Higazy 5/ considers to be intermediate between unaltered schist and his perthite pegmatites. Higazy 6/ found this type of rock in one outcrop only 36 yards long. This sort of material occurs in only very small quantities in relation to the great quantity of pegmatite in the Black Hills, though under Higazy's theory it should be abundant. It seems more appropriate to ascribe the origin of this rock to potassium-bearing fluids escaping from the nearby pegmatites.

1/ Op. cit., p. 566.

2/ Jahns, 1955, op. cit., p. 1093.

3/ Op. cit., p. 562-565.

4/ Idem, p. 579-580.

5/ Op. cit., p. 530.

6/ Idem, p. 557.

In a later article, Higazy indicated that his study of "potash-rich pegmatites" and the "chemical compositions and tectural features of the investigated rocks" 1/ showed that these pegmatites fall outside the thermal trough in the $NaAlSiO_4$ - $KAlSiO_4$ - SiO_2 residua system of Bowen and Schairer 2/. Actually, however, the composition of Black Hills pegmatites is in or near this thermal trough, and any implication to the contrary based solely on perthite analyses is unwarranted.

Higazy 3/ has also determined the trace element content of his perthite specimens. He showed that the content of various trace elements in perthite, which he again assumed is equivalent to "pegmatite", differs from the trace element content of certain magmatic and hydrothermal rocks, and by this process of elimination concluded that the pegmatites are metasomatic. He disregarded the likelihood that certain elements enter the feldspar lattice more readily than others.

Higazy also ignored the effects of physical conditions on the concentration of minor elements. Eugster has made the interesting discovery that the cesium content of sanadine crystallized from a fluid of fixed Cs/K ratio varies greatly according to the temperature of crystallization. "At about 700° C. the cesium content of feldspar is equal to that of the fluid phase in equilibrium with it. At 800° C. the feldspar growing from

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1/ Higazy, R. A., 1950, Significance of the orthoclase-albite-anorthite, and the $NaAlSiO_4$ - $KAlSiO_4$ - SiO_2 equilibrium diagrams in igneous petrology: Am. Mineralogist, v. 35, p. 1046.

2/ Bowen, N. L., 1937, Recent high-temperature research on silicates and its significance in igneous geology: Am. Jour. Sci., 5th ser., v. 33, p. 11-13.

3/ Higazy, R. A., 1953, Observations on the distribution of trace elements in the perthite pegmatites of the Black Hills, S. D.: Am. Mineralogist, v. 38, p. 172-190.

fluid phase of the same composition will be richer in cesium than the fluid phase by a factor of 1.2:1; whereas at 500° C. it will be poorer by a factor of 1:4." 1/ Higazy disregarded any such possibility as this.

A much stronger presentation of the metasomatic theory is by Ramberg 2/ in a paper on pegmatites of west Greenland, for which Ramberg proposes "a metamorphic-metasomatic theory in which diffusional transfer is essential." 3/ Higazy's Black Hills work was done in part under Professor Ramberg at the University of Chicago 4/. Furthermore, Ramberg's paper contains a photograph 5/ from the Black Hills that he apparently regards as indicating a metasomatic origin for these pegmatites.

Ramberg shows that the geometric relations between wall rock and some cross-cutting pegmatites indicate that the wall rock was not displaced. He also shows that the composition of many pegmatites is influenced by the composition of the wall rock. These pegmatites have gradational contacts, and the wall rock near many of them is altered. All of Ramberg's examples, however, are very narrow pegmatites; the maximum thickness among the really convincing examples in his many illustrations is only about 1 foot. It is not clearly shown whether or not any of these may be connected with larger pegmatites.

1/ Sugster, H. P., 1955, The cesium-potassium equilibrium in the system sanidine-water, in Abelson, P. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Year Book No. 54, for the year 1954-1955, p. 112.

2/ Ramberg, Hans, 1956, Pegmatites in west Greenland: Geol. Soc. America Bull., v. 67, p. 185-213.

3/ Idem, p. 209.

4/ Higazy, 1949, op. cit., p. 580.

5/ Op. cit., pl. 3, fig. 5.

In the Black Hills there is evidence both for alteration of wall rock and for contamination of pegmatites by material from the wall rock. The altered wall rock, however, is quantitatively insignificant in relation to the size of the adjacent pegmatite. There is no evidence for the large alteration halo that may be expected if such large pegmatites as those in the southern and southwestern parts of the Keystone district formed by metasomatism.

Similarly, the available evidence for contamination of the pegmatites indicates the addition of only a very small amount of material. The high tourmaline content of the outer few inches of many pegmatites may indicate addition of iron to the pegmatite fluid. Plagioclase in the outer 1 inch of many pegmatites has a significantly higher An content than the rest of the plagioclase in the pegmatite, and thus suggests that calcium was obtained from the wall rock. Sillimanite and andalusite occurring as large crystals and aggregates in the outer parts of some pegmatites, especially near Custer, may indicate contamination of the fluid by aluminous wall rock materials. At Kings Mountain, N. C., T. L. Kesler has demonstrated to the writer that pegmatites cutting quartz-mica schist have a concentration of muscovite in their outer few inches that is not to be found in pegmatites cutting amphibolite. The only undoubted contaminant that extends into the inner parts of any pegmatite known to the writer is the thinly disseminated graphite in pegmatites in the SE 1/4 sec. 15 (fig. 3). If large quantities of material had been inherited from the wall rock, the composition of pegmatites should change in accordance with the composition of the country rock, and no such relation is apparent. Furthermore, some zoned pegmatites probably would have anomalous divergences from the normal zonal sequence, and no such divergences have been observed.

Nevertheless, the very outer parts of Keystone pegmatites and thin offshoots from these pegmatites may occupy space formerly taken by country rock that entered the pegmatite liquid. No evidence has been found that any of the thin offshoots of these pegmatites have non-dilational geometric relations with the country rock, but it will not be surprising if such evidence is found. The question is not whether part of the pegmatitic material was obtained from wall rock, but whether all of it was so obtained.

Ramberg also argues convincingly that pegmatite-like quartz-feldspar fillings between boudins and wrapped around basic inclusions in gneiss were contemporaneous with metamorphism. Furthermore, it seems likely, as Ramberg says 1/, that this material formed by crystallization in the solid, rather than from an injected fluid. It is not clearly shown, however, that this material is petrographically the same as the more normal pegmatites, nor does it appear from Ramberg's illustrations 2/ that this material resembles Black Hills pegmatite.

Ramberg's other major arguments are essentially negative--that the pegmatites could not have crystallized from a fluid, and that metasomatism is the only alternative. He states that quartz cores are not to be expected, the composition of plagioclase does not change sufficiently, the temperature of crystallization is too low, and in other ways (some not applicable to the Black Hills) argues that crystallization from a magma or magma-like fluid is improbable. Most of these arguments are to the effect that field data are not entirely in accord with laboratory results on silicate melts. In the

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1/ Op. cit., p. 196-197.

2/ Idem, pl. 6, figs. 1 and 2.

discussion of the temperature, composition, and crystallization of Black Hills pegmatites on later pages, these arguments will not appear serious. Ramberg's diffusion process cannot be subjected to the same kind of examination because of the lack of adequate experimental data.

Thus Ramberg's most convincing argument that can be applied to the Black Hills is evidence that the outer parts of pegmatites, including small off-shoots from the pegmatites, were formed without displacement of the country rock. This is offset, however, by the absence of any but the most indirect evidence that the inner parts of large pegmatites formed by metasomatism.

Ramberg's theory as applied to the thousands of pegmatites in the Black Hills would require that the diffusion of material through the rocks have an extraordinarily complex movement pattern. In any area containing as many pegmatites as the southwest part of the Keystone district, the movement of some materials into and others away from a site of "pegmatization" would be accompanied by corresponding movements for hundreds of other pegmatites. It seems probable that there would be such notable changes in the country rock that the quartz-mica and quartz-mica-staurolite schist in secs. 16 and 17 would be quite different from the schist only a mile to the north, where pegmatites are much less abundant. No great differences, however, are apparent.

Zoned pegmatites that form multiple intrusives, as at the Edison mine in the SE 1/4 sec. 9 1/, raise additional difficulties for the Ramberg theory. The Edison consists of several pegmatites having wall zones of quartz, albite, and muscovite, and cores of quartz, albite, and spodumene. From the Ramberg theory each of these should have formed by migration of certain materials inward and others outward. In many places at the Edison, however,

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1/ Page and others, op. cit., p. 104-114.

the pegmatites come together, so that the wall zone of one is in contact with the wall zone of the next, and a succession of several independently zoned pegmatites forms a single multiple intrusive. The gradients controlling diffusion transfer at the Edison would have to have a very complex geometry.

Temperature of Crystallization

Evidence for the temperature of crystallization of South Dakota pegmatites has been obtained both by fluid inclusion work and by studies of the composition of muscovite and sphalerite.

Table 8 shows the temperatures obtained by fluid inclusion studies of Keystone pegmatites by P. L. Weis 1/. The temperatures range from 232° C. to 515° C. Temperatures from different inclusions even in the same crystal may have a very great range: one beryl crystal from the Peerless ranged from 257° C. to 405° C. These ranges are so great that the figures can be used only in a general way. It seems probable, however, that the average temperature, uncorrected for pressure, is between 320° C. and 400° C. The only data 2/ for correcting these temperatures for pressure caused by depth of burial are based on the properties of pure water, and no correction is shown above the critical temperature of water. Weis, however, had liquids at least as high as 515° C., and thus Kennedy's graph 3/ cannot be directly applied. Though Weis' liquid inclusions are probably aqueous 4/, they must

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1/ Weis, P. L., 1953, Fluid inclusions in minerals from zoned pegmatites of the Black Hills, S. D.: Am. Mineralogist, v. 38, p. 671-697.

2/ Kennedy, G. C., 1950, "Pneumatolysis" and the liquid inclusion of geologic thermometry: Econ. Geology, v. 45, p. 540-543.

3/ Idem, fig. 4.

4/ Weis, op. cit., p. 677-678 and 689-690.

Table 8. Temperature of disappearance of the vapor phase in primary fluid inclusions, Keystone pegmatite district, South Dakota 1/

Pegmatite	Material examined	Average temperature (°C)	Range in temperature (°C)
Peerless	1 beryl crystal from wall zone of assemblage 1	317	257-405
	4 beryl crystals from 1st intermediate zone of assemblage 1	359	232-450
	2 beryl crystals from assemblage 3	405	304-447
Hugo	1 beryl crystal, probably from assemblage 3	328	309-353
	Quartz, locality unstated	398	376-411
	Quartz, locality unstated	400	383-422
Bob Ingersoll No. 1	2 beryl crystals from assemblage 1	395	317-515
	2 beryl crystals from assemblage 9	355	308-489
Bob Ingersoll No. 2	1 beryl crystal from assemblage 1	Not stated	302-365
	2 beryl crystals from assemblage 8	335	290-349

1/ Weis, P. L., 1953, Fluid inclusions in minerals from zoned pegmatites of the Black Hills, South Dakota: Am. Mineralogist, v.38, p. 681-684.

contain materials in solution that increase the critical temperature and decrease the pressure correction 1/. The influences of these uncertainties can only be guessed, but it seems likely that the correction for temperatures of 320° C. to 400° C. at 2 to 4 miles depth is at least 50° to 100°, and thus the original temperature would be at least 370° C. to 500° C. Furthermore, it is probable that vapor pressure, supercritical phenomena, leakage of material in these inclusions, and other factors discussed by Weis 2/ introduce still more errors. Thus the most that can be said is that the fluid inclusions suggest a temperature in the order of 400° C. to 500° C.

Weis 3/ used his temperature data to suggest that inner zones crystallized at lower temperatures than outer zones, but as he points out, the great range in temperatures even from single crystals is such that his evidence is very weak. Furthermore, the apparent temperature increases inward at the Peerless pegmatite (table 8). The only other pegmatite in which Weis thought he had clear evidence for the temperature trend is the Highland Lode near Custer, where the temperatures are approximately the same in two intermediate zones and much lower in a unit that was called a plagioclase-quartz core of the pegmatite 4/. Actually, however, this pegmatite contains no plagioclase-quartz core; the only unit of plagioclase and quartz from which Weis could have collected specimens is the wall zone. The structure of this pegmatite is such that the wall zone is exposed in places near the center of the

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1/ Kennedy, op. cit., p. 543.

2/ Op. cit, p. 686-692.

3/ Op. cit., p. 695.

4/ Idem, p. 679-680.

pegmatite outcrop 1/, where it could be misinterpreted as the core. Thus, at the Highland Lode, like the Peerless, the apparent, uncorrected temperatures increase inward. It may be, however, that the alkali content of the fluid trapped in inclusions during crystallization is greater in inner than in outer zones. The pressure correction would be less in the alkali-rich material 2/, and although the uncorrected temperature may be higher, the original temperature may be lower than for alkali-poor material in outer zones.

Another approach to the temperature problem has been taken by Grootemaat and Holland 3/. They determined the sodium and potassium content of muscovite from various zones of the Peerless pegmatite, and found that the paragonite content of the muscovite ranges from 13 mol percent in the wall zone to 5 mol percent in the core. All of the muscovite is accompanied by albite, and it is assumed that "the sodium content of the muscovite is the maximum possible at the temperature and pressure of formation." 4/ Thus they can use the position of the solvus in the muscovite-paragonite system 5/ to show that the temperature of crystallization ranged from 500° C. in the wall zone to 350° C. in the core. If the muscovite were not saturated with sodium,

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1/ Page and others, op. cit., pl. 23.

2/ Kennedy, op. cit., p. 543.

3/ Grootemaat, T. B., and Holland, H. D., 1955, Sodium and potassium content of muscovites from the Peerless pegmatite, Black Hills, S. D. (abstract): Geol. Soc. America Bull., v. 66, p. 1569.

4/ Idem.

5/ Eugster, H. P., and Yoder, H. S., Jr., 1955, The join muscovite-paragonite, in Abelson, P. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Year Book No. 54, for the year 1954-1955, p.124-126.

temperatures would be higher; Eugster [1] considers that other possible sources of error are small.

Kullerud [2] previously used the FeS content of sphalerite in a similar fashion as a geological thermometer. Later he applied this method to sphalerite from the Dan Patch pegmatite and obtained a temperature of 260° C. This, however, is a minimum temperature, not an exact temperature, because the sphalerite was not accompanied by any iron sulphide mineral, and thus is probably not saturated in iron [3].

Higher temperatures are suggested by the presence of sillimanite associated with primary minerals in pegmatites in which there is no textural or structural evidence that the sillimanite itself is anything but primary. Ordinarily the sillimanite occurs only in the outer parts of pegmatites, especially in a small area northeast of Custer. A few small pegmatites on the south flank of the Harney Peak dome have sillimanite through their entire thickness; these same pegmatites wholly lack muscovite. This may be taken as evidence that the pegmatites crystallized in part at temperatures greater than 600° C. [4] Nevertheless, as Jahns [5] says, most of the quartz of pegmatites probably crystallized below the 573° C. inversion temperature. This, together with the scarcity of sillimanite in pegmatites, suggests that high temperatures are unusual. It has been shown

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1/ Eugster, H. P., personal communication, 1955.

2/ Kullerud, Gunnar, 1953, The Fe-ZnS system as a geological thermometer: Norsk. geol. Tidssk., v. 32, p. 61-147.

3/ Kullerud, Gunnar, personal communication, 1955.

4/ Yoder, H. S., 1952, The $MgO-Al_2O_3-SiO_2-H_2O$ system and the related metamorphic facies: Am. Jour. Science, Bowen volume, p. 600, 601, and 606.

5/ Op. cit., 1955, p. 1077.

by Roy, Roy, and Osborn 1/ that spodumene, which occurs only in inner zones of Black Hills pegmatites, "must have formed below 500° C. (or slightly higher at greater pressures)."

These data provide a reasonably consistent body of evidence that outer zones ordinarily crystallized at temperatures between 450° C. and 550° C., and that inner units crystallized at temperatures as low as 350° C. All but a small part of the rock in layered and homogeneous pegmatites is mineralogically similar to outer zones of zoned pegmatites, and it may be tentatively assumed that they crystallized at about the same temperature.

Crystallization in the dry albite-orthoclase-quartz system is at very much higher temperatures than these 2/. It has been shown, however, that the addition of water greatly lowers the temperature of crystallization in the systems H_2O-N_2O-SiO_2 3/, $NaAlSi_3O_8$-$KAlSi_3O_8$-H_2O 4/, and SiO_2-H_2O 5/. Thus the temperature data may be used as evidence that the pegmatite fluid was rich in water and other hyperfusibles, and cannot be used to indicate, as Ramberg says 6/, that the temperatures are too low for crystallization from a magma or magma-like fluid.

1/ Roy, Rustum, Roy, D. M., and Osborn, E. F., 1950, Compositional and stability relationships among the lithium aluminosilicates: eucryptite, spodumene, and petalite: Jour. Am. Ceramic Soc., v. 33, p. 159.

2/ Bowen, op. cit., fig. 7.

3/ Tuttle, O. F., and Friedman, I. I., 1948, Liquid immiscibility in the system H_2O-Na_2O-SiO_2: Jour. Am. Chem. Soc., v. 70, p. 919-926.

4/ Bowen, N. L., and Tuttle, O. F., 1950, The system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - H_2O: Jour. Geology, v. 58, p. 489-511, especially p. 509-511 and fig. 3.

5/ Tuttle, O. F., and England, J. L., 1955, Preliminary report on the system SiO_2 - H_2O: Geol. Soc. America Bull., v. 66, p. 149-152.

6/ Op. cit., p. 209.

Composition of the Pegmatite Fluid

Table 6 shows that the overall composition of Black Hills pegmatites is approximately: SiO_2 - 72 to 78 percent, Al_2O_3 - 12 to 17 percent, Na_2O - 3.5 to 5 percent, K_2O - 2 to 5 percent, and other constituents less than 5 percent. Despite the dominance of SiO_2, Al_2O_3, K_2O, and Na_2O, the mineralogy of the pegmatites suggests that the original fluid contained unusual quantities of boron (tourmaline), lithium (spodumene, amblygonite, and lepidolite), beryllium (beryl), fluorine (lepidolite), phosphorus (apatite and triphylite-lithiophilite), tantalum and columbium (tantalite-columbite), and tin (cassiterite).

Any differences between the composition of the rock and the composition of the original liquid should be accounted for by materials that have been added to the wall rocks. Only a small quantity of feldspar and muscovite has been added to the wall rocks, and consequently the loss of alkalies from the pegmatite was probably not great. Tourmaline is common in the schist, thus indicating transfer of boron.

Water, however, may have been lost in significant quantities. Prior to the intrusion of the pegmatites, the regional metamorphism had proceeded to the stage in which staurolite and sillimanite were formed, and thus was well beyond the stage in which hydrous minerals are ordinarily formed. In areas containing many pegmatites, however, staurolite and sillimanite have been altered to hydrous minerals, thus indicating that the pegmatites contributed water to the country rock. The abundance of mica produced by this alteration suggests that potassium was also added to the country rock, though the evidence is inconclusive.

Many authors have supposed that the pegmatite fluid was enriched in hyperfusible constituents. Bowen 1/ states that the principal effects of these constituents would be "to lower the temperatures of crystallization, to increase the fluidity, to facilitate the separation and interaction of phases, and to modify the course of crystallization only in moderate degree except in very late stages." The low temperatures, large crystals, separation into zones and layers, and the existence of replacement units going out from the cores of pegmatites all suggest a high content of hyperfusibles. The mineralogy of the pegmatites and of altered material in the country rock suggest that the predominant hyperfusibles were water, boron, and fluorine. Goranson 2/ has shown that silicate magmas of granitic composition can carry as much as 10 percent water by weight. Bowen and Tuttle 3/ suggest a possible maximum of 12 percent water in the low-melting albite-orthoclase mixtures. The mol percent water in silicate systems is, of course, much greater than the weight percent.

A high degree of fluidity in the pegmatite liquid is suggested by an unusual pegmatitic rock with many remnants of schist that is exposed discontinuously in the outer part of the Etta pegmatite. Unfortunately the principal exposures of this material are in an inaccessible place on the northeast wall of the glory hole. Probably the maximum thickness is about 20 feet. The many large blocks that have been observed on the floor of the glory hole consist of medium-grained pegmatite with many irregular remnants of schist

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1/ Bowen, N. L., 1928, The evolution of igneous rocks: Princeton, N. J. Princeton Univ. Press, p. 302.

2/ Goranson, R. W., 1931, The solubility of water in granite magmas: Am. Jour. Sci., 5th ser., v. 22, p. 481-502.

3/ Bowen, N. L., and Tuttle, O. F., 1950, The system $NaAlSi_3O_8$ - $KAlSi_3O_8$ - H_2O: Jour. Geology, v. 58, p. 510 and fig. 5.

that have an average length of 1 inch. The pegmatitic material consists of quartz, perthite, plagioclase, and muscovite. It is mineralogically very similar to material in the upper parts of many zoned pegmatites, and it probably crystallized directly from the pegmatite fluid, not from an escaping hydrothermal solution. The pegmatite liquid must, however, have been extremely fluid to permeate the schist in this fashion.

Relation between Layered, Homogeneous, and Zoned Pegmatites

The layered, homogeneous, and zoned pegmatites have such a close areal association and are so similar in mineralogy, texture, and chemical composition that there can be no reasonable question that they were derived from the same source.

In all varieties of pegmatite, whether layered, homogeneous, or zoned, the oldest units consist of quartz, plagioclase, and muscovite of mineral assemblages 1 and 2 (table 4). They are succeeded by perthite, quartz, and plagioclase of assemblage 3--either as coarse-grained layers in layered pegmatites, as the main body of homogeneous pegmatites, or as an intermediate zone or core of a zoned pegmatite. Quartz-perthite and quartz fracture-filling units and segregations are the only common units of layered and homogeneous pegmatites that correspond to assemblages 4 to 12 in zoned pegmatites. The greatest difference between layered, homogeneous, and zoned pegmatites is in their internal structure and the distribution of minerals within the intrusives.

The coarse-grained discontinuous layers or lenses in the layered pegmatites suggest trapping of rest liquid by rapidly crystallizing albite-quartz pegmatite. The thin tabular shape of many layered pegmatites, especially those that are discordant to schistosity, would favor loss of heat to the wall rocks, and consequent rapid crystallization. In the Peerless pegmatite layers 9 and 13 (fig. 8), containing albite, quartz, perthite, and muscovite, are surrounded by albite-quartz-muscovite pegmatite. The albite-quartz-muscovite pegmatite on either side of layer 9 is sugary in grain-size, and thus may have crystallized rapidly.

Rhythmical or repetitive crystallization may in part explain the layered structure. The repetition of layers in the many layered pegmatites of secs. 17 and 20 suggests the likelihood of this process. More convincing evidence, however, is to be found in the layered unit of the Peerless pegmatite. Discussion of figure 8 on previous pages has shown that the normal sequence of mineral assemblages is repeated at least once. The cause may have been temporary failure of convection in the liquid to maintain equilibrium, perhaps because crystallization was unusually rapid as a result of loss of heat to the wall rocks. The Peerless is the only major zoned pegmatite of the Keystone district that has conspicuously layered border and wall zones. It is also the only major zoned pegmatite that is discordant with country rock schist, and thus it might lose its heat more readily than any of the others.

Repetition of layers may also have been caused by changes in equilibrium, which can be attributed to loss of material to wall rocks or to the injection of new material from below during crystallization. Many of the layered pegmatites are multiple intrusives, and the younger parts of these intrusives may have been injected before the older parts had completely crystallized. Some zoned pegmatites are also multiple intrusives; the structure of these, however, indicates that solidified wall zone surrounding previously injected material was impermeable to material injected later 1/.

1/ Page and others, op. cit., plates 14 and 15.

Thus rapid loss of heat and repeated injection of new material during the crystallization of layered pegmatites may in large part explain the differences between these and the zoned pegmatites. Many recent writers [1] have agreed that zoned pegmatites formed in an essentially closed system. One of the most important factors may be that heat is retained in this system and a slowly declining temperature gradient is established. It is noteworthy that zoned pegmatites tend to be concordant with the enclosing schist and to have thick cross-sections (table 3); both of these conditions would favor retention of heat.

Homogeneous pegmatites are in many ways gradational in character between layered and zoned pegmatites. They are so similar to zoned pegmatites, however, that in spite of the likelihood that open system crystallization and rapid heat loss may explain why layered pegmatites differ from homogeneous and zoned pegmatites, they do not explain the differences between homogeneous and zoned pegmatites.

Though the content of SiO_2, Al_2O_3, Na_2O, and K_2O is essentially the same in all varieties of pegmatite, the content of H_2O, B, and F may have been greater in the fluid that formed zoned pegmatites than in the fluids that formed other varieties of pegmatites. Certainly the high content of muscovite and tourmaline in the border and wall zones of many zoned pegmatites suggests a higher content of water and boron than do the lower quantities of muscovite and tourmaline in the border phases of layered and homogeneous pegmatites. Also the zoned pegmatites are the ones that have the largest crystals, suggesting a higher content of hyperfusibles to facilitate coarse crystallization.

1/ Jahns, R. H., 1955, The study of pegmatites: Econ. Geology, Fiftieth Anniversary Volume, p. 1086.

Many of the zoned pegmatites have minerals bearing "rare elements" that are uncommon or unrecognized in the homogeneous and layered pegmatites--for example, Be in beryl and Li in spodumene, amblygonite, lepidolite and triphylite-lithiophilite. Some of these constituents may have influenced the crystallization process.

The layered and homogeneous pegmatites contain within them small zoned pegmatites in the form of fracture-filling units. These crystallized after the surrounding pegmatite, and their mineral composition corresponds chiefly to assemblages 3, 4, and 12, which ordinarily form intermediate zones and cores of zoned pegmatites. The outer part of the fracture-filling units commonly contains muscovite-rich aggregates that have less physical resemblance to assemblage 1 than they do to muscovite-rich aggregates that are characteristic of intermediate zones of zoned pegmatites. These fracture-filling units may indicate that at a late stage in crystallization of layered and homogeneous pegmatites water and other hyperfusible constituents become sufficiently concentrated to favor the formation of pegmatite with zonal structure, but of rock types that ordinarily are in inner zones of zoned pegmatites. The probability that water is concentrated in the rest liquid during crystallization of outer units, which consist chiefly of assemblages 1-3 in all types of Black Hills pegmatites, is shown by the mica-rich cores and replacement units in the Peerless and Hugo pegmatites.

Crystallization of Zoned Pegmatites

Zoned pegmatites of the Keystone district contain not only units having the mineralogic assemblages characteristic of layered and homogeneous, but also all the other mineralogic assemblages of pegmatites (table 4). The means by which this extreme segregation takes place have long been discussed in geologic literature. In the Keystone district, Hess [1] and later Landes [2] suggested that in the development of these pegmatites the first stage was crystallization of a relatively simple quartz-feldspar rock, and this rock was subsequently replaced by hydrothermal solutions. Later Page and his colleagues [3] proved the zonal structure of these pegmatites by detailed mapping. They suggested that zones form by fractionation, but in a few pegmatites they recognized replacement bodies that cross-cut the zonal structure and thus were formed at a late stage of crystallization.

Recent investigators have come to general agreement that primary crystallization of zoned pegmatites proceeded from the contact inward [4]. The most nearly direct evidence in the Keystone district is from the relation between fracture-filling units and zones. At the Big Chief pegmatite, for example, the quartz core has offshoots that form quartz fracture-fillings cutting outer zones (fig. 6), thus indicating that quartz pegmatite was the last rock to crystallize at the Big Chief.

At the Hardestey Homestead mine, Page and Hanley [5] mapped a quartz fracture-filling unit that not only cuts outer zones and even extends for 20 feet into the country rock, but also can be distinguished as a fracture-filling in the outer 10 feet of the quartz core before it merges with the core and becomes indistinguishable as a fracture-filling. These relations make it

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1/ Hess, F. L., 1925, The natural history of the pegmatites: Eng. and Min. Jour. - Press, v. 120, p. 289-298.

2/ Landes, K. K., 1928, Sequence of mineralization in the Keystone, S. D., pegmatites: Am. Mineralogist, v. 13, p. 519-530, 537-558.

3/ Page and others, op. cit.

4/ Jahns, 1955, op. cit., p. 1086.

5/ Page and others, op. cit., p. 127-128 and fig. 15.

apparent that the quartz fracture-filling formed while the central part of the quartz core was still crystallizing; it intruded the outer part of the quartz core, the outer zones, and country rock.

In the New York pegmatite, southwest of Custer, a fracture-filling unit contains two zones that are mineralogically identical with the two innermost zones of the pegmatite 1/. This fracture-filling must have been injected just before the innermost zones of the pegmatite crystallized.

Systematic variations in the composition of plagioclase, beryl, muscovite, and other minerals indicate crystallization from the contact inward. It has been shown (table 5) that plagioclase becomes increasingly albitic in inner zones, and thus it follows that inner zones are younger than outer zones. In beryl the BeO content decreases in inner zones. The paragonite content of muscovite decreases in inner zones, and this has been shown 2/ to indicate decreasing temperature. If the inner zones crystallized at lower temperatures than outer zones, they must also be younger than outer zones.

If crystallization was from the contact inward, it follows logically that after the border and wall zones crystallized and sealed the pegmatite chamber, crystallization thereafter must have been in an essentially closed system. In recent literature 3/ the phrase "restricted system" has been used.

1/ Norton, J. J., 1953, New York mica mine, in Page and others, op. cit., p. 167.

2/ Grootemaat and Holland, op. cit.

Eugster, H. P., and Yoder, H. S., Jr., 1955, The join muscovite-paragonite, in Abelson, P. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Year Book No. 54, for the year 1954-1955, p. 124-126.

3/ For example, Jahns, 1955, op. cit., p. 1087.

and appropriately so, because of the likelihood that hydrothermal or pneumatolytic fluids escaped from the pegmatite into the country rock. Under this concept of crystallization in a restricted system, the minerals of the zones formed chiefly by fractional crystallization from the pegmatite liquid. The border zone was the first and the core was ordinarily the last unit to form. A few pegmatites, like the Hugo (fig. 7), contain replacement units that were the last, or at least nearly the last, parts of the pegmatite to form.

The crystallization of zoned pegmatites was accompanied by the development of many replacement features. These can be divided into two categories: (1) replacement textures among the primary minerals of zones, and (2) replacement bodies that were formed after zones.

Replacement textures indicate corrosion of one mineral by another during the formation of zones, even where no replacement unit, in the strict sense, has been superimposed on the zonal structure. These textures are most abundant in inner zones of pegmatites. The perthite of assemblage 3 is embayed, veined, and irregularly replaced by quartz and plagioclase of the groundmass; so common is this relation that it has been described throughout the literature on pegmatites. The large crystals of subhedral to euhedral spodumene at the Etta are in part embayed and veined by quartz and feldspar of the groundmass. The Hugo pegmatite has a zone containing aggregates that are evidently pseudomorphs after spodumene; they have the bladed shape of spodumene and are surrounded by a sheath of cleavelandite, just like unaltered spodumene that occurs in the next zone inward. They consist, however, entirely of minerals that are also found in the groundmass, chiefly quartz, albite, perthite, and amblygonite, but also beryl, muscovite, and apatite.

Replacement textures are most common in the lithia mica-rich cores of the Hugo and Peerless pegmatites and the lepidolite-rich core of the Bob

Ingersoll No. 1 pegmatite. In these units, aggregates of cleavelandite form veinlets that cut across and embay all other minerals of the zone. The cleavelandite, however, is also in part replaced by the micas.

These textural relations do not, however, indicate that a single zone formed in two or more separate periods of crystallization. Studies to determine paragenesis, as at the Hugo pegmatite, indicate extensive overlap in the crystallization of minerals in each zone. Quartz, for example, may commonly embay plagioclase, yet also be embayed by plagioclase. Similarly, in a single zone, muscovite may be corroded by plagioclase, transgress plagioclase, and form subgraphic intergrowths with plagioclase. Firm evidence for two or more distinct stages of crystallization cannot be established, even though some minerals may have formed chiefly during the early part of the crystallization of a zone and others may have been chiefly late.

It can be argued that during crystallization in a restricted system, it is expectable that the liquid and solid phases would be essentially in equilibrium with each other, and textures indicating replacement of one mineral by another should not be as abundant as they are in zoned pegmatites. On the other hand, if a second fluid not in equilibrium with the crystallized material were injected, then the replacement features are to be expected. This argument is probably a basic reason for the many proposals that zoned pegmatites formed in two or more stages, though it does not seem to have been stated in this fashion in the literature.

Nonetheless, so long as there is no clear evidence that the minerals of zones formed in two or more stages, a better explanation for the replacement textures of zones should be sought. It may be that as the rest liquid crystallizes it also gives off a hydrothermal or pneumatolytic phase consisting of water and dissolved materials. Table 6 shows that the Hugo and Peerless pegmatites contain only 0.5 and 0.6 percent water, and although these figures include only the water in mica, tourmaline, amblygonite, and apatite, it seems unlikely that they can be greatly in error. Jahns [1] gives figures ranging from 0.43 to 0.6 percent for three pegmatites in New Mexico and California. If the original water content were greater than this, then as the relatively dry outer zones crystallized, the rest liquid would become enriched in water until it reached the point at which a watery fluid was given off as ~~by means of the resurgent boiling~~ described by Bowen [2]. This may well be the origin of the watery fluids that escape from pegmatites and cause pseudomorphic alteration of staurolite and sillimanite in the wall rocks.

The escape of such a fluid during the formation of zones may influence the course of crystallization in two ways. On the one hand, the internal pressure of the crystallizing system may change so that the rest liquid ceases to be in equilibrium with the solid material, and replacement features are then developed. On the other hand, the escaping fluid may corrode crystallized material and deposit new minerals having replacement relations with older minerals. Jahns [3] favors the second of these mechanisms. He suggests that the condensation of vapors given off by resurgent boiling of the rest liquid is the direct cause of crystallization of minerals that replace other minerals in zones. This is an extreme view; many zones consist

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1/ Jahns, R. H., 1953, The genesis of pegmatites: Am. Mineralogist, v. 38, p. 1100, table 6.

2/ Bowen, N. L., 1933, The broader story of magmatic differentiation, briefly told, in Ore deposits of the Western States: Am. Inst. Min. and Met. Eng., New York, p. 118-124.

3/ Jahns, 1955, op. cit., p. 1097; and 1956, Resurgent boiling and the formation of magmatic pegmatites (abstract): Geol. Soc. America, Program for the 1956 meeting of the Cordilleran Section, p. 20.

predominantly of the "replacement minerals," and thus would have formed chiefly from the vapor phase rather than from the rest liquid. In assemblage 3 throughout the Black Hills the quantity of perthite is subordinate to the quantity of quartz and albite that replace perthite. The zone at the Hugo containing pseudomorphs after spodumene consists entirely of minerals that replace the spodumene; none of the spodumene itself remains in this zone. It seems significant that these replacement features are confined to single zones. They are not in true cross-cutting replacement bodies, as would be expected if the dominant mechanism were deposition of minerals from the vapor phase. Though the vapor phase may have helped upset chemical equilibrium, and may also have helped corrode previously formed crystals, the absence of structural evidence that true cross-cutting replacement bodies formed during crystallization of outer zones indicates that the vapor deposited relatively little mineral matter. Thus it is likely the zones are formed chiefly by crystallization from the rest liquid, and any effects of resurgent boiling are less important.

The replacement bodies that go out from the cores and cut across outer zones of the Hugo and Peerless pegmatites have the structure that should be expected if resurgent boiling forms a fluid from which a large quantity of mineral matter is deposited. The abundance of mica and feldspar in the replacement bodies indicates that the fluid was rich in Al, K, Na, F, and H_2O. The content of dissolved materials must have been quite different from that of any fluid formed by resurgent boiling during the crystallization of outer zones, when no replacement bodies were formed.

This difference may be too great to be explained as a progressive change in the composition of the fluid produced by resurgent boiling. Another explanation is that the fluid forming the replacement bodies separated from the rest liquid as an immiscible phase. Tuttle and Friedman 1/ have demonstrated liquid immiscibility in the system H_2O - Na_2O - SiO_2. The only additional major constituents of the replacement bodies are Al and K.

Separation into two immiscible fluids would be helpful in explaining why the composition of the innermost units, or final products of crystallization, in Keystone pegmatites indicate that there are two general trends of crystallization: one is toward units rich in alkalies, Al, H_2O, and F, and the other is toward a final product rich in SiO_2. The first of these is illustrated by alkalie-rich cores and replacement bodies, as in the Hugo, Peerless, and Bob Ingersoll No. 1 pegmatites; in these same pegmatites, however, the inner intermediate zones are rich in SiO_2. On the other hand, among the 19 pegmatites in table 4, 9 have quartz cores and 6 others have cores that consist of quartzose varieties of assemblages 4, 5, and 6; some of these have muscovite-rich aggregates of possible replacement origin outside the quartzose inner zones 2/. These relations can be readily explained by separation of the rest liquid into two immiscible phases in the final stages of crystallization. Under this concept, the silica-rich phase dominates in most zoned pegmatites; in such pegmatites the alkali-rich phase occurs only as irregularly distributed mica-rich aggregates. In a few pegmatites, however, the alkali-rich phase contained enough material to form cores and replacement bodies.

Quartz cores have met theoretical objections as the final product of pegmatite crystallization, even though it has been commonly considered that

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1/ Tuttle, O. F., and Friedman, I. I., 1948, Liquid immiscibility in the system H_2O-Na_2O-SiO_2: Jour. Am. Chem. Soc., v. 70, p. 919-926.

2/ Page and others, op. cit., p. 15.

quartz veins are a late product of granite crystallization [1], and it is not surprising that the final product of pegmatites should also be quartz. Ramberg [2] states the problem by appropriately, though somewhat extremely, saying that "the core of most pegmatites, which should be the last part to consolidate on the liquidus theory and hence should have a complex eutectic composition, is almost invariably monomineralic quartz."

Though liquid immiscibility may be the key to solving this problem, as here suggested, Jahns [3] has supported resurgent boiling as the explanation. According to him, the alkalies would be carried off in the vapor phase, and the liquid phase would be enriched in silica. Though this view has much to commend it, it introduces still another problem: the alkali-rich vapor phase would form the core of the Hugo, Peerless, and Bob Ingersoll No. 1 pegmatites, rather than escaping entirely into the outer parts of these intrusives. Until more laboratory data have been obtained on the properties of the pertinent chemical systems, it is best to leave open two possible mechanisms, resurgent boiling and liquid immiscibility, as the cause of the formation of quartz cores and the segregation of the inner parts of pegmatites into silica-rich and alkali-rich materials.

1/ Emmons, W. H., 1933, On the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths, in Ore deposits of the Western States: Am.Inst. Min. and Met. Eng., New York, p. 344-345.

2/ Ramberg, Hans, 1952, The origin of metamorphic and metasomatic rocks: Chicago, Univ. Chicago Press, p. 244.

3/ Op. cit., 1955, p. 1094.

QUARTZ VEINS

The Keystone district has quartz veins ranging from minute veinlets less than 0.1 inch thick to large tabular masses as much as 10 feet thick and 600 feet long. Most of those that are large enough to show on the map (fig. 3) consist entirely of quartz and have no evident relation to the pegmatites. Some, however, contain feldspar and muscovite near their contacts; these may be considered silica-rich pegmatites consisting almost entirely of a quartz core.

Quartz is also a prominent mineral of the gold-bearing veins near Keystone, especially at the Holy Terror mine 1/. Detailed descriptions of these veins have never been published. The mines are now closed, and exposures of the veins are not accessible for study.

MINERAL DEPOSITS

The mineral products of the Keystone district are chiefly from pegmatite mining. Gold mines have been active in the past, and doubtless will be active in the future. The Bullion gold mine has also been operated for arsenopyrite as a source of arsenic.

Connolly and O'Harra 2/ and Allsman 3/ have described the gold mines. Because the mines are inaccessible, no additional data from underground workings were obtained during the present investigation. Nearly all of the mines

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1/ Connolly, J. P., and O'Harra, C. C., 1929, The mineral wealth of the Black Hills: S. D. School Mines, Bull. 16, p. 123-129.

Allsman, P. T., 1940, Reconnaissance of gold-mining districts in the Black Hills, S. D.: U. S. Bur. Mines Bull. 427, p. 91 and 101.

2/ Op. cit., p. 114-129.

3/ Op. cit.

and prospects are in amphibole schist. The principal mines are the Holy Terror, Keystone, Bullion, and Columbia in the immediate vicinity of Keystone, and the Bismark, 1 mile northwest of Keystone. This area is intensely faulted, and probably mineralization was controlled in part by faults. Future exploration for gold in this district should be chiefly in amphibole schist in faulted areas.

The Keystone district has long been a major pegmatite mining district. It is noteworthy partly for the diversity of minerals that it has produced in significant quantities--potash feldspar, scrap mica, spodumene, amblygonite, lepidolite, beryl, and tantalite-columbite. It is noteworthy also because a small area of only about 5 square miles contains 10 unusually large minable pegmatites, as well as many smaller ones. Furthermore, the pegmatites are extraordinarily well segregated into zones, fracture-filling units, and replacement bodies. The economic geology of the pegmatites is described in detail in other reports 1/. Certain characteristics of broad significance, however, will be discussed in the following pages.

Industrial minerals have been mined chiefly from zoned pegmatites. The most important reason is that only zoned pegmatites contain units rich enough in one or more industrial minerals to be profitably mined. A scarcely less important reason is that large crystals free of inclusions, and thus suitable for hand cobbing, are rarely found in the homogeneous and layered pegmatites. Though part of the mining in the Keystone district has been in layered and homogeneous pegmatites, it is not known to have been profitable.

The distribution of the principal deposits of industrial minerals in the major pegmatite mines is shown in table 9. The most important industrial

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1/ Especially Page and others, op. cit.; and Sheridan and others, op. cit.

Table 9. Distribution of the chief industrial minerals in the major pegmatite mines of the Keystone district [1]

Mineral Assemblages (from table 4)	Pegmatites									
	Big Chief	Bob Ingersoll No. 1	Bob Ingersoll No. 2	Dan Patch	Dyke Lode	Edison	Etta	Hugo	Peerless	White Cap
1. Quartz, plagioclase, muscovite			Be					M, Be	M, Be	Be
2. Quartz, plagioclase										
3. Perthite, quartz, plagioclase	K			K			K	K	K	
4. Perthite, quartz		K	K	K	K					K
5. Perthite, quartz, plagioclase, amblygonite, spodumene		A, Be	S, A, Be		S			A		
6. Plagioclase, quartz		Be								
7. Plagioclase, quartz, spodumene					S	S	S			
8. Quartz, spodumene			S		S	S	S			
9. Plagioclase, quartz, lepidolite		L								
10. Quartz, microcline								K		
11. Microcline, plagioclase, lithia mica, quartz										
12. Quartz										

[1] Symbols are: K = potash feldspar, M = scrap mica, S = spodumene, A = amblygonite, L = lepidolite, Be = ber

mineral of the Keystone district has been potash feldspar. Nearly all of the potash feldspar comes from hood-shaped intermediate zones in the upper parts of pegmatites. The largest and most productive of these units belong to mineral assemblage 3; a unit of this mineral assemblage at the Hugo mine has been the source of more potash feldspar than any other mine in the Keystone district. Mineral assemblage 4 has also been important. Quartz-microcline pegmatite of mineral assemblage 10 at the Hugo mine was the first potash feldspar deposit mined in the Black Hills, and was being mined again in 1956; ordinarily, however, units of this mineral assemblage are too small to warrant mining.

Spodumene has been obtained mostly from intermediate zones and cores consisting of mineral assemblages 7 and 8. Assemblage 5 also contains spodumene, but it has more commonly been a source of amblygonite. Lepidolite deposits are very rare, not only in the Black Hills but also elsewhere 1/. The only deposit that has been intensively mined is the core of the Bob Ingersoll No. 1 pegmatite, which consists of assemblage 9.

The most productive beryl deposits are in outer zones of assemblage 1 and inner zones of assemblage 5. These assemblages, together with assemblage 4, are probably the largest sources of beryl throughout the world 2/. Beryl has also been produced in the Keystone district from assemblage 6, and as a by-product of feldspar mining in assemblages 3 and 4.

Scrap mica and the small amount of sheet mica produced in the Keystone district have been mostly from assemblage 1, especially at the Hugo and Peerless mines.

1/ Norton, J. J., and Schlegel, D. M., 1955, Lithium resources of North America: U. S. Geol. Survey Bull. 1027-G, p. 339.

2/ Norton, J. J., 1953, Beryllium resources of the world, in Staff of U. S. Bur. Mines and Geol. Survey, 1953, Beryllium: National Security Resources Board, Materials Survey, p. III-6.

Homogeneous and layered pegmatites contain all of these minerals in various degrees of abundance. The only minable concentrations of cobbable material in these pegmatites, however, are in small fracture-filling units and segregations that can support only a one- or two-man mining operation. The rest of the rock in these pegmatites cannot be mined until milling methods are put in use by the pegmatite mining industry of the Black Hills.

For this reason, future exploration in the Black Hills should be chiefly for zoned pegmatites. Inasmuch as zoned pegmatites are known to occur in belts near the outer edge of pegmatite-bearing areas (fig. 1), exploration should be mostly in these belts.

In the mapped area (fig. 3), nearly all of the known zoned pegmatites are in a belt 1 to 2 miles wide that extends from the southeast corner of the map to the Hardestey Homestead mine in sec. 36. It is virtually certain that no large exposures of minable zoned pegmatite, comparable to the Hugo, Peerless, and Etta pegmatites, remain to be found in this area. It is still possible, however, that there are places in this area where only the very top of a large zoned pegmatite reaches the surface, and only the border and wall zones are exposed. Unexposed inner zones have been found by diamond drilling at the Monte Carlo pegmatite (sec. 17) and Ferguson pegmatite (east of the mapped area). At the Ferguson the deposit thus found was large enough to justify mining 1/.

Exploration for completely buried zoned pegmatites presents a more difficult problem. A detailed study of trace element distribution in wall rocks

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1/ Norton, J. J., and Sheridan, D. M., 1955, Exploration for concealed deposits in the Monte Carlo and Ferguson pegmatites, Pennington County, S. D. (abstract): Am. Inst. Min. and Met. Eng., Program for the Black Hills regional meeting, Oct. 2-5, 1955, p. 17-18.

for several hundred feet outward from exposed pegmatites may provide guides for exploration. It is also possible that geophysical methods can be adapted to the discovery of buried pegmatites that have the thickly lenticular shape so characteristic of zoned pegmatites. Any such body found in an area containing many large zoned pegmatites, as near the Hugo, Etta, and Peerless mines, would be well worth the expense of drilling.

At present, however, the only method for finding buried pegmatites would be by wildcat drilling. The geologic map shows that an area of less than 1 square mile south of Keystone contains the four largest and most productive pegmatites of the Keystone district--the Peerless, Etta, Hugo, and Edison--and also many smaller zoned pegmatites. The geology of the country rock suggests no reason why zoned pegmatites should be any more common at the present surface than at a depth of a few hundred feet. It seems likely that widely spaced diamond drill holes in this area might result in the discovery of a large zoned pegmatite.

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