Geology of the Beulah Area, Colorado

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GEOLOGY OF THE BEULAH AREA, COLORADO

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ABSTRACT

The purpose of this report is to describe the areal geology in the vicinity of Beulah, Colorado. Beulah is located in the approximate center of the 40 square-mile area considered and is 26 miles southwest of Pueblo, Colorado by state route 76 and 24 miles south of Florence by state routes 273 and 67.

The Beulah area is on the east flank of the Wet Mountains which are a southward en echelon extension of the Colorado Front Range. Sedimentary rocks which range in age from Ordovician to Cretaceous rest unconformably on a Precambrian complex of metamorphosed igneous and sedimentary rocks. Tertiary (?) diabasic dikes have been intruded into the Precambrian rocks. Of particular interest is the recognition of two sedimentary units between the Pennsylvanian Fountain formation and the Jurassic Morrison formation.

The major structural features of the area formed during the Laramide orogeny, but their formation has been influenced by Pennsylvanian structural features. The Wet Mountains fault probably was active during Pennsylvanian time. Precambrian structural trends are locally concordant with Laramide trends, but the general discordance indicates that they pre-date Laramide and probably Pennsylvanian structures.

Petrographic studies of Precambrian rocks show that the schists of the Idaho Springs formation have been metamorphosed to a moderate degree. They have been injected and intruded by numerous igneous rocks which include granite, adamellite, and pegmatite of Precambrian age.

INTRODUCTION

Location of Thesis Area

The area covered in this report is located in south-central Colorado (Fig. 1). It comprises the south one-half of T. 22 S., the north one-half and sections 21 and 22, T. 23 S., R. 68 W., Pueblo County, and sections 24 and 25, T. 22 S., R. 69 W., Custer County. The town of Beulah, which lies in the approximate center of this 40 square mile area, is 26 miles southwest of Pueblo by state route 76 and 24 miles south of Florence by state routes 273 and 67.

Purpose of Thesis

The purpose of this report is to describe the areal geology in the vicinity of Beulah, Colorado. Particular attention is given to structural geology, including Precambrian trends, igneous and metamorphic petrography and petrology, and stratigraphy and sedimentation. In addition, historical geology, geomorphology, and economic geology are discussed.

Geologic Setting

The Wet Mountains are a southward en echelon extension of the Colorado Front Range. They extend from the Canon City embayment southward to Huerfano Park and the Park Plateau. The Beulah area is on the east flank of the Wet Mountains.

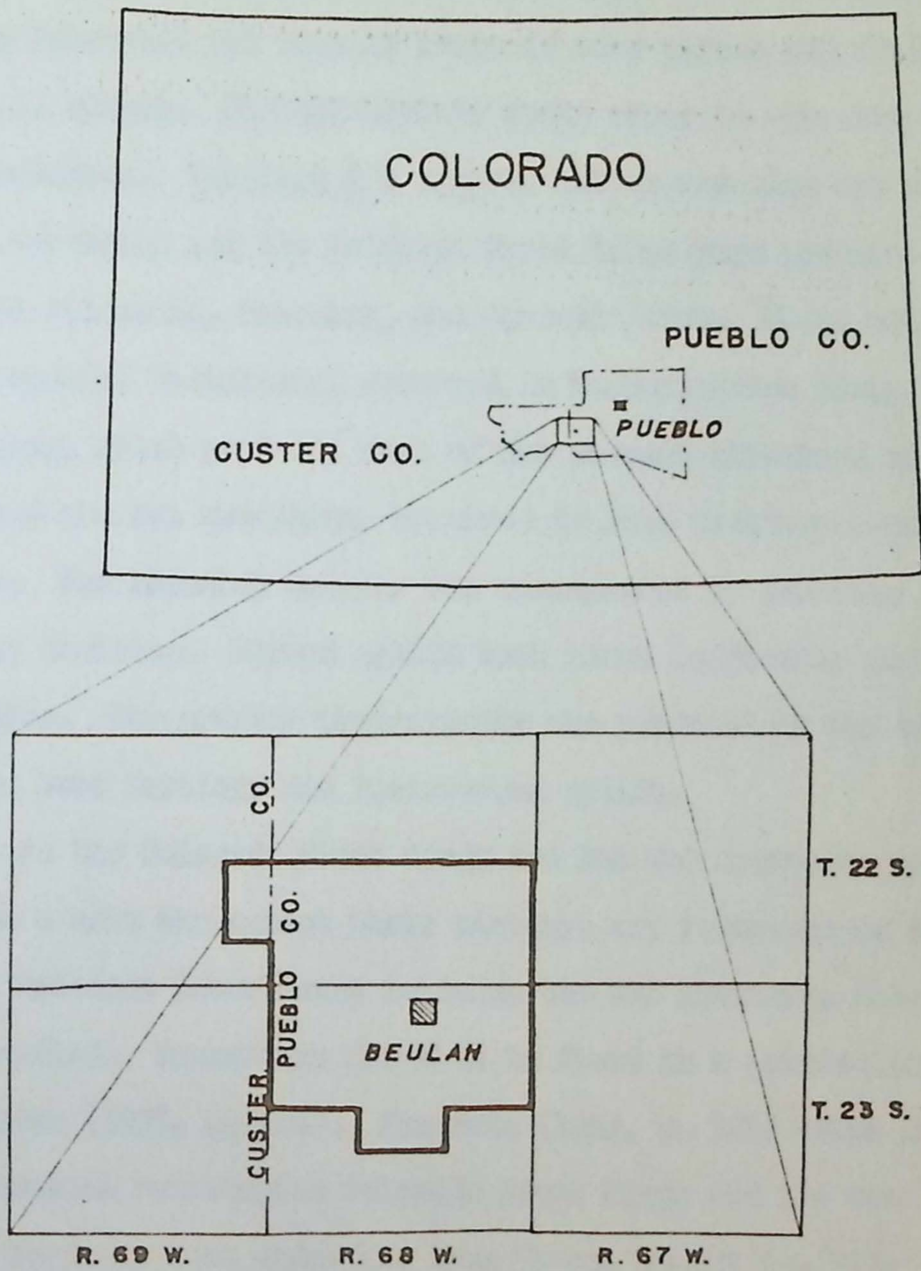


FIG. 1. Index map showing location of thesis area.

In the vicinity of Beulah, Precambrian rocks form a basement that is overlapped by Paleozoic and younger rocks in some places and faulted against them in others. The sedimentary rocks range in age from Ordovician to Cretaceous. Tertiary (?) igneous intrusives also are found.

The Wet Mountains and the Colorado Front Range were positive elements during much of Paleozoic, Mesozoic, and Cenozoic time. Major uplift, probably accompanied byfaulting, occurred in Pennsylvanian time. The Laramide orogeny, which produced much of the present structure of the Front Range and the Wet Mountains, occurred in late Cretaceous and early Tertiary time. The Laramide orogeny was accompanied by faulting and extensive thrust faulting. Marked uplift took place in Miocene and Pleistocene time. The present physiography was produced by the effects of erosion and late Tertiary and Pleistocene uplift.

Inasmuch as the Colorado Front Range and the Wet Mountains acted essentially as a unit throughout their history, any reference in this report to the Colorado Front Range includes the Wet Mountains unless otherwise specified. Precedence for this is found in a publication by Finch, and others (1933, p. 284). Fenneman (1931, p. 104) makes a definite distinction between the Colorado Front Range and the Wet Mountains but includes both under the term "Front Range" (p. 99).

Method of Work

The field work was done in the seven weeks between the 20th of July and the 10th of September, 1953. Mapping was done on U. S. Forest Service 10 by 14 inch aerial photographs. Owing to the similarity of most of the rock types, formation boundaries for much of the Precambrian were not plotted until thin section studies had been completed. The geological data were transferred to an enlarged U. S. Forest Service planimetric map of the Beulah area.

Previous Work

Earliest mapping in the thesis area by Gilbert (1896, 1897) and Darton (1904) was of a reconnaissance nature. In 1926 this earlier work was revised somewhat for preparation of the Geologic Map of Colorado by the U. S. Geological Survey in cooperation with the Colorado State Geological Survey (Burbank, and others, 1935). Stratigraphic studies have been made by Brainerd, Baldwin, & Keyte (1933), Brainerd & Johnson (1934), Heaton (1939), and Maher (1950a, 1950b, and 1953).

GEOGRAPHY

Topography

Relief within the area amounts to slightly more than 2,900 feet. Altitudes above sea level range from about 6,000 feet on the eastern border to about 8,900 feet on the western border.

East of Beulah, the topography is dominated by a hogback which faces west and trends roughly north-south. At its approximate midpoint, a water gap has been cut by the northern branch of the St. Charles River. The crest of the hogback north of the water gap is named "Lookout Mountain"; the crest south of the water gap is called "Hogback Mountain".

The more gentle portions of the dip slopes of Hogback and Lookout mountains have produced a relatively flat and monotonous terrain which is interrupted only by dry washes and the valley of the northern branch of the St. Charles River.

The steep westward facing scarp of the hogback overlooks Beulah Valley which has a gently rolling floor. West of Beulah Valley, the topography is more rugged. The mountains rise sharply, the slopes steepen, the valleys narrow, and the relief increases notably.

The main streams are North, Middle, and Squirrel creeks. They flow eastward into Beulah Valley where they merge to form the northern branch of the St. Charles River and flow through the water gap cut into the hogback. All other drainage is intermittent.

Vegetation

Pinon pine and cactus are the dominant growth along much of the eastern border of the area, particularly where altitudes are below 7,000 feet. Higher on the dip slope and on the scarp face of the hogback, conifers and scrub oak are common. In Beulah Valley, the vegetation consists largely of cultivated crops and pasturage, although poplars grow along parts of the creeks. On the west side of the valley, pine and scrub oak are dominant. Scrub oak thrives best on the south slopes of the hills, whereas conifers cover the north slopes; locally, there are grassy parks. Above altitudes of about 8,000 feet, conifers and a few aspen are the major growth.

Local Industry

Although tourists and summer residents provide most of the income for the local population, agriculture also plays an important role in Beulah Valley. The principal crops are wheat, hay, and corn. Some cattle are grazed in the valley, but much of the land is unused or unsettled.

In the late 1890's and until about 1930, limestone was quarried from outcrops of the Madison limestone just west of Beulah, but the quarries have been idle for many years.

STRATIGRAPHY AND SEDIMENTATION

General

The rocks in the thesis area range in age from Precambrian to Tertiary (?) (Fig. 2). They comprise sedimentary, metamorphic, and igneous units. The igneous and metamorphic rocks are described in greater detail under the heading of Petrography and Petrology.

Of particular interest is the recognition of two sedimentary units between the Pennsylvanian Fountain formation and the Jurassic Morrison formation. To the writer's knowledge, the units have been mentioned only once in the literature and never have been described elsewhere.

Precambrian

The Precambrian rocks are essentially the same as those found elsewhere along the Colorado Front Range. For mapping purposes, five types

ERA	SYSTEM	SERIES	FORMATION	THICKNESS
CENO-ZOIC	Tertiary (?)	Miocene (?) or Eocene (?)	Diabase dikes	---
MESOZOIC AND PALEOZOIC	Cretaceous	Upper Cretaceous	Greenhorn limestone Graneos shale Dakota sandstone	25 - 40 200 200 - 300
			UNCONFORMITY	
	Jurassic	Upper Jurassic	Morrison formation	200
			UNCONFORMITY	
	Permian (?) to Jurassic (?)	(?)	Unit B	0 - 40
			UNCONFORMITY	
		(?)	Unit A	0 - 190
			UNCONFORMITY	
	Pennsylvanian	Virgillian Missourian Desmoinsian	Fountain formation	2,100
			UNCONFORMITY	
	Mississippian	Kinderhookian (?)	Madison limestone	0 - 200
			UNCONFORMITY	
	Mississippian (?)	Kinderhookian (?)	Williams Canyon limestone	0 - 20
			UNCONFORMITY	
	Ordovician	Cincinnatian	Fremont limestone	0 - 20
			UNCONFORMITY	
		Mohawkian	Harding sandstone	0 - 75
			UNCONFORMITY	
PRECAMBRIAN	(?)	(?)	Pikes Peak granite Undifferentiated Precambrian rocks Adamellite gneiss Idaho Springs formation	--- --- (?)

FIG. 2. Time-rock divisions in the Beulah area, Colorado

have been differentiated in this report. They are: the Idaho Springs formation, an adamellite gneiss, undifferentiated Precambrian rocks, pegmatites, and the Pikes Peak granite. The outcrops of Precambrian rocks generally are restricted to the western half of the thesis area (Pl. 1) where three irregular zones can be defined. The Pikes Peak granite crops out along the western border of the area. East of that border is a zone of undifferentiated Precambrian rocks. Farther to the east, the Idaho Springs formation crops out in a belt which has been intruded by the adamellite gneiss.

Idaho Springs formation. The Idaho Springs formation was named by Ball (1906, p. 374) for rocks exposed in the hills around Idaho Springs, Colorado. This formation includes the oldest known rocks in the Front Range (Lovering & Goddard, 1950, p. 19).

As typically developed along the Front Range and in the thesis area, the Idaho Springs formation consists of metamorphosed pelitic sediments that have been injected by granites and pegmatites. The dominant rock types are quartz-biotite schists and quartz-biotite-sillimanite schists with lenses, layers, and fingers of granitic rocks intercalated along planes of foliation. The rocks of the Idaho Springs formation generally are highly contorted and foliate; foliation is parallel to the traces of former bedding.

Adamellite gneiss. The adamellite gneiss referred to here cannot be related definitely to any named igneous rocks along the Front Range. It is a pink, fine- to medium-grained rock that is composed primarily of quartz, feldspar, and biotite. Its well-developed gneissic structure and pale pink color serve to differentiate it from most of the other meta-igneous rocks. It forms bosses and irregularly shaped bodies which are intrusive into the Idaho Springs formation. Its marked foliation and higher degree of metamorphism suggest that it is older than the Pikes Peak granite in which foliation is poorly developed.

Undifferentiated Precambrian rocks. The rocks here denoted as "undifferentiated" range in composition from granite to adamellite. They are found in a belt between the Idaho Springs formation and the Pikes Peak granite. In addition, they occur as injections and intrusions into the Idaho Springs formation, and are dated, therefore as younger than that formation and because they are not intruded into the Pikes Peak granite, they are thought to be older than it.

Hand specimens of the rocks are difficult to classify because of similarities in texture and color. They are all medium- to fine-grained, pink in color, and contain more or less biotite and other dark minerals. Because of their lithologic similarity, they were not mapped as independent units in the field. A more complete consideration of the undifferentiated Precambrian rocks is given in the section on petrography and petrology.

Pegmatites. Three pegmatite dikes were mapped. They were intruded into the Idaho Springs formation and the undifferentiated Precambrian rocks. The pegmatites are composed mainly of quartz, microcline, and oligoclase with minor amounts of magnetite. They are younger than the Idaho Springs formation, but it is not known to which period of intrusive activity they are related.

Pikes Peak granite. The Pikes Peak granite was named and described by Cross (1894). The Pikes Peak granite is found in most parts of the

Front Range. Typically, it is a coarse-grained, porphyritic granite with a pink color and is composed primarily of quartz and microcline with lesser amounts of orthoclase, plagioclase, and biotite. "The coarse, granular texture of the Pikes Peak granite makes it an easy prey to the agents of weathering and erosion, and on aged erosion surfaces, where it has been long exposed to the elements, balanced residual boulders and grotesque erosion forms are characteristic of areas of this granite (Lovering & Goddard, 1950, p. 23)." It has been shown that the Pikes Peak granite is intrusive into the Idaho Springs formation and is, therefore, younger than that formation (Lovering & Goddard, 1950, p. 23).

Ordovician

Harding sandstone. The Harding sandstone of late Black Riveran or early Trentonian age (Johnson, 1945, p. 22; Kirk, 1930, p. 465) was first described at the Harding Quarry at Canon City, Colorado by Walcott (1892, p. 153 - 172). Its thickness there ranges from 85 to 115 feet. It is exposed in the hills west of Beulah where it was first recognized by Gilbert (1897) who mentioned a thickness of about 30 feet.

The Harding sandstone is widespread along the Front Range as well as elsewhere in Colorado (Johnson, 1945, p. 20). It thins southward from the type section at Canon City and disappears south of Beulah (Pl. 1). In the hills west of Beulah, it attains a maximum thickness of 76 feet and rests unconformably on Precambrian rocks. It is overlain disconformably by the Fremont and Williams Canyon limestones and locally is overlapped by the Fountain formation.

Exposures of the formation in the vicinity of Beulah exhibit similarity in lithology, but minor differences are to be observed from outcrop to outcrop. At some places, the basal Harding is marked by a white calcareous sandstone or by a conglomeratic sandstone made up of coarse white calcareous sand and white quartz pebbles. At other places, the basal Harding is marked by variegated siltstone, shale, and mudstone. These differences are attributed to the lenticular nature of the lower beds of the formation. About 8 to 11 feet above the base of the Harding is a fine-grained, dense, evenly-bedded orthoquartzite which is a consistent ledge-former.

Above the orthoquartzite, the formation consists of alternating fine-grained calcareous sandstone, siltstone, and variegated shale. The apparent sequence and thickness of these beds differs markedly from place to place. In general, however, shale increases in amount toward the top of the formation.

Generally, the sandstone is clean, white, friable, fine-grained, and somewhat calcareous. Intercalations of purple and green shale are common along bedding surfaces. Locally, the sandstone itself is stained purple, green, or brown. Fucoidal markings on bedding surfaces also are characteristic. The shale is variegated with shades of purple and green as the dominant colors.

The Harding sandstone is poorly fossiliferous in the thesis area. The best fossils are found in a silty zone underlying the orthoquartzite. They consist of detrital fragments which have not been identified positively. Many, however, closely resemble the fragments of ostracoderm plates portrayed by Walcott (1892, Pls. 3 - 5) and Bryant (1936, Pls. 1 - 13). In addition to fish plates, a good neritic fauna of late Black Riveran or early Trentonian age has been described at the type locality (Branson & Mehl, 1933, p. 19 - 39; Kirk, 1929, p. 494 - 496; Walcott, 1892, p. 153 - 172).

The section at Beulah is very similar to the type section at Canon City. A coarse somewhat conglomeratic sandstone is found at the base of the Harding at both Beulah and at the type locality. Likewise, a fossiliferous horizon is found just below a resistant ledge-forming sandstone member at both places. Brainerd, Baldwin, & Keyte (1933, p. 383 - 384) have noted the continuous nature of the fossiliferous bed along the Front Range. Above the more resistant sandstone beds, the formation becomes more friable, less evenly bedded, and contains more siltstone and shale.

It has been maintained that the Harding sandstone represents a late Mohawkian marine transgression (Maher, 1953, p. 2480; McCoy, 1953, p. 1879; Walcott, 1892, p. 22). This relationship is substantiated in the Beulah area where the basal coarse or conglomeratic sandstones also are found. The gradual upward increase in fineness of the sediments is evidence of deepening water after the initial marine invasion.

Romer (1945, p. 514) has specified that the deposits are in part estuarine. It is partly on this basis that a fresh-water origin of fishes has been proposed and generally accepted. The fish fragments are thought to have been transported to the sea and deposited under conditions of marine transgression. The writer has found no definite evidence of estuarine conditions in the Harding sandstone of the Beulah area. The lenticular nature of some of the lower Harding sediments might be indicative of estuarine conditions, but, "Reliance for determination of an estuarine deposit can be placed on no single characteristic ... (Twenhofel, 1950, p. 123)." Under conditions of a transgressing sea, however, the possibilities of estuarine sedimentation are not to be discredited.

Thin sections of two samples of Harding sandstone were cut and studied (Appendix B). The sections are from a sample of the orthoquartzite and a sample of an overlying fine-grained sandstone. They demonstrated the fine-grained nature of the sandstones and showed that the sediments originally were subrounded and subequigranular, but that the roundness of the sand grains has been masked by silica overgrowths. The fine size and the good sorting exhibited in the sections offers further evidence of deposition by a transgressing sea.

In addition to quartz, calcite, argillaceous matter, and small rounded grains of zircon were observed in the thin sections. In the orthoquartzite, the angular and commonly subhedral silica overgrowths mask the subrounded grains of the original sediment. One interesting feature (Fig. 5) observed in the thin sections was the replacement of the quartz grains by calcite. This feature is described in greater detail in the appendix.

<u>Fremont limestone</u>. The Fremont limestone is of late Cincinnatian (Richmondian) age (Johnson, 1945, p. 29). It was first described at Hardings Quarry near Canon City, Fremont County, Colorado by Walcott

(1892, p. 153 - 172). The occurrence of the Fremont limestone near Beulah was first noted by Brainerd, Baldwin, & Keyte (1933, p. 386). Fremont outcrops in the vicinity of Beulah were not mentioned by Gilbert (1897) or Darton (1906).

Along the Front Range, the Fremont limestone is thickest in the vicinity of Canon City. It is widespread in the southern portions of the Sawatch Range (Johnson, 1945, p. 24). Only lenticular remnants of the Fremont are present in the hills west of Beulah. Outcrops are widely scattered, most of the formation having been removed by erosion prior to deposition of the Williams Canyon limestone. The thickness of the Fremont in the area ranges from a knife edge to about 18 feet. Because of its erratic distribution and general thinness, the Fremont limestone is not shown on the map (Pl. 1).

The contact between the Fremont remnants and the Harding sandstone is disconformable with the Fremont resting on an irregular surface of Harding shales. The Fremont is overlain disconformably by the Williams limestone.

Although the upper and lower contacts generally are covered, the limited exposures of the Fremont west of Beulah show essentially the same lithology. At the base of the Fremont, a few inches of thin- and wavy-bedded coarsely crystalline red limestone locally may be exposed. This unit is not persistent and commonly is missing. Above the basal unit is a massive dolomite which may be 14 or 15 feet thick in places. The color grades from red and pink near the base to buff with tinges of pink at the top. The dolomite displays the characteristic rough surface associated with the Fremont formation. It is coarsely crystalline throughout and may be somewhat sandy.

A few fossils were seen in the outcrops, but the massive nature of the rock made collecting impossible. The fossils observed were rugose corals (Streptelasma (?)) and crinoid columnals.

The section at Beulah is very thin compared to the sections near Canon City, Colorado where the Fremont reaches thicknesses as great as 275 feet (Johnson, 1945, p. 24). The lithologies of the crystalline dolomites at both places, however, are generally comparable. The crinoid remains and rugose corals preserved in the rock and its lithologic character suggest deposition in a relatively stable, moderately shallow neritic environment.

Mississippian (?)

Williams Canyon limestone. The Williams Canyon limestone was named and described as a stratigraphic unit by Brainerd, Baldwin, & Keyte (1933, p. 387 - 389). It was named for the section exposed in Williams Canyon near Manitou Springs, Colorado. The occurrence of the formation at Beulah also was noted by Brainerd, Baldwin, & Keyte at that time. The unit, together with the overlying Madison limestone, had been mapped by Gilbert (1897) and by Darton (1906, p. 15) as the Millsap limestone. The Millsap limestone originally was named for the exposures north of Canon City between Oil Creek and Millsap Creek by Cross (1894) where a section of the Williams Canyon limestone about 30 feet thick crops out. No Madison limestone is present at Cross's type section of the Millsap

(Brainerd, Baldwin, & Keyte, 1933, p. 392). The name Millsap previously had been used for a Pennsylvanian unit in Texas (Wilmarth, 1938, p. 1374, 1375). Therefore, Brainerd, Baldwin, & Keyte (1933, p. 387 - 389) re-described and renamed the formation the Williams Canyon limestone.

The formation extends along the Front Range from Beulah to Grove Canyon in Douglas County (Maher, 1950a). At Beulah, the Williams Canyon limestone is exposed in the western part of the area where it is about 18 feet thick. It consist of two- to six-inch beds of wavy-bedded fine-grained limestones with partings of gray calcareous shale and sandstone lenses. The limestone ranges in color from mottled purple to gray and buff. No fossils were found by the writer at any exposure in the Beulah area. The Williams Canyon limestone rests disconformably on the older Fremont limestone and Harding sandstone, as is shown by the irregularity of the lower contacts. It is overlain unconformably by the Madison limestone (Mississippian) which displays a basal conglomerate containing reworked Williams Canyon limestone pebbles and boulders. Lithologically, the section at Beulah corresponds with sections measured by Brainerd, Baldwin, & Keyte (1933, p. 381, 392, 393) and by Maher (1950a, p. 1 - 19).

Cross (1894) assigned the formation to the Carboniferous system on the basis of Mississippian fossils found at the top of his measured section north of Canon City. Brainerd, Baldwin, & Keyte (1933, p. 392) considered the fossils as " ... coming from reworked Madison fragments in the basal Pennsylvanian (Fountain formation) and these thin limestones, to which the name, Williams Canyon has been given, ... as Devonian in age.

No Madison was found (at Cross's section), although isolated remnants may occur." Brainerd, Baldwin, & Keyte tentatively correlated the formation with the lower part of the Ouray limestone of central Colorado and the Elbert formation of southwestern Colorado, but suggested a closer correlation with the Parting quartzite of central Colorado and assigned it a Devonian age (Brainerd, Baldwin, & Keyte, 1933, p. 389, 390).

More recently, Cloud and Barnes (1948, p. 76) attempted to correlate the Williams Canyon limestone of the type section with the Harding sandstone which is exposed farther to the south. According to Maher (1950b), "The latter correlation is clearly not acceptable as the measured sections at Oil Creek, Priest Canyon, South Hardscrabble Creek, and Beulah localities show the Williams Canyon limestone lying above not only the Harding sandstone but the Fremont limestone as well." He further states:

> "In the absence of fossil evidence in the outcrops, the approach to this correlation problem is in the subsurface of eastern Colorado. The lithology and stratigraphic relations of the Mississippian and older rocks ... (are shown in) wells in eastern Colorado ... . The most important concept gained ... is that of the gradual westward overlap of Ordovician rocks by the Mississippian strata, with the thinning of the Mississippian due to loss of beds at the base. In Lincoln, Cheyenne, and Kiowa Counties (Colorado), the Mississippian is represented by Kinderhook, Osage, and Meramec groups; in Crowley County, by the Osage and Meramec groups, and in Pueblo County only by the

Meramec group ... .

Lithologically the Williams Canyon limestone is similar to the Spergen limestone in which the microfossil Endothyris (baileyi (?)) has been found in some wells in eastern Colorado. Stratigraphically it underlies the Hardscrabble (lower Madison) limestone which is identical with the St. Louis limestone in the wells. In view of these lithologic similarities and supporting stratigraphic relations, in view of the absence of Devonian strata in the subsurface of eastern Colorado and far western Kansas (Maher & Collins, 1949), and because of the impossibility of correlating the Williams Canyon and Harding formations, it is suggested ... that the Williams Canyon limestone is Mississippian in age and equivalent in part to the Spergen and Warsaw limestone (Meramecian) —— probably only Spergen."

It must be pointed out, however, that Maher's sections seemingly were based on only seven widely separated wells between the Front Range and western Kansas. Further, since Kinderhookian fossils have been found in the overlying Madison limestone (Brainerd, Baldwin, & Keyte, 1933, p. 391), some doubt is thrown on Maher's correlation of the Williams Canyon limestone with the Meramecian Spergen and Warsaw limestones.

The wavy-bedding, shale partings, and sandstone lenses of the Williams Canyon limestone suggest that it was deposited in a relatively shallow neritic environment where current action was effective.

Mississippian

Madison limestone. The Madison limestone of early Mississippian age was named and described by Peale (1893, p. 33 - 39). It was named from the exposures in the Madison Range near Three Forks, Montana. In 1903, Girty (p. 170), on fossil evidence, assigned an early Mississippian age to the upper part of a limestone sequence called the Millsap limestone which is exposed along the Front Range. The Millsap has been subdivided and the upper part is called the Madison limestone; the lower part is called Williams Canyon limestone (Brainerd, Baldwin, & Keyte, 1933, p. 387 - 392). Maher (1950a, 1950b) subdivided the Madison limestone into the Hardscrabble (lower) and Beulah (upper) limestones. For reasons to be discussed in the succeeding pages, the writer will use the name Madison rather than Maher's two-fold division.

Exposures of Madison limestone along the Front Range are few; the best outcrops are in the hills west of Beulah where the Madison ranges in thickness from a wedge edge to about 200 feet. In the area and elsewhere, the Madison limestone rests unconformably on the Williams Canyon limestone. The lower contact with the Williams Canyon limestone is very irregular and the base of the Madison displays a limestone conglomerate composed largely of reworked Williams Canyon limestone. The Fountain formation overlies the Madison and an angular unconformity separates the two, but more commonly the contact is extremely irregular owing to sink holes which formed in pre-Fountain time. The sink holes are filled with Fountain sandstone.

The lower portion of the Madison limestone is a prominent cliff-former in the area. The cliffs average about 50 feet in height and are made up of somewhat fossiliferous massive finely crystalline limestone. Thin cherty and sandy units and a somewhat oolitic zone are present near the tops of the cliffs. The color ranges from buff to gray. Cave fill is present, but relatively uncommon in this lower member.

Above the cliff-forming member is a less resistant, unfossiliferous fine-grained gray to buff limestone which contains considerable red chert. Towards the top it becomes quite sandy and is commonly cross-bedded. The upper parts of the Madison limestone contain considerable Fountain sandstone and mudstone that was deposited as cave fill in the markedly irregular upper surface of the limestone.

Fossils were found toward the top of the cliff-forming member of the Madison limestone. They include Camarotoechia subelliptica var. hardingensis (Girty, 1903, p. 299 - 300, Pl. I) and Spirifer rockymontanus (Girty, 1903, p. 383 - 385, Pl. VI; Shimer & Shrock, 1944, p. 325). The fossils are preserved as cherty molds and casts. Identification, therefore, was based primarily on internal structures.

The Madison limestone of the Front Range has been dated as Kinderhookian on the basis of fossil evidence (Brainerd, Baldwin, & Keyte, 1933, p. 391). Although no known outcrops of Madison limestone occur north of Perry Park, Colorado, the extension of the Madison limestone of the Front Range northward into Wyoming is indicated by the presence of reworked Mississippian material in the basal Pennsylvanian (Brainerd, Baldwin, & Keyte, 1933, p. 391; Brainerd & Johnson, 1934, p. 539). "Many of the horizons from which Mississippian fossils have been reported from the Front Range are believed to be basal Pennsylvanian, in which the fossils occur in chert nodules derived from the erosion of the Mississippian (Brainerd, Baldwin, & Keyte, 1933, p. 391)."

More recently, Maher (1950a, 1950b) proposed a two-fold division of the Madison limestone into the Hardscrabble (lower) and Beulah (upper) limestones as the result of his work near Beulah. The Beulah limestone, according to Maher (1950b), is almost restricted to the area west of Beulah and to one exposure on South Hardscrabble Creek ($S\frac{1}{2}$, Sec. 11, T. 22 S., R. 69 W., Pueblo County). He claims to have found evidence of an irregular unconformity at the base of the Beulah limestone at the Hardscrabble Creek exposure. He further states that the unconformable relationships "... at the locality where measurements were made at Beulah were obscured by caves filled with Pennsylvanian sandstone."

The writer was unable to detect any evidence of an unconformity at any point near the middle of the Madison limestone where it crops out west of Beulah. C. A. Martin of the University of Kansas (personal communication) states that neither he nor W. W. Hambleton of the University of Kansas could find any definite trace of an unconformity in the section at Hardscrabble Creek.

Because evidence for an unconformity is meagre, the writer favors the older terminology of Brainerd, Baldwin, & Keyte (1933). Therefore, no differentiation will be made between the Beulah and Hardscrabble limestones, and the rocks lying between the Williams Canyon limestone and the Fountain sediments will be called Madison limestone.

Maher (1950b) has placed some importance on the oolitic nature of the upper parts of the Madison limestone in his two-fold division of the unit. Megascopic studies in the field did not reveal the upper parts of the Madison to be nearly as oolitic as Maher's (1950a) detailed sections indicate. Martin reports (personal communication, J. C. Maher to C. A. Martin) that many of the characteristics attributed by Maher to the Madison limestone were determined in the laboratory by petrographic methods. Such detailed laboratory studies may account for the discrepancies between the writer's measured section and the ones prepared by Maher. However, such detailed determination of characteristics probably is of little value for mapping purposes unless the characteristics can be observed in the field. Thus, the writer further defends usage of the term Madison limestone in this report.

Maher (1950b) also has correlated the Madison limestone of the Front Range with Meramecian units in the subsurface of eastern Colorado and western Kansas. His correlation is largely lithologic and the sections displayed in his report seemingly were based on data from only seven widely separated wells between the Front Range and western Kansas. Inasmuch as Kinderhookian fossils, namely Actinocrinus marconi Collignon, have been found in the Madison outcrops near Williams Canyon (Brainerd, Baldwin, & Keyte, 1933, p. 391), some doubt is cast on Maher's correlation of the Madison limestone with the Meramecian Ste. Genievieve and St. Louis limestones. Therefore, Brainerd's correlation of the Madison limestone of the Front Range with that of Montana and Wyoming tentatively is accepted in this report.

The massive appearance, the chert, the minor oolites, and the brachioped fossils indicate a relatively shallow, stable neritic environment of deposition for the Madison limestone of the Beulah area.

Pennsylvanian

Fountain formation. The Fountain formation of Pennsylvanian age was named by Cross (1894) for a series of red arkosic sandstones and conglomerates exposed along Fountain Creek near Manitou Springs, Colorado. No detailed description of the rocks was given, nor was there any mention of the environment of deposition. The type section was described by McLaughlin in 1947 (p. 1936 - 1968). The Fountain formation was first noted in the vicinity of Beulah by Gilbert (1897).

About 2,100 feet of Fountain section was measured in Beulah Valley (approximately two miles north of Beulah) by the writer, assisted by C. A. Martin of the University of Kansas. Throughout the area and along the Front Range, the Fountain formation rests unconformably on older beds. The contact with the Madison limestone in the area is generally extremely irregular, and fingers of Fountain sediments project downward into the limestone. The contact with pre-Madison units is angular; the differences in dip commonly approach 20 degrees (Pl. 2, Section C-C'). Southwest of Beulah, in the NE¼, NW¼, Sec. 16, T. 23 S., R. 68 W., the Fountain formation overlaps the older Paleozoic units and rests directly on Precambrian rocks. The Fountain formation is unconformably overlain by younger units in the area, but no marked angular relationships have been observed.

The Fountain formation consists of red beds of arkosic sandstone and conglomerate and sparse thin-bedded micaceous shale. In contrast to most areas of Fountain outcrops in eastern Colorado, no limestone was observed in the formation in the thesis area.

Changes in lithology are abrupt, both vertically and laterally, because of the lenticular nature of the sediments. Festoon and torrential cross-bedding are common. The color of the Fountain formation is dominantly red, but browns, grays, pinks, and greens occur locally. The red color is due not only to the arkosic nature of the sediments, but primarily to the presence of hematite cement.

Some of the conglomerates of the Fountain formation are composed of cobbles and boulders of Precambrian granite and quartzite embedded in an arkosic matrix. The cobbles and boulders are subangular to rounded in shape and reach a maximum diameter of about 15 centimeters. The greater proportion of the conglomerates are made up of pebbles of quartz and orthoclase embedded in an arkosic matrix. The pebbles reach a maximum diameter of three centimeters. In general, conglomerates of both types are most abundant toward the base of the Fountain formation, and finer-grained rocks are more abundant toward the top.

Normally, the Fountain formation is poorly exposed in the vicinity of Beulah. The formation underlies most of Beulah Valley and is largely covered, except along the edges of the valley.

The age of the Fountain formation has not been fixed definitely (Vanderwilt, and others, 1948, p. 38). Indications are that the age ranges from Desmoinesian at the base to Virgilian at the top. At the north end of the Front Range, it is known to interfinger with the Virgilian Ingleside and Casper formations. The base of the Fountain is thought to interfinger with the Glen Eyrie formation which contains Desmoinesian or younger fossils.

McLaughlin (1947, p. 1975) has suggested that the Fountain sediments were deposited on the landward part of a coastal delta. As evidence for this, he has cited the presence of channel fills, the irregularity and lenticular nature of the bedding, and the presence of torrential and festoon cross-bedding. The climate is not thought to have been arid. An arid climate is not essential for the formation of red beds; the major requirement is the maintenance of oxidizing conditions. Oxidizing conditions generally prevail in the upper reaches of deltas. Furthermore, the bleached zones in parts of the Fountain formation indicate organic reduction of ferric iron in the sediments. Reduction of ferric iron commonly is accomplished by plants. Thus it is suggested (McLaughlin, 1947, p. 1890) that the climate at the time when the Fountain formation was deposited actually may have been humid, humid enough to support an active plant growth.

Permian to Jurassic Undifferentiated

Units A and B. In the northwest corner of the area, a series of rocks of undetermined age is found between the Fountain and the Morrison formations. Heaton (1939, p. 1126) has referred the rocks either to the

Lykins formation or the Entrada sandstone. To the author's knowledge, however, measured sections and descriptions of these rocks have not appeared in the literature.

The lower unit, which is here called "A", is a cyclic series of arkosic conglomerate, breccia, sandstone, and limestone. The thickness of unit A is about 190 feet where it is exposed in Sec. 24, T. 22 S., R. 69 W. and Sec. 19, T. 22 S., R. 68 W.. Unit A is not present elsewhere in the thesis area (Pl. 1).

Unit A either rests disconformably on the Fountain formation or is in fault-contact with Precambrian rocks. It is disconformably overlain by unit "B". The base of unit A is a white to gray conglomeratic fine- to coarse-grained arkosic sandstone. The sandstone is commonly cross-bedded and contains pebbles of pink feldspar embedded in the white sandy matrix. The lower sandy and conglomeratic part grades upward into an arkosic siltstone which in turn grades into a nodular dense arenaceous arkosic limestone. The first limestone is 149 feet above the base of the formation.

A coarse arkosic angular breccia rests disconformably on the lowest limestone. The breccia grades upward through arkosic sandstone and siltstone into a second nodular limestone. The cycle is repeated a total of five times. Thus, five nodular limestone layers occur in unit A. (See Appendix A for a detailed measured section of the unit.)

Unit B rests disconformably on unit A, and is in turn disconformably overlain by basal Morrison sandstone. In the thesis area, unit B is present only in Sec. 24, T. 22 S., R. 69 W. and Sec. 19, T. 22 S.,

R. 68 W.. The total thickness of unit B is about 37 feet. The base is marked by 2.6 feet of massive yellow lithographic limestone. Above the limestone, the unit generally is covered, but float and the limited exposures indicate that it consists of red siltstone, gray arkosic sandstone and siltstone, gray shale, and thin bands of yellow lithographic limestone.

Inasmuch as Heaton (1939, p. 1162) has provided no lithologic descriptions of the beds he classed as Lykins, Entrada, and basal Morrison in the Beulah area, the author has made no attempt to relate the units described above to any of these formations. Also, the lithology of units A and B is quite different from anything the writer has ever observed in the Lykins or Entrada formations. In addition, the lithology is quite different from the lithology that other writers have attributed to the Lykins, Entrada, and Morrison formations along the Front Range (Butters, 1913, p. 65 - 101; Finlay, 1916; Lee, 1927; Reeside, 1931, p. 192 - 207; Vanderwilt, and others, 1948, p. 37 - 46; Waldschmidt & Leroy, 1944, p. 1097 - 1114).

Although the outcrops of units A and B are limited in extent, certain conclusions concerning the environment of deposition can be reached. The rhythmic recurrence of the limestones in unit A suggests a marine environment for part of the sediments. The persistency of the limestones and their uniformity of thickness also indicate a marine origin.

The angularity, poor sorting, and irregularity of the conglomerates and breccias and the cross-bedding of the sandstone suggests a deltaic environment. The massive nature of the rock, the angularity of the grains, and the freshness of the feldspars suggests rapid burial and short transportation.

Thus, it might be concluded that each cycle starts with a conglomerate or breccia and ends with a limestone. The conglomerate and breccia represent an initial deltaic environment. The depth of water gradually increased and the sediments gradually became finer with a decreasing clastic ratio until limestone was deposited. One important thing to be noted is that the limestone beds do not represent a deep-water environment, because their nodular character probably can be attributed to current or wave action. Furthermore, the presence of detrital grains in the limestones also indicates current action.

Sudden uplift seems to have followed the deposition of each of the limestones. There is a disconformity at the top of each limestone. Each is overlain by a very angular poorly-sorted arkosic conglomerate or breccia. The breccias show no bedding or other sedimentary structures and appear to have accumulated very rapidly.

The thinner unit, B, has a dense lithographic limestone at its base. The lithographic limestone rests disconformably on the last nodular limestone of the cyclic sequence of unit A. The contact with the underlying knobby limestone is exceedingly sharp and regular. The sedimentology of unit B, however, is obscure because the exposures are not readily observed. Unit B forms a slope which is largely covered by talus and vegetation.

The predominance of the lithographic limestone, siltstone, and shale indicates a very definite change of environment. They doubtless represent quieter conditions and probably deeper water which succeeded the rapidly changing environment prevalent during the deposition of unit A.

Thin sections studies of samples from unit A support the conclusions reached. For a detailed description of the thin sections see Appendix B. Replacement of quartz and feldspar grains by calcite was observed in sections cut from samples from unit A. Similar replacement of quartz by calcite was observed in samples from the Harding sandstone.

Jurassic

Morrison formation. The type section of the Morrison formation at Morrison, Colorado was described by Emmons, Cross & Eldridge (1896, p. 22, 23, 60 - 62). It had been described previously by Cross (1894). More recently, the type section has been redefined by Waldschmidt & Leroy (1944, p. 1097 - 1114).

The formation everywhere consists of continental deposits of sandstone, shale, mudstone, marl, and fresh-water limestone and is noted for many dinosaur remains. It is widespread in the western and southwestern United States and has been considered both late Jurassic and early Cretaceous in age. More recently, on the basis of paleontologic evidence, the Morrison formation has been considered as late Jurassic (Heaton, 1933, p. 112; Lee, 1927, p. 17; Vanderwilt, and others, 1948, p. 46; Waldschmidt & Leroy, 1944, p. 1100; Wilmarth, 1939, p. 1423 - 1424).

The Morrison formation was first found in the thesis area by Gilbert (1897). It is exposed on the scarp-face of the hogback on the east side of Beulah Valley and in the northwest corner of the area. C. A. Martin and the writer measured a section of the Morrison formation approximately 200 feet thick. It rests unconformably on the Fountain formation and with probable unconformity on the unnamed units, A and B, in the northwest corner of the area.

The lower part of the Morrison formation is marked by an 85-foot series of sandstone and siltstone with minor fresh-water limestone and some shale. Most of the sandstone and siltstone is cream colored and slightly arkosic. The limestone generally is nodular and lenticular and has an olive-gray color. The shale is predominantly green.

Above the series of sandstone and siltstone, the formation is less resistant and forms slopes largely covered by vegetation. The limited exposures show the upper parts to consist mainly of gray and green shale and mudstone. Some siltstone and limestone also is present.

The contact with the Dakota sandstone generally is covered. Some exposures reveal, however, that the Morrison shales are unconformably overlain by basal Dakota conglomerate.

The thickness and lithology of the Morrison formation at Beulah generally is comparable to the thickness and lithology of the Morrison formation at the type locality (Waldschmidt & Leroy, 1944, p. 1100 - 1108), but the Morrison formation at Beulah contains considerably more sandstone, particularly in the lower parts. The lithology of the Morrison formation is evidence of deposition under continental conditions. The rocks are of fluviatile and lacustrine origin.

Cretaceous

Dakota sandstone. The Dakota sandstone of late Cretaceous age was named by Meek & Hayden (1861, p. 419 - 420) for the exposures near the town of Dakota, Dakota County, Nebraska. It was first noted in the Beulah area by Gilbert (1896).

The U. S. Geological Survey restricts application of the name Dakota sandstone to the areas east of the Front Range and applies the term Dakota (?) formation to the same strata west of the Front Range (Wilmarth, 1938, p. 566).

The Dakota sandstone is widespread along the Colorado Front Range where its thickness ranges between 200 and 300 feet. It has been divided into three sandstone and two shale units (Lee, 1927, p. 17 - 23.; Rankin, 1933, p. 424; Vanderwilt, and others, 1948, p. 46 - 47; Waldschmidt, 1933, p. 417 - 420). The "first" or upper sandstone may be either a single massive bed which forms the crests of the Dakota hogbacks along the Front Range, or it may be a series of discontinuous sandstone lenses intercalated with shale. It grades upward into the overlying Graneros shale. The upper sandstone is separated from the "second" or middle sandstone by a shale unit.

The middle sandstone is found in the northern parts of the Front Range, but it seems to thin southward and grade into the sandy shale which separate it from the lower or "third" sandstone.

The lower sandstone is commonly coarse grained and conglomeratic, and of a massive character. It is more conglomeratic near the base, although pebbles are distributed irregularly throughout its thickness.

The Dakota sandstone crops out in the eastern part of the thesis area where it forms the prominent hogback on the east side of Beulah Valley (Pl. 1). Its thickness is about 240 feet. The contact with the underlying Morrison shales in unconformable and irregular, but gradational with the overlying Graneros shale. Near Beulah, the middle sandstone and intervening shales are missing from the formation. North of the area, C. A. Martin reports (personal communication) that shale is present towards the middle of the Dakota sandstone.

The lower Dakota sandstone in the thesis area is massive, cross-bedded, and conglomeratic, particularly near the base. The grain size of the frosted quartz grains in the matrix ranges from medium to coarse. The pebbles of the conglomeratic portions are as much as three centimeters in diameter. The color of the lower sandstone generally is brown.

The upper sandstone is less cross-bedded and somewhat finer grained than the lower sandstone on which it rests disconformably. It is massive and shows prominent vertical jointing. Accordingly, it has a tendency to form cliffs along the hogback on the east side of Beulah Valley. Limonite nodules and liesegang rings are common. Like the lower sandstone, the quartz grains are frosted. The color is pink to tan on fresh surfaces but brown on weathered surfaces. The upper sandstone grades into the overlying Graneros shale through an interval of interbedded sandstone and dark-gray shale. The sandstones near the gradational contact are thin-bedded and ripple-marked.

The presence of a basal conglomerate, the good sorting, the widespread occurrence, and the upward gradation into the finer neritic sediments of the Colorado group strongly suggest that the Dakota sandstone was deposited under conditions of a transgressing sea.

Colorado group. The Colorado group includes the Benton and Niobrara subgroups of late Cretaceous age (Wilmarth, 1938, p. 492). Only the lower two units of the Benton subgroup are found in the thesis area. They are the Graneros shale and the overlying Greenhorn limestone which crop out in a gentle syncline in the southeastern portion of the area (Pl. 1). The sections for the Benton subgroup were measured in the SE¼, Sec. 14, T. 22 S., R. 67 W., Pueblo County, Colorado.

Graneros shale. The Graneros shale was named and described by Gilbert (1896, p. 564) for the exposures along Graneros Creek, Pueblo County, Colorado. He was also the first to note its occurrence in the thesis area (1897).

The Graneros shale is about 200 feet thick and crops out in a narrow belt along the Front Range and in broader areas on the flanks of anticlines in Pueblo, Huerfano, and Las Animas counties (Darton, 1906, p. 27). It shows a gradational contact with the underlying Dakota sandstone and the overlying Greenhorn limestone. It is generally a black fissile shale, but the upper and lower parts are commonly gray in color. Bentonite seams and rows of limestone concretions are present in the lower parts.

The upper contact with the Greenhorn limestone was placed at the base of a 1.6-foot bed of limestone. Thus, only a few thin beds of limestone were included in the upper Graneros shale. The lower contact with the Dakota sandstone was placed at the last thick bed of sandstone, thus including some thin sandstone beds at the base of the formation.

Greenhorn limestone. The Greenhorn limestone was described by Gilbert (1896, p. 564 - 565) at the exposures along Greenhorn Creek in Pueblo County, Colorado. Its exposures in the thesis area were first found by Gilbert (1897).

The thickness of the Greenhorn limestone ranges from about 25 to 40 feet. The writer measured 35 feet of section in Sec. 14, T. 22 S., R. 67 W.. About 27 feet of the limestone is exposed in the thesis area.

The base of the Greenhorn limestone is marked by a bed of limestone about 1.6 feet thick. The basal limestone is fine grained, argillaceous and gray, but it lacks the vertical jointing displayed by the next higher limestone. Above the basal limestone are thin-bedded shaly limestone beds which measure up to one foot in thickness and are separated by intervals of calcareous black shale which attain thicknesses of 1.5 feet. The thin-bedded limestones show prominent vertical jointing which combined with the thin bedding causes them to break into plates or flags. Specimens of Inoceramus labyatus Schlotheim are very numberous along bedding planes in the platy limestones.

The upper contact of the Greenhorn limestone with the Carlile shale is gradational. It was placed at the top of highest platy limestone bed exposed at the measured section. The Carlile shale is missing in the thesis area.

The lithology and paleontology of the rocks of the Colorado group indicate that they were deposited in a shallow neritic environment. The black shales in the Graneros shale indicate that it may have been deposited in a partly lagoonal environment.

Tertiary (?)

Three diabasic basalt dikes of probable early Tertiary age have been found in the thesis area. The dikes were intruded into Precambrian rocks along joints that transect the foliation of the Precambrian rocks. One dike is nearly horizontal, the others are nearly vertical. The horizontal dike is located along Middle Creek in the NE¼, NE¼, Sec. 5, T. 23 S., R. 68 W. and the others are located in the S½, Sec. 8, T. 23 S., R. 68 W.. The latter dikes are poorly exposed and were not studied completely. The dikes are of the same composition. Essentially, the dikes are diabasic basalts which have undergone considerable alteration. They are composed of labradorite, serpentine, actinolite, calcite, and magnetite. None of the dikes can be traced more than a few hundred feet along their outcrop. A detailed description of thin sections of the nearly horizontal dike is given in Appendix B.

The injection of the basaltic magma appears to have been passive rather than forceful. The joints were a well developed feature at the time of emplacement of the dikes. Inasmuch as there is no evidence of slippage along the joints in the Precambrian rocks, it is likely that they formed after the close of the Laramide compression and during the early Tertiary relaxational phases. The joints, furthermore, are seen to persist even across shears in the Precambrian rocks.

Because the joints in which the dikes are emplaced are probably post-compressional, it is probable that the dikes are also post-compressional. Further evidence of post-compressional intrusion of the dikes is found in the absence of strain phenomena such as loss of twinning, and the presence of bent twin lamellae in the plagioclase feldspar.

Similar diabasic rocks have been described by Cross (1896, p. 282 - 283) at the Silver Cliff-Rosita district on the southwest side of the Wet Mountains. He concluded that they are older than the volcanic rocks with which the ore deposits are associated, but that they were emplaced after the Precambrian rocks had been "... brought approximately into their present position, and also that they were eroded in common with the gneiss in producing the surface upon which the later rocks were poured out (Cross, 1896, p. 274)." Lovering has assigned the extrusive rocks at Silver Cliff and Rosita a Miocene age (Finch, and others, 1933, p. 395). Thus, it might be concluded that the dikes in the Beulah area post-date the Laramide compressive forces, but probably pre-date the Miocene flows of other areas. Thus, an early Tertiary, probably late Eocene to early Miocene, age might logically be assigned to them.

Lovering (1950, p. 47) has stated that diabasic rocks were intruded during the beginning of Eocene folding in the Front Range. There is, however, no evidence to indicate that the diabasic dikes of the Beulah area were intruded early in a compressive phase. They show no signs of deformation associated with forceful emplacement.

STRUCTURAL GEOLOGY

General

The major structural features of the Colorado Front Range and the Wet Mountains were developed during the Laramide orogeny and the later Tertiary relaxational phases. The Laramide features, however, were influenced to a great degree by older trends related to the development of the Ancestral Rockies (Lovering & Goddard, 1950, p. 57 - 58).

The salient structural features in the thesis area include the Wet Mountains fault, the Beulah arch, and the Three-R trough. Minor faults are associated with these features, as are deviations in the trend of foliation in Precambrian rocks. Also present in the northwest corner of the area is the south nose of a doubly-plunging syncline which parallels the Wet Mountains fault north of the thesis area. As shown on the map (Pl. 1), the nose of the syncline is partially truncated by the Wet Mountains fault. It is in the synclinal nose that the undated sedimentary units between the Fountain and Morrison formations are exposed.

Precambrian Trends

The Precambrian rocks display a well-developed secondary foliation that trends northeasterly but dips inconsistently to the northwest and southeast. The foliation is a regional feature which is developed, to a greater or lesser degree, in all Precambrian rocks near Beulah. The trend of the foliation has been changed along faults which were active during the Laramide orogeny so that the foliation approximately parallels the fault planes. The b-tectonite of the foliation, furthermore, lies nearly perpendicular to the Laramide b-tectonic axis which trends north-northwest. Thus, it can be concluded that the foliation pre-dates the Laramide deformation. Because, in the Beulah area, the Laramide orogeny has been influenced to a great degree by trends established during Pennsylvanian deformation, the foliation probably developed before the Ancestral Rocky Mountains formed.

Three sets of joints of somewhat irregular orientation are present in the Precambrian rocks. One set is near the horizontal; the other two sets show dominant northeasterly and northwesterly trends, but with considerable local difference in attitude. The horizontal joint set, in general, is undeformed adjacent to faults and commonly persists across shears in the Precambrian rocks. Thus, it can be concluded that it post-dates the Laramide thrusting and that the horizontal joints probably are related to the Tertiary relaxational phases of the orogeny. The diverse orientation of the joint sets makes it difficult to analyze their relation to the Beulah arch, the Wet Mountains fault, and the related structures.

Faults

Wet Mountains fault. The Wet Mountains fault is the major thrust fault along the east front of the Wet Mountains. As shown on the

Geologic Map of Colorado (Burbank, and others, 1935), it extends almost the whole length of the Wet Mountains from Rye at the south tip to Parkdale in the north. First mention of the fault in the literature was made by Maher in 1953 (p. 2476, Fig. 1), although portions of the fault had been mapped by Gilbert as early as 1897 (unpaged).

Generally, the fault shows a relatively straight trace. Throughout most of its length, it is a high-angle reverse fault which is upthrown to the east. North of the thesis area, however, the fault locally is a low-angle thrust with dips on the order of 22 degrees to the west (personal communication, C. A. Martin).

In the thesis area (Pl. 1), the fault follows a northwesterly trend from the south-central portion of the area in Sec. 22, T. 23 S., R. 68 W. to Sec. 24, T. 22 S., R. 69 W.. Throughout its extent in the area, the fault appears to be high-angle, as is evidenced by its relatively straight trace and the dip of the foliation on either side. In Sec. 16, T. 23 S., R. 68 W., it dips almost 80 degrees to the west; in Sec. 24, T. 22 S., R. 69 W., it dips about 60 degrees west.

Best exposures of the fault in the thesis area are in Sec. 16, T. 23 S., R. 68 W. and in Sec. 24, T. 22 S., R. 69 W.. In Section 16, the fault is in Precambrian rocks and appears as a shear zone which is mineralized with hematite and lesser amounts of copper. It is exposed especially well in a road cut in the south-central half of the section. In Section 24, the fault is between the Precambrian Pikes Peak granite and the Pennsylvanian Fountain formation. On the west side of the fault, the Precambrian rocks are intensely sheared with the foliation dipping about 60 degrees to the west. On the east side of the fault, the beds of the Fountain formation have been upturned so that they are vertical.

Between the two exposures described above, the fault is difficult to trace, but a series of mineralized shears are found at the base of a discontinuous scarp in the Precambrian rocks. The shears are found on the crests of a series of subparallel ridges which extend westward from Beulah Valley into the Precambrian mountains where a sharp break in slope marks the discontinuous resequent fault-line scarp. Generally, the shears are not exposed in the east-west stream valleys except along Middle Creek.

South of the thesis area, the resequent fault-line scarp of the Wet Mountains fault is easily observed and can be traced for many miles.

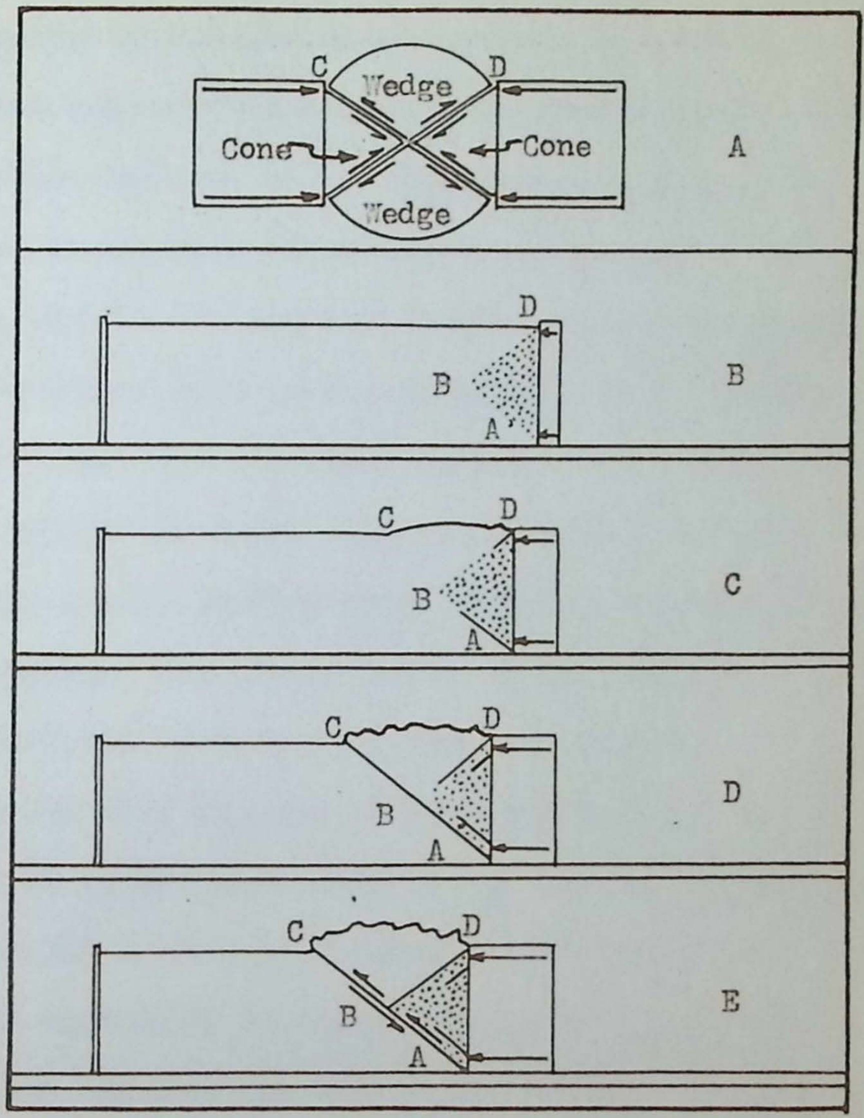
On the Geologic Map of Colorado (Burbank, and others, 1935), the Wet Mountains fault is shown to arc around the nose of Precambrian rock which forms the basement of the Beulah arch. Thus, a fault contact is depicted between the Fountain formation and the Precambrian rocks on the west side of Beulah Valley. Insufficient evidence for faulting was found along most of the Precambrian-Fountain contact, and in many places, clear-cut evidence of overlap of the Precambrian by younger rocks was observed. Therefore, it is likely that the Wet Mountains fault follows the straighter trend of the shears in the Precambrian mountains than the circuitous route along the west side of Beulah Valley.

The age of movements along the Wet Mountains fault is uncertain. Faulting has thrust Precambrian rocks against upper Cretaceous rocks to the north of the thesis area and produced drag in the Cretaceous rocks south of the area. It is likely, therefore, that major movements along the fault occurred during Laramide times, and because the major thrust faulting along the Front Range occurred at the end of the Paleocene (Lovering & Goddard, 1950, p. 58), it can be concluded that the major movements along the Wet Mountains fault probably took place at that time. Older movements along the fault also are indicated. Noticeable erosional thinning of the pre-Pennsylvanian rocks occurs on the east side of the fault and the Pennsylvanian Fountain formation rests on the older rocks with an angular unconformity which commonly approaches 20 degrees. The Fountain formation also overlaps directly on the Precambrian rocks just east of the fault. Such relationships are best shown in the south-central and northwest parts of the area. They indicate that the fault was active during the building of the Ancestral Rockies. The absence of any Paleozoic sediments on the west side of the fault might offer further support for the thesis of Pennsylvanian movements. It must be remembered, however, that post-Laramide erosion could have removed any sediments once deposited on the west side of the fault.

High-angle reverse faults. In addition to the Wet Mountains fault, three other high-angle reverse faults have been mapped in the area. All three of the faults are genetically related to the formation of Beulah arch and are within the limits of that structure (Pl. 1). One fault is along the east border of the Precambrian basement exposed in the arch. It dips approximately 50 degrees west and has thrust Precambrian rocks above the base of the Fountain formation. The fault is a thrust developed in the nose of the flexure which is Beulah arch.

The other two high-angle reverse faults are complementary to the thrust in the nose of Beulah arch. They dip eastward toward the nose and the northeast flank of the arch with their hanging walls the upthrown sides. One extends northwestward from the NW¼, NW¼, Sec. 3, T. 23 S., R. 68 W. where it merges with the thrust in the nose of the arch to the NE¼, SE¼, Sec. 30, T. 22 S., R. 68 W. where it could be traced no farther. It dips approximately 60 degrees to the northeast. The other fault, which trends almost north-south, is found west of Beulah along the section line between Sections 4 and 5, T. 23 S. and Sections 32 and 33, T. 22 S., R. 68 W.. It dips to the east at an angle of 66 degrees. Both faults, because movement along them was opposed to the direction of regional thrusting, are considered underthrusts.

Link (1928, p. 825 - 854) has developed similar faults in connection with pressure-box studies of the relationships between over- and underthrusting (Fig. 3). In the experiments, one side of the pressure-box was pushed against an artificial sequence of sediments. As the pressure was applied, a compacted wedge (zone of shear) of sediment developed adjacent to the push-block. With continued application of pressure, bulging of the material occurred at the surface adjacent to the push-block. At the surface of the sediments an underthrust plane also developed next to the push-block, and incipient planes of overthrusting formed at depth adjacent to the push-block. Finally, the plane of the overthrust broke the surface and the plane of the underthrust terminated against the overthrust, thus leaving the bulged sediments as a wedge between the two thrust planes.



From Link (1928)

FIG. 3. Results of pressure-box studies by Link: A) "Cross section of deformed sphere illustrating use of terms cone of shear and wedge." B) "Soon after application of pressure the first noticeable change is compacting of the material in front of the push-block in the area of the cone ABD." C) "Incipient bulging at the surface between D and C, slight wrinkling near D, incipient faulting in lower portion of cone and also in upper part near D. Continued compacting of the wedge area BDC." D) "Extension of the overthrust shear plane ABC to the surface and underthrust plane toward B. Continued deformation of the wedge and cone." E) "Growth of underthrust fault until reaching B, uplift of wedge DBC causing displacements along over- and underthrust fault planes as indicated by arrows."

In the case in question, the upthrown side of the Wet Mountains fault corresponds to the push-block and the thrust fault on the nose of the Precambrian core of Beulah arch corresponds to the overthrust plane (Pl. 2, Sections A-A' and C-C'). The two underthrust faults correspond, therefore, to the plane of underthrusting developed in the experiments. In actuality, the form of the arch itself could be attributed to the bulging of the rocks prior to the development of the faults. It also should be mentioned that the considerations outlined above conform to the requirements of the strain ellipsoid theory in which two opposed planes of shear should develop under conditions of compression.

Normal faults. Two normal faults of small displacement (not exceeding 60 feet) and southward dip have been mapped in the area. One is located in the SE¼, SE¼, Sec. 8 and the NW¼, SW¼, Sec. 9, T. 23 S., R. 68 W.. It is on the south flank of the Beulah arch and trends northeast from its termination against the Wet Mountains fault to the point where it appears to terminate in Section 9. The fault probably developed on the blank of the arch where tensional forces would develop normal to the direction of thrusting during the flexing of the arch. It is entirely within the Precambrian rocks and has produced only slight displacement of the Paleozoic sediments on either side.

The other normal fault trends northwest-southeast in S½, Sec. 13, T. 23 S., R. 68 W.. It is located on the east flank of the northeast trending portion of the syncline which is the northern end of the Three-R trough. Like the fault on the south flank of the Beulah arch, it probably is related to uplift along the arch.

Beulah Arch

The Beulah arch was named by Gilbert (1897). It is the prominent structural feature in the approximate center of the area and is an eastward plunging anticlinal nose which abuts against the Wet Mountains fault to the west (Pl. 1). The core of the arch is a Precambrian basement complex which is overlain by Paleozoic rocks. The Fountain formation, which wraps around the nose of the arch, has been eroded to form Beulah Valley. Next above the Fountain formation are the rocks of the Morrison formation and the Dakota sandstone which also wrap around the arch and have been eroded to form the prominent hogbacks on the east side of Beulah Valley. Doubtless, the Fountain, Morrison, and Dakota formations originally extended over the arch, but since have been removed by erosion. Only remnants of the Fountain formation are found in the core of the arch.

The Dakota sandstone dips off the flanks of the arch at angles between 15 and 25 degrees. At the water gap cut through the Dakota hogback by the north branch of the St. Charles River, the plunge of the arch is about 18 degrees to the east.

A partial explanation of the origin of Beulah arch already has been given in the preceding section on faults. It is thought that the arch is the direct result of bulging of the rocks during Laramide time as movement took place along the Wet Mountains fault and pressure was applied to the rocks east of the fault by the mass west of the fault which served as a push-block. The b-tectonic axis of the arch, therefore, has a north-south trend and runs at right angles to the axial trace of the flexure shown on the map (Pl. 1). The arch is actually a salient developed on the east side of the Wet Mountains fault.

Inasmuch as a section of upper Pennsylvanian, upper Jurassic, and upper Cretaceous rocks probably was present prior to the formation of the arch, more than 3,000 feet of overburden would have covered the Precambrian basement now exposed in the core of the arch. Thus, the arch probably developed under conditions whereby a considerable component of horizontal thrust could have been transmitted across the Wet Mountains fault. The horizontal thrust thus produced probably is responsible for the development of the Beulah arch and the associated high-angle faults in accordance with the experiments performed by Link (1928, p. 825 - 854). The arch is analagous to the bulge which developed in his experiments prior to and during the formation of the thrusts.

Three-R Trough

The Three-R trough was named by Gilbert (1897). It is a doubly-plunging synclinal structure which passes through the Three-R Ranch. The best developed portions of the trough are south of the thesis area, but its southwestward plunging nose is present in the southeast corner of the area (Pl. 1 and Pl. 2, Section B-B'). Cretaceous rocks crop out in the syncline. The syncline probably is the result of compression and drag along the Wet Mountains fault, but in the thesis area, its trend and form have been influenced by the development of the salient Beulah arch. The trough is located on the southwest flank of the arch and trends northwestward rather than parallel to the Wet Mountains fault.

PETROGRAPHY AND PETROLOGY

Precambrian Rocks

General. The Precambrian rocks, which crop out in the west half of the thesis area, include igneous, meta-igneous, and metasedimentary types. For mapping purposes, the writer has divided them into five units: the Idaho Springs formation, an adamellite gneiss, undifferentiated Precambrian meta-igneous rocks, pegmatite dikes, and the Pikes Peak granite. Although not all the rock types found in the Precambrian have been mapped independently, they are discussed in the following pages. Descriptions of representative thin sections are provided in Appendix B.

Idaho Springs formation. The Idaho Springs formation crops out in a north-south trending belt just west of Beulah Valley. It includes the oldest rocks known in Colorado and is a sequence of pelitic metasediments which has been injected by granitic and pegmatitic rocks. The pelitic sediments have been metamorphosed primarily to dark gray, quartz-biotite schists. Also present within the limits of the Idaho Springs formation is an area of andesine amphibolite which is probably meta-igneous in origin. The rocks of the Idaho Springs formation show well developed bedding plane foliation along which the lit-par-lit injections of igneous material have been introduced.

Schists. Microscopically, the schists are composed of quartz, microcline, plagioclase, and biotite. Minor constituents include hornblende, magnetite, sphene, epidote, apatite, sillimanite, and zircon. The texture of the schists is xenoblastic-inequigranular. Foliation is well developed.

Cataclastic structures are seen in most thin sections of schist from the Idaho Springs formation. Anhedral to subhedral porphyroblasts of quartz and feldspar are surrounded by smaller grains of the same minerals. Poikiloblastic structures are common in the feldspars and hornblende. The poikiloblastic or sieve textures are produced by rounded inclusions of quartz in the feldspars and of quartz and feldspar in the hornblende. The inclusions lend the host grains a "perforated" or sieved appearance.

Biotite forms anhedral to subhedral books with shredded ends. Inclusions of zircon are surrounded by pleochroic halos. The biotite is interstitial to the other minerals of the schist. Microcline and sodic oligoclase are the important feldspars. Together with the quartz, they form a granular mosaic in which the biotite and other minerals are dispersed. Much of the plagioclase displays myrmekitic intergrowths with quartz. The intergrowths probably result from the replacement of microcline by plagioclase and accompanying exsolution of silica.

The hornblende forms subhedral crystals which display shredded ends and hold rounded inclusions of quartz and feldspar. Epidote is present as euhedral to anhedral grains that are interstitial to and included in the other minerals, notably hornblende and biotite. The sphene is anhedral; magnetite forms irregular and subhedral grains that are closely associated with the biotite. Traces of sillimanite are present in much of the schist, but it is best developed and most abundant near the igneous injections. Traces of calcite are present as small, irregular replacements in the quartz and feldspars.

Andesine amphibolite. Within the mapped limits of the Idaho Springs formation one small area of andesine amphibolite was mapped in the SW¼, SW¼, Sec. 28 and SE¼, SE¼, Sec. 29, T. 22 S., R. 68 W., Pueblo County, Colorado. The amphibolite consits of alternating layers of a dark green amphibole with minor amounts of feldspars and layers composed almost completely of feldspar. The alternate light and dark alyers of feldspar and amphibole are one millimeter or less in thickness. The boundaries of the amphibolite are conformable with the surrounding schist.

In thin section, the rock shows a gneissic fabric and a xenoblastic-inequigranular texture. It is composed primarily of andesine and dark amphibole. The andesine forms anhedral to subhedral grains of unequal size. The amphibole is strongly pleochroic with X = light greenish-yellow, Y = green, and Z = dark green. The optic sign is negative. $2V = 7.9 \pm 0.1°$; $Z \wedge c = 33 \pm 1°$. The birefringence is low with the highest interference colors in the upper first order, but they are commonly masked by the dark color of the mineral. Available information, although it is somewhat contradictory, indicates that the mineral may be related to pargasite, a magnesium-rich, dark-colored variety of hornblende with large extinction angles.

In addition to the amphibole and andesine, the rock is composed of lesser amounts of microcline, quartz, and sphene, with traces of apatite. The composition of the amphibolite indicates that it is meta-igneous rather than metasedimentary in origin since it lacks the typical assemblage of minerals found in metasedimentary amphibolites. It may have been derived from a diorite or an andesite. The andesine amphibolite actually may be the rock unit termed the Swandyke hornblende gneiss which is found in most areas along the Front Range. The Swandyke hornblende gneiss shows the same degree of metamorphism as the Idaho Springs formation and is thought to be a metamorphosed quartz diorite or dacite (Lovering & Goddard, 1950, p. 20).

Igneous injections. Igneous material was injected into the Idaho Springs formation along bedding schistosity. The thickness of the injected material ranges from a fraction of an inch to about 20 feet. The rock types studied in thin section include granite, chlorite adamellite, and pegmatitic adamellite.

The granitic injections are composed of quartz and microcline with lesser amounts of biotite, plagioclase, and orthoclase. Accessory minerals include apatite, zircon, calcite, and epidote. The texture is xenoblastic-inequigranular.

Sillimanite is present in the granite injections. It indicates that either the granite has been metamorphosed somewhat or that it has reacted with the pelitic metasediments into which it has been injected. Contacts with the schist are gradational. Furthermore, the schist adjacent to the granite injections is richer in microcline than that more distant from the granite.

The relations between the chlorite adamellite injections and the schist were not studied microscopically, but the contacts between them were found to be relatively sharp in the field. The chlorite adamellite is discussed in some detail in the section on undifferentiated Precambrian rocks.

The pegmatitic adamellite injections are most common. They are composed of quartz, oligoclase, and microcline with lesser amounts of magnetite. Microscopically, the texture is hypallotriomorphic-inequigranular and coarse-grained. A well developed zonation is found in the pegmatites. The quartz forms a core which is bordered by the feldspars and lesser amounts of quartz.

The contacts with the schist are very sharp. There is much granulation of the schist adjacent to adamellite pegmatite injections. Biotite in the schist is altered to penninite and magnetite. Alteration products derived from the feldspars include sericite and clay minerals.

The rocks of the Idaho Springs formation generally fall into the amphibolite facies and represent a moderate grade of regional metamorphism. The metasediments belong to the cordierite-anthophyllite subfacies, but K_2O is present in amounts too great to have permitted the formation of andalusite, cordierite, almandine, or anthophyllite in the schists. Instead, the assemblage is one of biotite-hornblende-plagioclase-microcline-quartz (Turner & Verhoogen, 1951, p. 446 - 451). Only adjacent to the igneous injections has the grade of metamorphism progressed to the stage where minor amounts of sillimanite have formed. The schists have been derived from impure shaly sediments.

The andesine amphibolite exhibits the same grade of metamorphism as the schists, but it is thought to be derived from the metamorphism of a dioritic igneous rock.

The igneous injections not only had a role in locally increasing the grade of metamorphism, but also, they have had retrograde affects.

Adjacent to the adamellite pegmatite injections where the schist has been granulated, the biotite has been altered to chlorite and magnetite. Seemingly, the pegmatitic injections took place after regional metamorphism had been largely accomplished. The injection of granite probably contributed to metamorphism of the schist. Certainly, the granite injections produced no retrograde affects. The schist adjacent to the granitic injections is richer in potash feldspar. It is likely that the surplus microcline was added to the schist and that it was derived from the granite. The addition, however, is a local feature; it was not widespread enough to warrant use of the term granitization. The absence of replacement textures in schist adjacent to granite injections may be due in part to later recrystallization.

It is probable that the original sediments have been subjected to several stages of metamorphism which are related to the different generations of igneous intrusions. The writer, however, has been unable to define any different stages of metamorphism.

Adamellite gneiss. The adamellite gneiss has been intruded into the Idaho Springs formation. It crops out in the W½, Sec. 16, T. 23 S., R. 68 W. and in the S½, Sec. 29 and the N½, Sec. 32, T. 22 S., R. 68 W.. The contacts between the adamellite gneiss and the Idaho Springs formation are very sharp, but the regional trend of the foliation persists across the contacts. At both exposures, the adamellite gneiss bodies are faulted against other Precambrian rocks by the Wet Mountains fault.

The rock is pink and medium-grained. Fresh samples show a gneissic segregation of light and dark minerals. Microscopically, the rock is composed of quartz, microcline, and sodic oligoclase with lesser amounts of biotite. Accessory minerals include magnetite, apatite, and zircon. The texture is xenoblastic-inequigranular. Poikiloblastic and cataclastic structures are common in the quartz and feldspars. Myrmekitic intergrowths of quartz and plagioclase are abundant. These are interpreted as the result of replacement of microcline by plagioclase and accompanying exsolution of silica. Much of the quartz in the rock is segregated into stringers, but grains may appear as inclusions in other minerals or present lobate outlines against them.

The adamellite gneiss is younger than the Idaho Springs formation which it intrudes. Age relationships with the Pikes Peak granite could not be determined. Indications are, however, that it is older than the Pikes Peak granite, one of the youngest Precambrian intrusive rocks (Lovering & Goddard, 1950, p. 28). Evidence for this conclusion is the well developed gneissic fabric and metamorphic texture in the adamellite. The Pikes Peak granite near Beulah is only faintly gneissic. It is recognized, however, that the gneissic texture of the adamellite might be primary and have no bearing on its age. The grade of metamorphism may be indicative of a younger or older age for the adamellite gneiss compared to the Pikes Peak granite. If metamorphosed to the same degree as the Idaho Springs formation, however, a rock of quartz monzonitic composition may be effectively reconstituted and need not contain any minerals particularly different from those in an unmetamorphosed rock (Harker, 1939, p. 313 - 314).

Undifferentiated Precambrian rocks. The rocks here classified as "undifferentiated Precambrian" include those rocks which were not mapped as independent units. The rock types are lithologically similar and are present in such small bodies that they could not be mapped satisfactorily. They crop out in a north-south trending belt between the areas of Pikes Peak granite and Idaho Springs schist in the western half of the thesis area. One other area of undifferentiated Precambrian rocks is found in Sec. 33, T. 22 S., R. 68 W..

The undifferentiated Precambrian rocks include a gneissic granite, a gneissic-aplitic granite, a gneissic chlorite adamellite, and the adamellite gneiss. The age relationship of these rocks could not be determined, but all are probably younger than the Idaho Springs formation. Structural and petrologic relationships also are unknown.

Both the adamellite gneiss and the gneissic chlorite adamellite have been found within the limits of the Idaho Springs formation. The adamellite gneiss was mapped as two intrusive bodies which have been discussed on pages 52 and 53. The gneissic chlorite adamellite has been found injected into the schists of the Idaho Springs formation. Both of these rocks are definitely younger than the Idaho Springs formation.

Gneissic granite. Megascopically, the rock is a medium- to coarse-grained gneissic granite which shows moderate parallelism of biotite books and the long dimensions of quartz and feldspar grains. Pink feldspar phenocrysts stand out from the medium-grained matrix which contains feldspar, quartz, and biotite. The color of the rock ranges from pink to gray.

Microscopically, the rock is hypallotriomorphic-inequigranular, gneissic, and shows porphyritic development of subhedral feldspar. The essential constituents of the rock are microcline, quartz, sodic oligoclase, and biotite. Accessory minerals include magnetite, epidote, sphene, zircon, apatite, and sillimanite.

Microcline forms subhedral to anhedral grains and phenocrysts. Quartz occurs as anhedral stringers and grains dispersed through the rock, as myrmekitic intergrowths in plagioclase, and as poikilitic inclusions in grains of microcline. It is somewhat rutilated, but otherwise free of inclusions. Plagioclase (sodic oligoclase) forms subhedral to anhedral grains and phenocrysts. Some of the plagioclase seemingly formed at the expense of microcline: there are myrmekitic intergrowths of quartz in plagioclase grains which are in contact with grains of microcline. Biotite is a minor constituent in the rock. It forms anhedral books which are largely interstitial to the other minerals. The sillimanite is apparently derived from the plagioclase while sericite is a metamorphic product in the microcline.

The presence of sillimanite probably indicates that the rock once achieved a grade of metamorphism comparable to the schists of the Idaho Springs formation where they have been injected by granite. The presence of sericite may be the result of retrograde metamorphism of the microcline.

Gneissic aplitic granite. The gneissic aplitic granite is a fine-grained sacharoidal rock with a pink to gray color. It is composed of clear quartz, pink and gray feldspar, and minor biotite and magnetite. Microscopically, it displays a fine-grained, allotriomorphic-inequigranular texture and a distinct gneissic fabric produced by the parallel alignment of the long dimensions of the constituent minerals, none of which shows any strong porphyritic tendencies.

Quartz and microcline are the dominant minerals in the rock. Biotite and plagioclase are present in minor amounts. The accessory minerals include sericite, zircon, and sphene. All the minerals, excepting the accessories, are anhedral. The plagioclase is sodic oligoclase.

Gneissic chlorite adamellite. The rock is found in the belt of undifferentiated rocks as well as in injections in the Idaho Springs formation where, in the exposure on Middle Creek, it has been intruded by a Tertiary (?) diabase dike. It is a dense, medium-grained, inequigranular adamellite with a distinct gneissic structure. The color is salmon-pink with streaks of gray. Megascopically, quartz and feldspar are seen to be the dominant constituents of the rock. The feldspar is largely plagioclase which is difficult to distinguish from the less important microcline. The dark minerals include a dark-colored chlorite that is almost indistinguishable from biotite. Magnetite and pyrite also are present. Minor amounts of white clinochlore which closely resembles sericite and small amounts of epidote can be observed in hand samples of the rock.

Microscopically, the adamellite is xenoblastic-inequigranular with slight porphyritic developments of plagioclase. It has a distinct gneissic structure, and in places, cataclastic structures are found between grains. The essential constituents include quartz, microcline, and plagioclase. The accessory minerals include chlorite, magnetite, pyrite, epidote, sphene, zircon, and apatite. The quartz is intersertal to the other minerals and forms anhedral grains. The microcline is generally anhedral. It displays no strong porphyritic tendencies. The plagioclase (sodic oligoclase) forms small anhedral grains and less commonly subhedral phenocrysts. It contains inclusions of chlorite, apatite, zircon, and magnetite. Chlorite occurs in irregular subparallel stringers that are much intergrown with the other minerals. Two types of chlorite are present. The most abundant chlorite mineral is penninite; the other is clinochlore, which is present only in minor amounts and is intergrown with the penninite.

The epidote and sphene are closely associated. They form anhedral blebs and stringers which are dispersed through the rock. The magnetite and pyrite form anhedral grains. Zircon and apatite are present in trace proportions and form small euhedral grains included in the other minerals.

The extreme xenoblastic-inequigranular texture of the rock may be due in part to recrystallization under metamorphic conditions. The loss of twinning, bent twin lamellae, and undulose extinction displayed by the constituent minerals suggest considerable strain. Metamorphism may account for the abundance of chlorite, epidote, and sphene, and the exclusion of biotite. These minerals suggest a low grade of metamorphism. The rock, however, is anomalous in that it does not contain other constituents indicative of an intermediate rock which has been subjected to low-grade metamorphism.

Adamellite gneiss. The bodies of adamellite gneiss which have been intruded into the Idaho Springs formation have been considered in the preceding section. The reader is referred to that discussion for a description of the rock. The adamellite gneiss was found in the belt of undifferentiated rocks, but it was not mapped as an independent unit in that belt. It displays essentially the same characteristics as the rock previously discussed on pages 52 and 53.

Pegmatite dikes. Three pegmatite dikes were mapped in the vicinity of Beulah. The two dikes in NW¼, SW¼, Sec. 8, T. 23 S., R. 68 W. and in SE¼, SE¼, Sec. 33, T. 22 S., R. 68 W. are intruded into undifferentiated Precambrian rocks, but they have been eroded and weathered to such a degree that only residual pegmatitic quartz and coarse-grained feldspars provide the indications of their presence.

The third dike is exposed along Middle Creek in the NE¼, NW¼, Sec. 5, T. 23 S., R. 68 W. where it has been intruded into the Idaho Springs formation. Field studies show that it is oriented transversely to the bedding plane foliation of the schists of the Idaho Springs formation. It strikes northeastward and dips southeast. The dike is approximately two feet thick and it is more than 50 feet in length. The contact with the country rock is sharp and the adjoining schists have been granulated along the contact. The outer parts of the dike are composed primarily of anhedral oligoclase and microcline which border a core of pegmatitic quartz. In addition to the feldspar and quartz, the dike contains minor amounts of magnetite. The simplicity of its composition, texture, and zonation indicate that the pegmatite is related closely to the pegmatitic adamellite injections found in the Idaho Springs formation.

__Pikes Peak granite.__ The Pikes Peak granite is widespread along the Front Range where it forms intrusives of batholithic dimensions (Lovering & Goddard, 1950, p. 28). It is one of the youngest Precambrian intrusives in the Front Range. It crops out along the west margin of the thesis area. Contacts with the other Precambrian rocks are sharp, but the trend of regional foliation persists across the contacts. Within the area, the rock is relatively uniform. It is a coarse-grained porphyritic granite with a faint gneissic structure. The color is pink to brown. The predominant minerals are quartz and pink feldspar with lesser amounts of biotite. The feldspars form large phenocrysts which appear euhedral because of well developed cleavages.

Microscopically, the rock shows a hypidiomorphic-inequigranular texture with prominent feldspar phenocrysts and cataclastic structures. The faint gneissic structure is not readily seen in the small area of a thin section. The quartz is anhedral and somewhat rutilated. Its form is determined by the shapes of the other minerals and seemingly it was the last mineral to crystallize in the rock. The dominant feldspar is microcline. The microcline is commonly subhedral, somewhat perthitic, and forms large phenocrysts. The plagioclase occurs in large subhedral phenocrysts which display irregular borders against the quartz and microcline. The biotite forms subhedral books with feathered ends. The books of biotite are clustered about the phenocrysts of feldspar.

Tertiary (?) Rocks

Diabasic basalt. The age of the diabasic basalt has been discussed in the section on stratigraphy where a late Eocene or early Miocene age as postulated.

The rock is fine-grained and greenish-black in color. Plagioclase laths are the only recognizable mineral grains. The basalt was found at three localities: one is in the NE¼, NE¼, Sec. 5, T. 23 S., R. 68 W.; two are in the S½, Sec. 8 of the same township and range. It forms dikes that were intruded into Precambrian rocks along joints. The exposures in Section 8 are highly weathered, generally covered, and could not be studied satisfactorily.

At the exposure in Section 5, the dike crops out on the north side of Middle Creek in a nearly vertical wall. It is approximately 12 feet thick and has intruded the gneissic chlorite adamellite along a nearly horizontal joint which dips about 10 degrees east-south-east. The major constituent of the rock is plagioclase, which has been partly altered to clay minerals. It shows both albite and Carlsbad twinning. Extinction angles indicate that it is labradorite and that it is at least as calcic as Ab40 An60. The plagioclase boundaries are commonly transected by skeletal magnetite and fibrous actinolite.

Two generations of magnetite are present in the rock. One is primary and forms skeletal crystals. The other is secondary and has formed through the alteration of the dark constituents of the rock. It forms anhedral blebs dispersed between the plagioclase laths. Other alteration products in the rock include actinolite, serpentine, calcite, clay minerals, and limonite.

Indications are that the alteration products have been derived largely from a pyroxene, probably augite, and from minor amounts of olivine. The former presence of a pyroxene is indicated by the absence of chlorite from the rock. Chlorite is the normal alteration product of most amphiboles. The alteration products present are those normally derived from a pyroxene and the abundance of calcite indicates that it was relatively high in calcium, i.e., augite.

The former presence of olivine is inferred from the habit of some of the calcite. It forms masses which have continuous optic orientation within a given mass. The masses are transected by irregular cracks similar to those developed in olivine. Furthermore, the pseudomorphs have preserved no traces of cleavage that might be expected if they were pseudomorphs after a pyroxene.

The chilled margins of the dike show a diabasic arrangement of lath-like plagioclase microlites and dark colored intersertal material. The plagioclase microlites show both Carlsbad and albite twinning. Their composition is about Ab40 An60. The laths are both randomly oriented and arranged in radial clusters. The intersertal material could not be identified. Part of it is feathery, green in color, and shows slight birefringence. The remainder of the material consists of well-developed longulites which are opaque in transmitted light and black under reflected light. They cross one another and produce a distinct telegraph pole pattern. They probably represent early stages of crystallization of the skeletal magnetite which is found towards the center of the dike. Minor amounts of calcite are discernable in parts of the chilled margins.

The intrusion of the dike has produced only slight granulation of the gneissic chlorite adamellite. Adjacent to the dike, the adamellite is highly altered, but the affects have penetrated the adamellite no more than two inches. Clinochlore is a common alteration product derived from the felspar in those portions of the rock adjacent to the dike. Clay alteration products also are abundant. Ferrite (presumed ferruginous red-brown amorphous alteration products) and irregular blebs of limonite are readily seen in the granulated quartz. The slight granulation of the country rock indicates that emplacement of the dike probably was passive. Furthermore, the intruded materials show no impressed orientation produced by flow. The basaltic magma probably welled in between the joint surfaces and cooled in place.

HISTORICAL GEOLOGY

Precambrian

If the Precambrian rocks in the Front Range could be studied in detail, "... a Precambrian tectonic history involving at least one and probably several tectonic cycles ... could be reconstructed and interpreted (McCoy, 1953, p. 1376)." Impure pelitic sediments of the Idaho Springs formation were deposited to great but undetermined thickness in the Beulah area. Dioritic flows or sills were emplaced in the Idaho Springs formation during or sometime after the deposition of the sediments. The sediments and the enclosed dioritic rocks were metamorphosed regionally and intruded by igneous rocks during later Precambrian time.

The sediments were transformed to quartz-biotite and quartz-biotite-sillimanite schists and were injected by granitoid igneous rocks. The dioritic rocks were metamorphosed to andesine amphibolite.

Two stages of igneous intrusion are represented by the Pikes Peak granite and an older adamellite gneiss. The other igneous rocks which have been classed as undifferentiated Precambrian may represent other independent stages of igneous activity.

The close of Precambrian time, as is evidenced by the unconformity between the crystalline rocks and the Paleozoic sediments, was marked by extensive erosion and uplift.

Paleozoic

Pre-Pennsylvanian. During the Paleozoic era, the Front Range proper and the Wet Mountains were positive elements (Maher, 1953, p. 2477). A trough separated the Colorado Front Range from the Wet Mountains. The trough, which included the Canon City embayment, received great thicknesses of pre-Pennsylvanian sediments (Maher, 1953, p. 2479; McCoy, 1953, p. 1876 - 1883).

The seas probably did not encroach on the Wet Mountains positive element as far south as the thesis area until Ordovician time when the late Mohawkian Harding sandstone was deposited (Maher, 1953, p. 2480; McCoy, 1953, p. 1876). After a period of erosion, a second transgression of Ordovician seas occurred and the Richmondian Fremont limestone was deposited.

If the Williams Canyon limestone is of Mississippian age (See Stratigraphy and Sedimentation.), the Devonian period probably was a time of nondeposition all along the Front Range: there are no Devonian rocks along the Front Range or in the subsurface of eastern Colorado (Maher, 1953, p. 2481; McCoy, 1953, p. 1881). In the Beulah area, pre-Williams Canyon uplift and erosion have left only thin lenticular remnants of Fremont limestone.

The advance of early Mississippian (?) seas was accompanied by the deposition of the Kinderhookian (?) Williams Canyon limestone. After a short period of erosion, the Kinderhookian (?) Madison limestone was also deposited.

With the deposition of each younger unit, the pre-Pennsylvanian seas probably encroached a little further on the Wet Mountains positive element.

Pennsylvanian and Permian. With the close of the Mississippian period, a great change in conditions took place. Early Pennsylvanian and probably late Mississippian time was a period of pronounced uplift that resulted in the building of the Ancestral Rocky Mountains (Lovering & Johnson, 1933, p. 371; Ver Wiebe, 1930, p. 781 - 782). The Colorado Front Range, including the Wet Mountains, was an important positive feature resulting from early Pennsylvanian deformation (Heaton, 1933, p. 133; Ver Wiebe, 1930, p. 769, 772). At this time, the Wet Mountains fault (See Structural Geology.) may have originated or been accentuated (Maher, 1953, p. 2486). Early Pennsylvanian and late Mississippian erosion probably is responsible for the pinching out of pre-Fountain sedimentary rocks in Sec. 16,

T. 23 S., R. 68 W. (Pl. 1).

The first sediments deposited in the Beulah area, as well as elsewhere along the Front Range, were the coarse, continental and near-shore rocks of the Fountain formation which has been dated as Desmoinesian at the base and Virgilian at the top (Vanderwilt, and others, 1948, p. 38; Maher, 1953, p. 2484 - 2485).

In most regions along the Front Range, there was almost continuous sedimentation along the flanks of the highlands during Pennsylvanian and Permian time (McCoy, 1953, p. 1885). Deposition of the Fountain formation was followed by the Permian Lyons sandstone and the lower portion of the Lykins formation as the seas gradually encroached on the land. At the close of Permian times a gradual recession began.

No positive record of Permian sedimentation, however, has been found in the Beulah area. The only rocks between the Pennsylvanian Fountain formation and the upper Jurassic Morrison formation are the rocks designated as units A and B (See Stratigraphy and Sedimentation.). Their age has not been satisfactorily determined.

Permian orogenic movements have been recognized in the Ancestral Rockies (McCoy, 1953, p. 1887) and it seems likely that the absence of recognizable Permian rocks in the thesis area can be attributed to these movements. Furthermore, if units A and B are of Permian age, their coarse angular conglomeratic nature indicates orogenic movements of Permian age in the Beulah area of the Wet Mountains.

Mesozoic

The oldest proven Mesozoic rocks in the thesis area are those of the upper Jurassic Morrison formation. Units A and B could be Triassic, Jurassic, or Permian in age. They indicate crustal disturbances during deposition whereas the absence of other sediments between the Morrison and Fountain formations indicates that the region was positive for much of the time between the close of Pennsylvanian and late Jurassic time.

Triassic. There is no positive record of Triassic sedimentation in the thesis area. In contrast, most other districts of the Front Range show record of rather extensive Triassic subaerial and marine sedimentation (Heaton, 1933, p. 150 - 154).

Jurassic. After the close of the Triassic, there was no further marine sedimentation along the Front Range until Cretaceous time (McCoy, 1953, p. 1288; Reeside, 1931, p. 1095 - 1103). Only continental sediments accumulated during Jurassic time. Of these, only the upper Jurassic Morrison formation has been recognized positively in the Beulah area.

The Morrison formation is widespread throughout the Front Range and other parts of the Rocky Mountain region. It is thought to comprise fluviatile and lacustrine sediments which were deposited on broad, sweeping flood plains. If this is the case, the Front Range was a positive element during the Jurassic period. However, relief must have diminished during late Jurassic time inasmuch as rocks of the Morrison formation exhibit a decrease in grain size towards the top of the formation.

Cretaceous. At the beginning of Cretaceous time, marine invasion of the Colorado Front Range took place once again. The earliest Cretaceous deposits, however, comprise both marine and continental sediments. None of these are present in the thesis area. Either they have been removed by erosion or they never were deposited (McCoy, 1953, p. 1886 - 1889). The oldest Cretaceous sediments in the thesis area are of late Cretaceous age and include marine Dakota sandstone, Graneros shale, and Greenhorn limestone. The unconformity at the base of the Dakota sandstone is evidence of crustal movements prior to the deposition of the late Cretaceous sediments.

Still younger Cretaceous sediments doubtless were deposited in the Beulah area because great thicknesses of them are to be found near the eastern border of the area. They probably have been removed by subsequent erosion.

Laramide Orogeny

During latest Cretaceous and early Tertiary time, the entire Rocky Mountain system was affected by orogenic folding and faulting followed by extensive uplift. These pulsations are referred to as the Laramide orogeny (Eardly, 1950, p. 284).

Extensive thrust faulting and monoclinal folding occurred on the eastern side of the Front Range as a result of rapid uplift and intense compression (Lovering, 1931, p. 94). The effects of these movements are to be seen in the thesis area. The Laramide orogeny was accompanied by both intrusive and extrusive igneous activity. Evidence of igneous activity is lacking in the thesis area except for minor diabasic intrusives which, in all probability, post-date the orogeny.

During the Laramide orogeny, most of the present structure of the Beulah area was developed. Some of the faulting, particularly along the Wet Mountains fault, probably represents renewal of movement along lines of weakness that date back to Pennsylvanian time.

Cenozoic

Laramide orogenic activity extended into the early part of the Tertiary. By Oligocene time most of the uplift of the Front Range had been completed. It was a period of quiescence and erosion (Lovering, 1931, p. 95). Oligocene rocks are widely scattered along the Front Range, but are not to be found in the Beulah area. However, minor diabasic intrusives of probable late Eocene or early Oligocene age are found in the thesis area.

Strong uplift and volcanic activity accompanied the rejuvenation of the Front Range in Miocene time, but no evidence of the volcanic activity is seen in the thesis area. The Rocky Mountain peneplain was developed during late Miocene time and Pliocene time. Marked uplift occurred during the Pleistocene epoch. During Pleistocene and Recent time, the present topography was cut and alluvium accumulated.

There is evidence for at least two periods of Pleistocene glaciation in the Front Range (Lovering, 1931, p. 104), but none was observed near Beulah. Pleistocene terrace gravels and geomorphic features indicative of glaciation are absent.

GEOMORPHOLOGY

Much of the area is in a stage of middle or late youth. This is particularly true in the mountainous areas of Precambrian rocks where the valleys are narrow and the divides are sharp. The streams follow consequent courses down-slope from the mountains. Falls and rapids are relatively common. In spite of their youthful development, the streams show some adjustment to structure. Impressed meanders follow lines of weakness such as foliation and joint sets in Precambrian rocks. The streams that flow down from the mountains into Beulah Valley show further adjustment to structure. In the valley, their courses no longer trend east-west, but veer to a north-south trend owing to the resistant Dakota hogback on the east side of the valley. They merge in the valley to form a branch of the St. Charles River and flow out of the valley through a water gap cut in the hogback.

The hogback is the outstanding landform in the area. It is formed by the resistant Dakota sandstone which dips between 20 and 25 degrees to the east. Beulah Valley, on the west side of the hogback, has been cut into the less resistant Fountain formation, which is stratigraphically below the Dakota sandstone.

A wind gap is present in the Dakota hogback at the north end of Lookout Mountain in the $N\frac{1}{2}$, Sec. 27, T. 22 S., R. 68 W.. The wind gap seemingly was cut by North Creek as it followed a consequent course eastward off of the Precambrian highlands. Early in the development of Beulah Valley, however, North Creek was either captured or diverted so that it now follows a subsequent course southward parallel to the hogback. The elbow of capture (or diversion) is in Sec. 21, about 1.25 miles west of the wind gap.

A resequent fault line scarp is located just west of the Wet Mountains fault. It appears as a sharp break in the slope of the east-west trending Precambrian ridges which extend downward toward Beulah Valley.

ECONOMIC GEOLOGY

Although the economic geology of the area is of minor importance, certain mineral resources should be mentioned. The massive lower portion of the Madison limestone has been quarried for building stone. The industry was started in the late 1890's and was closed down by 1930. The cost of transportation of usable limestone had proven prohibitive. The limestone is dense and resistant and, therefore, well suited for the building industry. However, Beulah is too far from railroads and good roads to make a venture in quarrying worthwhile at the present time.

Ground water is a matter of importance to the local residents. In past years, the water supply for Beulah has been taken from streams and shallow wells in alluvium. Due to the drought conditions prevalent in

1952 and 1953, the standard sources for water gradually have been depleted. During the summer of 1955, two deep water wells were drilled in Beulah Valley. One was still being drilled in the NE¼, NW¼, Sec. 2, T. 23 S., R. 68 W. when the writer left the area in September 1955. The other well had been completed in the SE¼, NW¼, Sec. 10, T. 23 S., R. 68 W. at a depth of about 350 feet in the Fountain formation. The well, however, was improperly completed and caved a few days after completion. Had the well been purged and screened, the writer thinks that a good source of potable water would have been found.

The Fountain formation, in spite of its marked lateral and vertical variations in lithology, offers the best possibility as an aquifer in the area, particularly on the east side of Beulah Valley, where it dips under the hogback.

The Precambrian mountains, as numerous "diggings" testify, have been prospected for economic mineral deposits. No commercial ventures, however, have resulted. The pegmatites are small and are simple in composition. They are composed primarily of quartz and feldspars, and it is unlikely that they contain exploitable minerals. Faults and shear zones show evidence of considerable hematite mineralization and a little malachite stain to indicate the presence of ore minerals. The hematite is of the massive metallic type. It replaces breccia and country rock along faults (Fig. 4). The quantity of hematite does not seem to warrant commercial operation.

No exploration for petroleum or gas has been conducted in the area. The only likely reservoir rock, the Dakota sandstone, crops out in the

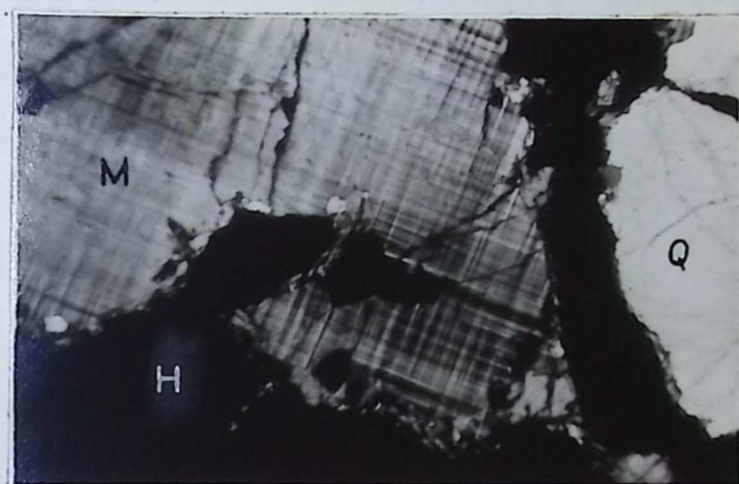


FIG. 4. Photomicrograph of hematite (H) replacement of microcline (M) and quartz (Q) in Precambrian granite. Crossed nicols, X 7.5

area, but no oil seeps have been found.

SUMMARY

The sedimentary rocks near Beulah range in age from Ordovician to Cretaceous. They include both continental and marine sediments and rest unconformably on a Precambrian basement complex which is composed of igneous and metamorphic rocks. A cyclic series of arkosic, breccia, sandstone and limestone is present between the Pennsylvanian Fountain formation and the Jurassic Morrison formation. The age of these rocks could not be determined.

The major structural features of the Beulah area were formed during the Laramide orogeny, but their formation has been influenced by Pennsylvanian structural features. The Wet Mountains fault probably formed during Pennsylvanian time. Other structural features have developed in response to Laramide thrusting along the Wet Mountains fault. Trends of foliation in Precambrian rocks have changed locally to conform to Laramide structures, but the general discordance of Precambrian and Laramide trends indicates that the foliation was established prior to the Laramide orogeny and that it probably pre-dates the Pennsylvanian disturbances.

Petrographic studies show that the Precambrian rocks include metasedimentary and meta-igneous types. At least two stages of intrusion are represented by an adamellite gneiss, the Pikes Peak granite, and numerous other igneous types. Igneous injections may have been important in regional metamorphism of the Idaho Springs formation and other Precambrian rocks, but locally, certain injections have had retrograde effects. The rocks of the Idaho Springs formation fall into the amphibolite facies and represent a moderate grade of regional metamorphism. They include schists and igneous injections. Diabasic dikes of Tertiary (?) age have been intruded into the Precambrian rocks along joints. More work is needed for a complete study of the igneous and metamorphic rocks in the area.

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APPENDIX A

Measured Sections

Cretaceous System

Colorado Group, in SE Sec. 14, T. 22 S., R. 67 W., Pueblo County, Colorado; Measured North of State Route 76

	Thickness Feet
Upper Cretaceous Series, Colorado group	
Greenhorn limestone (Total thickness, 35.4 feet)	
Contact of the Greenhorn limestone and the overlying Carlile formation is gradational; it was placed at the top of the uppermost thin-bedded limestone underlying a sequence of fissile black shale. . .	
9. Limestone and shale interbedded. Limestone: vertically jointed, thin-bedded, beds from 0.25 to 4 in. thick, fine-grained, argillaceous, grey, weathers light grey, fossiliferous, contains <u>Inoceramus, labiatus</u>, sequence about 60 percent limestone. Shale: fissile, black	33.8
8. Limestone, massive, coarse-grained, gray, weathers light gray and buff	1.6
Graneros shale (Total thickness 213.1 ft., covered, 81 ft.)	
Contact with overlying Greenhorn limestone is gradational; contact placed at the base of the massive, 1.6-ft. thick limestone bed.	
7. Shale and limestone. Shale: calcareous, black, weathers gray, sequence about 80 percent shale. Limestone: thin-bedded, beds 1 to 2 in. thick, coarse-grained, gray, weathers light-gray	25.4
6. Shale, calcareous, black, weathers gray	6.6

	Thickness Feet
5. Covered interval	37.8
4. Shale, fissile, black to dark-gray, contains rows of black limestone concretions 2 ft. from top, concretions about 2 ft. long	30.0
3. Covered interval	43.2
2. Shale, fissile, black to gray, contains rows of black limestone concretions, seams of bentonite	64.9
1. Shale and thin sandstone. Shale: fissile, black to gray. Sandstone: vertically jointed, ripple-marked, thin-bedded, beds from 1 to 3 inches thick, fine-grained, tan. Sequence about 40 percent sandstone	5.2

Contact with the Dakota sandstone next below is gradational; contact placed at the top of uppermost thick sandstone bed.

Dakota sandstone, in SW Sec. 1, T. 23 S., R. 68 W., Pueblo County,

Colorado; Measured North of State Route 76

	Thickness Feet
Upper Cretaceous Series, Dakota sandstone (Total thickness, 241.1 feet, covered, 132.1 feet)	
Contact with the Graneros shale not present, but estimated to be about 6 feet above topmost exposure of sandstone at place of measurement.	
6. Sandstone, vertically jointed, massive, medium-grained, frosted grains, tan, weathers brown, contains limonitic layers, forms cliffs	30.8
5. Covered interval	92.1
4. Sandstone, massive, cross-bedded, coarse- to medium-grained, subrounded and frosted grains, silicic cement, tan, weathers brown	4.6

	Thickness Feet
3. Sandstone, massive, somewhat cross-bedded, medium-grained, subrounded and frosted grains, silicic cement, white, weathers light tan, contains limonite nodules, calcareous in top 4.6 feet. .	35.0
2. Covered interval.	40.4
1. Sandstone, massive, cross-bedded, medium-grained, conglomeratic, particularly near base, grains subrounded and frosted, silicic cement, white, weathers light tan, unconformable on Morrison formation	32.2

Jurassic System

Morrison formation, SW Sec. 27, T. 22 S., R. 68 W., Pueblo County, Colorado; Measured North of Beulah on East Slope of Hogback Mountain

	Thickness Feet
Upper Jurassic Series, Morrison formation (Total thickness, 201.9 feet, covered, 83.8 feet)	
Contact with the overlying Dakota sandstone covered, but unconformable elsewhere.	
27. Covered interval to top of Morrision formation, but float contains fragments of fresh-water limestone, variegated shale, siltstone and sandstone	41.4
26. Sandstone, massive, cross-bedded, medium-grained, arkosic, calcareous, light-tan, weathers tan, contains limonite specks.	4.8
25. Covered interval with scattered exposures of gray to green shale and mudstone and dark-gray fresh-water limestone	42.4
24. Limestone, knobby, dense, medium-grained, gray, shale partings.	2.0
23. Mudstone and siltstone, interbedded, calcareous, gray-green	7.0

	Thickness Feet
22. Sandstone, wavy-bedded, thick-bedded, beds from 1.5 to 3.0 feet thick, fine-grained, arkosic, calcareous, white, weathers tan, has 6-inch separations of gray-green mudstone	5.5
21. Shale, calcareous, variegated, pink, green and gray	12.6
20. Sandstone, massive, medium-grained, arkosic, light gray, weathers white, sparse bedding in upper part is ripple-marked	18.0
19. Limestone, smooth-bedded, beds from 0.5 to 6 inches thick, medium-grained, arenaceous, gray-green to brown, weathers yellow to tan, green shale partings, upper 2 feet are wavy-bedded .	10.3
18. Sandstone, massive, medium-grained, arkosic, calcareous, light gray, weathers gray to tan, has limonite specks	6.5
17. Sandstone, thick-bedded, beds from 1.0 to 1.5 feet thick, compact, fine-grained, arkosic, calcareous, cream-colored, weathers tan, interbedded with 3-inch intervals of gray-green limestone and shale	7.0
16. Limestone, nodular, wavy-bedded, beds from 1 to 10 inches thick, arenaceous, gray-green, gray shale partings, grades upward into fine-grained arkosic sandstone	3.0
15. Shale, calcareous, gray	0.5
14. Sandstone, massive, fine-grained, arkosic, gray, weathers buff	0.9
13. Mudstone, silty, gray-green, limonite stains . .	2.0
12. Sandstone, massive, fine-grained, arkosic, calcareous, cream-colored, weathers tan to brown	3.3
11. Shale, beds about 0.25 inches thick, silty, calcareous, gray-green	1.3
10. Sandstone, massive, fine-grained, arkosic, calcareous, light-gray to tan, weathers cream-colored	2.6

	Thickness Feet
9. Shale, beds from 0.1 to 0.5 inches thick, silty, calcareous, gray-green, silty layers brown . . .	1.2
8. Sandstone, thick-bedded, beds from 1.5 to 3.0 feet thick, cross-bedded, medium-grained, light gray to tan, weathers tan. 1-foot shale and silty shale break 6 feet below top. Forms cliffs . . .	10.0
7. Shale and mudstone, beds from 0.25 to 3.0 inches thick, silty, calcareous, light green, limonite stains parallel to bedding	1.5
6. Sandstone, massive, fine-grained, arkosic, light-gray, weathers buff, limonite streaks	1.0
5. Shale, beds 0.5 to 1.5 inches thick, sandy, silty, calcareous, red to tan, 0.2-foot thickness green siltstone at top	2.2
4. Sandstone, knobby, wavy-bedded, silty laminae, fine-grained, calcareous, red to tan, limonite concretions	2.5
3. Sandstone, massive, fine-grained, slightly calcareous, yellow to tan	0.8
2. Limestone, thin-bedded, beds 1.0 inches thick, shaly, light gray-green	2.0
1. Shale and siltstone, gray-green and tan, unconformable on bleached Fountain sandstone	3.3

Permian to Jurassic Undifferentiated

Units A & B, in SW Sec. 19, T. 22 S., R. 68 W., Pueblo County,

Colorado; Measured North of North Creek

Thickness
Feet

Unit B (Total thickness, 36.3 feet, covered, 33.7 feet)

Contact with the Morrison formation next above covered, but disconformable elsewhere.

	Thickness Feet
23. Largely covered interval of arkosic sandstone and siltstone with thin buff, lithographic limestone	33.7
22. Limestone, cherty fracture, massive, lithographic, gray to buff, weathers yellow-brown. .	2.6

Unit A (Total thickness, 190.2 feet)

Contact with Unit B next above disconformable.

21. Limestone, nodular, dense, fine-grained, arenaceous, arkosic, dark-gray, weathers gray. . .	1.1
20. Sandstone and siltstone, massive, cross-bedded, slightly conglomeratic, coarse-grained to silt-size particles, arkosic, calcareous, white to gray, weathers gray to pink, becomes more silty towards top and grades upward into nodular limestone	9.4
19. Breccia, massive, particle diameters from 0.1 mm. to 3.0 cm., grains angular to subrounded, arkosic, calcareous, argillaceous, orange to buff, weathers red to brown, grades upward into overlying sandstone, disconformable on nodular limestone below	2.5
18. Limestone, nodular, dense, fine-grained, arenaceous, arkosic, dark-gray, weathers gray . .	0.9
17. Sandstone and siltstone, massive, cross-bedded, slightly conglomeratic, coarse-grained to silt-size particles, arkosic, calcareous, white to gray, weathers gray to pink, grades upward into nodular limestone	4.0
16. Breccia, massive, particles diameters from 0.1 mm. to 2.0 cm., grains angular to subrounded, arkosic, calcareous, argillaceous, orange to buff, weathers red to brown, grades upward into overlying sandstone, disconformable on limestone next below	2.6
15. Limestone, nodular, dense, fine-grained, arenaceous, arkosic, dark-gray, weathers gray	1.3

	Thickness Feet
14. Sandstone and siltstone, massive, cross-bedded, slightly conglomeratic, coarse-grained to silt-size particles, arkosic, calcareous, white to gray, weathers gray to pink, grades upward into nodular limestone, becomes more silty toward top.	4.3
13. Breccia, massive, particle diameters from 0.1 mm. to 2.0 cm., grains angular to subrounded, arkosic, calcareous, argillaceous, orange to buff, weathers red to brown, grades upward into sandstone next above, disconformable on underlying limestone . .	2.8
12. Limestone, nodular, dense, fine-grained, arenaceous, arkosic, dark-gray, weathers gray	1.0
11. Sandstone and siltstone, massive, cross-bedded, slightly conglomeratic, coarse-grained to silt-size particles, arkosic, calcareous, white to gray, weathers gray to pink, finest at top, grades upward into overlying nodular limestone. .	4.4
10. Breccia, massive, particle diameters from 0.1 mm. to 2.0 cm., grains angular to subrounded, arkosic, calcareous, argillaceous, orange to buff, weathers red to brown, grades upward into overlying sandstone, disconformable on underlying limestone	2.5
9. Limestone, nodular, dense, fine-grained, arenaceous, arkosic, dark-gray, weathers gray	4.2
8. Sandstone and siltstone, massive, cross-bedded, conglomeratic, silt-size particles to coarse-grained, sand, arkosic, calcareous, white to gray, weathers pink, grades upward into nodular limestone next above	58.7
7. Sandstone, massive, fine- to medium-grained, arkosic, limonitic, buff, weathers yellow	2.6
6. Sandstone, massive, cross-bedded, conglomeratic, fine- to coarse-grained, maximum long diameter of pebbles about 1 cm., arkosic, calcareous, white to gray and buff, weathers pink and gray. .	53.2

	Thickness Feet
5. Conglomerate and sandstone, massive, conglomeratic layers 1 to 3 inches thick, fine- to medium-grained sand, arkosic, calcareous, white to gray, weathers pink to gray	2.9
4. Sandstone, massive, cross-bedded, conglomeratic, fine- to medium-grained, slightly arkosic, calcareous, white to gray, weathers pink and gray.	14.4
3. Sandstone, massive, slightly conglomeratic, fine-grained, arkosic, calcareous, contains magnetite, light-gray to light-gray-green, weathers light gray	16.3
2. Shale, arkosic, silty, micaceous, green	0.6
1. Limestone, thin-bedded, beds 1 inch thick, medium-grained, crystalline, dark-gray, weathers gray-green, 0.25-inch red silty shale partings, unconformable on red-brown Fountain sandstone . .	0.5

Pennsylvanian System

Fountain formation, in SE Sec. 28 and SW Sec. 27, T. 22 S., R. 68 W., Pueblo County, Colorado; Measured East and West of State Route 273

	Thickness Feet
Pennsylvanian System Fountain formation (Total thickness, 2,100 feet, covered, 2,026 feet)	
Contact of the Fountain formation with the overlying units is unconformable.	
23. Sandstone, wavy- and thick-bedded, medium- to coarse-grained, conglomeratic, red-brown, bleached to tan	2.0
22. Shale, micaceous, maroon and gray-green, maroon predominates	1.5
21. Sandstone, wavy- and thick-bedded, medium- to coarse-grained, conglomeratic, arkosic, red, weathers red	4.1

	Thickness Feet
20. Covered interval	136.0
19. Sandstone, massive, medium- to coarse-grained, conglomeratic, arkosic	0.4
18. Covered interval	83.0
17. Sandstone, nodular, compact, fine-grained, red-brown, abundant interstitial hematite, white argillic specks, 0.1 ft. thick light gray argillic band at base	3.0
16. Sandstone, thin-bedded, fine-grained, argillaceous, red	1.8
15. Covered interval	135.3
14. Sandstone, massive and thick-bedded, sparse cross-laminae beds 2.0 to 10.0 ft. thick, medium- to coarse-grained, conglomeratic, pebbles 0.5 to 3.0 in. in diameter, arkosic, red-brown, weathers to rounded and pitted forms, light gray argillic laminae, white argillic specks from alteration of feldspar	23.0
13. Covered interval	502.4
12. Sandstone, thick- and wavy-bedded, sparse cross-bedding, beds from 4.0 to 10.0 ft. thick, medium- to coarse-grained, red to red-brown, medium-grained purple sandstone stringers parallel bedding	15.0
11. Covered interval	396.3
10. Sandstone, massive, medium-grained, arkosic, red.	0.8
9. Covered interval	293.9
8. Sandstone, massive, cross-bedded, beds from 3.0 to 7.0 ft. thick, medium-grained, conglomeratic, arkosic, red-brown, argillic white specks . . .	18.3
7. Covered interval	236.2
6. Sandstone, massive, medium- to coarse-grained, arkosic, red-brown	0.7
5. Covered interval	75.3

	Thickness Feet
4. Sandstone, massive, medium- to coarse-grained, arkosic, red-brown	0.5
3. Covered interval	106.7
2. Sandstone, thick- to thin-bedded, beds 0.1 to 0.6 ft. thick, medium- to coarse-grained, conglomeratic, pebbles up to 3 in. in diameter, red-brown, thin-bedded sandstone commonly shaly, purplish to light gray	6.5
1. Covered interval to base of Fountain formation . .	6.0

Contact with the Harding sandstone at this point based on Fountain float and Harding bedrock, angular unconformity here and with other pre-Pennsylvanian units elsewhere.

Mississippian System

Madison limestone, in NE Sec. 4, T. 23 S., R. 68 W., Measured on North Side of Middle Creek

	Thickness Feet
Mississippian System, Madison limestone (Total thickness, 149.8 feet)	
Contact with overlying Fountain formation unconformable; fingers of Fountain sandstone and rounded to subangular breccias penetrate top of Madison limestone along solution channels.	
3. Limestone, dense to finely crystalline, gray and buff, weathers gray to light red-brown, locally contains zones of fine- to medium-grained quartz aligned parallel to bedding, sandiest near top, sparse red chert, locally finely oolitic, penetrated by solution channels containing Fountain sandstone and rounded to subangular limestone breccia, nonresistant	89.0

Thickness
Feet

2. Limestone, dense to finely crystalline, gray and buff, weathers gray to light red-brown, sparse irregular bands of gray, red-orange and brown chert, sparse sandy zones with fine- to medium-grained quartz, locally finely oolitic, sparse solution channels filled with rounded solution breccia and Fountain debris, surface weathers rough and pitted, forms cliffs, locally contains brachiopod fossils . . . 51.0

1. Limestone conglomerate, dense to medium crystalline, gray to buff, pink and yellow, sparse red chert, locally contains fine-grained quartz sand, cobbles of reworked Williams Canyon limestone with long diameters up to 0.8 ft. 9.0

Contact with underlying Williams Canyon limestone very irregular.

Madison limestone (Beulah and Hardscrabble limestones), in NW Sec. 4, T. 23 S., R. 68 W. and SE Sec. 32, T. 22 S., R. 68 W., Pueblo County, Colorado; Adapted from Maher (1950A, p. 2); Measured on North Side of Middle Creek

Thickness
Feet

Mississippian System, Beulah limestone (Total thickness, 53.0 feet)

14. Limestone, red-stained buff fine sandy with red-stained buff calcareous, fine-grained sandstone layers and yellow-mottled red dense chert at top 5.5

13. Limestone, yellowish-buff, very oolitic, slightly sandy 1.0

12. Sandstone, yellow, very limy, very fine, grading downward into pink-tinged buff oolitic medium-crystalline limestone. Oolites are oblong in part 4.5

11. Limestone, yellowish-buff, finely oolitic 3.0

	Thickness Feet
10. Limestone, buff, finely crystalline to dense, containing red-mottled gray-buff dense chert	0.7
9. Limestone, platy, buff, shaly	1.0
8. Limestone, reddish buff, fine sandy, finely oolitic	0.8
7. Limestone, gray buff, very oolitic, medium crystalline, grading downward into red to yellow finely oolitic finely crystalline limestone	5.5
6. Limestone, finely red-banded, yellowish buff, finely oolitic, finely crystalline	5.5
5. Limestone, red- and yellow-mottled buff, faintly oolitic, finely crystalline	5.5
4. Limestone, red to yellowish buff, oolitic, slightly sandy. Oolites range from fine to medium in size.	5.5
3. Limestone, cream-colored, very oolitic. Oolites are fine to medium in size	5.5
2. Limestone, gray buff, very oolitic, finely crystalline to dense	5.5
1. Sandstone, yellow to white, calcareous, medium- to coarse-grained, might be cave-fill	3.5

Mississippian System, Hardscrabble limestone (Total thickness, 125.0 feet, covered, 38.0 feet)

	Thickness Feet
11. Limestone, gray, finely oolitic, finely crystalline, and gray dense limestone containing a trace of orange dense chert	4.5
10. Limestone, gray, finely oolitic, finely crystalline to dense	5.5
9. Limestone, rubbly, gray buff, dense	5.5

	Thickness Feet
8. Covered interval from base of upper cliff to top of lower cliff	38.0
7. Limestone, dark-buff to brown, finely crystalline to dense. Top of lower cliff	5.5
6. Limestone, slightly pink-tinged cream-colored, finely crystalline to dense	27.5
5. Limestone, slightly pink-tinged, fossiliferous, finely crystalline to dense, containing small brachiopods	5.5
4. Limestone, cream-colored to buff, finely crystalline to dense	16.5
3. Limestone, purple-mottled buff to dark-buff, dense	9.5
2. Limestone, pink-mottled buff, chalky, very fine sandy	1.5
1. Limestone, buff, medium crystalline, grading downward into soft pink-mottled grey finely crystalline limestone containing pebbles of reworked Williams Canyon limestone. Distinctly irregular basal surface	5.5

Mississippian (?) System

Williams Canyon limestone, in NE Sec. 4, T. 23 S., R. 68 W., Pueblo County, Colorado; Measured on North Side of Abandoned Dirt Road South of Limestone Quarry

Thickness
Feet

Mississippian (?) System, Williams Canyon limestone (Total thickness, 18.0 feet)

Contact with the overlying Madison limestone is unconformable.

	Thickness Feet
1. Limestone and dolomite, wavy thick- and thin-bedded with shaly partings, bedding thicknesses between 0.3 and 0.8 ft., finely to coarsely crystalline, gray to blue-gray and mottled purplish, weathers light gray to buff	18.0

Irregular contact with underlying units.

Williams Canyon limestone, in SE Sec. 32, T. 22 S., R. 68 W., Pueblo County, Colorado; Adapted from Maher (1950A, p. 2); Measured on North Side of Middle Creek

	Thickness Feet
Mississippian (?) System, Williams Canyon limestone (Total thickness, 16.3 feet, covered, 1 foot)	
6. Limestone, yellow, coarsely crystalline	1.0
5. Dolomite, hard, purple-mottled lavender, very finely granular, with conchoidal fracture	3.0
4. Sandstone, red, yellow, and gray, limy, fine-grained, and purple- and maroon mottled gray finely crystalline limestone	1.3
3. Dolomite, lavender to gray, finely granular, containing one layer of pinkish-white finely granular to dense chert nodules. Upper 2 ft. weathers bright yellow	5.5
2. Dolomite, lavender to purple, finely crystalline, and dolomitic limestone with thin veins of calcite	4.2
1. Covered interval. Contact with Fremont limestone not exposed	4.3

Ordovician System

Fremont limestone, in NE Sec. 4, T. 23 S., R. 68 W.; Measured on North Side of Middle Creek

	Thickness Feet
Cincinnatian Series, Fremont limestone (Total thickness, 10.8 feet)	
Lenticular erosional remnants unconformably overlain by Williams Canyon limestone.	
2. Limestone, dolomitic, coarsely crystalline to medium-grained, red-brown to buff, red-brown predominates at base, massive, sandy, commonly forms ledges, calcite veinlets and masses, fossiliferous, contains crinoid columnals and coralites, weathers to rough pitted surface	10.5
1. Limestone, coarsely crystalline, thin-bedded, beds 0.5 in. thick, red-brown, unconformable on Harding sandstone	0.3

Fremont limestone, in SE Sec. 32, T. 22 S., R. 68 W., Pueblo County, Colorado; Adapted from Maher (1950A, p. 3); Measured on North Side of Middle Creek

	Thickness Feet
Cincinnatian Series, Fremont limestone (Total thickness, 18.5 feet, covered, 3 feet)	
4. Dolomite, pinkish buff, finely to coarsely crystalline	5.0
3. Dolomite, pinkish buff to red, finely to coarsely crystalline, with thin beds of brick-red finely granular dolomite	5.0

	Thickness Feet
2. Dolomite, massive, pitted, pink to red, coarsely crystalline	5.5
1. Contact of Fremont limestone and Harding sandstone is not exposed but estimated to be within 3 ft. of bed described above	3.0

Harding sandstone, in SW Sec. 4, T. 23 S., R. 68 W., Pueblo County, Colorado; Measured on North Side of Wash

	Thickness Feet
Mohawkian Series, Harding sandstone (Total thickness, 71.5 feet)	
Contact with overlying units unconformable and irregular.	
3. Sandstone interbedded with variegated mudstone and shale. Sandstone; fine-grained, white to light gray with faint pink and purple stains, beds up to 2 in. thick, locally calcareous, fucoidal markings on bottoms of sandstone beds. Mudstone and shale; red-brown and purplish to gray-green, red-brown dominant, locally sandy, bedding from 1/16 to 1/2 in. thick. Sequence grades from 70 percent sandstone at base to 50 percent sandstone at the top	55.0
2. Orthoquartzite interbedded with calcareous sandstone, beds 3 to 10 in. thick, fine-grained, white to gray, with gray and green stains, variegated shale partings, vertically jointed, forms a ledge	8.5
1. Shale and mudstone, variegated red-brown to gray-green and purple, mudstone most abundant at top, color banding prominent near top, mudstone commonly sandy, bedding from 1/16 to 1/2 in. thick	8.0
Rests on gently undulating surface of Precambrian gneiss and schist.	

Harding sandstone, in NE Sec. 4, T. 23 S., R. 68 W., Pueblo County, Colorado; Adapted from Maher (1950A, p. 3); Measured on North Side of Middle Creek

	Thickness Feet
Mohawkian Series, Harding sandstone (Total thickness, 76 feet, covered, 38.0 feet)	
10. Covered interval which, judging by incomplete exposures and float, includes hard, purple and green, limy, fine-grained sandstone at top and purple, red, and green sandy shale at bottom. .	16.5
9. Sandstone, medium-bedded, white, very fine grained	4.0
8. Sandstone, thin-bedded, white to pink, limy, very fine grained.	11.0
7. Covered interval, in part purple and red shale. .	22.5
6. Shale, red to brown, fissile; green very fine grained sandstone, and green-spotted red to purple waxy shale	3.0
5. Sandstone, green, very fine grained, and maroon, green, and purple waxy shale.	3.5
4. Sandstone, thin-bedded, white, very fine grained, with two hard quartzitic layers about 6 in. thick. This unit forms a distinct ledge. . . .	4.5
3. Sandstone, pale-green, limy, very fine grained. .	2.0
2. Sandstone, purple-mottled and green-spotted white, limy, very fine grained	4.5
1. Sandstone, pink-mottled white, limy, very fine grained, with large white quartz boulders at base.	5.0

APPENDIX B

Descriptions of Thin Sections

General

The following generalized descriptions of thin sections are intended to supplement information provided in the text of the report under the sections on petrography and petrology and on stratigraphy and sedimentation.

Sedimentary Sections

Harding sandstone. Orthoquartzite. The rock is a dense orthoquartzite of very fine grain size. Smooth bedding laminae are spaced about every two to three inches. The rock is gray, but shows faint yellow and lavender stains which either parallel the bedding or follow seams normal to the bedding. Hydrochloric acid reveals the presence of calcite in the seams.

Thin sections (Fig. 5) display an even-grained quartz mosaic with faint orientation of the long dimensions of the quartz grains roughly parallel to the bedding. The quartz grains are subangular because of silica overgrowths on the more nearly rounded detrital quartz. A few well-rounded grains of zircon are dispersed through the rock.

Seams of calcite transect the rock normal to the bedding. The calcite cuts through and replaces the quartz grains. In places, the calcite seams spread out and form irregular replacements of the quartz. Some of the veinlets of calcite bifurcate.

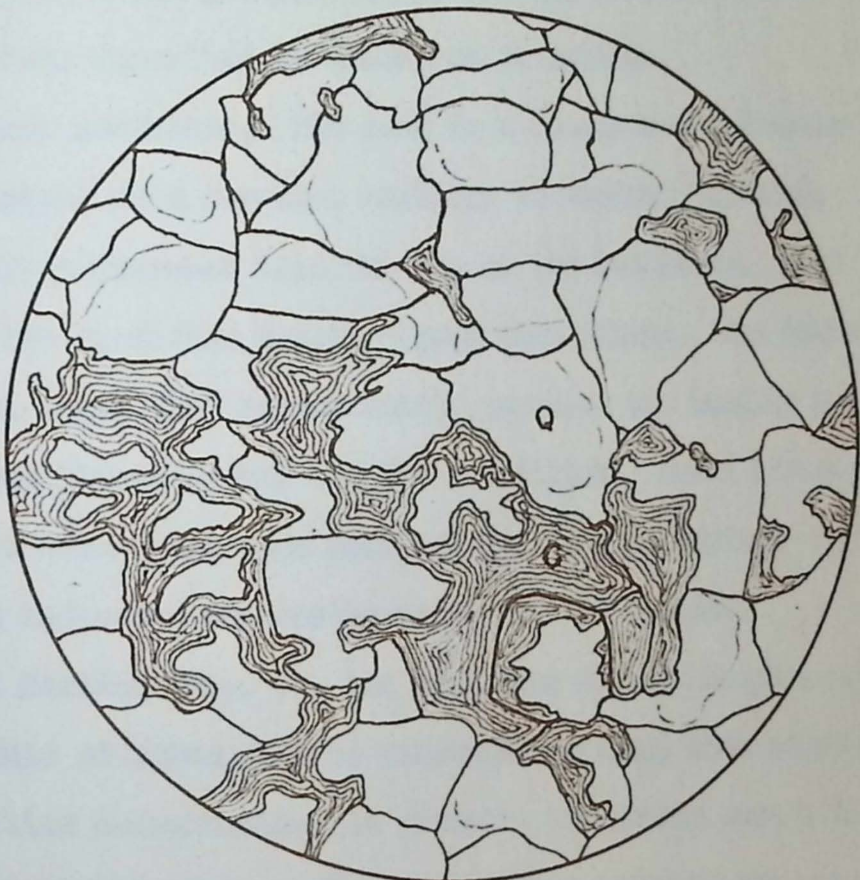

FIG. 5. Thin section of Harding sandstone showing quartz grains (Q) with quartz overgrowths. Calcite (C) replaces the quartz. X 150.

The calcite has been introduced after the quartz overgrowths formed, and after consolidation of the rock. It appears to have been introduced along small joints. It is likely, therefore, that the calcite has been deposited by ground water action.

Calcareous sandstone. The rock is a cloudy-white friable fine-grained sandstone with fucoidal markings on bedding surfaces. The markings project downward into the top of the bed below. Some portions of the sandstone appear denser than others. The denser portions form zones that approximately parallel the bedding and have been formed by the secondary addition of silica. Faint irregular variations in color have been produced by limonite stains. Hydrochloric acid indicates the spotty occurrence of calcite.

In thin section (Fig. 5), the sandstone shows a compact subequigranular mosaic of subangular to subrounded grains, some of which show secondary silica overgrowths. In general, the grains have a fused appearance at their margins. Thus, they have imparted the very compact nature of the mosaic. There is, however, no indication of strain such as undulose extinction of the quartz to account for the "fused" borders. Bedding is not readily seen in thin sections.

Irregular areas of optically continuous calcite after quartz also are to be observed. In places, the calcite has completely replaced grains of quartz and assumed their form, but more generally, the calcite has attacked only the margins of the quartz and displays lobate penetrations into the quartz. The calcite has replaced both the detrital and secondary silica, but in general, it is found only in those portions of the rock where addition of secondary silica has not closed most of the pore space. The calcite replacements of quartz probably developed under the influence of ground water action.

Also present in the sections are limited amounts of limonite and clay matter between the quartz grains. In places associated with the calcite, they form patches and less obvious bands parallel to the bedding. Small rounded grains of zircon are dispersed irregularly through the sections.

Unit A. Arkosic breccia. The rock is a coarse unsorted arkosic breccia or conglomerate with a fine- to medium-grained calcareous and argillaceous sand matrix in which angular to subrounded fragments of quartz and pink feldspars are held. The detrital grains, other than those in the matrix, range in size from two to 15 millimeters. Some of the feldspar grains have been weathered to clay minerals and display a chalky-white color. The majority of them, however, are quite fresh and appear as pink fragments imbedded in a gray groundmass. Small flakes of biotite and grains of magnetite also appear in the rock. Limonite stains are common.

Microscopic studies (Fig. 6) reveal the rock to be an angular to subrounded arkosic conglomeratic breccia with detrital grains ranging in size from a fraction of a millimeter in the matrix to those with long diameters commonly exceeding a centimeter.

The matrix is composed of fine- to medium-grained angular and rounded detrital grains of quartz, feldspars, ilmenite and/or magnetite, and biotite. Clay, limonite, and calcite with minor amounts of sericite

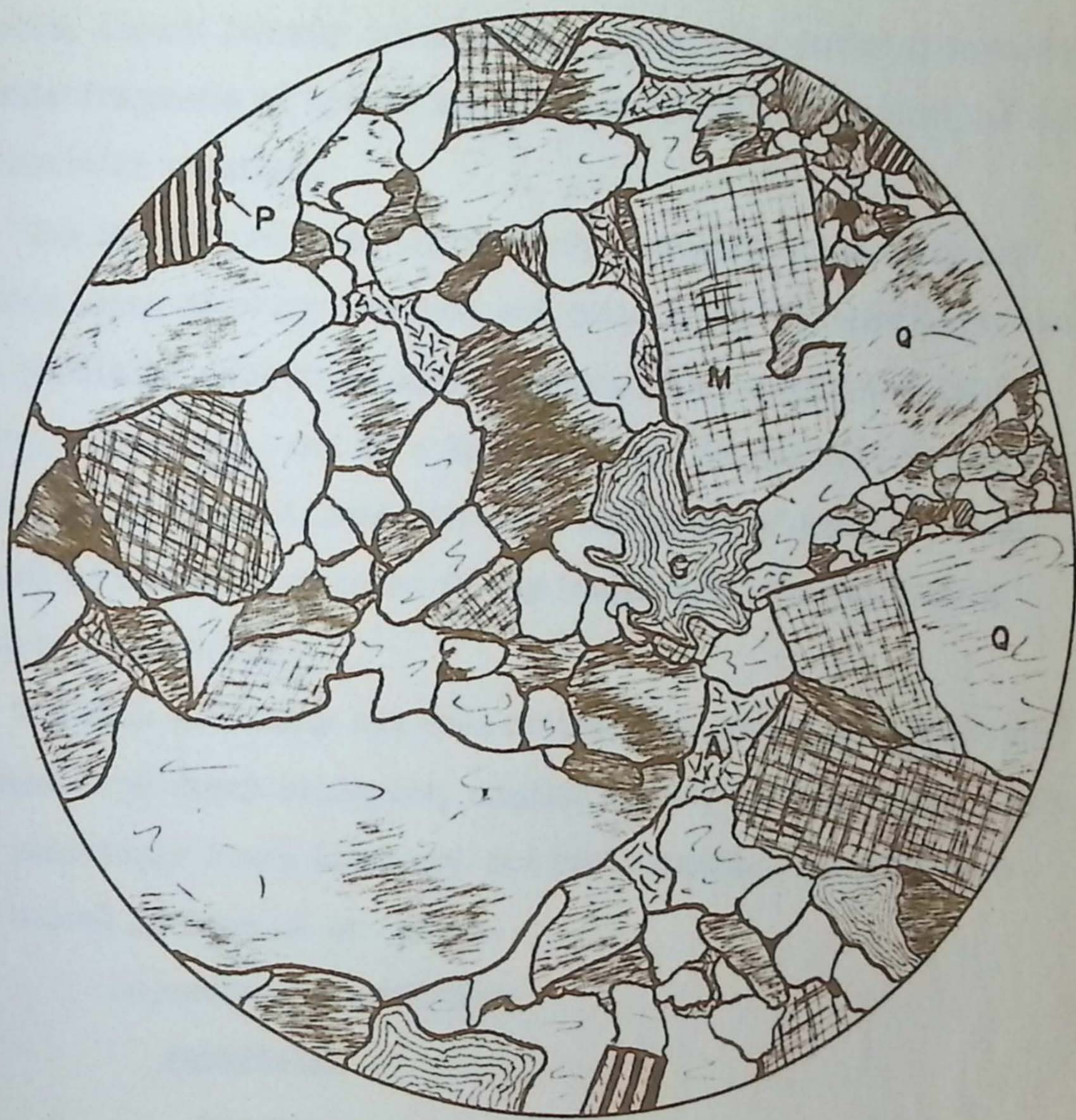

FIG. 6. Thin section of arkosic breccia from Unit A. Quartz (Q), microcline (M), and plagioclase (P) are detrital. Clays (A) are interstitial and calcite (C) replaces other minerals. Crossed nicols, X 100.

and microcrystalline chert occur between the detrital grains. The calcite, though largely interstitial, replaces in differing degree the clastic fragments of quartz and feldspar as well as the chert and other interstitial material.

The larger grains of the rock are generally angular (only the corners being slightly rounded) and quite fresh, but the feldspars have been partially altered to clay minerals. The larger grains include quartz, microcline, and to a lesser degree, plagioclase. Some of the quartz grains are rutilated and hold inclusions of apatite. As is typical of Precambrian rocks in the Beulah area, the quartz shows undulose extinction.

The rock seemingly has been derived from nearby Precambrian exposures. Its fresh feldspars, angular nature, and poor sorting indicate relatively short transport and rapid burial. Its composition (see below) is that of an arkose.

Percentage Composition:

Detritals:

Quartz	39%
Microcline	30
Plagioclase.	06
Ilmenite and/or magnetite.	01
Biotite.	-01
Clay matter.	10
Others	trace
	87

Non-detritals:

Calcite.	08
Limonite	05
Chert.	trace
	13
Total:	100%

Calcareous siltstone and silty limestone. The rock is very fine-grained, light-grey, arkosic, calcareous, and argillaceous. It contains a few coarser detrital grains (with long diameters up to 0.5 centimeters) of quartz and feldspar. In the outcrop, the rock is a siltstone at its base, but the calcite content increases upward and the upper parts are a silty limestone. Bedding is not visible in hand specimens, but massive bedding is apparent in the outcrop.

Thin section studies (Fig. 7) indicate a gradation from an angular to subrounded calcareous and somewhat argillaceous arkosic siltstone to a slightly argillaceous silty arkosic limestone. The detrital grains are embedded in a fine-grained calcareous matrix which contains considerable disseminated clay matter. The long diameters of the detrital grains range from 0.5 centimeters down to 0.03 millimeters with the greater percentage of grains having long diameters between 0.05 and 0.1 millimeters. Some portions of the rock show as irregular calcareous patches with as little as 15 percent detrital material, but such areas are relatively insignificant.

The predominant detrital mineral is quartz, but lesser amounts of microcline, plagioclase, and orthoclase are present. Detrital grains of

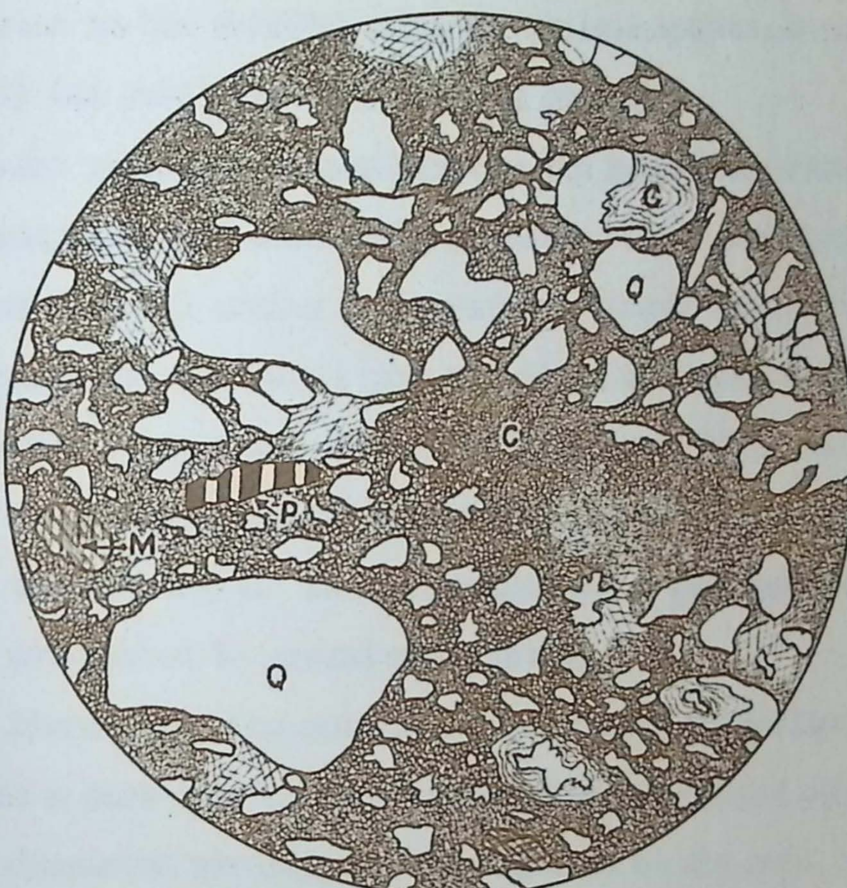

FIG. 7. Thin section of silty limestone or calcareous siltstone from Unit A. Quartz (Q) is partly replaced by calcite (C) which forms the matrix and shows differing degrees of crystallinity. Microcline (M) and plagioclase (P) are detrital grains. Crossed nicols, X 100.

rounded zircon and angular magnetite or hematite also are present. The magnetite or hematite has been partially altered to limonite in places. Inclusions found in the detrital minerals include apatite, sericite, and rutile (?) (as rutilated inclusions in quartz).

The calcite generally is argillaceous and quite fine grained, but locally is recrystallized and coarser grained. The calcite replaces almost all the detrital grains to a greater or lesser degree, but very few of the grains are entirely replaced. Where the calcite replaces the detrital minerals (quartz and feldspar), it presents lobate outlines against them and shows irregular penetrations which are localized mainly along cracks and cleavages. The recrystallization and replacement features are attributed to ground water action.

Arkosic limestone. The rock is a dense finely crystalline arkosic limestone with a dark gray color. Prominent angular grains of pink feldspar are dispersed randomly through the rock as are small quartz grains. No bedding is apparent in the hand sample, but the nodular nature of the rock is readily seen at the outcrop.

Thin sections (Fig. 6) show the rock to be a finely crystalline arenaceous and arkosic limestone with sufficient argillaceous material to color the calcite a dark gray. The detrital minerals present are angular to subrounded. The long diameters of the particles range from slightly less than one centimeter to about 0.03 millimeters. The detrital grains include quartz with lesser amounts of microcline, plagioclase, and orthoclase. Very minor amounts of magnetite are also present.

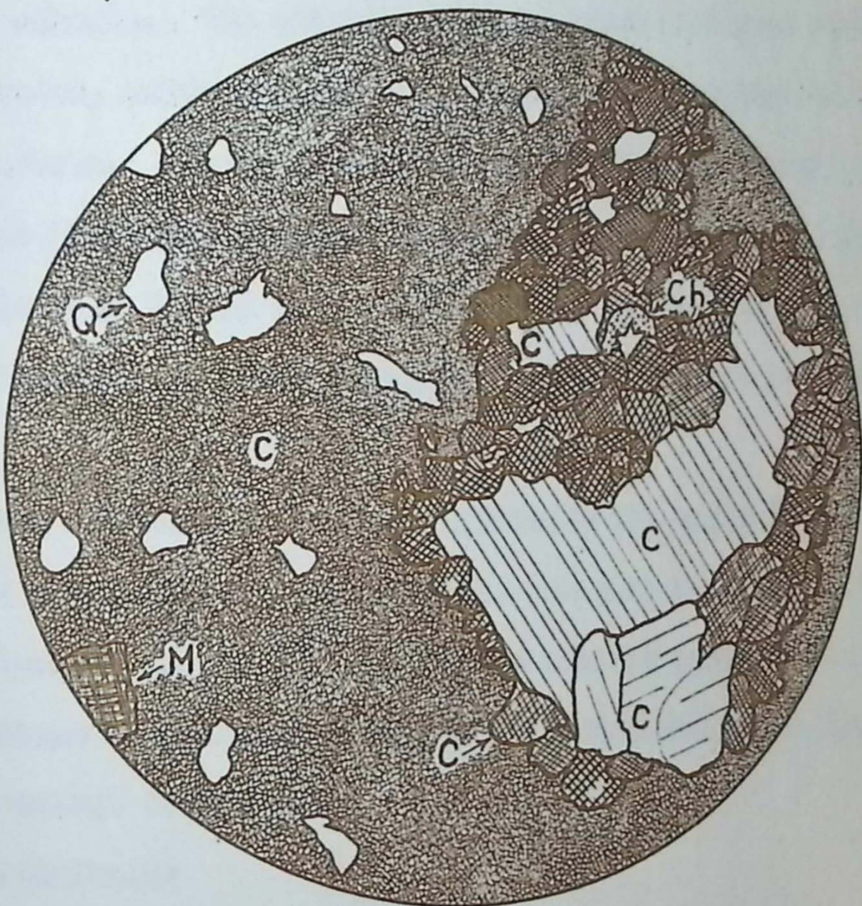

FIG. 8. Thin section of arkosic limestone from Unit A. Calcite (C) shows three degrees of crystallinity and replaces detrital minerals which include quartz (Q) and microcline (M). Chert (Ch) fringes partly replaced quartz grain. Crossed nicols, X 100.

Most of the calcite is exceedingly fine-grained, but some of it has been recrystallized into coarser grains. All of the detrital minerals, with the exception of the magnetite, show signs of secondary replacement by calcite. The calcite presents lobate outlines against the detrital grains, holds them as inclusions, and penetrates them along cleavages and cracks. Lesser amounts of cryptocrystalline chert present in the rock also have been attacked by the calcite. The chert, furthermore, appears to have formed as a wave ahead of the calcite replacements. All of the replacement features described probably are due to ground water action.

The feldspars present in the rock generally are quite fresh. Only the plagioclase shows significant alteration to clay minerals. Minerals present as inclusions in the detrital grains include apatite and sericite.

The percentage composition of the rock is estimated as follows:

Percentage Composition:

Detritals:

Quartz	09%
Microcline	03
Others	01
	13

Non-detritals:

Calcite and associated clay matter . .	87
	87
Total:	100%

Igneous and Metamorphic Sections

__Idaho Springs formation (Precambrian)__. Quartz-biotite schist. The schist is medium-grained, foliate, and dark gray in color. Megascopically it is composed of subparallel books and flakes of black biotite, gray granular quartz, pink and gray granular feldspar, and hornblende needles.

In thin section (Fig. 9), the xenoblastic-inequigranular and foliate nature of the schist is readily seen. The essential constituents of the schist are quartz, microcline, plagioclase, and biotite. Accessory minerals include hornblende, magnetite, sphene, epidote, apatite, sillimanite, zircon, and calcite.

A well developed cataclastic structure is seen in the sections. Anhedral porphyroblasts of quartz and feldspar are surrounded by small irregular, commonly subangular, grains of quartz and feldspar. Much of the cataclastic material has a fused appearance produced by the rounding of corners and the lobate edges of many of the grains.

Quartz is the most abundant constituent of the schist. It is anhedral and in part rutilated. It forms myrmekitic intergrowths with plagioclase and rounded inclusions in the microcline in addition to being the predominant mineral in the granular mosaic of the schist. Evidence of strain is found in the strong undulose extinction of the quartz.

The biotite forms anhedral to subhedral books with shredded ends. They show subparallel alignment and impart a schistosity to the rock.

FIG. 9A.

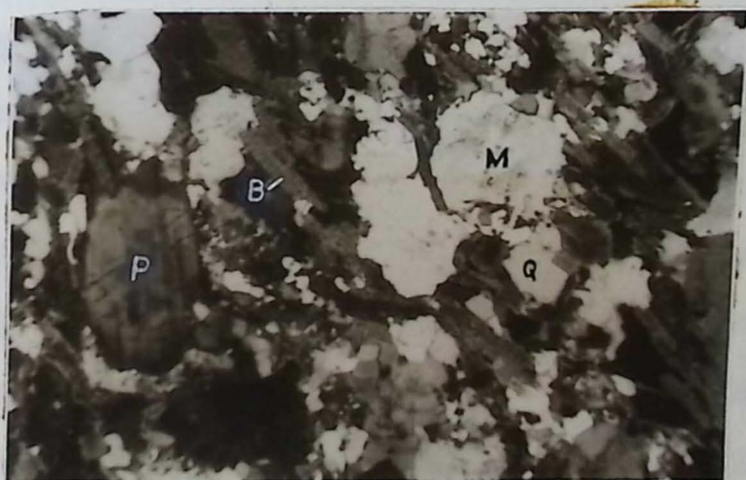

FIG. 9B.

FIG. 9. Photomicrographs of thin sections of Precambrian Idaho Springs schist. Cataclastic structures of small grains of quartz and feldspar surround porphyroblasts of quartz (Q), microcline (M), and plagioclase (sodic oligoclase) (P). Foliate nature is imparted by the subparallel alignment of biotite books (B). Microcline (M) in Fig. 9B holds poikiloblastic inclusions of quartz. Crossed nicols, X 25.

The biotite is pleochroic from light brown and green normal to the cleavage to dark brown parallel to the cleavage. Pleochroic halos about inclusions of zircon are present in some biotite books. The biotite is interstitial to the other minerals of the rock.

The microcline is generally anhedral although some subhedral porphyroblasts are present in thin sections. It displays typical quadrille structure produced by combined albite and pericline twinning, but many grains show partial loss of twinning. Some of the microcline contains numerous rounded quartz inclusions which impart a prominent poikiloblastic structure to it. Other grains show faint perthitic developments of plagioclase. Alteration to clay minerals has proceeded only to a slight degree in the microcline.

The plagioclase is less abundant than the microcline. It commonly shows albite twinning, but many grains are untwinned. Presumably such grains have lost their twinning through strain. The plagioclase is normally porphyroblastic and anhedral, but some grains show subhedral tendencies. Myrmekitic intergrowths with quartz are abundant along contacts with grains of microcline. The vermicular intergrowths indicate that the plagioclase in part formed through the replacement of microcline with the exsolution of excess silica. Albite extinction angles indicate that the plagioclase is sodic oligoclase. The plagioclase is somewhat more altered than the microcline but still quite fresh.

The hornblende forms subhedral crystals which are commonly sieved by other minerals of the rock and which display shredded ends. It is strongly pleochroic with X = light green, Y = yellowish-green, and

Z = blue-green. The hornblende, which is generally oriented in the plane of the schistosity, has imparted no distinct lineation to the schist. Epidote is present as euhedral grains interstital to and included in the other minerals, notably hornblende and biotite. It also appears as irregular developments along twin planes and cleavages in the feldspar. Traces of anhedral sphene also are present in the rock. Magnetite forms irregular to subhedral grains which are closely associated with the biotite. Zircon and apatite are present as inclusions in the feldspars and biotite. Traces of sillimanite are developed in the plagioclase. The fine crystals of sillimanite are commonly oriented with their c axes in the (010) plane of the feldspar. Traces of calcite are present as small irregular replacements in the quartz and feldspars.

The percentage composition of the schist is approximately as follows:

Percentage Composition:

Light Minerals:

Quartz	25%
Microcline	16
Plagioclase.	14
	55

Dark Minerals and Accessories:

Biotite.	32
Hornblende	07
Magnetite.	04

Epodote.	01
Sphene	trace
Zircon	trace
Apatite.	trace
Sillimanite.	trace
Calcite.	trace
	45
Total:	100%

Andesine amphibolite. The rock is distinctly banded, fine-grained, gneissic, and has a salt and pepper appearance. The layers of the rock have thicknesses on the order of one millimeter or less and are composed either of a dark amphibole (pargasite (?)) with minor amounts of gray feldspar or are composed almost wholly of feldspar. The feldspar is largely andesine, but twin striations indicative of plagioclase are not readily observed in hand specimens. No lineation of the amphibole is apparent.

Thin sections show a gneissic xenoblastic-inequigranular amphibolite composed of plagioclase and a dark green amphibole (paragasite (?)) with lesser amounts of microcline, quartz, sphene, apatite, and magnetite (Fig. 10). The plagioclase, which is the most abundant mineral in the rock, is sodic andesine (about Ab64 An46). It forms subhedral to anhedral grains of unequal size with albite and, less commonly pericline twinning. The andesine is commonly untwinned and, when twinned, the twin lamellae are commonly deformed. The loss of twinning and curved twin lamellae probably are the result of strain.

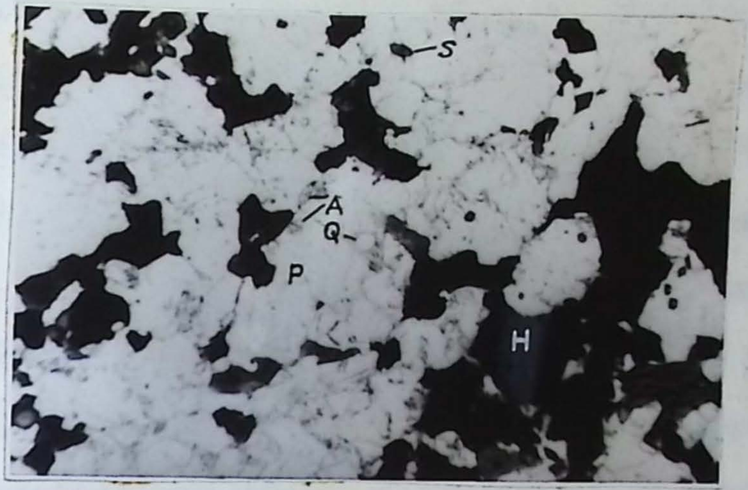

FIG. 10A.

FIG. 10B.

FIG. 10. Photomicrographs of a thin section of andesine amphibolite from the Precambrian Idaho Springs formation. Plagioclase (sodic andesine) (P) and a dark-colored amphibole (H) are the major constituents of the rock. Apatite (A) and granules of sphene (S) occur as inclusions in plagioclase in Fig. 10A. Quartz (Q) occurs as rounded inclusions in plagioclase and interstitially to the plagioclase and amphibole. Fig. 10B is under crossed nicols, X 25.

The amphibole is next in abundance after the plagioclase. It is strongly pleochroic with X = light greenish-yellow, Y = green, and Z = dark green. The optic sign is negative with 2V = 7.9 ± 0.1°; $Z \wedge c$ = 33 ± 1°. The birefringence is low with the highest interference colors in the upper first order, but the birefringence is generally masked by the dark color of the mineral. Available information, although it is contradictory, indicates that the mineral is related to pargasite, a magnesium-rich, dark-colored variety of hornblende with large extinction angles.

The pargasite (?) forms irregular to subhedral grains with ragged ends. Their shape has been determined largely by the andesine to which the grains are interstitial. The amphibole is closely associated with and commonly holds inclusions of sphene, apatite, and very minor amounts of magnetite.

The other minerals in the rock are minor constituents. The microcline is anhedral and interstitial to the plagioclase and the amphibole. It is twinned according to the albite and pericline laws and has commonly suffered partial loss of twinning. Quartz is present as an accessory mineral in irregular or rounded anhedrons which are interstitial to the other minerals. Undulose extinction is common in the quartz; it indicates that the quartz has been strained.

Small rounded granules of sphene and apatite are present as inclusions in the feldspars and the amphibole. They are closely associated with the amphibole as are the anhedral grains of magnetite.

The percentage composition of the rock is estimated as follows:

Percentage Composition:

Light Minerals:

Sodic andesine	49%
Microcline	09
Quartz	02
	60

Dark Minerals and Accessories:

Pargasite (?).	38
Sphene	01
Magnetite.	01
Apatite.	trace
	40
Total:	100%

The composition of the rock indicates that it is meta-igneous rather than metasedimentary since it lacks the typical assemblage of minerals found in metasedimentary amphibolites.

Granitic injections. The granitic injections occur as tabular and irregularly shaped bodies which extend parallel to the foliation of the schists of the Idaho Springs formation. They are pink in color, gneissic, and medium- to fine-grained. Quartz, pink feldspar, and flecks of biotite are seen readily in hand samples. The contacts between the granitic injections and the surrounding schists appear gradational.

Thin sections (Figs. 11 and 12) show a medium- to fine-grained rock with a strongly developed xenoblastic-inequigranular texture in which a gneissoid alignment of the micas is readily apparent. Poikiloblastic textures and cataclastic structures are common. The essential minerals are quartz, microcline, and biotite with lesser amounts of plagioclase and orthoclase. The accessories include epidote, zircon, apatite, calcite, sphene, sillimanite, and magnetite.

Quartz, the most common mineral, is anhedral and commonly presents sutured outlines against other minerals in the rock. It appears to be in part rutilated, and commonly forms myrmekitic intergrowths with plagioclase, particularly along the contacts between grains of plagioclase and microcline. Evidence of strain is seen in the conspicuous undulose extinction shown by the quartz.

The microcline of the rock is generally anhedral, but it may display tendencies toward subhedral outlines. It shows typical quadrille structure produced by combined albite and pericline twinning, but the twinning in some grains has been partly lost through strain. Carlsbad twinning in combination with albite and pericline twinning is uncommon. Perthitic developments of plagioclase in microcline are rare. Alteration of the microcline to clay minerals has proceeded only to a slight degree.

Some grains of microcline contain numerous rounded inclusions of quartz. Such grains appear to have formed at the expense of quartz. Some of the microcline also appears to have formed at the expense of what little orthoclase is present in the rock.

FIG. 11A.

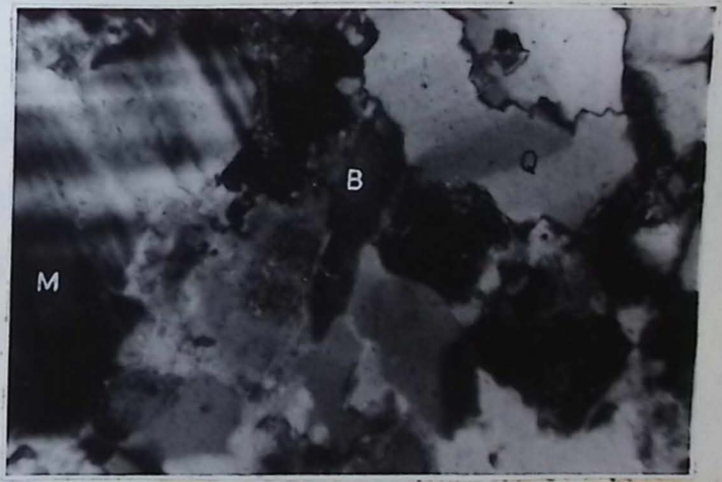

FIG. 11B.

FIG. 11. Photomicrographs of a thin section of a granitic injection into the Idaho Springs schist. Fig. 11A shows a microcline porphyroblast (M) in an xenoblastic groundmass of fine- to medium-grained quartz, feldspar, and biotite. The microcline porphyroblast shows partial loss of twinning. Crossed nicols, X 25. Fig. 11B shows an edge of the microcline porphyroblast, biotite (B), and quartz (Q). Crossed nicols, X 50.

Plagioclase, which is much less abundant than microcline, commonly shows albite twinning, but some grains are untwinned. The extinction angles and positive sign of the plagioclase indicate that it is either calcic albite or sodic oligoclase. The plagioclase normally is porphyroblastic and anhedral, but locally, subhedral grains are observed in thin sections. The plagioclase is rather more altered than the other feldspars.

Myrmekitic intergrowths of quartz in plagioclase are common along the contacts between grains of plagioclase and microcline. It is thought that the intergrowths indicate replacement of microcline by plagioclase with the exsolution of excess silica.

Orthoclase is relatively uncommon in the rock. It forms anhedral and subhedral phenocrysts which are difficult to distinguish from untwinned plagioclase or sections of plagioclase cut parallel to the (010) direction. No definite relationships have been determined between the orthoclase and the other minerals.

Biotite is the prominent dark mineral in the granite injections. It forms anhedral and subhedral books with a pronounced parallel alignment, thus giving the rock its gneissic fabric. The biotite is pleochroic from light brown and green normal to the cleavage to dark brown, almost black, parallel to the cleavage. Pleochroic halos about inclusions of zircon are numerous.

Among the accessory minerals, apatite and zircon are common as inclusions in the other minerals. Magnetite, epidote, and sphene are present as euhedral to anhedral grains closely associated with the biotite. Some epidote, however, is developed along cleavages and twin planes in the feldspars. Sillimanite is present in the plagioclase where it occurs as minute crystals oriented about parallel to the (010) direction. Traces of calcite appear as replacements in the quartz and feldspars.

The composition of the granitic injections is estimated as follows:

Percentage Composition:

Light Minerals:

Quartz	41%
Microcline	33
Plagioclase.	11
Orthoclase	02
	87

Dark Minerals and Accessories:

Biotite.	10
Magnetite.	01
Sillimanite.	01
Apatite.	01
Zircon	trace
Epidote.	trace
Sphene	trace
Calcite.	trace
	13
Total:	100%

Under the microscope, the boundary between the schists and the granite injections is seen to be gradational (Fig. 12). The major differences between the two types of rock are the greater preponderance of biotite and the presence of hornblende in the schists. There is also an increase in the percentage of magnetite in the schist when compared to the granite and a decrease in the amount of sillimanite in the schist farther away from the contact with the granite. The schist adjacent to the granitic injections, furthermore, is richer in microcline and poorer in plagioclase than that more distant from the granitic injections.

The composition of a sample of quartz-biotite schist from the contact with a granite injection is cited below. For comparison, see page 110 for the composition of the schist more distant from the granitic injections.

Percentage Composition:

Light Minerals:

Quartz 25%
Microcline 21
Plagioclase. 09
Orthoclase 01
56

Dark Minerals and Accessories:

Biotite. 32
Hornblende 07
Magnetite. 04

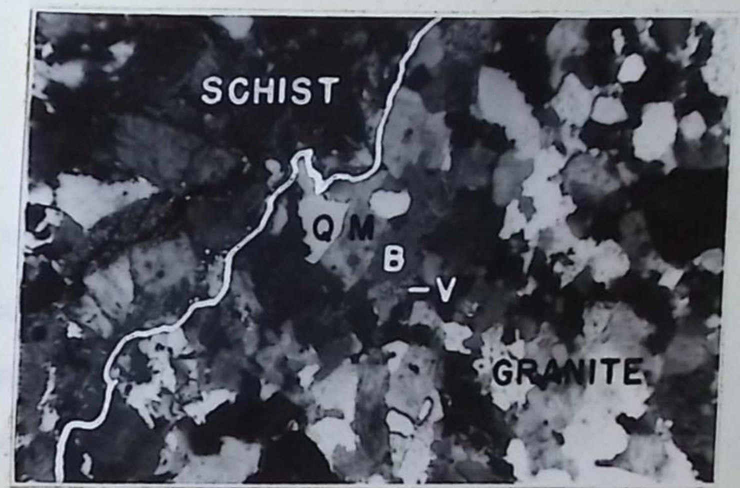

FIG. 12. Photomicrograph of a thin section showing the gradational contact between a granitic injection and the Idaho Springs schist. Irregular white line marks the approximate contact. Q, quartz, M, microcline, P, plagioclase, B, biotite, V, vermicular intergrowths of quartz in plagioclase. Crossed nicols, X 25.

Zircon	00.5
Sillimanite.	trace
Apatite.	trace
Epidote.	trace
Sphene	trace
Calcite.	trace
	44
Total:	100%

Indications are that the original sediments have not only been metamorphosed and injected by igneous material, but that a certain amount of igneous material has been added to the metasediments, perhaps by replacement.

Pegmatitic adamellite injections. The pegmatitic adamellite injections range in thickness from less than an inch up to several feet or more. They are injected along the planes of foliation of the schist and show sharp contacts with the schist.

The pegmatites are allotriomorphic-inequigranular and coarse-grained. They are composed of quartz, plagioclase, and microcline, with lesser amounts of magnetite. They show a distinct zonation with quartz forming a central core and the feldspars arranged along the outer edges of the injections (Fig. 13). Cataclastic structures and shears are well developed in the pegmatites as well as along the contacts with the schist.

The quartz of the pegmatities is anhedral with strong undulose extinction. It is generally fractured and free of inclusions. Most

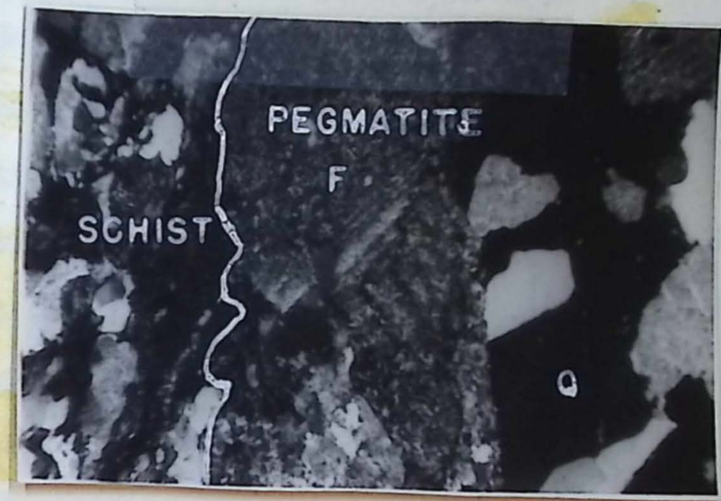

FIG. 13. Photomicrograph of a thin section of pegmatitic adamellite injection into Idaho Springs schist. Contact between the pegmatite and the schist is marked by the irregular white line. The schist is highly granulated along the contact. The pegmatite has a core of quartz (Q) which is bounded by feldspars (F) which comprise highly altered oligoclase and microcline. Crossed nicols, X 25.

of the quartz is concentrated in the central portions of the injections where little or no feldspar is present.

The feldspars of the pegmatites are concentrated along the contact with the schist. They are oligoclase and microcline. Both feldspars have suffered considerable alteration and loss of twinning. The alteration products include clays and sericite.

Magnetite is present in large anhedra. It seems to be a late introduction into the pegmatites since it fills fractures and has developed reaction rims against the feldspars. The reaction rims are composed of chlorite and biotite rather than clay minerals.

The percentage composition of the pegmatites is estimated as follows:

Percentage Composition:

Light Minerals:

Quartz	41%
Oligoclase	31
Microcline	20
	92

Dark Minerals and Accessories:

Magnetite	07
Chlorite and Biotite	01
	08
Total:	100%

In thin section, the schist found adjacent to the pegmatites is essentially the normal quartz-biotite schist of the Idaho Springs formation. It has, however, undergone certain changes as a result of the emplacement of the pegmatites. Along the contacts with the pegmatites, the schist has been granulated and sheared. The quartz and feldspars form a fine-grained and highly altered mosaic of irregular grains which have a fused appearance. Alteration products derived from the feldspars include sericite and clay minerals. The biotite in the altered zone of the schist has been converted in part to penninite and magnetite. Thus the granulated feldspars and quartz are intimately associated with shredded books of intergrown chlorite, biotite, and magnetite.

The introduction of the pegmatites took place along planes parallel to the foliation of the schist. It was, furthermore, forceful, as is evidenced by the intense shearing and granulation of the schist along the borders of the pegmatite injections. Some retrograde thermal metamorphism of the schist also took place when the pegmatites were injected. The biotite of the schist was partially converted to chlorite and magnetite; clay minerals and sericite developed in the feldspars.

Adamellite gneiss (Precambrian). Megascopically, the rock is pink, inequigranular, medium-grained and shows a gneissoid segregation of light and dark minerals. Under the hand lens, it is seen to be composed of anhedral quartz, subhedral to anhedral pink feldspar, and small flakes of biotite. The feldspar includes both microcline and plagioclase, but the albite twinning of the plagioclase is not readily determined by megascopic means.

Microscopically (Fig. 14), the rock is a medium-grained, xenoblastic-inequigranular gneiss. Slight porphyroblastic developments are shown by some of the plagioclase grains. Sieve structures and cataclastic affects are also present. Subparallel alignment of biotite and quartz gives the rock its gneissic texture. The rock is leucocratic, containing less than eight percent dark minerals. The essential constituents are quartz, microcline, and sodic oligoclase.

The quartz is anhedral with irregularly rounded outlines. It is largely interstitial to the other minerals, but may include flakes of biotite or appear as inclusions in microcline and plagioclase. Minor amounts of the quartz are myrmekitically intergrown with the plagioclase. Undulose extinction in the quartz is evidence of strain.

The microcline is characterised by quadrille structure produced by combined albite and pericline twinning. It forms subhedral to anhedral grains of uneven size that are slightly altered to clay minerals. It holds inclusions of biotite, plagioclase, and quartz. Some of the microcline appears to have been replaced by plagioclase. Much of the microcline appears partly untwinned. Any loss of twinning probably is the result of strain. Some of the microcline is perthitic.

Plagioclase forms subhedral to anhedral porphyroblasts as well as subhedral and anhedral grains in the groundmass of the rock. It displays albite twinning. Some grains of plagioclase show combined albite and Carlsbad twinning, but much of the plagioclase appears untwinned. The apparent lack of twinning probably is the result of

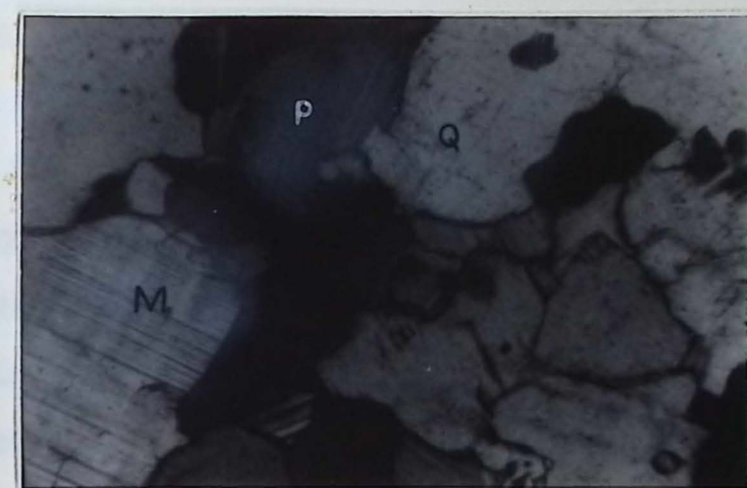

FIG. 14. Photomicrograph of a thin section of the Precambrian adamellite gneiss. M, microcline, P, plagioclase (sodic oligoclase), and Q, quartz. Crossed nicols, X 50.

preferred orientation of the plagioclase with the (010) direction about parallel to the plane of the thin sections. Myrmekitic intergrowths of plagioclase and quartz are present in some grains, particularly where the plagioclase borders on microcline. It is thought that the plagioclase has replaced the microcline with the exsolution of the excess silica from the microcline. Extinction angles and optic sign indicate that the composition of the plagioclase is about that of sodic oligoclase. Much of the plagioclase shows a high degree of agrillic alteration.

Biotite is the major dark mineral. It forms anhedral and subhedral fine-grained books and flakes. The biotite is pleochroic from green normal to the cleavage to brown and almost black parallel to the cleavage. Although the biotite is present as inclusions in other minerals, it is largely interstitial in occurrence. Pleochroic halos about grains of zircon are common in the biotite books.

Minor amounts of euhedral apatite and zircon are present as inclusions in grains of the other minerals. Anhedral blebs of hematite replacing quartz are also present. Interstitial limonite is dispersed through the rock. Clay matter present is an alteration product of the feldspars, particularly the plagioclase. Two generations of magnetite seem to be present in the rock: one is primary and forms euhedral grains; the other is probably secondary and appears to be derived from the alteration of biotite.

The percentage composition of the rock is estimated as follows:

Percentage Composition:

Light Minerals:

Quartz	31%
Microcline	33
Plagioclase.	28
	92

Dark Minerals and Accessories:

Biotite.	06
Limonite and hematite.	01
Magnetite.	01
Apatite.	trace
Clay matter.	trace
Zircon	trace
	08
Total:	100%

The composition and texture of the rock warrant its classification as an adamellite gneiss.

Undifferentiated Precambrian Rocks. The rocks described under the heading "Undifferentiated Precambrian Rocks" include those that were not mapped as independent units.

Gneissic granite. The rock is a medium- to coarse-grained porphyritic gneissic granite. It shows subparallel alignment of biotite books and the long dimensions of quartz and feldspar grains. Pink microcline and plagioclase phenocrysts stand out from the medium-grained groundmass which megascopically is seen to be composed of similar feldspars, quartz, and biotite.

Thin sections (Fig. 15) show a medium- to coarse-grained hypallotriomorphic granite with a gneissic structure and subhedral porphyritic feldspars. Poikilitic inclusions and cataclastic structures are common. The essential constituents of the rock include microcline, quartz, sodic oligoclase, and biotite. Accessory minerals include magnetite, epidote, sphene, zircon, apatite, and sillimanite. Clays, leucoxene, sericite, and limonite are present as alteration products of the other minerals.

Subhedral microcline occurs as grains in the groundmass and as phenocrysts. It is twinned according to the albite and pericline laws and some phenocrysts show Carlsbad twinning as well. Rounded inclusions of quartz have produced prominent sieve structures. Lesser amounts of epidote occur as anhedral grains and irregular stringers along cleavages and twin directions. Clay minerals, sericite, and traces of sillimanite are present as minute crystals in the microcline.

Quartz forms anhedral stringers and grains. It also occurs as inclusions in the microcline and in myrmekitic intergrowths with plagioclase near the contacts between plagioclase and microcline. The quartz is commonly rutilated, but holds no other inclusions. It shows strong undulose extinction and is commonly fractured.

Plagioclase forms subhedral to anhedral grains and phenocrysts. It shows albite and less commonly Carlsbad twinning. Extinction angles measured on albite twinning and the 2V of almost 90 degrees indicate that it is sodic oligoclase. Myrmekitic intergrowths with quartz near the contact of the plagioclase with grains of microcline are common.

FIG. 15. Photomicrograph of a thin section of Precambrian gneissic granite. M, microcline, Q, quartz, P, plagioclase (sodic oligoclase), and B, biotite. The quartz shows undulose extinction and fracturing. Note the rounded inclusions of quartz in the microcline grains. Crossed nicols, X 25.

They indicate that some of the plagioclase may have formed at the expense of microcline during metamorphism. The plagioclase holds inclusions of apatite, zircon, magnetite, and epidote. Also present in the plagioclase are minor amounts of sillimanite and considerable clay matter. Ferritic pigment seems to account for the pink color shown by the plagioclase in hand specimens.

Biotite, like plagioclase, is a minor constituent of the rock. It forms subhedral to anhedral books that are largely interstitial to the other minerals and have a highly feathered appearance. The biotite is strongly pleochroic from light greenish-brown normal to the cleavage to dark brown parallel to the cleavage. Pleochroic halos about inclusions of apatite and zircon are common.

Magnetite is present in anhedral blebs that are closely associated with biotite, epidote, and sphene. The sphene forms wedge-shaped crystals and anhedral grains with a dark brown color which masks the high birefringence of the mineral. Much of the sphene has undergone partial decomposition to leucoxene and a metamict alteration product. Epidote is present in anhedral grains interstitial to the other minerals and as irregular stringers along cleavage and twin planes in the feldspars. Traces of sillimanite are also present in the feldspars as are minor amounts of sericite. Clays and limonite are common alteration products in the rock.

The approximate percentage composition of the rock is:

Light Minerals and Accessories:

Microcline	41%
Quartz	32
Plagioclase.	12
	85

Dark Minerals and Accessories:

Biotite.	08
Magnetite.	03
Sphene	01
Epidote.	01
Zircon	trace
Apatite.	trace
Sericite	trace
Sillimanite.	trace
Leucoxene.	trace
	15
Total:	100%

Gneissic aplitic granite. The rock is a fine-grained, pink to gray granite with a distinct gneissic structure. With the aid of a hand lens, the following minerals are identified readily: quartz, pink feldspar (largely microcline), and small amounts of biotite and magnetite. The gneissic structure is produced by the parallel alignment of the long dimensions of the quartz and feldspar grains the subparallel alignment of mica books.

Thin sections (Fig. 16) display a fine-grained allotriomorphic-inequigranular granite in which no mineral shows strong porphyroblastic tendencies. The rock is leucocratic and contains eight percent dark minerals. The gneissic fabric is readily apparent under the microscope. The essential constituents of the rock are microcline, quartz, sodic oligoclase, and biotite. The accessory minerals include magnetite, limonite, zircon, apatite, and leucoxene. Most of the feldspar grains have undergone more or less alteration to clay minerals.

Microcline is the most abundant mineral. It forms anhedral to subhedral grains which display both albite and pericline twinning, but some of the microcline has lost its twinning, probably through strain. Further indications of strain are seen in the bent twin lamellae shown by some grains. The microcline has been only slightly altered to clay minerals.

Quartz is anhedral with lobate grain boundaries. It is commonly collected into stringers and minor amounts of quartz are myrmekitically intergrown with plagioclase. The strong undulose extinction shown by much of the quartz indicates that the rock has been subjected to considerable strain.

Plagioclase is a relatively minor constituent. It forms subhedral to anhedral phenocrysts and finer grains in the groundmass of the rock. Some plagioclase grains show a faint zonation of their margins where the composition approaches calcic albite, but the plagioclase is largely sodic oligoclase. Small myrmekitic intergrowths of quartz are present in many plagioclase grains along the contacts with grains of microcline.

FIG. 16. Photomicrograph of a thin section of Precambrian gneissic aplitic granite showing quartz (Q), microcline (M), and plagioclase (P). Vermicular intergrowths of quartz (V) in plagioclase occur adjacent to the microcline grain marked M. Crossed nicols, X 25.

Twinning has been according to the albite law, and the twin lamellae are commonly bent, thus indicating that the rock has been subjected to considerable strain. Clay minerals are present as an abundant alteration product of the plagioclase.

Biotite forms small subhedral books which are pleochroic from almost black parallel to the cleavage to light yellow-green normal to the cleavage. The pronounced subparallel alignment of the biotite books in part contributes to the gneissic fabric of the rock. Pleochroic haloes about zircon inclusions are apparent in some of the biotite.

Magnetite and small amounts of ilmenite are commonly associated with the biotite. Zircon and sphene occur as small euhedral crystals included in the other minerals of the rock. Limonite and leucoxene are associated with the magnetite, ilmenite, and biotite.

The percentage composition of the rock is estimated as follows:

Percentage composition:

Light Minerals:

Quartz	38%
Microcline	46
Plagioclase.	07
	91

Dark Minerals and Accessories:

Biotite.	05
Magnetite and ilmenite	03
Limonite	00.5

Leucoxene	trace
Apatite	trace
Sphene	trace
	99
Total:	100%

Gneissic chlorite adamellite. The rock is a dense, medium-grained, inequigranular adamellite with a distinct gneissic structure. Its color is salmon-pink with streaks of grey. The rock was found to overlie and underlie the Tertiary (?) dike. Its lateral extent is not known.

Megascopically, quartz and pink feldspar are the predominant minerals in the rock which contains between 10 and 15 percent dark minerals. The feldspar is largely plagioclase, but it is difficult to distinguish the plagioclase from the less abundant microcline. The dark minerals include a dark-colored chlorite that is almost indistinguishable from biotite, magnetite, and pyrite. Small amounts of white clinochlore which closely resemble sericite and small amounts of epidote can be observed.

In thin section (Fig. 17), the adamellite is xenoblastic-inequigranular with some plagioclase phenocrysts and a distinct gneissic fabric. Locally, cataclastic structures are observed between the constituent grains. The leucocratic components are most abundant; they total approximately 87 percent of the rock. They include quartz, plagioclase, and microcline as the prevalent minerals. Chlorite is the most important dark mineral. Other minerals include epidote, sphene, magnetite, white clinochlore, clay matter, and minor amounts of limonite,

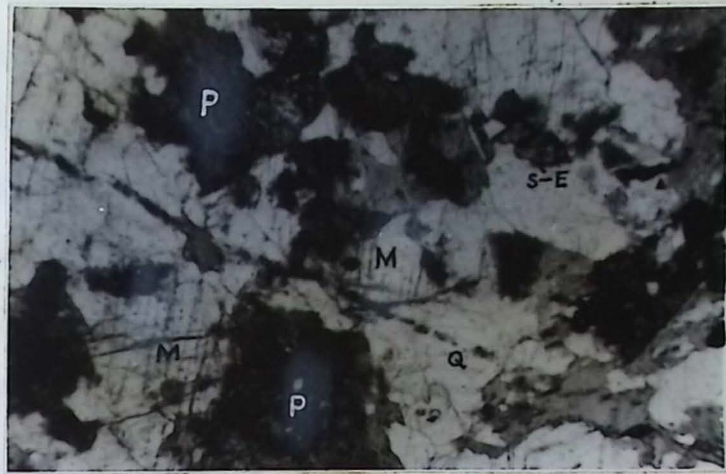

FIG. 17A.

FIG. 17B.

FIG. 17. Photomicrographs of a thin section of the Precambrian gneissic chlorite adamellite. Fig. 17A shows highly altered plagioclase (P), microcline (M), quartz (Q), chlorite (C), and sphene and epidote (S-E). The rock is highly fractured. X 25. Fig. 17B shows the same section under crossed nicols. Some unaltered plagioclase (P) is apparent in the upper left corner. Note the rounded inclusions of quartz in the feldspars.

pyrite, zircon, and apatite.

The feldspars constitute approximately 55 percent of the rock. In general, they are highly altered to clay minerals and contain considerable ferritic pigment, thus imparting the salmon-pink color to the rock. The dominant feldspar is plagioclase. Measurement of albite extinction angles indicates that it is sodic oligoclase (Ab87 An13). It forms small anhedrons and less commonly, subhedral phenocrysts. The plagioclase shows albite twinning and some of the phenocrysts show Carlsbad twinning as well. The albite twin lamellae in some of the phenocrysts of oligoclase have been distorted by strain. Evidence of the albite twinning persists although the plagioclase may be highly altered to clay minerals. In most cases, the plagioclase presents irregular outlines against the other minerals, but some grains show subhedral outlines. The plagioclase holds inclusions of chlorite, apatite, zircon, and magnetite.

The microcline is anhedral except where it has formed adjacent to subhedral plagioclase grains. Most grains display quadrille structure produced by combined albite and pericline twinning, but some of the grains have lost part of their twinning, presumably by strain. The microcline is less intensely altered than the plagioclase, but like the plagioclase, is stained by iron.

The quartz is relatively free of inclusions, but some seems to be rutilated. The grains are anhedral with very irregular rounded outlines. Undulose extinction evidences considerable strain. Cataclastic structures are found between some of the quartz grains and the adjacent feldspars.

Nearly the last mineral to form, the quartz is interstitial to the other minerals, but very strongly interlocked with them. The quartz also appears as inclusions in the plagioclase and microcline.

The chlorite occurs in irregular subparallel stringers that are much intergrown with the other minerals. Two types of chlorite are apparent. One is pale green and only faintly pleochroic; it displays an anomalous berlin-blue interference color. It is penninite, the more abundant type of chlorite. The other, which is almost clear with low first order interference colors is probably clinochlore. The clinochlore occurs in somewhat rounded or ellipsoidal flakes that can be resolved only under higher magnification. It is commonly present as an intergrowth with the penninite.

The epidote and sphene commonly occur together in anhedral blebs and stringers dispersed through the rock. The epidote is distinguished from the sphene by its yellowish-green color, faint pleochroism, and high birefringence. The sphene is brown in color and its high birefringence is somewhat masked by the color. Both have suffered alteration to an opaque amorphous material, part of which is leucoxene.

The magnetite and pyrite occur as anhedral blebs dispersed through the rock. They are commonly, but not consistently, associated with the epidote and chlorite. Zircon and apatite occur as minor constituents, a number of euhedral grains of each being dispersed through the rock.

The following is the estimated percentage composition of the rock:

Percentage Compositions

Light Minerals:

Plagioclase	31%
Microcline	24
Quartz	26
	81

Dark Minerals and Accessories:

Chlorite	08
Magnetite	04
Epidote	03
Sphene	02
Pyrite	01
Limonite	trace
Zircon	trace
Apatite	trace
	19
Total:	100%

The ratios of quartz, sodic oligoclase, and microcline warrant classification of the rock as an adamellite or quartz monzonite.

The extreme xenoblastic-inequigranular nature of the rock may be due in part to recrystallization of the rock under metamorphic conditions. The loss of twinning in the microcline, the bent twin lamellae in the plagioclase, and the strong undulose extinction of the quartz indicate that the rock has been subjected to considerable strain. Recrystallization under metamorphic or even deuteric conditions may account for the presence of chlorite rather than biotite, and also for the abundance of epidote and sphene.

Adamellite gneiss. The adamellite gneiss found in the zone of undifferentiated rocks is identical with that described on pages 124 to 128 and is not described here.

Pegmatite dikes (Precambrian). Pegmatite dikes in the thesis area are petrographically identical to the pegmatitic adamellite injections in the Idaho Springs formation except for their structural relations to the host rocks. Accordingly, they are not discussed here and the reader is referred to the description of the pegmatitic adamellite injections on page 121.

Pikes Peak granite (Precambrian). The rock is a medium- to coarse-grained porphyritic granite with a faint gneissic texture. The color is pink to brown. The predominant minerals are quartz and pink feldspar, some of which is plagioclase. The quartz forms anhedral crystals which commonly are segregated into faint bands between the porphyritic feldspars. The feldspar phenocrysts appear euhedral because of well developed cleavages. Biotite, some of which is bleached, is the only other mineral readily recognized in hand specimens. Its subparallel alignment adds to the gneissic character of the rock.

Thin sections (Fig. 18) show a hypidiomorphic-inequigranular rock with prominent feldspar phenocrysts and cataclastic structures. Generally highly weathered, the rock contains only two or three percent dark minerals, and the plagioclase feldspar has been highly altered to clay minerals. The faint gneissic structure seen in hand specimens is not

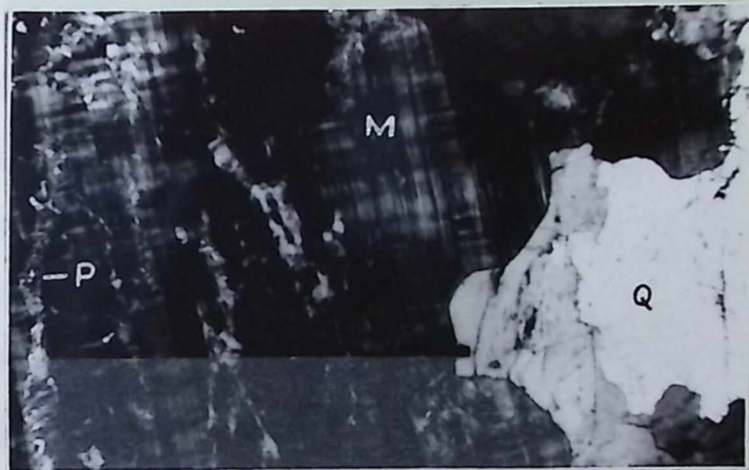

FIG. 18. Photomicrograph of a thin section of Precambrian Pikes Peak granite showing microcline phenocryst (M) and quartz (Q). Perthitic plagioclase intergrowths (P) are the same composition (albite) as the plagioclase in the remainder of the rock. Crossed nicols, X 25.

recognized readily in the small area of a thin section.

Quartz is a dominant mineral in the rock. It is anhedral in form and displays strong undulose extinction. The extreme anhedral nature of the quartz probably can be attributed to its late crystallization whereby it filled interstices in the granite. The quartz is somewhat rutilated, but is free of other inclusions.

The dominant feldspar is microcline. It displays prominent quadrille structure and is somewhat perthitic. The plagioclase intergrowths in the microcline are of the same composition as the plagioclase in the remainder of the rock (albite). The larger microcline crystals may hold plagioclase inclusions as well as the perthitic intergrowths. The microcline is slightly altered to clay minerals and commonly contains ferritic pigment.

Plagioclase in the thin sections forms large phenocrysts with prominent albite twinning; Carlsbad twinning is uncommon. The plagioclase is albite (Ab96 An4). In general, it is highly altered to clay minerals, but ghosts of the albite twinning commonly persist. The crystals are subhedral and commonly show irregular borders against the quartz and microcline. Ferritic pigment imparts the salmon-pink color to the plagioclase.

Biotite is in subhedral books with feathered ends. It is pleochroic from light brown normal to the cleavage to dark brown parallel to the cleavage.

Limonite and hematite are present in the cataclastic portions of the rock and in stringers filling cracks between grains. Magnetite forms subhedral grains dispersed through the rock. Minor traces of sericite are developed in the microcline as are traces of epidote in the plagioclase.

The percentage composition of the rock is approximately:

Light Minerals:

Quartz	36%
Microcline	35
Plagioclase	23
	94

Dark Minerals and Accessories:

Biotite.	03
Limonite and hematite	02
Magnetite	01
Sericite	trace
Epidote	trace
	06
Total:	100%

The cataclastic structures and the weak allotriomorphic texture of the rock probably reflect the influence of tectonic stress during weak regional metamorphism.

Diabase Dike (Tertiary (?)). The following descriptions are of samples selected from the Tertiary (?) diabase dike in Sec. 5, T. 23 S., R. 68 W., Pueblo County. The samples were taken from the contact of the dike with the Precambrian chlorite adamellite, the chilled margin, and the center of the dike.

Contact with the Precambrian chlorite adamellite. The specimen shows a dark-colored, fine-grained argillaceous rock in contact with the dense salmon-pink medium-grained adamellite. Red hematitic stringers are arranged roughly parallel to the contact in the hand sample.

In thin section, the hematitic bands are seen to be granulated and altered zones of the adamellite between less intensely altered zones of the adamellite and the intruded material. The chilled margin of the dike in the sample is altered to chlorite, serpentine and clay minerals. Considerable amounts of calcite, limonite, and magnetite are also present. Small xenoliths of the adamellite are included in the chilled diabase. They are highly granulated and replaced by calcite. The feldspars in the xenoliths have been altered to clays where unreplaced by calcite.

The adamellite bordering the dike is highly altered and granulated. Clinochlore is a common alteration product of the feldspars in those portions of the rock adjacent to the dike. Clayey alteration products are also abundant. They are primarily derived from the feldspars. Hematitic material and irregular blebs of limonite are readily apparent in the granulated quartz.

Chill zone. The hand sample is a dark greenish-black and extremely fine-grained. Some very fine-grained plagioclase laths can be recognized with the aid of a hand lens.

Microscopically, the rock shows a diabasic texture of fine-grained (less than one millimeter long) lath-like plagioclase microlites and dark colored interstitial material. Even in the thin section, the rock is dark green in color.

The plagioclase microlites show both Carlsbad and albite twinning. The composition is about that of medium labradorite. The laths are both randomly oriented and arranged in radial clusters. The interstitial material is difficult to determine. Some is feathery and green, showing slight birefringence. The remainder of the interstitial material is composed of well developed black longulites which are opaque and black in color. They cross one another to produce a distinct telegraph-pole pattern. The longulites probably represent the early stage of crystallization of the skeletal magnetite found in the center of the dike. Small amounts of calcite are also discernable in the rock.

Center of dike. The hand sample is a fine-grained greenish-black rock in which the plagioclase laths are the only recognizable minerals. Their random orientation and lath-like shape indicate a diabasic or ophitic texture.

In thin section (Fig. 19), the rock is fine-grained and melanocratic with a diabasic arrangement of plagioclase and interstitial remnants and alteration products of dark minerals. The dominant minerals in the rock are plagioclase, magnetite, serpentine, actinolite, and calcite.

The plagioclase, which has been partly altered to clay minerals, is the major constituent of the rock. It shows both Carlsbad and albite twinning. Extinction angles indicate that it is labradorite at least as calcic as Ab40 An60. The plagioclase boundaries are commonly penetrated by other minerals, namely the earlier formed skeletal magnetite and the later formed actinolite which is presumed to be an alteration product

FIG. 19A.

FIG. 19B.

FIG. 19. Photomicrographs of a thin section from the center of the Tertiary (?) diabase dike in Section 5, T. 23 S., R. 68 W., Pueblo County. Fig. 19A shows the diabasic arrangement of the plagioclase (P) and the interstitial remnants and alteration products (G) of the dark minerals. Two generations of magnetite (M) are present. X 25. Fig. 19B shows the two generations of magnetite under higher magnification (X 50). The skeletal magnetite is primary; the anhedral magnetite was formed through the alteration of the primary dark minerals.

after augite.

Two generations of magnetite are present in the rock. One is primary magnetite which is formed as skeletal crystals. The other is secondary magnetite which has formed through the alteration of the original dark minerals. Also present as alteration products are actinolite, serpentine, calcite, clay minerals, and limonite.

Indications are that the alteration products have been derived from a pyroxene, probably augite, and from minor amounts of olivine. Chlorite, which is the normal alteration product of most amphiboles, is totally absent from the rock. The alteration products present are those normally derived from a pyroxene and the abundance of calcite in the rock indicates that it was relatively rich in calcium, i.e., augite.

The former presence of olivine is inferred from the habit of some of the calcite. Crystalline calcite shows continuous optic orientation within each isolated grain. The grains are traversed by irregular cracks similar to those developed in olivine. Furthermore, the calcite has preserved no traces of cleavage as might be expected if it were pseudomorphous after a pyroxene.

The percentage composition of the rock is estimated as follows:

Percentage Composition:

Labradorite	49%
Magnetite: primary.	11
secondary.	04
Calcite	14

Serpentine 12

Actinolite 06

Clays: other than those derived
from plagioclase. 03

Limonite . . . . trace to 01

Total: 100%

From the above information, it can be concluded that the original rock was composed of labradorite laths with interstitial pyroxene, probably augite, magnetite, and perhaps minor amounts of olivine. The texture indicates that crystallization occurred in place since neither the rock described above nor the chilled margins show any flow structure.