

**GEOLOGIC SETTING AND XENOLITHS OF THE LODGEPOLE  
INTRUSIVE AREA: IMPLICATIONS FOR THE NORTHERN  
EXTENT OF THE STILLWATER COMPLEX, MONTANA**

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A Thesis Submitted  
to the Temple University Graduate Board

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in Partial Fulfillment  
of the Requirement for the Degree

**MASTER OF ARTS**

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by

Robert A. Brozdowski

May 1983

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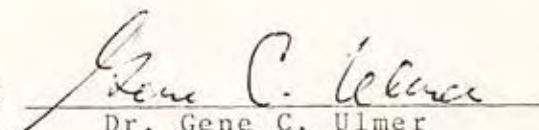
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Master of Arts in Geology

College of Arts and Sciences

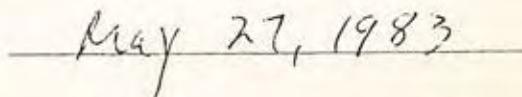
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### Abstract

Northerly dipping compositional layering in the central and western portions of the Stillwater Igneous Complex, the moderate northward slope of the Beartooth Front north of these outcrops, as well as gravity data (Bonini, 1981) provide structural evidence for the continuation at depth of the Complex north of the middle Cambrian unconformity along its northern boundary.

The Lodgepole, Enos Mountain and Susie Peak plutons represent multiple intrusions of intermediate magmas at emplacement depths ranging from 2 km to near-surface conditions during late Cretaceous time. These intrusions lie respectively 8, 9, and 12 km north of the nearest outcrops of the Stillwater Complex. The Lodgepole Intrusion consists of an early dacite phase and a later diorite phase, the latter containing abundant xenoliths (up to 31 cm in diameter) in the area north of Clover Basin near its western margin. These xenoliths include foliated mafic amphibolites, gneisses, Paleozoic sediments, and cumulate textured basic rocks. Smaller xenoliths of similar lithologies are found in the Enos Mountain and Susie Peak intrusions.

The cumulate textured xenoliths have magmatic textures, basic silica contents, and tholeiitic normative mineralogies.

The euhedral to subhedral, medium to coarse grained, tabular plagioclase in the xenolith sample suite has a total span of An62 to An86 (mole %) with variability in a single sample generally 1 to 5 mole % An. Minor primary-appearing augite is found in anorthositic specimens, but most of the primary mafic minerals have been altered to calcic amphibole and chlorite. The external habit and mineralogy of some mafic mineral domains suggest that they are pseudomorphic after primary pyroxenes and olivine. Based on interpretation of mineralogy and texture, cumulate xenoliths were classified as anorthosites, gabbros, norites, gabbro-norites, troctolites, and altered ultramafic lithologies. One xenolith contained chromite, one contained graphite, and a few contained minor Fe and Cu sulfides.

Mineral compositions and textures lead this author to conclude that the xenoliths were brought up from the underlying Stillwater Complex. Based on estimates of the fluid properties of an andesitic magma above its liquidus, ascent rates of greater than 1.7 m/second were needed to have raised the cumulate xenoliths. The lack of xenoliths with plagioclase compositions  $< \text{An}_{62}$ , as well as structural space constraints imposed by the existence of non-cumulate basement lithologies north of the East Boulder Fault lead this author to question the existence of the thick differentiated Hidden Zone postulated by Hess (1960).

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Chapter I

Introduction

## INTRODUCTION

The Stillwater Complex is a well-studied layered basic intrusion of Archean age (DePaolo and Wasserburg, 1979), located in south-central Montana. It is a repository for deposits of platinum group metals, chromite, and base metal sulfides. Structural and geophysical data (Bonini, 1981) provide evidence that the Complex extends at depth to the north of its outcrop belt. Hess (1960) proposed that a stratigraphically higher, more differentiated Stillwater Complex Hidden Zone exists beneath the middle Cambrian sediments which unconformably overlie the uppermost exposed layers of the Complex.

The late Cretaceous Lodgepole, Enos Mountain, and Susie Peak intrusions lie from 8 to 12 km north of the nearest Stillwater Complex outcrop, and therefore should have cut across any northern subsurface continuation of the Complex during their emplacement. Based on hand specimen examination, early workers (Howland et al., 1936; Rouse et al., 1937) interpreted cumulate textured xenoliths found in these Cretaceous intrusions as having been brought up from the underlying Stillwater Complex. The primary focus of this study is to characterize the chemistries, textures, and trends in mineral compositions of these

xenoliths in an attempt to support or refute their origin from the Stillwater Complex. No systematic study of the xenoliths had been carried out previously.

Both the regional and detailed structural settings of the Lodgepole, Enos Mountain, and Susie Peak intrusions were studied in order to determine the mode of emplacement and relationship to basement of these intrusions.

Possible correlations between the xenolith suite collected from these intrusions and Bonini's (1981) gravity model for the northern continuation of the Stillwater Complex are discussed.

## GOALS OF STUDY

The following points outline the goals of this investigation:

- (1) Summarize the regional geologic setting of the Stillwater Complex and review the existing lines of structural and geophysical evidence for the northern continuation of the Stillwater Complex.
- (2) Integrate the late Cretaceous Lodgepole, Enos Mountain and Susie Peak intrusions into the regional structural setting described in (1) above in order to provide a framework in which to further study these intrusions and the xenoliths they contain.
- (3) Map the detailed contact relations of the Lodgepole Intrusion both in relation to its contact with the country rock and with regard to internal relationships among its intrusive phases.
- (4) Study the lithology, size, angularity, and geographic distribution of xenoliths with regard to their abundance among the intrusive phases of the Lodgepole Intrusion, and attempt to explain any observed differences in the nature and distribution of the xenoliths with reference to the geology and structural setting of the pluton.

(5) Select a diverse suite of cumulate textured plutonic xenoliths from among the samples collected for a detailed study of whole rock chemistries, meso- and micro-scopic textures and fabrics, and mineral compositions. On the basis of the petrologic, textural, and mineralogical data gathered, attempt to support or refute the hypothesis offered by Rouse et al. (1937) and repeated by Garbarini (1957), that the cumulate textured xenoliths were brought up from the underlying Stillwater Stratiform Complex. Use the detailed petrologic and mineralogic studies of Jackson (1961), Hess (1960), and Raedeke (1979, '82) as a basis for comparison.

(b) From a consideration of the relationships between the Lodgepole intrusion and the xenoliths, attempt to explain any metamorphic mineral assemblages in the xenoliths.

(7) From a consideration of the intrusive phase compositions within the Lodgepole Intrusion, from the contact relations of the intrusive phases with the country rocks, and from the size and density of the xenoliths, attempt to place constraints on the physical parameters associated with the Lodgepole pluton, such as the magma temperature at the time of emplacement, the style of emplacement and the possible range of emplacement rates.

(8) Conduct a reconnaissance level field investigation of the Enos Mountain and Susie Peak intrusions to verify the presence of xenoliths (Rouse et al., 1937) and to determine their nature and abundance. Use the xenoliths to define the possible nature of the underlying basement lithologies, and compare the suites collected at Enos Mountain and Susie Peak to the suite collected from the Lodgepole intrusion.

As this study progressed, consideration of data gathered in (1) through (8) above defined additional goals:

(9) Compare the compositional and mineralogical data gathered in (5) above with the inferred composition of the postulated Upper Hidden Zone (Hess, 1960) of the Stillwater Complex. (Hess predicted the composition of a stratigraphically higher hidden zone in the Stillwater Complex by considering the composition of chill margin rocks taken to represent the original magma composition, the composition of the exposed Complex, and the continuation of a fractional differentiation trend beyond the mineral compositions measured in the exposed Complex, to produce more iron- and alkali-enriched rocks.) Do the compositional and mineralogical

data gathered in (5) support the existence of a Hidden Zone?

(10) From a consideration of the lithologies and chemistries of the xenoliths in (5), what predictions can be made relative to the continuation of chrome and platinum deposits in the northern Stillwater Complex and to the potential for the existence of magnetite and/or vanadiferous magnetite in the Upper Hidden Zone?

(11) From a consideration of regional structure, what site recommendations can be made for reconnaissance exploratory drilling to maximize the information return per drilling dollar spent as to any northern extent of the Stillwater Complex and as to the depth of the Complex to the north of its outcrop belt.

## GENERAL GEOLOGY

The study area containing the central portion of the Archean Stillwater Complex and the Cretaceous Lodgepole, Enos Mountain, and Susie Peak intrusions is located in Southwestern Montana along the northeast side of the Beartooth Mountain Block (location map, Figure 1, p. 11). The area covers portions of the Squaw Peak and Sliderock Mountain 7½' quadrangles and the northernmost portions of the Mount Douglas and Mount Wood 15' quadrangles.

Figure 2, page 12 shows a simplified structural map of the area outlined in Figure 1. The area can be viewed as consisting of a Precambrian crystalline block composed of granitic gneisses, amphibolites, mafic dikes, iron formation, and minor quartzites at the south (Poldervaart and Bentley, 1958), intruded by the 2,701 m. y. old ultramafic to gabbroic Stillwater Stratiform Complex (DePaolo and Wasserburg, 1979), which forms the northern boundary of the Beartooth Plateau in the field area. Compositional layering in the Stillwater Complex dips steeply to the north at the present time (Page, 1977), and the Complex is overlain in angular unconformity by less steeply dipping Paleozoic to Mesozoic sediments deposited in dominantly marine environments from middle

Cambrian time onward (Garbarini, 1957). The high angle East Boulder Fault (Vail, 1955) cuts this sedimentary section, exposing Precambrian amphibolites and green-schists at the base of the uplifted northern plate. These amphibolites are unconformably overlain by the Cambrian Flathead Sandstone (Vail, 1955), which lies lower in the stratigraphic section than the Cambrian shales and carbonates that immediately overlie the Stillwater Complex (Jones et al., 1960).

The gently northward dipping sedimentary units north of the East Boulder Fault continue from the Cambrian Flathead Formation, in unconformable contact with the amphibolites, northward through Cambrian to late Cretaceous section (Garbarini, 1957). A stratigraphic column for the northern Beartooth Front is included as Figure 4, p. 14. At the north end of the field area, volcanic breccias and volcanoclastic sediments of the Livingston Formation overlie the Cretaceous sediments (Parsons, 1942).

The late Cretaceous Lodgepole, Enos Mountain, and Susie Peak intrusions, of dioritic to dacitic composition, are emplaced at various stratigraphic horizons in the Cambrian to Cretaceous sedimentary units north of the East Boulder Fault (Rouse et al., 1937). The petrology, structure and relation to tectonics of the above intrusions

were discussed by Rouse et al., (1937) in their reconnaissance study of "porphyry" intrusions along the Northern Beartooth Front (Figure 5, p. 15 ). An abbreviated geologic history of the Northern Beartooth Mountains is included in Table 1, p. 16.

The Lodgepole, Enos Mountain, and Susie Peak intrusions contain abundant xenoliths, as discussed earlier. (Xenolith is used here in the sense defined in the 1980 American Geological Institute Glossary of Geology: a foreign inclusion in an igneous rock: Synonyms: exogenous inclusion, accidental inclusion.)

**Figure 1**

Location map showing the geographic location of the study area, outlined here with a heavy solid line.

The Cretaceous Lodgepole, Enos Mountain, and Susie Peak intrusions, and a portion of the Archean Stillwater Complex are shown (see Figure 10, p. 59 for complete map of the Stillwater Complex).

The study area outlined here with a heavy solid line is also outlined in Figure 2 (heavy dashed line) and Figure 3 (heavy dashed line), and is the area covered by Plate I, "Geologic Map of the Lodgepole Intrusive Area".

(Base Map from the U. S. Dept. of Agriculture, Custer Natl. Forest Visitors Map, 1976)

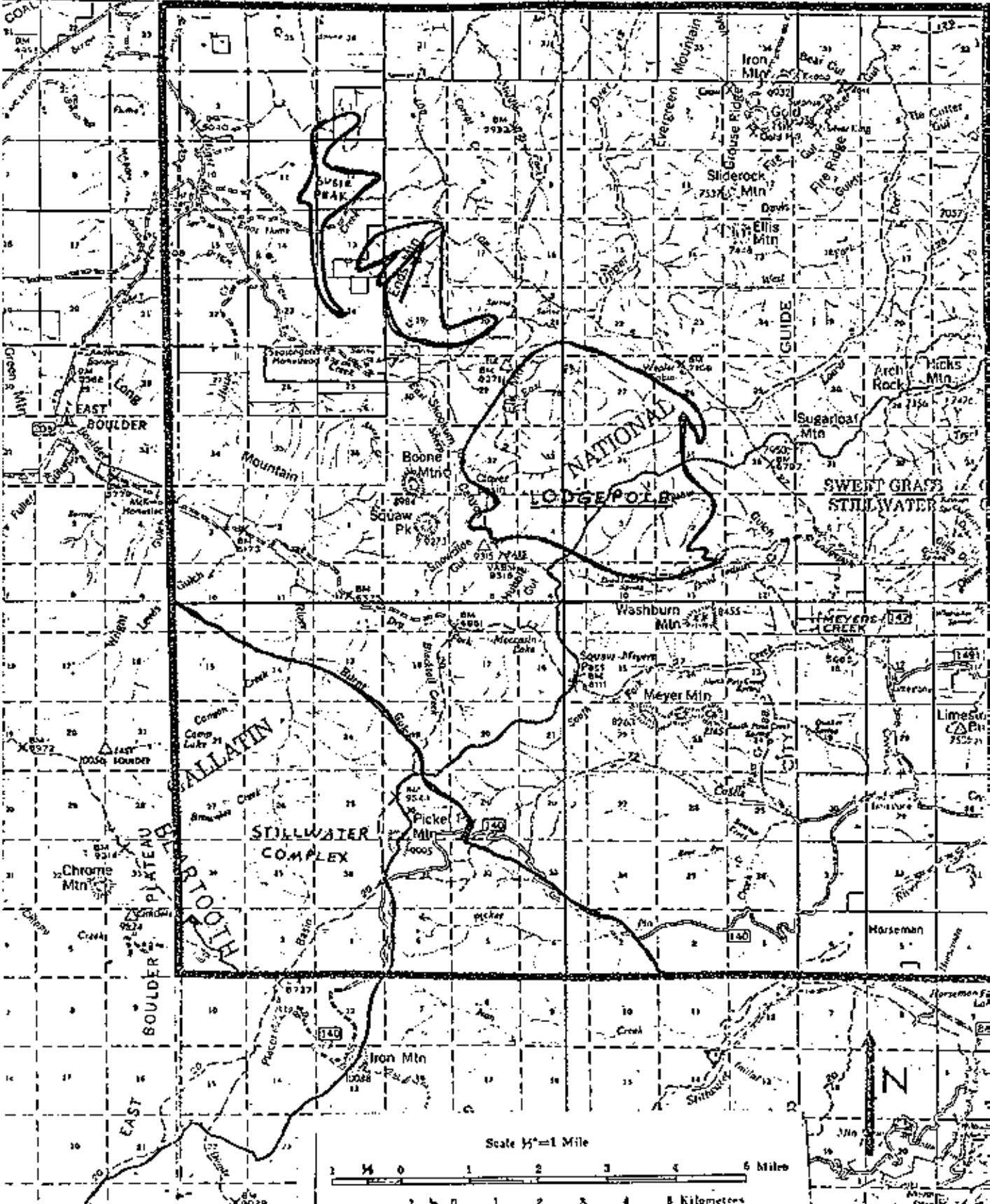
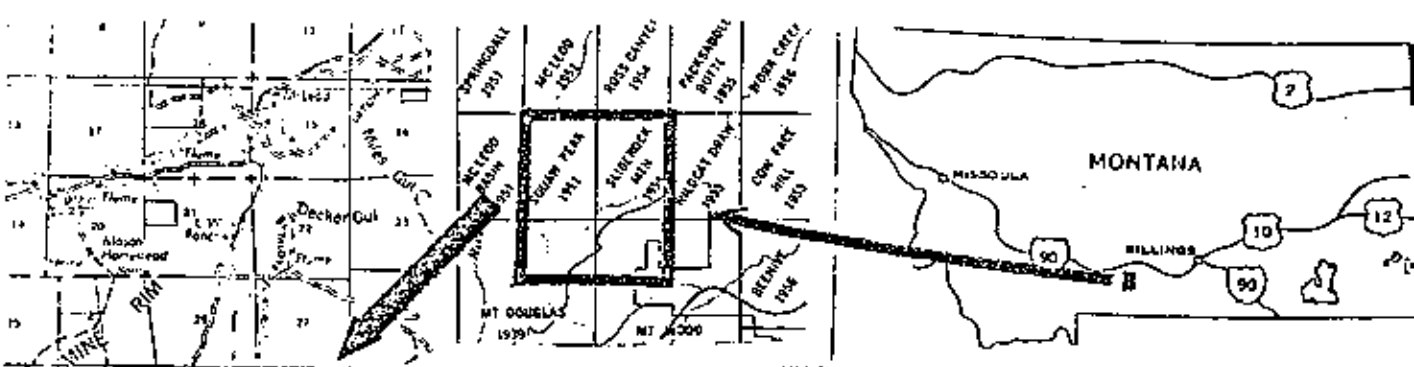


Figure 2

Simplified geologic map of the Lodgepole area, showing the major structural units, from southwest to northeast:

- (1) PGg - granitic gneisses, mafic dikes  
+ PG hfs - meta-sediments (greater than  
2,701 m.y.)
- (2) PGsw-Stillwater Stratiform Complex,  
ultramafic to gabbroic (Archean, 2,701 m.y.)
- (3) E → J - Cambrian to Jurassic sedimentary rocks  
E → K - Cambrian to Cretaceous sedimentary rocks
- (4) East Boulder Fault - high angle, north side up.
- (5) PEs - amphibolites and greenschists (Vail, 1955).
- (6) E → K - Cambrian to Cretaceous sedimentary  
rocks.
- (7) Ki- late Cretaceous intrusive bodies,  
(Lodgepole, Enos Mountain and Susie Peak  
are labeled).

The area outlined here in heavy dashed lines is the area outlined by the heavy solid line in the location map of Figure 1 (Geologic contacts after Foose, Wise, and Garbarini, 1961) and by the heavy dashed line in the Geologic Map (Figure 3), except that the northernmost one mile of the outlined area is deleted here.

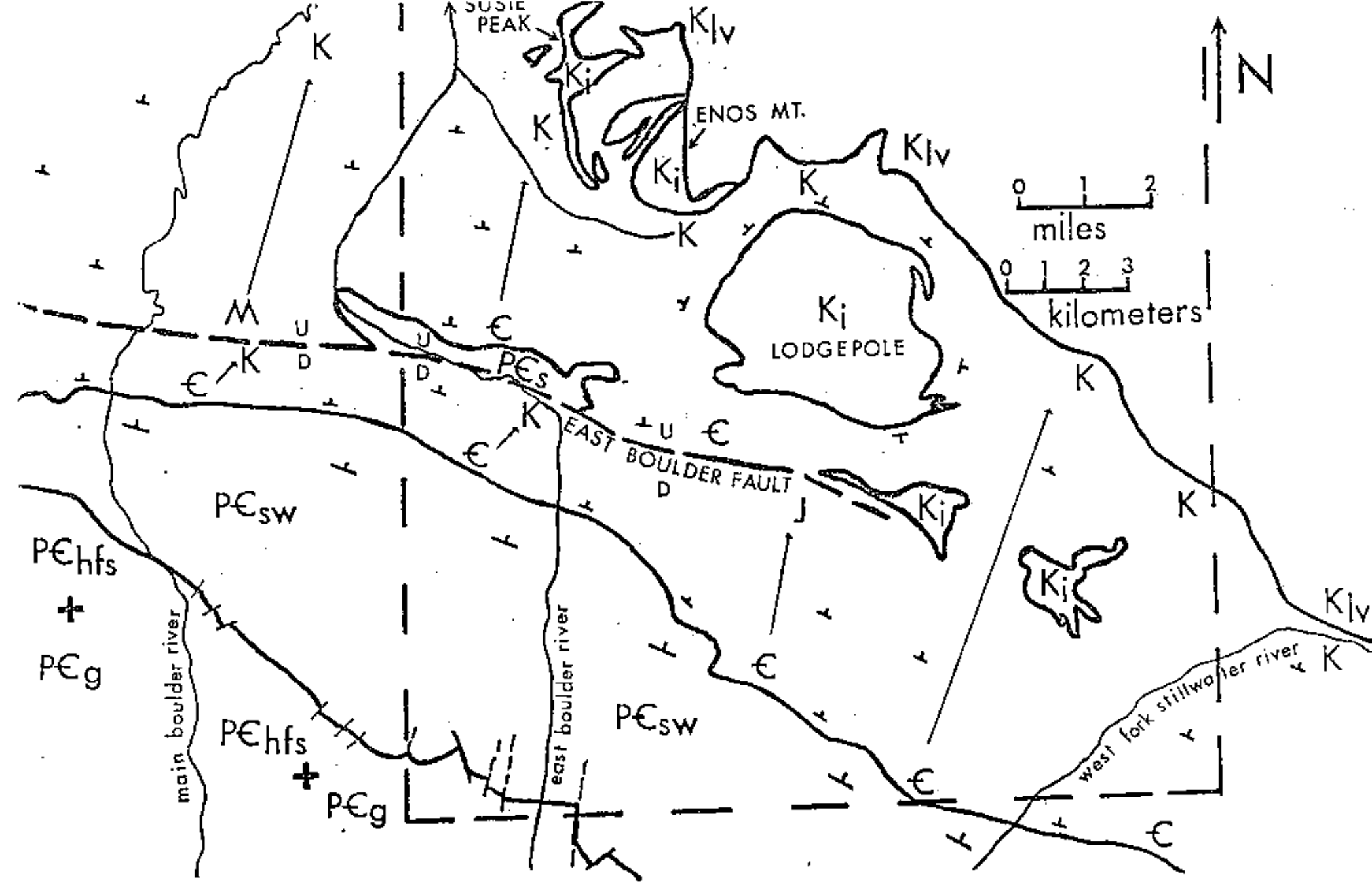


Figure 3

Geologic Map of the Stillwater Area along the Northeast Beartooth Front, showing the location of the Lodgepole, Enos Mountain, and Susie Peak intrusions.

The area outlined by the heavy solid line in the location map, Figure 1, is shown here in heavy dashed lines. The line A - A' - A'' denotes the cross section line of Plate III.

(Geologic base map after Foose, Wise and Garbarini, 1961, Plate 1, Geologic Map of the Beartooth Mountains.)

## LEGEND

## Quaternary

Qu Alluvium, terrace gravels, moraine

## Tertiary

Ti Intrusive igneous rocks

Te Extrusive igneous rocks

NOTE: The age relations discussed on pp.

80 and 104 assign

a late Cretaceous

age to these igneous rocks.

## Eocene

Tw Willwood Formation

## Paleocene

Tf Fort Union Formation

## Cretaceous

Klv Livingston Formation

K3 Eagle Formation and younger Cretaceous strata

K2 Frontier, Cody, Telegraph Creek formations

K1 Kootenai - Cloverly, Thermopolis, Mowry formations

## Jurassic

Ju Morrison Formation, Ellis Group, Sundance Formation

## Triassic

Tc Chugwater Formation

## Permian, Pennsylvanian and Mississippian

MPp Phosphoria, Tensleep - Quadrant, Amsden formations

## Mississippian

Mm Madison Limestone

## Devonian

Du Threeforks and Jefferson formations

OM

undifferentiated

Ordovician to

Mississippian

## Ordovician

Ob Bighorn Dolomite

## Cambrian

Cu Grove Creek, Snowy Range, Maurice Park, Meagher, Wolsey, Flathead formations

## Precambrian

P6s Stillwater Igneous Complex

P6 Granitic gneiss and migmatites with mafic dikes indicated.



AGE	FORMATION		LITHOLOGY		THICKNESS (Feet)	
	North	East	McLeod Area (North)	Deep Lake Area (East)	North	East
Quaternary			Terrace gravels, fluvial			
Eocene		Wilwood	Aconit			2500
Paleocene	Not named	U n d e r	Silt, shaly			
	Union		Limestone, shaly, with thin sandstone beds		7500	2100
	Edge		Light-gray massive sandstone, gray shale, thin coal beds		750	2700
	Telegraph Creek		Light-gray thin-bedded sandstone, shaly bedded with dark-gray shale		375	
Cretaceous	Cody		Black shales with thin calcareous chert nodules and thin silty sandstone partings throughout		350	1625
	Frontier		Gray massive to thin-bedded sandstone, dolomite shale, calcareous chert in the bed of characteristic conglomerate		630	500
	Thermopylae and Vasey		Dark-gray shales with thin sandstone, thin gray silty sandstones		375	1165
	Kootenai	Cloverly	Charl-pebbly conglomerate (shell or pebble beds) sandstone (shell of base, and claystone in middle, gray sandstone at top)		450	620
Jurassic	Maurice		Pink and gray shales and claystones, light-gray sandstone		360	160
	Swift	Sundance	Greenish-gray, highly calcareous glauconitic sandstone		95	
	Reid		Tan and gray calcareous shale, thin white bed at base		160	510
	Piper		Pink claystone, gray calcareous shale and gray limestone		350	
Triassic	Chugwater		Bright-red sandstone, siltstone, and shale		0-110	760
Permian	Phosphoria		Gray waxy limestone and dolomite, light-gray, very calcareous sandstone		0-43	40
Pennsylvanian	Deerfoot	Tancred	Light-gray to tan massive sandstone, locally clay-bedded		40-50	280
Mississippian	Madison		Red shale and siltstone, gray dolomite, gray cherty sandstone and limestone		80-155	80
	Medison		Thin bedded to massive, light-gray to tan, coarsely crystalline to oolitic limestone, locally dolomitic, cherty in some		1800	780
Devonian	Hickoria		Brown silty dolomite and gray-green shale		12-30	125
	Jefferson		Gray to brown limestone and dolomite, breccias in some, some fine-grained sandy beds		345-400	345
		Seagrain Butte	Aconit	Local lens of dolomite, brown bedded, slightly calcareous sandstone		0-55
Ordovician	Sighorn		Massive, tan, rough-weathering dolomite and dolomitic limestone, thin bedded shale at top		100-150	310
Cambrian	Grove Creek and Snowy Range		Limestone flat-pebble conglomerate, oolitic gray limestone, dark-gray shale		320	420
	Maurice		Gray to brown oolitic and coarsely crystalline limestone, some thin beds of limestone flat-pebble conglomerate		125	90
	Park		Interbedded dark-gray shale, tan silty sandstone and siltstone, gray calcareous limestone, and level thin beds of limestone flat-pebble conglomerate		485	550
	Meagher		Light-gray, waxy bedded limestone, some interbedded green shale		100	55
	Watney		Dark-gray shale, waxy silty limestone and siltstone		40	210
	Flathead		Light to white, medium-grained sandstone, locally conglomeratic		0-60	35-60
Precambrian			Green to gray amphibolite and schist, granitic gneiss intruded by basic rocks of the Silurian igneous complex			

Figure 4.

Stratigraphic Column for the Northern Beartooth Front.

The columns labeled "North" and "McLeod Area (North)"

are from Garbarini's 1957 work and were measured in the

Main Boulder and East Boulder River areas, and are

included as a figure in Foose *et al.*, 1961. (after Foose *et al.*, 1961, p. 1147, Table 1).

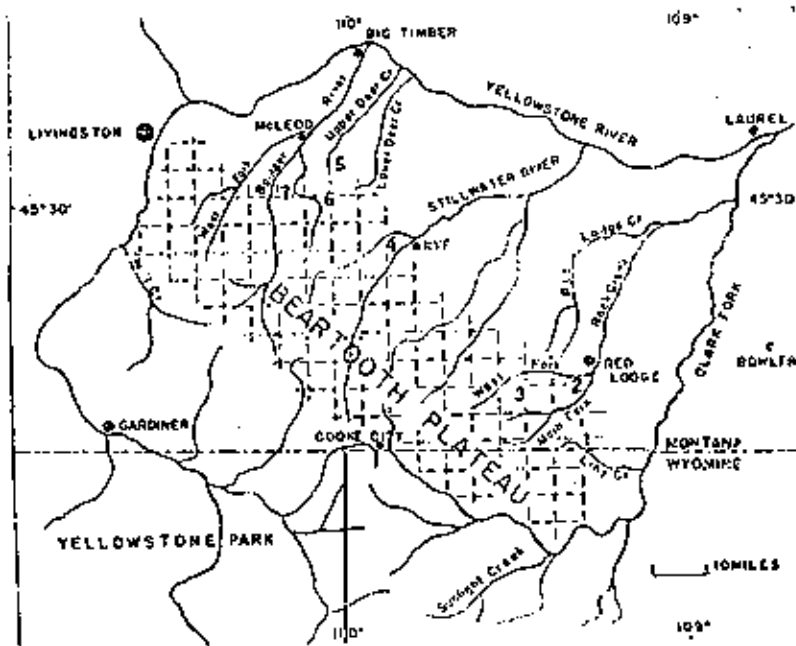


Figure 5.

Sketch map of the Beartooth Mountains area showing location of porphyry bodies along the Northern Beartooth Front. (1) Line Creek, (2) Red Lodge Front, (3) Beartooth Plateau, (4) Nye Quadrangle, (5) Gold hill, (6) Lodgepole Intrusion, (7) East Boulder Plateau.

(after Rouse et al., 1937, p. 718, Figure 1).

Table 1.

Generalized Geologic History of the Northern Beartooth  
Mountains, Montana.

(after David P. Gold, personal communication,  
expanded and revised after Gold et al., 1979)

Time intervals of greatest interest in this study  
are marked with an (←→).

Generalized Geologic History of the Northern Beartooth  
Mountains, Montana

Pleistocene to Recent	Erosion and Periodic glaciation
Miocene through Pliocene	Uplift and erosion.
Mid-Eocene to early Miocene	Erosion.
Early Paleocene through early Eocene	Major uplift and deformation of Laramide Orogeny (thrust, tear, and glide faulting; drape and gravity folds associated with uplifts; intrusion of felsite and dacite porphyries, and rhyolite sills, stocks, and laccoliths.
Late Cretaceous →	Beginning of Laramide deformation. Extrusion of the Livingston volcanic rocks and emplacement of Lodgepole and Enos laccoliths.
Mid-Cambrian to mid-Cretaceous	Almost continuous deposition of marine and continental sedimentary rocks 8,000 to 10,000 feet thick.
Middle Cambrian.	Subsidence.
Pre-Middle Cambrian	Differential rotation, tilting and erosion.
Late Proterozoic (0.74 b.y.)	Intrusion of quartz-tholeiite dikes
Proterozoic (1.3 b.y.)	Intrusion of olivine normative diabase dikes.
" (1.7 b.y.)	Intrusion of granite stocks.
" (2.2 to 2.1 b.y.)	Intrusion of mafic dikes.
Early Proterozoic to Late Archean (2.5 to 2.8 b.y.)	Early diabase dikes, some intruding the Stillwater Complex.
Archean ? (2.6 b.y.)	Intrusion of quartz monzonite stock into Basal and Ultramafic zones of Stillwater Complex.
" (2.7. b.y.) →	Fractionation of the Stillwater magma; crystal accumulation and magmatic sedimentation of at least 18,000 and possibly 30,000 feet of cumulate rocks of the Stillwater Complex
" (2.75 b.y.?)	Intrusion of the Stillwater magma; thermal metamorphism of "basement" paragneisses and iron formation.
" (2.8 b.y.)	Regional deformation, folding, metamorphism and migmatization. Intrusion of Long Lane granite body.
" (3.1 b.y.)	Regional metamorphism and granitization. Intrusion-extrusion of Chain Lakes mafic gneiss.
" (pre 3.2 b.y.)	Deposition of sedimentary rocks and iron formation.
" (3.3 b.y.)	Intrusion of Quad Creek tonalites
" (3.6 to 3.7 b.y.)	Metamorphism and intrusion of HR migmatite protolith.
" (3.7 to 3.9 b.y.)	Formation of supracrustal sequence.
" (3.9 b.y.)	Formation of source rocks for the metasediments. (zircon cores), and intrusion/extrusion in the protolith of some K-poor gneisses at Quad Creek.

## PREVIOUS WORK

A large volume of geological literature exists on the Beartooth Mountain region and particularly on the Stillwater Complex, which forms part of the northeast boundary of the Beartooth Plateau. Only those works directly relevant to this study, in that they refer to geographic areas included in the field area (Figures 1, 2, 3 and Plate I), to structural trends affecting the field area, or to possible source units for the xenoliths found in the Lodgepole and other intrusions, are included here.

Poldervaart and Bentley (1958) discuss the geological evolution of the Precambrian rocks which form the Beartooth Plateau, and refer to the metasediments underlying the Stillwater Complex in the southwest portion of the field area. Casella (1969), Wooden et al. (1981), and Mueller and Wooden (1982) provide integrated summaries of work on the Precambrian rocks of the Beartooth Plateau. Bucher et al. (1933) and Spencer (1958) discuss structural trends which affected the development of the Beartooth Region. Foose et al. (1961) studied the geology of the perimeter of the Beartooth Mountains, and a portion of their geologic map is reproduced here as Figure 3, p.13 which covers the area of interest in this study. The Precambrian terrane

at, and immediately south of, the southern boundary of the area outlined in Figure 2, p.12 was studied by Harris (1959) (Western portion), and Butler (1962) (Eastern portion).

The structural setting of the Stillwater Complex has been described by Jones et al. (1960) and Page (1977). The upturned, exposed portion of the Complex consists of a thin Basal Zone of noritic rocks (Page, 1979), a 900 - 1200 meter thick Ultramafic Zone composed of dunite, bronzitite, and harzburgite (characterized by Jackson, 1961, in his work on textures and mineral associations), and a 4300 meter thick Upper Zone consisting of norite, anorthosite, troctolite, and gabbro (Raedeke, 1979, '82). The detailed stratigraphy, petrology and mineral compositions of sections through the Complex are described by Raedeke (1979, '82). The work of Hess (1960) and McCallum (1969) provide quantitative studies of mineral compositions and relations in the Stillwater Complex. DePaolo and Wasserburg (1979) used Sm-Nd dating techniques to determine an age of  $2,701 \pm 8$  m.y. for the Complex. Bonini (1969, 1981) used gravity data to interpret the areal extent of the Stillwater Complex to the north and east of its outcrop area under the Bighorn Basin. Page and Nokleberg (1974) mapped the surficial geology of the Stillwater Complex with emphasis on the Ultramafic Zone,

and Segerstrom and Carlson (1977, '79, '80) mapped the Upper and Banded Zones of the Complex.

Garbarini (1957) mapped most of the area underlain by Cambrian through Cretaceous sedimentary rocks north of the Stillwater Complex (see Figure 3, p. 13) including the Lodgepole, Enos Mountain, and Susie Peak intrusions. Whay (1934) mapped the geology in the area from Limestone Butte to Nye in the southeast corner of the same Figure. Vail (1955) mapped the East Boulder Fault and studied the amphibolites to the north of this fault in the East Boulder River Valley (Figure 2 and Figure 3, west-center of areas). Wilson (1936) suggested that the East Boulder Fault represented the westward extension of the Nye-Bowler Fault Zone, a major basement fault in the Bighorn Basin to the East.

The geology of the Lodgepole, Enos Mountain, and Susie Peak intrusions was described by Kouse et al. (1937), and Booker (1957) produced a detailed map of the Enos Mountain - Susie Peak Area. Morton (1979) mapped the geology of Limestone Butte (a roofed intrusion) near Nye. Parsons (1942) undertook a regional reconnaissance study of the Livingston Volcanic rocks which cover the northeastern portion of the field area.

Specific features from the works of the above authors which relate to the geologic setting of the Stillwater Complex and the Lodgepole, Enos Mountain, and Susie Peak intrusions are referred to in the following chapter.

## FIELD PROCEDURES

Two one-week-long xenolith collecting trips to the Lodgepole Intrusion were undertaken in August of 1980 and in August of 1981.

One and one half months were spent in the field in the Summer of 1982 in detailed mapping of the Lodgepole Intrusion, and in reconnaissance investigations in the Enos Mountain, Susie Peak, East Boulder Valley, and Stillwater Complex areas.

Regional Reconnaissance

A reconnaissance study of selected areas on the Beartooth Plateau, in the East Boulder Valley, and in the Paleozoic and Mesozoic sediments to the north of the Beartooth Front in the area of the Lodgepole, Enos Mountain, and Susie Peak plutons was carried out in order to delineate the structural setting of these Cretaceous bodies, and to gain familiarity with possible source units for the xenoliths found in the above intrusions. Areas of interest are shown in Figure 2, p. 12.

The study involved the use of available text (see Previous Work Section for a summary of relevant works) and mapping by earlier workers covering the areas shown in Figure 3, p.13.

Features of critical importance in understanding the structural setting of the Cretaceous intrusions, such as the attitude of the upper unconformable contact of the Stillwater Complex in the vicinity of Picket Pin Mountain, the direction and magnitude of movement on the East Boulder Fault, and the amphibolites (lying below the basal Cambrian Flathead Formation) immediately north of the East Boulder Fault (Figure 2, west-center) were mapped in detail and sketches and photographs of critical field relations were prepared. Chapter II, Section 1 provides an integration of the available literature and field data on the lines of evidence for the northern extent of the Stillwater Complex and the regional structural settings of the Lodgepole, Enos Mountain, and Susie Peak intrusions.

#### Detailed Mapping

Field mapping was done using U. S. Department of Agriculture aerial photographs as a base. These photographs are from the GS-VEUM series flown for the U.S.D.A. in 1980 at an approximate altitude of 16,000 feet to give an effective scale at the center of each photograph of 1:16,180.

Mapped information was then transferred manually to U.S.G.S. 1:24,000 scale orthophotoquads (prepared from 1:80,000 aerial photographs, with photo-imagery rectified

by automatic correction, available from Rocky Mountain Mapping Center, U.S.G.S., Denver Federal Center). A final copy was then made by overlaying the 1:24,000 scale geologic map which was produced on the orthophotoquads onto a topographic base produced from standard 7½ minute U.S.G.S. 1:24,000 scale quadrangle maps.

The use of orthophotoquads as a mapping base allowed greater detail in mapping the contact relations of the Lodgepole Intrusion with the country rocks, because individual sills, dikes, and resistant limestone beds could be located on the orthophotoquad. Such features are not normally precisely locatable on the smoothed contours of standard topographic maps.

The primary objective of the detailed mapping was to define the contact relations of the Lodgepole Intrusion with the country rocks and to investigate the internal intrusive phase relations within the Lodgepole Pluton. In order to understand the regional structural setting of the Cretaceous intrusions, some detailed field mapping was done locally as part of the reconnaissance studies of the upper unconformable contact of the Stillwater Complex at Picket Pin Mountain and of the amphibolites in the East Boulder Valley to the southwest of the Lodgepole intrusion. Geologic mapping in the Enos Mountain and Susie Peak

intrusive areas was used to provide a geological framework for the collection of xenolith samples in both areas.

The geologic map resulting from the above studies is included as Plate I (Pocket) which covers the area outlined in Figures 1 (heavy solid line), 2 (heavy dashed line), and 3 (heavy dashed line), pp. 11, 12 and 13.

#### Sampling Traverses

Samples collected were designated by traverse name or number, year, and sample number in order to allow an evaluation of the abundance and type of xenoliths for different areas within the Lodgepole, Enos Mountain, and Susie Peak intrusions.

Xenolith distribution is discussed in more detail in Chapter II, Sections 2 and 3 for each of the intrusions studied.

## LABORATORY PROCEDURES

A diverse suite of xenolith samples were selected from among the 418 xenolith samples collected in this study from the Lodgepole Intrusion. Whole rock specimens were analyzed for major and trace elements by x-ray fluorescence; mineral phases in selected samples were analyzed for chemical compositions by electron microprobe; and hand sample and thin sections petrography were performed as discussed in the following sections.

A sample index (Table 8, p.119 ) lists the type of information available for each sample, along with the sample number and a descriptive name assigned according to the classification scheme proposed in Chapter III, p. 165.

The Appendices contain tabulations of whole rock major and trace element data (1, 2), normative mineralogies (3), mineral compositions determined by electron microprobe (4), and a catalog of hand sample and thin section petrographic descriptions (5).

Analytical work was performed by the author from September, 1981 to March, 1983 at Temple University, or by the author at The Pennsylvania State University (electron microprobe) and at Franklin and Marshall College (x-ray fluorescence).

### Major and Trace Element Analysis

Whole rock samples were jaw-crushed and disc-pulverized. A 5 gm. split was then powdered to approximately (-200) mesh by agitation in a Wiggle-Bug for ten minutes.

Xenolith samples were prepared for whole rock analysis by removing all traces of the diorite or dacite porphyry host material, and, the outer one centimeter of the xenolith to obtain the freshest possible samples. Samples of the intrusive phases selected for analysis were taken from xenolith-free localities.

Sample pellets for major element analysis were prepared by fusing a mixture of  $0.4000 \pm .0005$  grams of (-200) mesh sample with  $3.6000 \pm .0005$  grams of lithium tetraborate. Pellets for trace element analysis were prepared by mixing  $1.0000 \pm .0005$  grams of (-200) mesh sample with  $0.5000 \pm .0005$  grams of powdered microcellulose and pressure-forming the mixture into a pellet using a hydraulic ram (Steven Sylvester, 1980).

Samples were analyzed for major elements (Si, Al, Fe, Mg, Ca, Na, K, Ti, P, and Mn) and trace elements (Rb, Sr, Ni, and V) using the Diano 8300 computerized x-ray fluorescence system equipped with automated spectrometer at Franklin and Marshall College, Lancaster, PA.

Operating conditions for the system are listed in

Table 2, p. 27. U.S.G.S. Hawaiian Basalt BHVO-1 was used as a standard for comparison purposes, and replicate analyses were performed on selected samples. (Appendices 1 and 2).

Loss on ignition was determined by heating a known amount of powdered sample to 900° C for 60 minutes, and recording the weight loss. (Appendix 6). Ferrous iron (FeO) was determined by sample dissolution in a mixture of H<sub>2</sub>SO<sub>4</sub> and hydrofluoric acid, and standard titrametric method using potassium permanganate and standardization with sodium oxalate (Ulmer and Smothers, 1968).

The overall analytical precision was based on the cumulative % standard deviation for all elements, calculated as  $\pm 1.29$  wt %.

Diano 8300 X-ray Fluorescence System Operating Parameters

Table 2

Element	Dispersing Crystal	2θ for K	Target	KV	mA	Counting time (Seconds)	% deviation **	(Calculated as wt % oxide)
Na	TAP*	54.78	Cr	50	40	100	0.12	Na <sub>2</sub> O
Mg	TAP	44.95	Cr	50	40	75	0.12	MgO
Al	TAP	37.50	Cr	50	40	75	0.26	Al <sub>2</sub> O <sub>3</sub>
Si	TAP	31.78	Cr	50	40	75	0.41	SiO <sub>2</sub>
P	Ge	140.78	Cr	50	40	60	0.02	P <sub>2</sub> O <sub>5</sub>
K	LiF(200)	136.56	Cr	50	10	40	0.07	K <sub>2</sub> O
Ca	LiF(200)	112.86	Cr	50	55	40	0.12	CaO
Ti	LiF(200)	85.88	Cr	50	25	40	0.03	TiO <sub>2</sub>
Mn	LiF(200)	95.04	W	30	40	50	0.01	MnO
Fe <sub>TOT</sub>	LiF(200)	57.21	W	50	55	50	0.13	Fe <sub>2</sub> O <sub>3</sub>
							standard deviation	concentration in standard ppm
Rb	LiF(220)	37.72	W	50	40	100	4.7 ppm	18.4
Sr	LiF(220)	35.55	W	50	40	60	6.5 "	187
Ni	(LiF(220)	70.98	W	50	40	60	5.3 "	70
V							2.7 "	237.8

\* Thallium acid phthalate

\*\* Standard error of estimate for linear regression based on standards used for calibration of XRF for each element. Between 19 and 27 standards were used, depending on the element.

### Hand Sample and Thin Section Petrography

Hand samples from the selected suite of xenoliths (Table 8, p. 119) were described according to the percentage of felsic and mafic minerals, using the "Charts for Estimating Percentage Composition" by Terry and Chillinger (1955). (As discussed in Chapter III, pp. 137 to 160, the dominant felsic mineral is plagioclase feldspar but the mafic minerals consist of fine granular to blady aggregates, with individual grains usually not identifiable in hand specimen). Mesoscopically visible textures and fabric were also described (Appendix 5).

Circular thin sections (0.95 inch) were prepared by taking cores with a bench mounted diamond drill press through the xenoliths and then slicing wafers from the cores. In most cases, wafers from near the centers of the xenoliths were used to prepare thin sections, except for a number of cores selected to show the contact relationship of the host intrusive phase with the xenolith. The emphasis in thin section description was placed on describing the habit of the various mineral phases and their textural relationships, and in attempting to recognize and interpret any post-primary mineralogical and textural change visible in the thin sections. The mineral phases were identified using standard optical microscopy methods, and the

compositions of selected mineral phases were analysed by electron microprobe in most thin sections (see Electron Microprobe Analysis, p. 30.

X-ray diffraction on selected mafic mineral phases was performed to assist in identification of mineral phases.

Photographs, and textural and mineralogical descriptions are catalogued in Appendix 5.

### Electron Microprobe Analysis

Electron microanalysis of mineral phases in xenoliths was performed at The Pennsylvania State University using the ETEC AUTOPROBE electron microprobe. Procedures followed those specified in Collins et al. (1975), and used the automated data reduction programs of Bence and Albee (1968) with later modifications by Albee and Ray (1970). Standard circular glass-mounted polished thin sections were used. Operating conditions for the AUTOPROBE were 15 KV excitation voltage and 0.012 microamps specimen current. A 30 micron beam was used for routine analysis of plagioclase feldspar, mafic minerals, alteration products, and other silicate phases to determine whole grain mineral compositions in the xenoliths and in the fine-grained diorite samples. A 1 micron beam was used for analysis of spinel grains in a chromite-containing specimen, for limited analysis of plagioclase and pyroxene lamellae and for analysis of sulfide and oxide phases. In general, two analyses were performed per mineral grain and two or three grains of a particular mineral were analyzed per sample. (Appendices 4A to 4H). Standards used for major element analysis were from The Penn State General Analytical Standard Plug (GASP) and are listed in Table 3, p. 31. The routine precision of the ETEC AUTOPROBE is summarized in Table 4, p. 32.

Table 3

Electron Microprobe Standards from GASP (General Analytical Standard Plug), H.B. Collins and D. H. Egglar, Penn State University. All standards are frequently used and well characterized.

Element Standardized For	Standard Number	Wt.% Oxide (ele- ment in Column 1	Standard Name
Na	10	11.36	AB Amelia (Na,Al,Si)
Mg	3	18.62	DI CaMgSi <sub>2</sub> O <sub>6</sub> glass (Ca,Mg,Si)
Al	12	19.98	ENAL 20 glass (Mg,Al,Si)
Si	3	55.47	DI CaMgSi <sub>2</sub> O <sub>6</sub> glass (Ca,Mg,Si)
K	9	16.10	KSP K feldspar (K)
Ca	3	25.90	DI CaMgSi <sub>2</sub> O <sub>6</sub> glass (Ca,Mg,Si)
Ti	1	100.00	S-141-Ru (Sphene- glass)(Ca,Ti,Si)
Cr	6	49.31	53-IN-8 chromite (Cr, Al)
Mn	2	19.82	S-216 SPALM garnet (Mn,Fe,Si,Al)
Fe	16	17.10	HUNT olivine (Mg,Fe,Si)

Table 4

Routine Precision for Penn State University ETEC  
 AUTOPROBE, (Lee Eminhizer, personal communication,  
 November, 1982)

Concentration of Element Analyzed for (as wt.% of Total)	Approximate Precision (as wt.% of Amount of Element Present)
100% -- 20%	$\pm 1$ -- 1.5%
10%	$\pm 2\%$
1%	$\pm 4$ -- 5%
(for SiO <sub>2</sub> in 50% range)	$\pm .2$ -- 1%

### Differential Thermal Analysis

Differential thermal analysis of recrystallized carbonate rock samples from the contact of the Lodgepole Intrusion with the country rocks was performed to determine whether the country rocks had been heated past their decarboxylation temperature by the intrusion of the dacite magma.

Powdered carbonate samples of 0.500 gm were heated against MgO reference material of equal weight in an Aminco Thermoanalyzer DTA furnace equipped with an x - y recorder.

The reader should refer to Hutchinson (1974, pp. 439-457) for a more detailed discussion of differential thermal analysis techniques.

Chapter II

Field Investigations

Section 1

Regional Geology, and Structural  
and Geophysical Evidence for the  
Northern Extent of the Stillwater Complex

## REGIONAL GEOLOGY

Purpose of Study

The lithologic units and structural trends of the north-eastern border of the Beartooth Mountains are reviewed here to establish the geologic setting of the late Cretaceous Lodgepole, Enos Mountain, and Susie Peak plutons, and to provide some background for interpreting the xenoliths found in these intrusions. Structural and geophysical evidence for a northern continuation of the Stillwater Complex at depth is presented in this section, and the exposed basement (greenschists and amphibolites) north of the Complex is investigated.

Crystalline Core of the Beartooth Range

The Beartooth Mountains are an uplifted 130 x 64 km Precambrian crustal block on the Montana-Wyoming border in the Middle Rocky Mountains. The block is highest near its steep northeastern border and slopes gently southwest where it is overlapped by the Tertiary Yellowstone-Absaroka volcanic field. It is bounded to the east by the Bighorn Basin and to the north by the Crazy Mountain syncline (Figure 8, p. 57).

To the south of the study area, the Precambrian rocks have been grouped into broad classes based on lithology, mineralogy and chemistry (Page, 1977, p. 5). Page proposes a group of regionally metamorphosed rocks formed prior to 2,750 m. y. ago from pelitic sedimentary rocks at least 3,120 m. y. old. This interpretation is

based on detrital-appearing zircons yielding minimum ages of 3,120 m. y. (Cantanzaro and Kulp, 1964), and micas and microclines (from the same granitic gneiss) yielding ages of 2,750 m. y. (Gast, Kulp and Long, 1958). The 2,750 m. y. date is interpreted as the age of granitization.

The lithologies represented in this group consist of granitic gneiss, biotite gneiss, plagioclase gneiss, amphibolitic gneiss and biotite schist.

#### Hornfelsed Metasedimentary Units

Closer to the northeast edge of the Beartooth front is a northwest trending band of hornfelsed metasedimentary units (Figure 2, p-12, "P6hfs" at southwest corner.) Within this sequence of hornfelses are thin units of blue metaquartzite and iron formation. Although these units were complexly deformed prior to 2,700 m. y. ago (i.e., pre-Stillwater Complex intrusion), they still form recognizeable outcrop bands (Butler, 1966, p. 52; Howland, et al., 1949, p. 67).

#### The Stillwater Complex

The Stillwater Complex is a layered stratiform basic intrusion, ranging in outcrop from ultramafic to gabbroic (Figure 10, p. 59). The upturned, exposed edge forms a 50 km long by 5 km wide outcrop along the northeast

edge of the Beartooth Front and consists of a thin Basal Zone composed of dunite, bronzitite, and harzburgite and a  $\leq 4300$  thick Banded and Upper Zone consisting of norite, anorthosite, troctolite, and gabbro (Jones, et al., 1960, p. 281). The various igneous stratigraphic divisions proposed for the Complex are illustrated in Figure 11, p. 60.

Jones et al. (1960, p. 285) provide evidence for the concordant nature of the Stillwater lopolith by noting that the thin iron formation forms a unit paralleling the base of the Stillwater Complex throughout most of its length.

It was intruded into the Hörfelses (described above)  $2,701 \pm 8$  m. y. ago (DePaolo and Wasserberg, 1979).

Continuously traceable, cumulate layers in the Complex are considered evidence for slow cooling in a non-orogenic environment (Page, 1977, p. 75).

#### Post-Stillwater Complex Intrusion Metamorphism

A low grade regional greenschist facies metamorphism and associated penetrative deformation occurred in the region between 1,600 and 1,800 m.y. ago (Page, 1977, p. 43). Page cites the following points as evidence for this deformation:

- (1) A widespread penetrative foliation (east-west strike,

steep northerly dip) is present in granitic gneisses of the Northeastern Beartooth Plateau; in the Stillwater Complex (as serpentine-magnetite veins and flattened orthopyroxene oikocrysts in the Ultramafic Zone, and as epidote and parallel chlorite flakes in the Upper and Banded Zones); and as alligned chlorite flakes in the quartz monzonite which intrudes the eastern base of the Stillwater Complex. Therefore, a post-quartz monzonite age can be assigned to the foliation based on the above textural criteria. The foliation averages east-west/ $60^{\circ}$  N in the Stillwater River area and N78W/ $75^{\circ}$  N in the West Fork Stillwater area in the hornfelses below the Stillwater Complex (Page, 1977, p. 55).

- (2) U-Pb ages determined by Nunes and Tilton (1971) in the Stillwater Complex give model Pb ages of  $1,700 \pm 300$  m. y., which are interpreted by Page (1977, p. 43) as being reset by a regional metamorphic event at that time. The close agreement of age dates of 2,730 m.y. for the quartz monzonite intruding the Stillwater Complex (Nunes and Tilton, 1971), and 2,701 m. y. for the Stillwater Complex (DePaolo and Wasserberg, 1979), by U-Pb and Sm-Nd dating respectively, rule out the younger, 1700 m.y.

value as an original Stillwater Complex crystallization age.

The metamorphic event described above also appears to have affected the band of greenschists and amphibolites exposed north of the Beartooth Front along the north side of the East Boulder Fault (Figure 2, p.12 ), because the latest foliation in these rocks has a near east-west trend and a  $55^{\circ}$  -  $70^{\circ}$  N dip (Vail, 1955, p. 45 ; and confirmed by this author from reconnaissance traverses in the East Boulder Valley : Plate I, and Figures 12 and 13, pp.61 and 62.

#### Amphibolites and Greenschists North of the Beartooth Front

The relationship of the Stillwater Complex to the amphibolites and greenschists occurring north of the East Boulder River along the base of Long Mountain is uncertain. The Cambrian depositional relations (described on p.44 ) place these amphibolites and greenschists stratigraphically above the Stillwater Complex by the time of middle Cambrian deposition in the area. The geometric correspondence of the foliation in the amphibolites with the latest foliation present in the rocks of the Beartooth Plateau to the south suggests that they were near their present position (exclusive of high angle Laramide fault movement, which is discussed later) by the time of development of this penetrative foliation.

Based on field observations by this author, the amphibolites and greenschists have not undergone the polyphase deformation, including episodes of isoclinal folding, that is visible in the crystalline core of the Beartooth Range and in the hornfelses and metaquartzites which underlie the Stillwater Complex. Therefore, these amphibolites and greenschists probably represent younger lithologies, based on the absence of intense deformation. However, no age dates on these amphibolites and greenschists exist to confirm this hypothesis.

Various workers have discussed possible origins for these amphibolites and greenschists, and their observations are reviewed below.

Vail (1955, p. 46) characterized the rocks as amphibolite schists, mafic amphibolites, albite amphibolite, and chlorite schists and described a mineralogy dominated by "amphibole, albite, and clinozoisite, with minor quartz, calcite, clinocllore, and penninite". He interpreted this assemblage as evidence of albite-epidote-amphibolite grade metamorphism (ibid., p. 48) and suggested that the rocks represent metamorphically recrystallized troctolites, gabbros, and anorthosites of the Stillwater Complex which were altered by hydrothermal activity and shearing (Vail, p. 55).

This author does not agree with Vail because

texturally unaltered cumulate gabbroic xenoliths, and texturally and mineralogically unaltered anorthositic xenoliths (see Chapter III) collected by the author from the Lodgepole Intrusion, two miles northeast of the exposed amphibolites, offer evidence that these amphibolites and greenschists do not represent Stillwater Complex lithologies.

Garbarini (1957, p. 6) characterized these rocks as amphibole schists, amphibolites, chlorite schists, and altered diabase dikes or sills. He described a mineralogy dominated by tremolite-actinolite, hornblende, albite, and chlorite, with minor quartz, calcite, and epidote, a mineral assemblage typical of greenschist facies metamorphism. Garbarini (1957, p. 7) interpreted these rocks as products of the recrystallization of lavas, tuffs, and hypabyssal intrusions by heat and solutions emanating from the cooling Stillwater Complex. The Suce Creek fault (Richards, 1957), which occurs north of the Beartooth Front 16 km west of the East Boulder amphibolites, and is similar to the East Boulder Fault in geometry and position with respect to the Beartooth Front (Vail, 1955), exposes gneisses and schists much like the Precambrian terrane of the Main Beartooth Plateau to the south. This provides some evidence for the occurrence of the East Boulder amphibolites only in the area north of the Stillwater Complex, but lack of exposure of Precambrian basement to the north or east of

No other wells penetrating the Paleozoic section were located between the towns of Limestone and McLeod (far northeastern corner of Figure 1).

#### Precambrian/Cambrian Unconformable Contact

At some time before deposition of the middle Cambrian sediments (Garbarini, 1957, p. 17), the Stillwater Complex and underlying rocks were tilted gently to the northeast. Jones et al. (1960, p. 305) estimate this tilt at  $25^{\circ}$  -  $35^{\circ}$  north, based on the average dip discordancy between the steeply northeast dipping compositional layering in the Stillwater Complex and the less steeply dipping middle Cambrian sediments unconformably overlying the Complex.

North of the East Boulder Fault, the Cambrian Flathead (stratigraphic column, Figure 4, p. 14) overlies greenschists and amphibolites with an angular unconformity of  $20^{\circ}$  -  $35^{\circ}$  (Vail, 1955, p. 45; and this study: Plate I and Figure 12, p. 61.)

Middle Cambrian Wolsey Shale, which is stratigraphically above the Flathead Sandstone, unconformably overlies the Upper Zone of the Stillwater Complex south of Nye (Whay, 1934, p. 25-26), the Upper Zone north of Picket Pin Mountain (Garbarini, 1957, p. 15; and this study: Plate I - mapped interval at Stillwater Complex upper contact, and Figure 14, p. 63), and the Middle Banded Zone in an

the East Boulder amphibolite outcrop belt precludes an evaluation of their regional distribution.

The above supposition was reinforced by an examination of well-log records of the Montana Oil and Gas Commission by the author (August, 1982). Apparently no wells penetrated Precambrian basement in the area between the towns of Limestone and McLeod north of the Beartooth Front. However, a basement elevation can be projected from a well located 4 km northeast of Limestone, MT., which penetrates Jefferson Limestone at 1813 m (5,949 ft.) below the present surface (well location: T4S, R15E, sec. 3, abandoned 1959, Shoreline Petroleum Company. Limestone MT. is near the southeastern corner of Figure 1, location map. The well is located approximately 16 km east of the exposed basement amphibolites and greenschists discussed above, but is off the map to the northeast and does not appear in Figure 1). Based on Garbarini's (1957) maximum formation thicknesses, (Figure 4, p.14 stratigraphic column), basement would lie approximately:

1813 m (surface to top of Jefferson Fm) +  
 539 m (top of Jefferson Fm. to base of Flat-  
 head Fm) = 2352 m (7716 ft) below the ground  
 surface. (Surface elevation is approximately  
 1820 m above sea level at this location.)

infaulted Cambrian inlier south of the Iron Creek Fault (Plate I, south-center).

Remnants of Flathead Sandstone unconformably overlie the Precambrian gneisses 8 km south of the Stillwater Complex (Wilson, 1936) on the Main Boulder Plateau, and further south near the Wyoming-Montana border at Beartooth Butte and Little Bear Creek (Pierce and Nelson, 1971).

The above evidence suggests that the Stillwater Complex formed a mild topographic high by middle Cambrian time in the area that is now the Northeast Beartooth Front, with layering dipping  $25^{\circ}$  to  $35^{\circ}$  to the northeast. The middle Cambrian sediments were deposited on greenschists and amphibolites to the north, on the Stillwater Complex to the south, and on hornfelses and granitic gneisses further south of the present day Stillwater Complex outcrop.

#### Cambrian Through Late Cretaceous Units

Garbarini's (1957) thesis "The Geology of the McLeod Area" provides evidence that from the time of Flathead Sandstone deposition (middle Cambrian) through lower Livingston Formation deposition (late Cretaceous), there is no record of periods of deformation severe enough to produce any angular unconformities in the stratigraphic section, although disconformities do exist at the bases of the Ordovician, Devonian, Mississippian, Jurassic, and

Cretaceous sections (Garbarini, 1957, p. 5).

Approximately 884 meters (2900 feet) of this section consists of Paleozoic strata (dominantly marine shales and limestones), with the remainder being Mesozoic strata (dominantly mixed continental and marine clastics). Using Garbarini's minimum and maximum formation thickness values for the area, the total thickness of the Cambrian Flathead Formation through late Cretaceous lower Livingston Formation sedimentary package can be calculated as approximately  $2554 \text{ m} \pm 65 \text{ m}$  (8380 feet  $\pm$  215 feet). The lower Livingston Formation (late Cretaceous) is overlain by up to 610 meters (2,000 feet) of upper Livingston Formation (late Cretaceous) volcanic breccias, tuffs, and agglomerates of intermediate composition to the north of Enos Mountain area (Parsons, 1942, p. 1183; and "Kiv", Plate I). This volcanoclastic unit thins to the north.

No units younger than the upper Livingston Formation agglomerates and breccias (other than glacial deposits and Quaternary alluvium) are present in the study area.

#### Laramide and Later Uplift

Foose *et al.* (1961, p. 1165) place the timing of intrusion of the line of porphyries from Limestone Butte to Lodgepole (Plate I) as occurring during the earliest stages of Beartooth uplift. (These intrusions are discussed in Sections 2 and 3, Chapter II).

The present structural configuration along the Northeast Beartooth Front is largely the result of Laramide deformation in latest Cretaceous (upper Livingston Formation) through Eocene (Wasatch) time, with current topographic expression resulting from later Miocene-Pliocene uplift (Foose et al., 1961, p. 1164-5).

#### Basement Configuration

A block diagram depicting the configuration of Precambrian basement along the Northeast Beartooth Front as interpreted by Foose et al. (1961) is shown in Figure 9, p. 58. Note that along most of the Northeast Beartooth front high-angle thrust faults dip back under the Front, but in the area south of the East Boulder Fault, the basement forms a gentler ramp out to the north, and is cut by the high angle East Boulder Fault. Vail (1955, p. 25) calculated a minimum of 1220 meters (4000 feet) of vertical displacement upward of the block north of the East Boulder Fault, at the point where Cretaceous Kootenai Formation on the south side of the fault is in contact with the Precambrian amphibolites north of the fault on Long Mountain. This estimate is based on measured stratigraphic thicknesses from the Flathead Formation to the Kootenai Formation in the north block plus the 153 meters of exposed amphibolites.

To the author's knowledge, no conclusive evidence of any extensive southward thrusting of the north block

exists. A northward movement of the north block to its present position is ruled out by the fact that inliers of Cambrian sediments younger than the Flathead Sandstone are in unconformable contact with the Stillwater Complex, whereas these same Cambrian units are preserved in conformable contact above the Flathead Sandstone on the north side of the East Boulder Fault.

Both Vail (1955, p. 25) and Garbarini (1957, p. 149) characterize the surface expression of the fault as high-angle reverse, and vertical or steeply north-dipping, based mostly on the fault's nearly straight-line trace across mountainous topography between the Main Boulder and East Boulder River (Figure 3, p. 13.)

The tightly folded E-W trending synclines with steep southward dipping north limbs (on the south side of the East Boulder Fault) and the northward dip of the E-W trending sedimentary bedding on Long Mountain (north of the East Boulder Fault) suggest that these folds in the sedimentary strata were produced by faulting which broke through along the crest of the folds, uplifting the northern block (Garbarini, 1957, Plate I, "Geologic Map of the McLeod Area".) No evaluation of whether the fault flattens to the north at depth was possible based on the author's field observations and a review of existing literature. The trend of the fault is  $N 65^{\circ} - 75^{\circ} W$  through the study area (Vail, 1955, p. 24).

Foose et al., (1961) depict the East Boulder Fault as an extension of the Nye Bowler Lineament (Figure 9, p. 58 ). Wilson (1936, p. 1172) described the Nye Bowler Lineament as a "series of anticlines, domes, and half domes in alignment along a regional anticlinal trend extending from the Beartooth Mountain Front to the Pryor Mountains", and having a regional strike of N 65° W (Figure 8, p. 57 ). Rouse et al. (1937, p. 737) believe that the line of intrusions comprising Limestone Butte, Round Mountain and the Lodgepole Intrusion were "controlled by pre-existing doming along the Nye Bowler Lineament". Foose et al. (1961, p. 1150) state that "a left-lateral sense of movement exists throughout most of the zone."

The location of the study area (as defined in Figures 1, 2 and 3) is outlined with a dashed line on the block diagram of Figure 9 (p. 58 ), and the outcrop area of the Stillwater Complex is shown in red. This author speculates that the presence of the Stillwater Complex, which attains a maximum exposed thickness of approximately 5,500 meters in the area south of the gentle ramp-type front, and thins to the east and west, might have acted as a resistant strut or abutment during deformation of the Beartooth Front, causing a different style of deformation than along the remainder of the front. Where the ramp type front exists, compositional layering dips in the central portion of the Stillwater Complex are dominantly between 50° and 70° NE

in the Upper and Banded zones (Seegerstrom and Carlson, 1979, 1980) with strikes averaging N 78° W (Page, 1977, p. 59).

The dip of compositional layering in the Stillwater Complex steepens then overturns to the south near the southeastern end of the Complex, east of the Stillwater River (i.e., toward the left end of Stillwater outcrop as viewed in Figure 9, p.58 ), where the exposed Complex thins and/or is faulted out.

#### Laramide Sedimentary Structures

The northeastward dipping basement ramp discussed in the previous section provides a platform on which the Paleozoic and Mesozoic strata are draped in the study area. The present trends of the sedimentary strata on the Beartooth Front north of the upper unconformable contact with the Stillwater Complex strike approximately WNW, with dips in the Cambrian strata of 30° to 40° NE and dips in the Madison Limestone of 50° to 80° NE (Vail, 1955, p. 21). Locally, roughly E-W trending folds occur in the strata, possibly reflecting sliding of strata off the front during Beartooth uplift and/or minor high angle faults in the basement (Garbarini, 1957).

This sedimentary section covers an unknown portion of the Upper Zone of the Stillwater Complex where the Cambrian units lie in unconformable contact with the Complex, because the dips of compositional layering in the Complex

are greater than the dips of the overlying sediments (p. 44). No roof rocks in direct contact with the Complex have been seen along this angular unconformity (Carlson and Segerstrom, 1980 Map).

North of the East Boulder Fault. WNW trending Paleozoic sedimentary units dip  $20^{\circ}$  to  $45^{\circ}$  north along Long Mountain (Vail, 1955; p. 23). Northward, the dips flatten to less than  $20^{\circ}$  north in the Cretaceous section (Garbarini, Geologic map, 1957) except where disrupted by the intrusion of the Lodgepole (in the Paleozoic section) and Enos Mountain and Susie Peak plutons (in the Cretaceous Section).

#### Gravity Studies

Geophysical studies published by Bonini (1981) suggest that the Stillwater Complex extends north and east of its outcrop area at depth, based on gravity data from the Bighorn and Crazy Mountain Basins. Figure 6, p. 52 shows a Bouguer Gravity Anomaly Map of portions of the Northern Beartooth Mountains and the Bighorn and Crazy Mountain Basins. Bonini's proposed outline of the areal extent of the Stillwater Complex in the subsurface is shown. Bonini marked the boundaries of the Complex as follows:

- A steep gravity gradient coincides with the southern edge of the exposed Stillwater Complex and continues

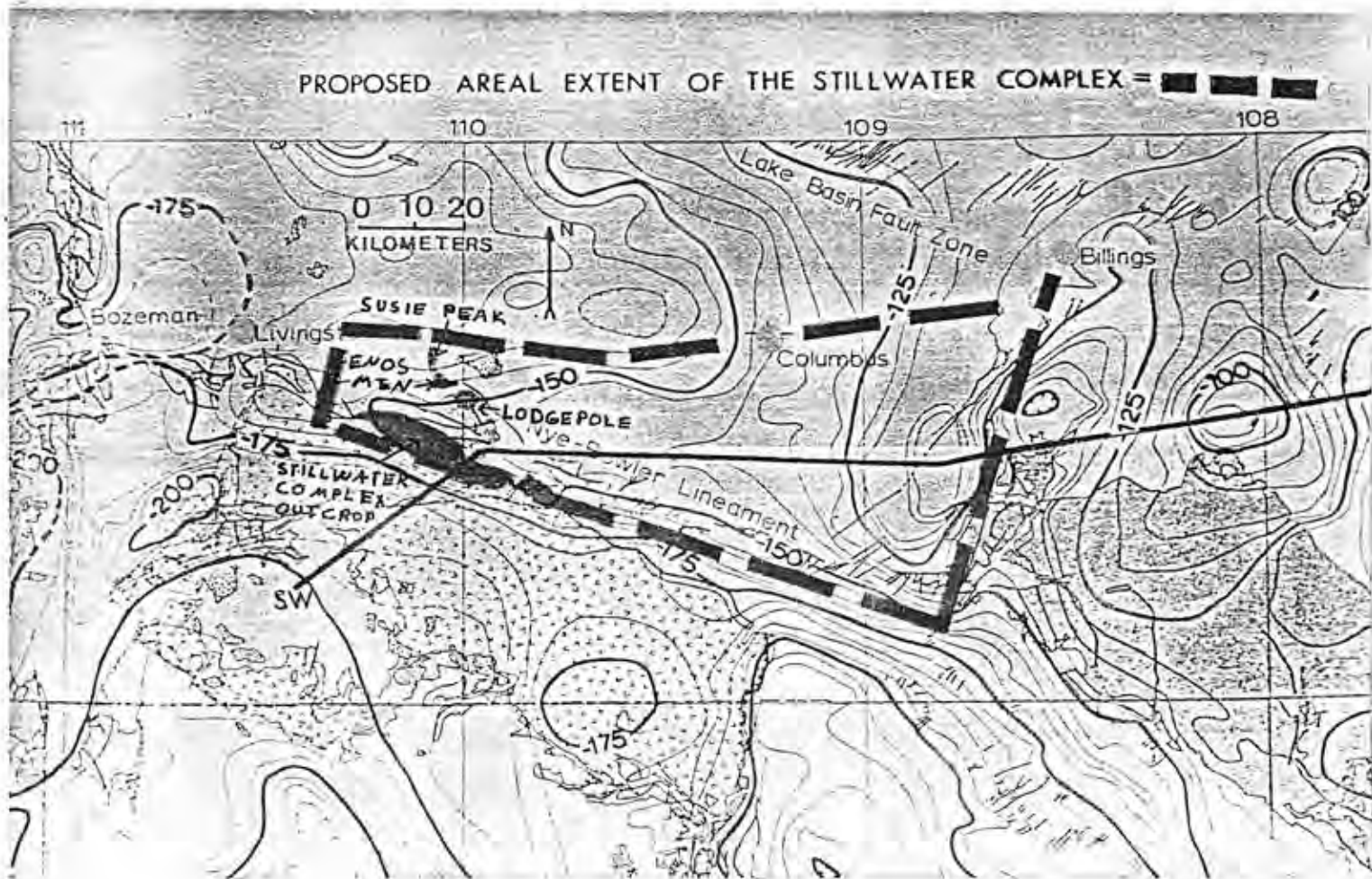


Figure 6. Proposed areal extent of the Stillwater Complex (after Bonini, 1981).

southeast along the Nye Bowler zone.

— The eastern boundary is marked by a steep gravity gradient defined by a high closure to the west and a low closure to the east.

— The Complex may thin or increase in depth on the northern edge because the gravity gradient is more subtle here.

Bonini constructed a Bouguer gravity anomaly cross-section and model (Figure 7, p 54) along the cross-section line shown in Figure 6. This model uses suitable densities averaged from hand specimens for the sediments, the gneissic basement, and the exposed Stillwater Complex. Bonini calculated a density of  $3.02 \text{ gm/cm}^3$  for an assumed Upper Hidden Zone composition from Hess (1960, p. 101).

The calculated 3rd degree gravity residual for the model (dashed line, top of Figure 7, p. 54) is in good agreement with the observed gravity residual (upper solid line, top of Figure 7).

From a comparison of the model (Figure 7, bottom) with the 3rd degree gravity residuals (Figure 7, top) note the following points (left to right):

- The strong gravity spike corresponding to the dipping Stillwater Complex outcrop.
- The high but flat gravity residual suggests a flat lying but dense body out under the Bighorn Basin.

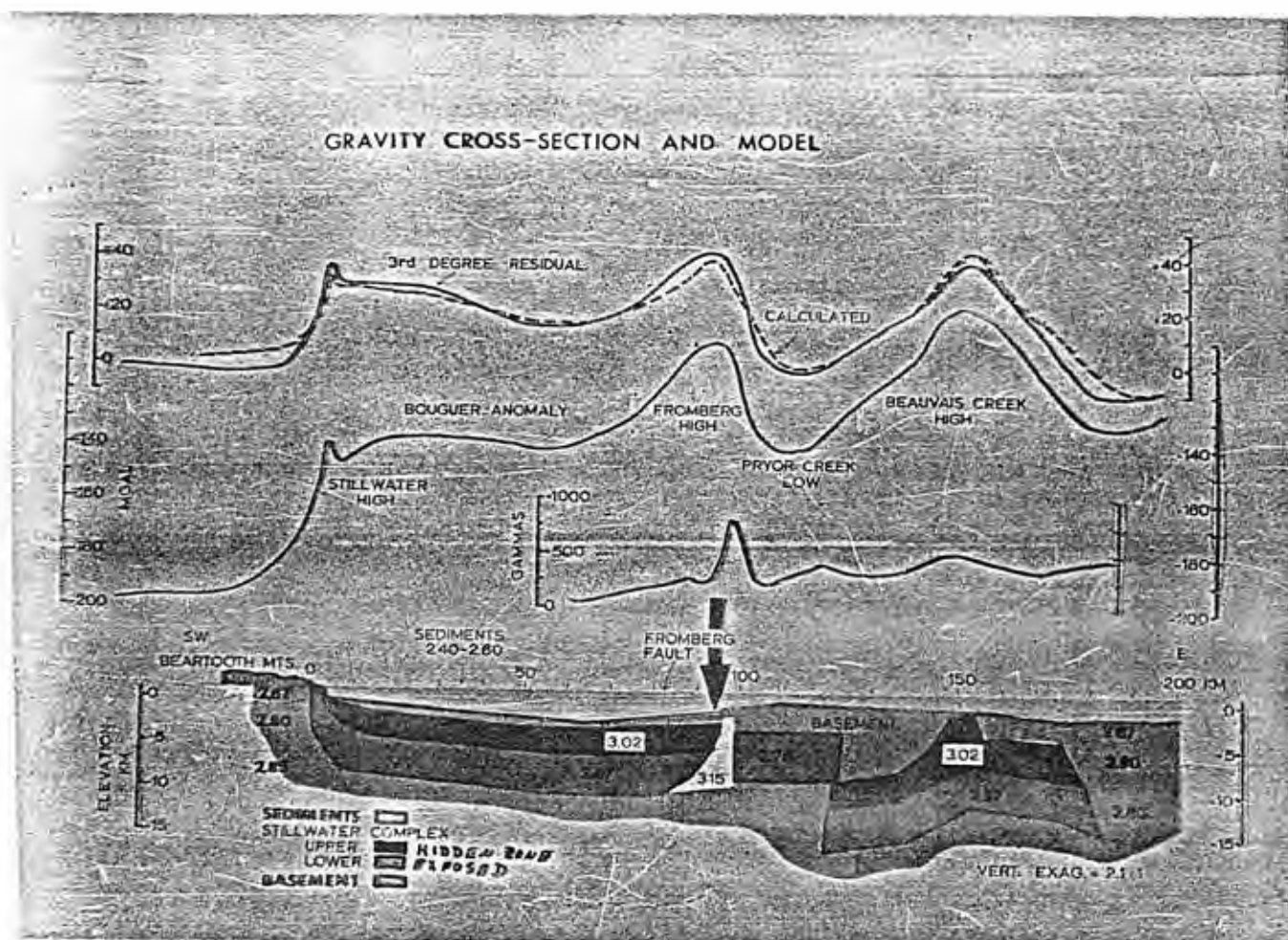


Figure 7.. Gravity cross-section model of the Stillwater Complex (after Bonini, 1981)

- \_\_\_ The steep gravity gradient toward the center of the figure suggests an abrupt termination of this portion of the Complex.
- \_\_\_ A gravity low modeled as a less dense intrusion.
- \_\_\_ A gravity high further east, also modeled as Stillwater Complex material by Bonini (this section is not included in the outlined area of Figure 6, p. 52 which includes only the area up to the arrow (↓) at the center of Figure 7.

#### Regional cross-section

A composite geologic cross section (Plate III) was constructed from Iron Mountain (south) to Susie Peak (north) along the line A - A' - A" shown in Figure 3, (p. 13 ) using the geologic maps and/or cross-sections of Segerstrom and Carlson (1979, 1980) (for the Stillwater Complex area), and Garbarini (1957), Vail (1955), and Booker (1957) (for areas north of the Stillwater Complex). Page (1977, pp. 67-69) offers a more complete analysis of faults in the Stillwater Complex. Garbarini (1957, pp. 149-152) describes faults affecting the sedimentary section to the north of the Stillwater Complex. Only faults which significantly offset the regional structure in the line of section are shown.

Modifications were made based on the author's own

work in the Lodgepole Intrusive area. The cross-section line A - A' - A'' is not shown on the Plate I map to avoid obliterating structural details in the Clover Basin area.

Figure 15 (p.64 ) shows a low-angle airphotograph looking East along the East Boulder Valley. Important geologic contacts, structural attitudes, and location names are provided on the photograph. The line of cross-section A - A' extends from Iron Mountain through Picket Pin Mountain and just east of Squaw Peak. The area crossed by the segment A' - A'' lies to the north of Squaw Peak and does not appear in this photograph.

#### Summary of Results

The steep northerly dips of compositional layering in the central and western portions of the Stillwater Complex (p.49 ) along with gravity data (p.51 ) provide evidence for a northern continuation of the Complex at depth north of the middle Cambrian unconformity (p.44 ) along its northern boundary. The stratigraphic and spatial position of the greenschists and amphibolites (p.61 ) exposed north of the Stillwater Complex along the upthrown north side of the high angle East Boulder Fault (p. 47 ) is used in Chapter IV to estimate the likely maximum thickness of any possible Stillwater Complex Upper Hidden Zone. Sedimentary section thicknesses (p. 45 ) are used to estimate the original depth of intrusion of the Lodgepole Pluton (Chapter II).

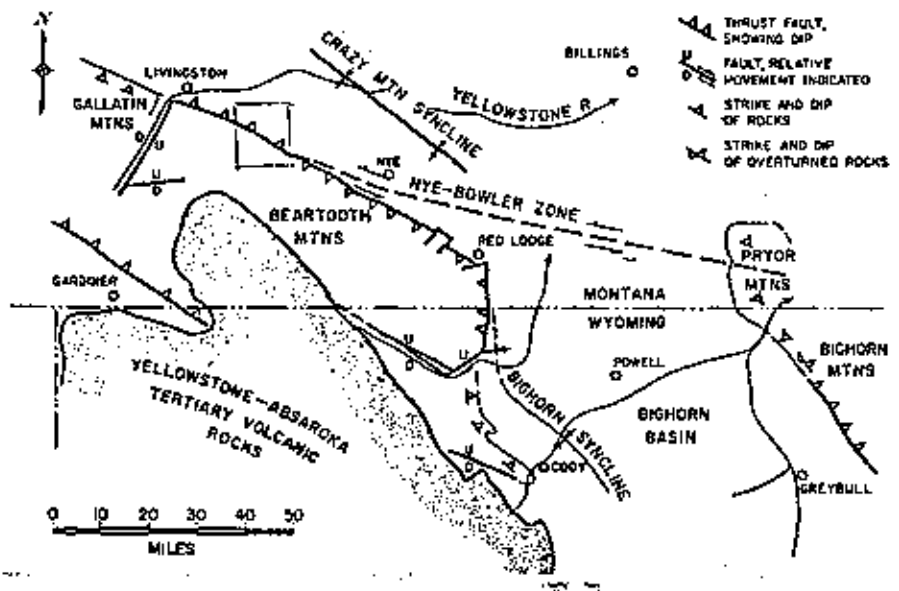


Figure 8. Major tectonic features of the Beartooth Area (after Foose *et al.*, 1961, Figure 2, p. 1149). The red outlined area shows the approximate location of the study area outlined by the dashed line in Figure 3, p. 13.

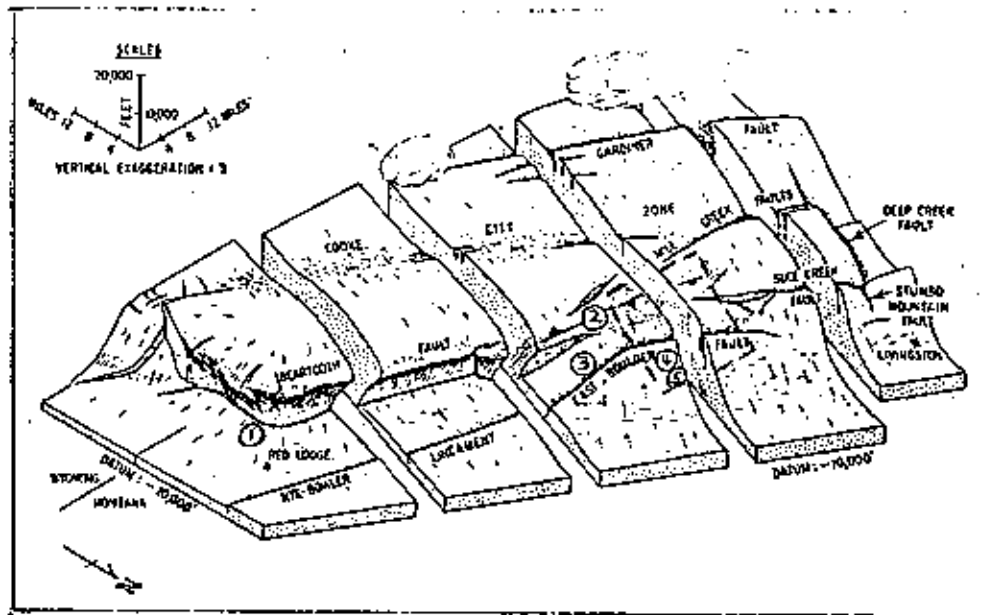


Figure 9. Structural interpretation of the northeast side of the Beartooth block, (after Foose *et al.*, 1961, Fig. 3, p. 1151). Note the orientation of the north arrow in the bottom left corner of the figure: north is toward the viewer.

The study area outlined with a dashed line in Figure 3, p.13 is outlined with a dashed line here.

Important structural features are numbered:

- (1) Beartooth Fault: 3050 m - 7000 m of structural relief (Foose *et al.*, 1961, p. 1152)
- (2) Stillwater Complex: 5500 meters maximum true thickness (Jones *et al.*, 1960, p. 281). Dip of compositional layering through central portion =  $50^{\circ}$  -  $70^{\circ}$  NE (Sagerstrom and Carlson, 1979, '80)
- (3) East Boulder Fault: 1220 meters upward displacement of north block, (Vail, 1955, p. 25)
- (4) Lodgepole Intrusion: located in Paleozoic section above the spot shown.
- (5) Enos Mountain and Susie Peak intrusions: located in Mesozoic section above the spot shown.

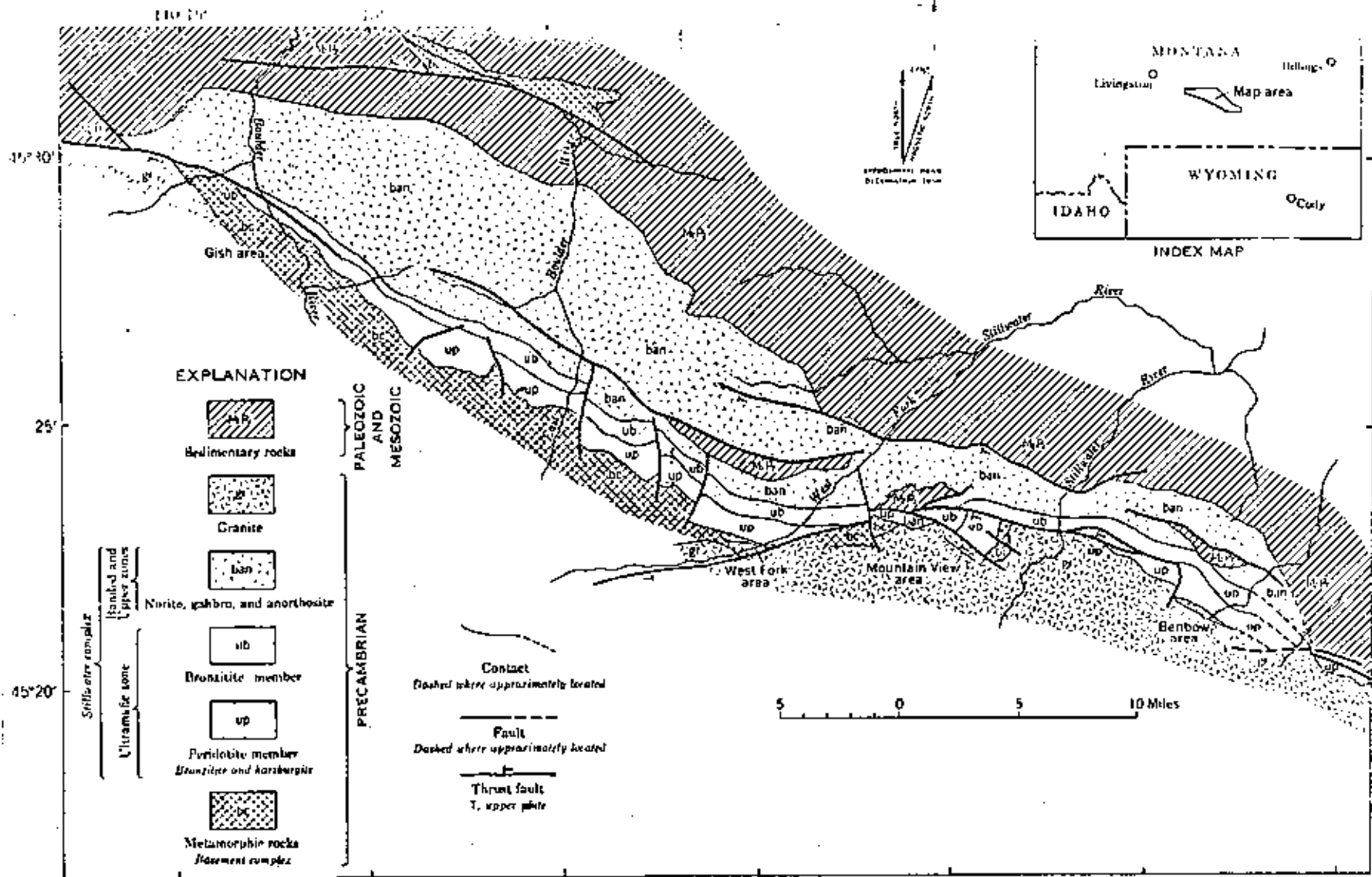


Figure 10. Generalized Geologic Map of the Stillwater Complex (after Jackson, 1961, Figure 1, p. 3)

**DIVISIONS OF STILLWATER COMPLEX**

	Page and Nokleberg, 1974	Hess, 1960 (from "Dead Tree" traverse near Long. 110°07'30")		McCallum, Raedeke * and Mathez, 1979 (from Chrome Min. - Contact Min. Section)		Sagerstrom and Carlson, 1982		
	Banded and Upper zones		Upper Gabbro and Hidden zones	Gabbro norite III	Upper Banded zone	Upper anorthosite member Upper gabbro member	Banded upper zone	
		Anorthosite 3		Olivine Subzone V		Upper mixed member		
		Gabbro		Anorthosite II	Middle anorthosite member			
		Anorthosite zone	Anorthosite 2	Olivine Subzone IV	Middle mixed member	Middle Banded zone		Middle gabbro member
			Gabbro	Olivine Subzone III	Lower mixed member			
			Anorthosite 1	Anorthosite I	Lower anorthosite member			
		Ultra- mafic zone		Lower Gabbro zone	Olivine Subzone II	Lower Banded zone		Lower gabbro member
Bronzite member					Gabbro norite II			Norite member
Peridotite member				Norite II	Olivine Subzone I	Bronzite member		Ultra- mafic zone
Basal bronzite cumulate			Gabbro norite I	Norite I	Peridotite member			
Basal norite	Basal zone				Ultra- mafic zone	Basal bronzite and basal norite member	Basal zone	
				Basal Series				

Figure 11. Comparison of Stillwater Complex Stratigraphic Divisions, as proposed by various workers (after Segerstrom and Carlson, 1982).

\*N.B. Banded Series refers to the Lower, Middle and Upper Banded zones of the McCallum et al. (1979) nomenclature above.

Figure 12.

Cross-section sketch of amphibolites in East Boulder Valley near eastern end of amphibolite outcrop belt.

Located as cross-section F - F' on map, Plate I.

Not to scale, approximate N to S distance in sketch is 1.1 kilometers, approximate vertical shown is 370 m from East Boulder River to top of Maurice Formation.

From south to north:

- Grits, conglomerates, and red mudstone of Cretaceous Kootenai Fm. (Kk). 115° / 80° N to vertical at this locality.
- East Boulder Fault (EBF), 10 m unexposed interval.
- Mafic amphibolites, chlorite schists, carbonate-chlorite-amphibole schists (grouped as P6s)
- Altered diabase dikes (P6db) intruding P6s, 5-20 m thick, 085° / vertical at this locality. Age of these dikes is not known (possible affinity to group of metamorphosed mafic dikes in Beartooth region dated at 2,562 ± 126 m.y. by Mueller (1971)?)
- Coarse porphyritic dacite (C) and rhyodacite porphyry (rdp). Intrusive age relations only as post-PreCambrian at this locality, but they are similar in lithology to late Cretaceous porphyries elsewhere in the Northern Beartooth Region (Rouse, et al., 1937).
- Gf - Gma Cambrian Flathead Fm. through Cambrian Maurice Limestone. Flathead Sandstone: 073° / 20° N at this locality.

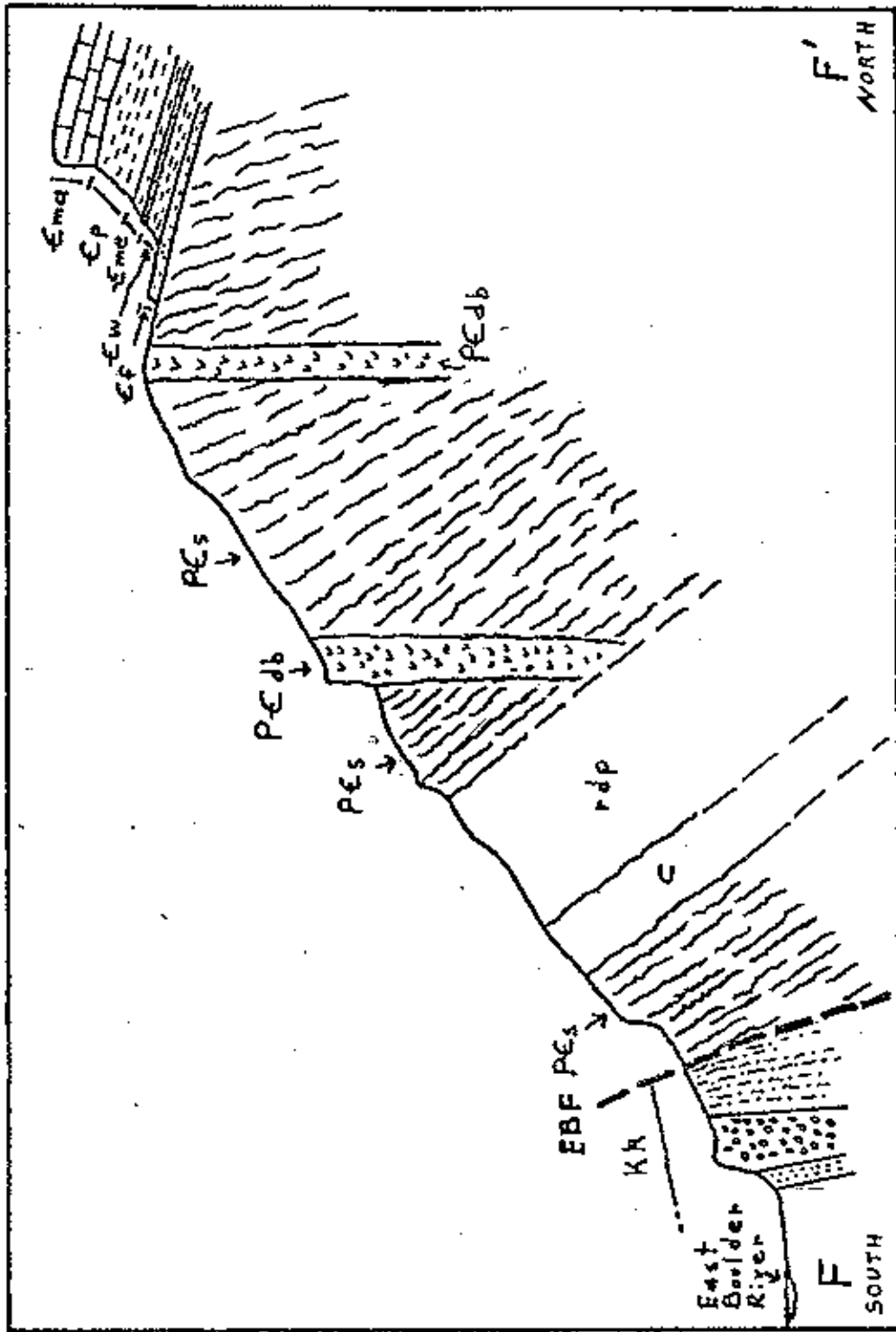




Figure 13. Photograph of amphibolites north of East Boulder Fault showing prominent foliation striking from upper left toward viewer and dipping back into hill toward lower right. Note: 10 cm thick black laminated chert layer at hammer. (Location is 2.8 km east of F - F' cross-section sketch referred to in Figure 12, p. 61.)

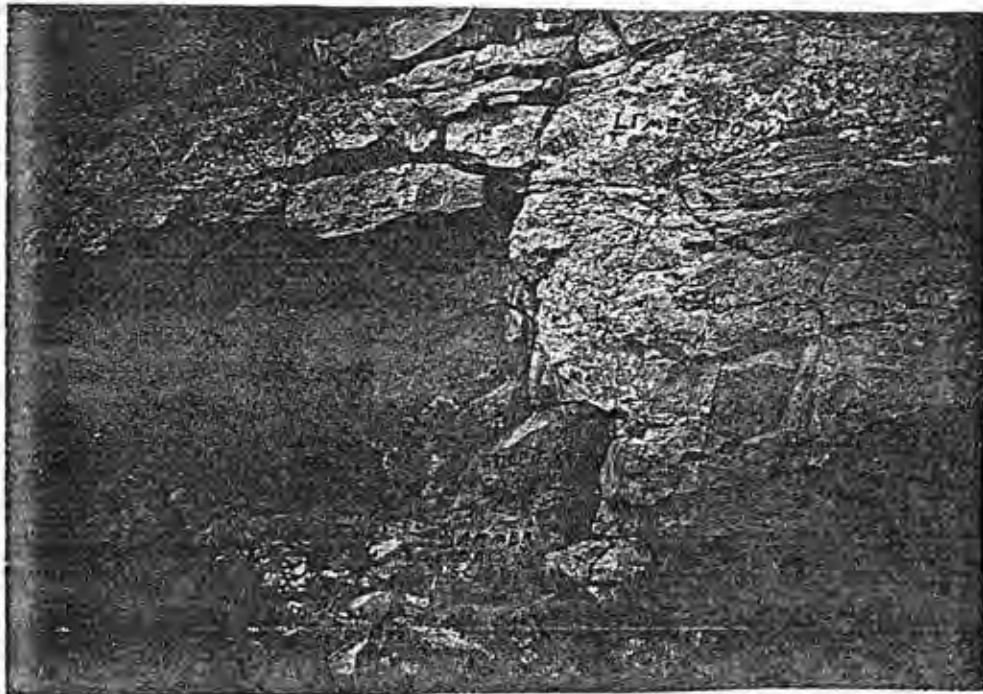


Figure 14. Detail of upper unconformable contact of the Stillwater Complex with Cambrian Meagher Limestone at the head of Castle Creek, 1 km north of Picket Pin Mtn., showing irregular middle Cambrian erosional surface.

Figure 15. Low-angle airphoto looking east along East Boulder Valley. Geologic symbols follow legend of Plate I. Cross-section line (discussed on p.55 ) extends from Iron Mountain (A) to Lodgepole area (A') in photograph.

Note from right to left:

- Stillwater Complex dipping to NE (P6sw)
- Cambrian to Cretaceous sediments dipping NE (G → Kk)
- East Boulder Fault (north side up)
- Amphibolites and greenschists north of East Boulder Fault (P6s)
- Cambrian Flathead (Gf) unconformably overlying P6s
- Lodgepole Intrusion in Paleozoic Section north of East Boulder Fault (upper left)



Section 2  
Lodgepole Intrusion

## LODGEPOLE INTRUSION

Purpose of Study

The Lodgepole Intrusion was studied in order to determine the stratigraphic horizons of intrusion, the internal contact relations among the intrusive phases, the sequence and style of emplacement of these intrusive phases, and the distribution of xenoliths within the intrusion.

Introduction

In their reconnaissance study of "porphyries" along the Northeast Beartooth Front, Rouse et al. (1937, p. 721) characterized the Lodgepole Intrusion as a complex laccolith of late Cretaceous age with a dacite porphyry border facies and marginal sills, and a central diorite facies.

The intrusion is centered 8 km north of the upper contact of the Stillwater Complex at Picket Pin Mountain, in the headwaters of the Deer Creek drainage (Plate I, center. Refer to Plate I for all areas discussed in this section).

Elevations within the intrusion are highest along its southern (2750 m, 9000 ft.) and western (2590 m, 8500 ft.) borders and decrease toward the north and east, declining to approximately 2075 m (6800 ft.) where Lower Deer Creek exits the eastern boundary of the intrusion.

Bedrock is well exposed along the western, southern and northern borders. Outcrops are generally confined to the steeper walls of stream cuts and to ridge crests elsewhere within the intrusion. Talus from the intrusion covers most of the interior slopes, colluvium fills the Lower Deer Creek drainage toward the eastern margin, and timber growth is heavy in the valleys and on north facing slopes.

Garbarini (1957) mapped the boundaries of the intrusion in his regional mapping of the McLeod Area. This study attempted to refine the contact relations with the country rocks and to map the distribution of the internal intrusive phases, as an aid to understanding the distribution of xenoliths (p. 89) among the intrusive phases.

#### Intrusive Phases

Four texturally and chemically distinct intrusive phases were noted within the Lodgepole Intrusion. They were fine-grained diorite, coarse porphyritic dacite, medium porphyritic dacite, and felsite (of rhyodacite composition).

Whole rock compositions are listed in Appendix 1-A for each of the intrusive phases described below. Normative mineralogies are listed in Appendix 3. (Rock names assigned follow the guidelines of Carmichael et al. (1974, pp. 32-39) and grain size modifiers follow the guidelines of Compton (1962, p. 275).

### Fine-Grained Diorite ( $\approx 56\% \text{SiO}_2$ )

In hand specimen the rock is a medium grey equigranular ( $\approx 1 \text{ mm}$ ) diorite, characterized by the presence of dark green tabular hornblende crystals, and weathers to a dark green-brown color (Figure 16, p. 71).

In thin section the rock consists of approximately 50% euhedral phenocrysts (0.2 - 1.0 mm) of (in decreasing order of abundance) andesine (both normal and reverse zoned), tabular hornblende, sanidine, biotite, and minor ( $< 1\%$ ) granular opaque oxides ( $\approx 0.2 \text{ mm}$ ), in a groundmass ( $\approx 20 \text{ }\mu\text{m}$  to glassy) containing abundant plagioclase, minor quartz, and dark glassy patches.

This rock is referred to as "diorite" rather than "andesite" because it is approximately 50% well crystalline.

Compositions of phenocrysts determined by electron microprobe are listed in Appendix 4-A for plagioclase and Appendix 4-B for hornblende.

The fine-grained diorite is designated with the symbol "F" on map Plate I.

### Coarse Porphyritic Dacite ( $\approx 61\% \text{SiO}_2$ )

In hand specimen the rock is a light grey porphyritic dacite characterized by conspicuous white (3 - 6 mm) phenocrysts of feldspar in a light grey aphanitic groundmass, and weathers to a dark grey color with a blocky fracture (Figure 16, p. 71).

In thin section the rock consists of approximately 30% euhedral phenocrysts of (in decreasing order of abundance) tabular andesine, sanidine, equant to blady hornblende, and biotite, ± quartz, in a light grey groundmass ( $\approx 20 \mu\text{m}$  to glassy) of plagioclase, quartz, and hornblende. The feldspar phenocrysts generally are highly sericitized and kaolinitized.

This rock is referred to as "dacite" even though field relations indicate it is intrusive, because of the high ( $\approx 70\%$ ) percentage of groundmass relative to phenocrysts.

The coarse porphyritic dacite is designated with the symbol "C" on map Plate I.

#### Medium Porphyritic Dacite ( $\approx 65\% \text{SiO}_2$ )

In hand specimen the rock is a light grey porphyritic dacite characterized by 1-3 mm white phenocrysts of plagioclase and potassic feldspar in a light grey aphanitic groundmass. It is identical mineralogically to the coarse porphyritic dacite described above except for the consistently smaller feldspar phenocrysts and the higher  $\text{SiO}_2$  content of the medium porphyritic dacite.

Although the medium porphyritic dacite phase was noted only in samples from the southeastern corner of the intrusion,

it was not mapped as a separate unit because of the close textural and compositional similarity to the coarse porphyritic dacite. It was grouped with the coarse porphyritic dacite in mapping.

#### Felsite ( $\approx 73\% \text{SiO}_2$ )

In hand specimen this rock is a cream colored aphanitic felsite (of rhyodacite composition) with rare ( $< 0.5\%$ ) highly altered phenocrysts ( $\approx 1 \text{ mm}$ ) of mafic minerals and feldspar. It weathers to a light olive-green color and has a semichonchoidal fracture.

The felsite is designated as "felsite" or "f" on map Plate I.

#### Latite

A thick (100 - 200 m) latite (?) sill (cream-colored in hand specimen, containing feldspar phenocrysts but no mafic minerals) was mapped 1 km east of the main Lodgepole Intrusion. Its chemistry and petrography were not studied because of the lack of xenoliths in the sill. Presumably it is an earlier intrusive phase than the main mass of the Lodgepole Pluton because it is conformable in the updomed sediments off the east flank of the Lodgepole Intrusion.

#### Areal Distribution and Contact Relations of Intrusive Phases

Detailed mapping showed that the sills extending into

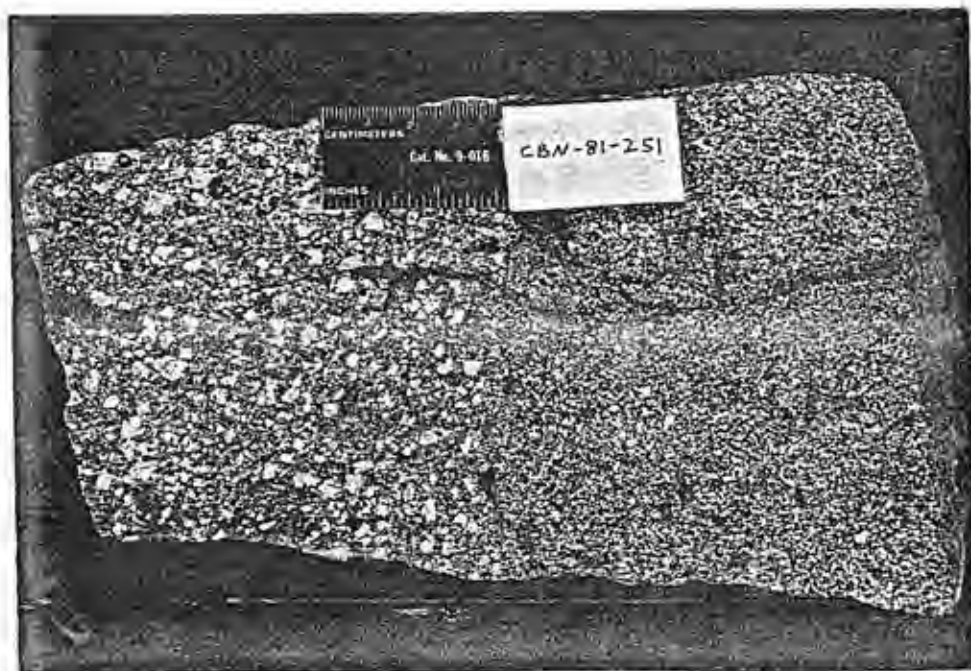
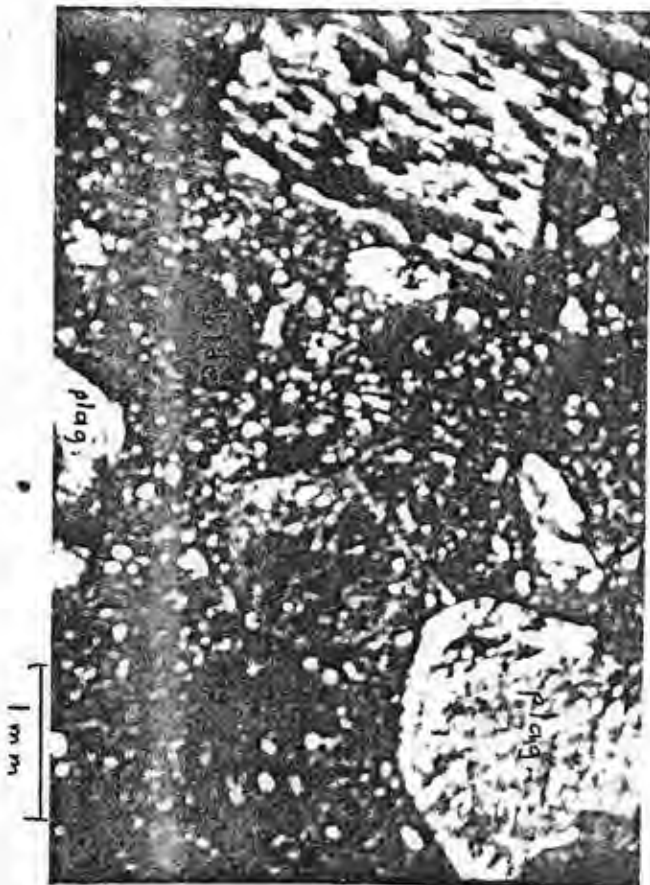


Figure 16. Contact (center, vertical) between coarse porphyritic dacite (on left) and fine-grained diorite (on right). Sample from 0.2 km north of Clover Basin area. (See text, pp. 70-75 for discussion of intrusive relationships).

Figure 16a. Photo-micrographs of intrusive phases.  
(plane polarized light, scale bar = 1 mm)

- (1) Coarse porphyritic dacite with phenocrysts of plagioclase, biotite, and hornblende labeled (see text, p. 68 for detailed description)
- (2) Fine-grained diorite, with phenocrysts of plagioclase and hornblende labeled (see text, p. 68 , for detailed description).



(1)



(2)

the Paleozoic sediments (as discussed on p. 75) are coarse porphyritic dacite. Where intrusive contacts could be observed directly, the coarse porphyritic dacite was in contact with the surrounding sediments, except for two localities.

Large expanses of the northern, southern, and eastern portions of the main mass of the intrusion consisted of coarse porphyritic dacite.

The most abundant occurrences of the fine-grained diorite were localized in a broad band, about 1 km wide, extending from north of Clover Basin near the western margin of the pluton eastward for approximately 4 km, where it is complexly intruded into the coarse porphyritic dacite (Figure 17, p. 76).

The largest discrete areas of fine-grained diorite mapped occupied approximately 1 km<sup>2</sup> in the area immediately north of Clover Basin, forming a massive peak (Clover Basin Peak). A second area of fine grained diorite covering approximately 0.5 km<sup>2</sup> lies immediately to the east along the same ridge. Dikes of fine-grained diorite occurred further eastward along the ridge and in the valley of lower Deer Creek immediately to the south.

In the far southeastern corner of the intrusion (1.1 km north of Washburn Mountain) the fine-grained diorite occurs in contact with the Madison Limestone. The fine-grained diorite may also be in contact with the Bighorn

Dolomite 2 km northwest of Clover Basin, but the exact contact is obscured by talus.

Where contacts between the fine-grained diorite and coarse porphyritic dacite were observed they were nearly planar and commonly vertical and no apophyses of either phase into the other could be found (Figure 16, P. 71).

This author believes that the fine-grained diorite is a later intrusive phase than the porphyritic dacite based on the following evidence:

- (1) In the valley of Lower Deer Creek immediately east of Clover Basin, and along the ridge approximately 1.5 - 2.0 km ENE of Clover Basin, near-vertical dikes of the fine-grained diorite were observed in apparent cross cutting relation to the coarse porphyritic dacite (no chill margins or apophyses, as mentioned earlier, could be found to substantiate this observation).
- (2) The coarse porphyritic dacite forming the marginal sills along the western and northwestern borders of the pluton have been overturned, possibly by the later intrusion of the massive fine-grained diorite (see northern end of cross-section B - B', Plate II). In contrast, where coarse porphyritic dacite dominates, such as along the eastern and southern margins of the

pluton, the adjacent sedimentary strata dip respectively moderately eastward and shallowly northward. (See southern ends of cross-sections B - B' and C - C', Plate II).

The felsite was observed on the ridge 0.5 km north of Clover Basin where it occurred as a northward dipping sill, approximately 50 m thick, intruding both the fine-grained diorite and coarse porphyritic dacite (Figure 17, p. 76). A dike approximately 20 m thick cuts the fine-grained diorite, approximately 0.4 km north of the first occurrence. It is the latest intrusive phase because it cuts across both the fine-grained diorite and the coarse porphyritic dacite.

#### Structure and Stratigraphic Horizons of Intrusion

Along the western and northern borders of the Lodgepole Intrusion, detailed field mapping revealed that the bulk of the pluton is emplaced stratigraphically below the Ordovician Bighorn Dolomite, with marginal sills occurring in the Devonian Jefferson Limestone (Figure 18, p. 78 ) and upsection toward the base of the Mississippian Madison Limestone. Exposures of the Cambrian Snowy Range and Grove Creek formations are widespread toward the southwestern corner of the pluton in the area of Clover Basin where they form shallowly northward dipping beds

Figure 17. View looking north across interior of Lodgepole Intrusion from a point 1.2 km ESE of Squaw Peak, along the southern border of the pluton. White material in foreground is dip slope of Threeforks Limestone. Grassy area beyond is coarse porphyritic dacite sill. Dips of the limestone bedding and sills are shallowly northward (away from viewer).

Prominent massive peak at left-center is large area of fine-grained diorite. Location of Clover Basin is marked at left center. The fine-grained diorite also occurs at intervals eastward along the high ridge across center of photo. Rounded, tree covered hills toward viewer from ridgeline are coarse porphyritic dacite. Low hills beyond high W-E ridge are dominantly of the Livingston Volcanics Formation.