A petrographic and economic evaluation of the White Cow Intrusion Little Rocky Mountains Montana

Janet Sue Roemmel

The University of Montana

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A Petrographic and Economic Evaluation
Of the White Cow Intrusion,
Little Rocky Mountains, Montana

by

Janet Sue Roemmel
B.S., Purdue University, 1980

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

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[Signatures]
Chairman, Board of Examiners

Dean, Graduate School

Date

May 22, 1982
The White Cow Intrusion crystallized from a dry, moderately viscous silicate melt that forcefully intruded along basement weaknesses. Lateral injection along the Archean-Paleozoic unconformity resulted in a floored intrusion that domed the overlying sedimentary rocks. Later high-angle normal faults cut the intrusion.

Textures in orthoclase and plagioclase of the syenite/monzonite porphyry indicate feldspar crystallization in disequilibrium with the remaining melt.

The White Cow Intrusion lacks alteration by subsequent hydrothermal solutions. The statistical results from stream sediment analyses for gold also support the lack of hydrothermal alteration and mineralization. However, fresh rock and stream sediments contain an anomalously high amount of primary gold.
ACKNOWLEDGMENTS

I wish to express my gratitude to Dr. John P. Wehrenberg for his guidance and concern throughout the study. Thanks are due to Dr. David D. Alt, Dr. Ian M. Lange, and Dr. Howard E. Reinhardt for their assistance in the preparation of this paper. Also, I wish to thank the Fort Belknap Tribal Community Council for their support of this project. Special thanks go to Joseph Klingshirn for his understanding and encouragement.
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INTRODUCTION

The information in this paper results from work during 1981 and 1982: field mapping and sample collection in the White Cow study area during the summer of 1981, and chemical and statistical analyses during the following months at the University of Montana, Missoula, Montana. Fieldwork included compilation of a geologic map (Fig. 2), and collection of rock and stream sediment samples for further study and analysis.

The White Cow study area (Fig. 1) lies on the northern edge of the Little Rocky Mountains in southern Blaine County, Fort Belknap Indian Reservation, Montana (T.26N., R.24E., Sec. 9-11, 13-16, 22-24; T.26N., R.25E., Sec. 18). The rocks include Archean metamorphic, Paleozoic sedimentary, and Paleocene intrusive units.

The purposes of this study include 1) examining the nature of the White Cow Intrusion, and 2) determining its potential for hydrothermal gold mineralization. This study developed as a part of a resource evaluation for the Tribal Council of the Fort Belknap Indian Reservation, Montana.
Figure 1. Location map of the White Cow study area, Fort Belknap Indian Reservation, Montana.
GENERAL GEOLOGY

Little Rocky Mountains

The Little Rocky Mountains were formed by several Paleocene igneous intrusions that domed the concordant overlying sedimentary rocks. Later high-angle normal faults have cut the intrusions and country rocks. Erosion has exposed the top of the intrusions, as well as sedimentary and metamorphic roof pendants of country rock.

Archean rocks of the Little Rocky Mountains include several metamorphic rock types of amphibolite facies: amphibolites, amphibolite gneisses, quartz-feldspar gneiss, biotite schists, and kyanite-garnet schist (Peterman, 1980; Bailey, 1974; Knechtel, 1959). The Archean outcrops occur in many orientations relative to each other; this suggests the intrusions reoriented them. Metamorphic rocks also occur as small inclusions within the intrusion (Bailey, 1974; Dyson, 1938).

Paleozoic and Mesozoic sedimentary rocks of the Little Rocky Mountains nonconformably overlie the Archean rocks. Knechtel (1959) described a Paleozoic and Mesozoic stratigraphic section over 2 km thick. In the Paleozoic section marine carbonates dominate; in the Mesozoic section marine and nonmarine shales dominate.

The Little Rocky Mountains consist of a floored intrusive dome of Paleocene age (67-60 m.y. ago) (Marvin, et al., 1980). Steeply dipping concordant sedimentary units flank the intrusion, and they shallow away from the intrusive dome. The melt intruded along basement fracture
conduits (Thomas, 1974) and forcefully raised the overlying sedimentary cover that lay horizontal before intrusion; now sedimentary roof pendants lie flat over the middle of the intrusion. Finally, movement along underlying basement weaknesses caused subsequent shearing and faulting within the intrusion and the adjacent country rocks (Thomas, 1974).

The intrusive rocks of the Little Rocky Mountains appear genetically related to the alkaline rocks of Central Montana (Larsen, 1940; Pirsson, 1905). Kirchner (1982) plotted variation diagrams that include rocks from the White Cow Intrusion showing its relationship to the intrusive rocks of the Judith Mountains. Though the rocks of the Little Rockies exhibit an alkaline affinity, its whole rock chemical data (App. A; Weed and Pirsson, 1896) do not fit most alkaline classifications (Sørensen, 1974). Perhaps before contamination by Archean inclusions, the whole rock chemistry was more alkaline.

Intrusive rocks of the Little Rocky Mountains include syenite and monzonite porphyries (Streckeisen, 1967). Major primary minerals include orthoclase (also sanidine), plagioclase (albite and oligoclase), and minor quartz. Typically the intrusive rocks contain more orthoclase than plagioclase; locally the rocks contain more plagioclase than orthoclase. The rocks rarely contain more than 10% primary quartz.

The country rocks near the Paleocene intrusions of the Little Rocky Mountains lack contact metamorphism. This reflects the lack of water with the melt. Presumably, ground water in the country rocks near the intrusive contacts flowed into the dry melt, thus lowering the temperature
of the contact zone so that no contact metamorphism occurred. This
effect contrasts the effects of a water-saturated melt that intrudes
similar country rocks: heated water expelled from a water-saturated melt
raises the temperature of the country rocks, thus forming a contact meta-
morphic aureole (Turner, 1968, p. 20).

White Cow Study Area

The country rock in the White Cow study area (Figs. 2, 3) consists
of lower Paleozoic sedimentary (App. B) and Archean metamorphic rocks.
Sedimentary units as young as the Mississippian Lodgepole Formation lie
in faulted contact with the intrusion. Archean metamorphic rocks include
thinly banded quartz-feldspar-hornblende gneiss, amphibolite, and muscovite-
quartz-feldspar gneiss. Various foliations occur in the Archean rocks,
and ignorance of their initial foliations prevents determining how much
the intrusion reoriented them.

The White Cow Intrusion is connected at depth to the main intrusive
body of the Little Rocky Mountains. The White Cow Intrusion consists of
a uniform grey mass of syenite/monzonite porphyry with about 65% ortho-
clase and 35% plagioclase (An$_3$-An$_{13}$). Plagioclase laths vary in length
between 0.1 and 0.7 cm. Orthoclase occurs both as large crystals (≤3.5 cm)
that commonly contain inclusions of plagioclase, and as the fine-grained
matrix. Small subangular and subrounded inclusions (0.5-5 cm) of Archean
amphibolites and amphibolite gneisses occur haphazardly scattered through-
out the top of the intrusion.
Geologic Map of the White Cow Study Area
Fort Belknap Indian Reservation, Montana

by Janet S. Roemmel
1982

EXPLANATION

Pre cambrian
Archean
Cambrian
Ordovician
Devonian
Mississippian
Tertiary
White Cow Intrusion
Lodgepole Fm.
Jefferson Fm.
Bighorn Fm.
Emerson Fm.
Undifferentiated

Contacts
known, approximate, inferred
Faults
known, approximate with relative motion
Strike and dips
bedding foliation

SCALE 1:24,000

Base maps taken from Hays and Lodge Pole U.S. Geological Survey 7 1/2' Quadrangles

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Figure 3

CROSS SECTION A-A'

White Cow Study Area

EXPLANATION

- Tertiary
- Mississippian
- Devonian
- Ordovician
- Cambrian
- Archean
- Precambrian

Contacts
- known, approximate, inferred

Faults
- known, approximate with relative motion

by

Janet S. Roemmel
1982
Faults of the White Cow area cut the country rocks and the intrusion. High-angle normal faults bound blocks of Paleozoic units that were downdropped towards the porphyry (Fig. 2). Evidence for post-crystallization vertical stresses and movement includes offset of sedimentary units and occurrence of brittle fracture. Broken fossils and offset chert beds lie along the periphery of a downdropped fault block of Lodgepole Formation (T.26N., R.24E., 1/4NE, 1/4SW, 1/4NW, Sec. 15). The small fault block of the Emerson Formation against the intrusion exposes a shear zone oriented nearly E-W (T.26N., R.24E., 1/4SE, 1/4SE, 1/4NE, Sec. 9). Smeared crystals in the intrusion next to the Emerson Formation are aligned parallel to the fault plane and the presumed direction of movement. At another location the Bighorn Formation downdropped along the strike of a fault that also offsets Paleozoic units outside of the intrusion (T.26N., R.24E., 1/4SE, 1/4SE, Sec. 9).

Offset of sedimentary and metamorphic units is the major criterion used in mapping faults in the White Cow study area. Offset sedimentary units commonly lie along the trend of what appears to be offset intrusive contacts, suggesting that faults continue into the intrusion, even though they are obscured by the lack of bedding offset.

Similar to the rest of the Little Rocky Mountains, the White Cow area lacks contact metamorphism of the adjacent country rocks. At one exposed intrusive contact, no metamorphism was seen in hand specimen. Even thin sections of intrusion-country rock contacts show slight contact effects as shown in Figure 4.
white w/spaced dots = siltstone
black = carbonate
striped = plagioclase
white = orthoclase
white w/dash = amphibole
stippled = potassium feldspar
matrix

Figure 4. Intrusive contact between the White Cow Intrusion and the Emerson Formation. The Emerson siltstone is virtually unaffected by the intrusion. Some carbonate from the Emerson has recrystallized in the intrusion and as veinlets in the siltstone.
Crystallization History of the White Cow Intrusion

Textures and minerals in the White Cow Intrusion reveal a crystallization history of orthoclase and plagioclase feldspars from a silicate melt. The porphyritic texture of the White Cow Intrusion indicates a two-stage crystallization history of the melt: crystallization of plagioclase feldspar (0.1-0.7 cm) and orthoclase feldspar (≤3.5 cm) crystals during the first stage, and fine-grained potassium feldspar matrix during the second stage.

Plagioclase and orthoclase are the two major primary minerals, and form euhedral to subhedral crystals with normal-oscillatory zoning. Plagioclase also contains patchy zoning. Furthermore, it contains Carlsbad, albite, and pericline twins; orthoclase usually contains no twins, or less commonly contains Carlsbad twins. Primary apatite forms small euhedral grains that comprise less than one percent of the rock.

During the first crystallization stage anorthite-rich plagioclase (An_{13}) formed. As crystallization continued, the normal oscillatory-zoned plagioclase existed in disequilibrium with the melt. While zoning occurred, the crystals did not completely react with the melt as it locally alternated between sodic-rich and calcic-rich. This oscillatory zoning differs from normal zoning by alternating sodic-rich and
calcic-rich zones, rather than a continual enrichment in sodic-plagioclase. Although, the sodium content increases to An$_3$ outward from the core of the crystals.

Hills (1936) suggested that oscillatory zoning forms by changes in local melt composition during slow crystallization. His diffusion-supersaturation theory supported by recent experimental evidence (Smith, 1974, p. 237), involves four steps in forming such zones:

1) Crystallization of An-rich plagioclase in equilibrium with the melt.
2) Crystallization continues as the temperature drops so that the melt near the crystal becomes Ab-rich and the crystal becomes Ab-rich. Slow diffusion of Ab-plagioclase molecules towards the growing crystal occurs so that melt farther away becomes An-rich, and supersaturated.
3) Diffusion of more An molecules from supersaturated parts toward the crystal, especially during slow cooling, causes an An-rich zone on the crystal.
4) Repetition of processes with outer zones becoming more Ab-rich.

Patchy zoning of the plagioclase (Fig. 5a) also results from disequilibrium conditions (Fig. 5b). Vance (1965) suggested one method of patchy zoning formation--pressure release of a dry melt (Fig. 6). A dry melt, such as the White Cow, undergoing a rapid pressure decrease relative to a temperature decrease, crosses its melting curve (A), so that remelting of patches occurs along the (010) plane of the early calcic plagioclase cores. As temperature continues to drop, the melt crosses
outer white = orthoclase
striped = plagioclase
black of core = sodic plagioclase
white of core = calcic plagioclase
stippled = potassium feldspar matrix

Figure 5a. Patchy zoning in the plagioclase core of an orthoclase crystal. It also contains an oriented lath of plagioclase.

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Fig. 5b. The causes and effects in the formation of patchy zoning.
Figure 6. Behavior of crystals in a rapidly rising dry melt. With a rapid pressure decrease the crystals begin to melt. (A) With subsequent temperature decrease, crystallization resumes. (B) (Modified from Hyndman, 1972, Fig. 3-11)

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its melting curve (B) and returns to the stability of the solid phase. Thus, crystallization resumes before the entire plagioclase crystals remelt, and a patchy pattern results in some plagioclase cores: the early patches of the core are more calcic and the newly filled patches of the core are more sodic. In addition, the new sodic patches generally parallel the long axis of the plagioclase crystal due to the preferential melting along (010). Finally each generation of patches occurs in optical continuity with itself.

Another possible method of patchy zoning formation in the White Cow Intrusion is the addition of feldspars from Archean inclusions (usually high albite content (Marvin, et al., 1980)) that melted into the remaining White Cow melt causing disequilibrium between the early calcic feldspar crystals and the melt of new composition. This new melt attempted to attain equilibrium with the earlier feldspar crystals, thus remelting patches of them. Once crystallization of the new melt resumed, a new generation of feldspar filled the patchy voids. The void-filling feldspar contained less calcium than the original core material that melted by adding Archean feldspars.

Late in the first stage, orthoclase formed following earlier plagioclase crystallization. Inclusions of plagioclase served as nuclei for the orthoclase, forming cores of the large orthoclase crystals; other inclusions lie along crystallographic directions within the orthoclase (Fig. 7). As the orthoclase grew, the plagioclase crystals suspended in the melt became attached to the crystal faces of the orthoclase in
white w/dots = orthoclase
striped = plagioclase
white w/dashes = amphibole
cross-hatch = amphibole
white = sphene
stippled = potassium
feldspar matrix

Figure 7. Large orthoclase crystal containing oriented single-grain inclusions of plagioclase, amphibole, and sphene.

mechanically stable positions so that the long axis of the two feldspars laid parallel (Hibbard, 1965).

During first-stage crystallization, the melt incorporated inclusions of mafic Archean basement rock. Small mafic inclusions (0.5-5 cm) of amphibole and sphene are typically subangular to subrounded, and are roughly foliated to massive. Similar amphibole and sphene grains abound in outcrops of Archean basement rock of the Little Rocky Mountains (Knechtel, 1959; Marvin, et al., 1980; Bailey, 1974; Brockunier, 1936). This is especially true in the White Cow area.

Many mafic inclusions broke up during first-stage crystallization of orthoclase scattering many single grains of sphene and amphibole haphazardly throughout the melt. Furthermore, orthoclase crystallized
around these single grain inclusions of amphibole and sphene. Similar to plagioclase inclusions in orthoclase, the single grains lie along crystallographic directions as shown in Figure 7.

Archean amphibole and sphene grains were not melted in the White Cow Intrusion, since it could not melt mineral inclusions that form at higher temperatures than those minerals crystallizing from it (Hyndman, 1972, p. 84). In contrast to the rocks of Archean roof pendants, few foliated or massive Archean inclusions contain feldspar and quartz. Presumably as the White Cow melt was crystallizing feldspar, the Archean feldspar and quartz, being lower temperature minerals, were melted by the intrusion.

Melting of the Archean feldspar and quartz limited the size and composition of the Archean inclusions that occur in the White Cow Intrusion. These inclusions broke apart along the quartz- and feldspar-rich layers, so that only the thin mafic layers remain.

During the first-stage crystallization, sanidine locally formed instead of orthoclase. Upon intrusion sanidine formed in a chill zone as the high temperature melt cooled and crystallized quickly against the country rocks (Hyndman, 1982, p. 172-173). The presence of sanidine further suggests that the present surface of White Cow is near the original top of the intrusion.

During second stage crystallization, the remaining melt formed the fine-grained orthoclase matrix. Rapid loss of heat induced spontaneous crystallization of the remaining potassium feldspar-rich melt (Smith, 1974, p. 202) at the top of the intrusion.
Following matrix growth, the Archean amphiboles altered to chlorite and hematite (Loughnan, 1969, p. 95). The feldspars, being more stable at lower temperatures, show less alteration than amphiboles, but show some alteration to clays.
Nature of the White Cow Melt

Field and experimental evidence suggest that the White Cow Intrusion crystallized from a dry, moderately viscous melt. Field evidence shows that the White Cow melt was nearly dry because of the lack of the water-induced contact metamorphic effects upon the surrounding country rocks, and absence of common primary hydrous minerals, such as biotite or hornblende.

Contact metamorphic effects exist next to most intrusive bodies that contained water. Typically a heated water-rich phase separates from the melt during crystallization (Hyndman, 1972, p. 81-84). The less dense water-rich phase tends to rise upward from the melt to an area of lower pressure. The rising water transports the more volatile ions that separate from the melt with the water. Then hot circulating water and ions interact with the country rocks to equilibrate thermal and chemical conditions between the melt and the adjacent country rocks. This chemical and thermal interchange between the rocks and water, or contact metamorphism, manifests itself in the rock record as a gradational zone in the country rocks next to the crystallized melt. More intense contact metamorphism occurs closer to the intrusion; less intense contact metamorphism occurs farther from the intrusion. In contrast, the White Cow intrusive contacts show contact metamorphism limited to only a few millimeters in width. This narrowness shows that very little water accompanied the melt (Hyndman, 1982, p. 516).
Because the White Cow Intrusion crystallized from a dry melt, some theoretical constraints are placed upon temperatures of crystallization. Dry melts crystallize at relatively high temperatures that exceed those necessary for crystallization of a melt with the same composition that contains even a small amount of water (Fig. 8). For a dry melt the relationship between maximum crystallization pressures and temperatures is direct; to induce crystallization from a dry melt lower (higher) pressures require lower (higher) temperatures. This occurs because pressure and temperature have opposite effects upon crystallization, or freezing, of a dry melt. In accordance with Le Chatelier's principle a lower pressure would allow for volume increase (melting), whereas a lower temperature would allow for a volume decrease (freezing). Thus, as the dry White Cow melt rose through the crust to lower pressures, the temperature needed for crystallization must decrease directly to the pressure (Hyndman, 1982, p. 135-136).

Upon intrusion of the White Cow melt, its temperature was relatively high. A chill zone of sanidine near the top of the White Cow Intrusion indicates that high temperature induced formation of this feldspar instead of the more common orthoclase feldspar. Sanidine only forms under low pressure (shallow emplacement) and high temperature (Hyndman, 1972, p. 308, 383, 396).

**Viscosity of the White Cow Melt**

Experimental evidence suggests that the dry White Cow melt was moderately viscous. Studies show that silica and alumina tetrahedra in
Figure 8. Comparison of melting conditions for melts of similar composition with different water contents. The White Cow Intrusion underwent dry melting.

(Modified from Hyndman, 1972, Fig. 3-11).
a silicate melt join before crystallization by a process called polymerization (Barth, 1969, p. 206-209; Bowen, 1934). (This occurs most efficiently in dry silicate melts, that contain abundant silicon and aluminum.) Polymerization causes tetrahedral structures to join together at each apex to form macroions. This tightly-jointed arrangement prevents free fluid movement. Polymerization may proceed uninhibited if the melt contains few elements besides silicon and aluminum. However, its efficiency decreases with the addition of cations: the polarizing cations (Ca > Na > K > Si > Al) weaken tetrahedral joins so that they break easily. Breakage of macroions allows movement and decreases the viscosity.

Abundant sodium and potassium cations in the White Cow melt—a dry silicate melt—lowers its viscosity. The viscosity of the White Cow melt would have been lower if more alkalis had been present, and higher if less strongly polarizing cations had been present.

Bowen (1934) published temperature-viscosity curves for melts of different compositions (Figs. 9a, 9b). The curves shown in Figure 9b, for Sample 3 and albite bracket the viscosities expected for the White Cow melt. It contained more potassium and less sodium than Sample 3. This means higher viscosities than Sample 3. Furthermore, the White Cow melt contained more silica and less alumina than albite. This means lower viscosities than albite. Thus, the White Cow melt viscosity curve should lie between the experimental curves for Sample 3 and albite.

The experimental curves for Sample 3 and albite were drawn for surface pressures, but the increase in viscosity due to higher pressure
is small (Hyndman, 1982, p. 139). Thus, the temperature-viscosity values of the graph would be similar for higher pressures.

Figure 9a. Comparison of melt compositions for the White Cow Intrusion, Sample 3 and albite. Sample 3 and albite contain no $K_2O$.

(Modified from Bowen, 1934, Fig. 1)
Figure 9b. Observed viscosity-temperature curves for Sample 3 and albite. The White Cow melt viscosity-temperature curve must have fallen in the cross-hatched area between the other two observed curves.

(Modified from Bowen, 1934, Fig. 2)
Melt Emplacement in the Little Rocky Mountains

Basement weaknesses may have helped localize much of the post-Laramide igneous activity in Central Montana. Major surface lineaments in the area presumably reflect the underlying structure of the basement rocks (Thomas, 1974).

The Laramide Orogeny subjected the rocks of eastern Montana and western Dakotas to compressive stresses from the southwest. The underlying basement blocks underwent simple-shear block-coupling mechanics that caused strain, or rotation of them relative to each other. Differential shear on opposite boundaries of the blocks led to coupling across them represented by the lateral adjustment in drag-fold uplifts, faults, and fractures.

Thomas (1974) suggests that the northwesterly-trending Bearpaw, Cleveland, and Little Rocky Mountain uplifts are drag-folds that lie within the bounds of one of these basement blocks (Fig. 10). The uplifts parallel the direction of elongation of the strain ellipsoid that describes the deformation of that block. The drag developed as movement occurred along the basement weaknesses (the localized couples), while the drag-fold uplifts decreased the temperature-pressure gradient so melts could form and rise, hence the many intrusions and extrusions of the area.

Within the same block, the strong northeasterly trend represents a crossfold lineament that was subjected to tension in the Early Tertiary (post-Laramide) time. This tensational zone also allowed more melts to form and rise.
The above discussion implies that planar conduits for melts extend deep into the crust. The drag-fold uplifts and tension in the Little Rocky Mountains (as well as the Judith, Moccasin, Highwood, and Crazy Mountains) allowed pressure release within the dry lower continental crust (Hyndman and Hyndman, 1968) that induced partial melting (Hyndman, 1982, p. 180). The resulting dry melts rose to near surface levels under great pressure that caused forceful intrusions.

In the case of the Little Rockies, the melts spread laterally upon reaching the unconformity between the Archean metamorphic and the Paleozoic sedimentary rocks (Alverson, 1965; Brockunier, 1936). Successive intrusions (Bailey, 1974; Marvin, et al., 1980) coalesced along the discontinuity to form a large dome as shown in Figure 11. The dome characterizes the forceful intrusion of the melts by rocks that are pushed away from the center so that those in contact with the intrusion usually appear concordant. In addition, the intrusions show little evidence of stoping.

Roof pendants of Archean rocks remain attached to the sedimentary cover (Bailey, 1974). These blocks may have broken along foliation planes or other weaknesses from underlying basement during forceful intrusion of the melts, and raised upward with the sedimentary cover.

Post-intrusive movements along the basement fractures caused high-angle normal faulting within the Little Rocky Mountains. These faults cut both country rocks and the intrusions.
Figure 10. Location of basement-induced surface lineaments showing relative movements and relationships to the Bearpaw, Cleveland, and Little Rocky Mountain uplifts. Strain ellipsoid shows the appropriate direction of tension for the deformation.

(Thomas, 1974, Fig. 11A)

Figure 11. Intrusion of melts along a basement fracture conduit. Melts coalesce along the unconformity between the Archean basement and domed sedimentary cover.
ECONOMIC GEOLOGY

Geochemical Stream Sediment Survey

A stream sediment survey was chosen as the best way to gain reconnaissance level geochemical information about the White Cow Intrusion. Stream sediments were chemically and statistically analyzed to aid in the search for hydrothermal alteration and gold mineralization similar to that in the southern and central Little Rocky Mountains.

Sediment sampling is based upon the idea that stream sediments represent a composite of the weathering rocks upstream in the catchment area. Elements from weathered rock materials, such as metals, of varying mobility disperse accordingly, and then concentrate in stream sediments due to chemical and physical barriers (Levinson, 1980, p. 16-19). For example, in the case of hydrothermal gold ore, genetically related trace elements, such as gold, silver, antimony, tellurium and arsenic, may concentrate in the stream sediments downstream from weathering ore.

Thirty samples taken from drainages of the White Cow Intrusion were analyzed by atomic absorption spectrometry for gold (App. D). Statistical methods were then applied to the geochemical data to determine the significance of element concentrations.
Statistical Results and Interpretations

Statistical analysis of geochemical data aids in determining the potential for hydrothermal alteration and gold mineralization in the White Cow Intrusion of the Little Rocky Mountains. Further, results are used to infer genetic relationships between the rocks and gold concentrations in stream sediments of the White Cow area.

Hydrothermally altered intrusive rocks in the central and southern Little Rocky Mountains host gold-silver mineralization. While depositing gold ore nearby, hydrothermal solutions altered the host rock by adding secondary gangue minerals including silica (both free quartz and chalcedony), fluorite, pyrite, and sericite. These minerals fill open spaces of breccia zones and replace primary minerals of the host rock (Bailey, 1974; Dyson, 1938; Brockunier, 1936). In addition, hydrothermal ore minerals include native gold, a gold-silver telluride (?sylvanite), and gold-bearing pyrite. Galena, sphalerite, and molybdenite occur in minor amounts.

Similar alteration from hydrothermal solutions is absent near breccia zones along normal faults in the White Cow area. For example, rocks contain no hydrothermal quartz, fluorite, or pyrite, and primary feldspars show little alteration to sericite.

The statistical analysis of geochemical data (App. D, F) confirmed field observations that the White Cow Intrusion remains unaltered, and thus, contains no hydrothermally-induced gold mineralization. The cumulative frequency plot of gold values plotted on logarithmic
probability paper, resulted in a single background population suggesting that the rocks have not been altered (Figs. 12, 13).

Unaltered White Cow rocks contain only background amounts of gold, so that their concentrations result only from their primary occurrence in the melt that formed the intrusion—not from later hydrothermal alteration. Thus, the White Cow melt transported and deposited any trace elements present in the rocks. But, unaltered White Cow rocks and their derived stream sediments contain higher gold amounts than expected. Typically rocks of syenite/monzonite composition contain only 0.00X ppm gold (Turekian and Wedepohl, 1961). However, the White Cow rocks stream sediments contain 100 times more gold than that.

Since the White Cow Intrusion contains only primary gold, other related unaltered post-Laramide Central Montana intrusions may contain similar amounts of primary gold. Similar sources for these intrusions may have contributed similar amounts of primary gold to their melts.
Figure 12a. Histogram of gold concentrations. The distribution is positively skewed.

Figure 12b. Histogram of logarithms of gold concentrations.
Figure 13. Cumulative frequency plot for gold showing one lognormally distributed population.

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SUMMARY

The White Cow Intrusion was studied petrographically and chemically to determine its character and its potential for hydrothermal gold mineralization. The White Cow Intrusion formed from a melt that intruded forcefully along planar conduits in the basement rock. Upon reaching the weakness between the Archean and Paleozoic rocks, the moderately viscous melt spread laterally, doming the overlying sedimentary rocks.

The melt contained abundant silica, alumina, and alkalis that formed syenite and monzonite porphyries. Patchy and oscillatory zoning of the feldspars show that the minerals crystallized while in disequilibrium with the remaining melt.

No rock alteration of hydrothermally introduced gold mineralization exists in the White Cow Intrusion. It contains only background concentrations of gold, as confirmed by chemical and statistical analyses. However, the rocks contain higher amounts of primary gold than expected for an unaltered syenite/monzonite.
APPENDIX A
Table 1. Whole Rock Chemical Analyses

<table>
<thead>
<tr>
<th>Element</th>
<th>JR67</th>
<th>JR94</th>
<th>JR143</th>
<th>JR195</th>
<th>Mean Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>65.55</td>
<td>65.90</td>
<td>64.28</td>
<td>66.28</td>
<td>65.50 68.65</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>18.25</td>
<td>17.06</td>
<td>18.18</td>
<td>17.42</td>
<td>17.73 18.31</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.24</td>
<td>0.39</td>
<td>0.30</td>
<td>0.26</td>
<td>0.30  0.20</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.38</td>
<td>2.09</td>
<td>1.63</td>
<td>1.42</td>
<td>1.63  0.56</td>
</tr>
<tr>
<td>FeO</td>
<td>1.58</td>
<td>2.39</td>
<td>1.87</td>
<td>1.62</td>
<td>1.87  0.08</td>
</tr>
<tr>
<td>MnO</td>
<td>0.08</td>
<td>0.11</td>
<td>0.07</td>
<td>0.09</td>
<td>0.09  trace</td>
</tr>
<tr>
<td>MgO</td>
<td>2.71</td>
<td>2.35</td>
<td>3.31</td>
<td>2.31</td>
<td>2.67  0.12</td>
</tr>
<tr>
<td>CaO</td>
<td>0.62</td>
<td>1.00</td>
<td>0.88</td>
<td>0.53</td>
<td>0.76  1.00</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.34</td>
<td>4.14</td>
<td>4.52</td>
<td>4.80</td>
<td>4.45  4.86</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.17</td>
<td>4.41</td>
<td>4.89</td>
<td>5.18</td>
<td>4.91  4.74</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.08</td>
<td>0.16</td>
<td>0.08</td>
<td>0.09</td>
<td>0.10  trace</td>
</tr>
</tbody>
</table>

*a* Analyses done at Washington State University, Pullman, Washington reflect the presence of mafic Archean inclusions that probably were not in the rock analyzed by Weed and Pirsson, 1896.

*b* Weed and Pirsson, 1896.
SEDIMENTARY ROCKS OF THE WHITE COW STUDY AREA

The sedimentary rocks contained within the study area generally encircle the Paleocene intrusion which caused their uplift. In some instances the sedimentary rocks lie next to igneous rocks along fault contacts. Carbonates dominate the stratigraphic section of the lower Paleozoic rocks. Only descriptions of formations located near the White Cow Intrusion follow.

Middle and Upper Cambrian Series

Knechtel (1959) demonstrated that the formations representing the Middle and Upper Cambrian Series total between 300 and 350 m in thickness. The Flathead Formation nonconformably overlies the pre-Belt Precambrian metamorphic rocks. The weathered, unconformable surface provided a zone weakness along which the Paleocene melt commonly intruded. From 290 to 335 m of the younger Emerson Formation blankets the Flathead Formation.

**Flathead Formation.** White to pink, well-sorted quartz sandstone of the Middle Cambrian Flathead Formation crops out in very few places within the study area. Quartz cements the well-indurated rock that contains no carbonate. The coarse and medium grains (≤ 1 mm) range from subangular to subrounded, and coarser grains concentrate in layers to form a pebble conglomerate.

Thin horizontal laminae characterizes the bedding. The limited thickness of the unit (≤15 m) presumably accounts for the meager exposures adjacent to the Archean and Paleocene rocks.
Emerson Formation. The Emerson Formation of Middle to Upper Cambrian age commonly lies in contact with the intrusive rocks. The highly calcareous unit of limestones, shales, and lesser sandstones measures between 290 and 335 m at the type section of the Emerson (Knechtel, 1959). This unit weathers to poor exposures of thin-bedded grey, yellow, brown, and red limestone. In addition, the Emerson contains thin interbeds of mostly micaceous, green glauconitic, grey, and black calcareous shale, with subordinate red calcareous shale. The intraformational limestone conglomerate prevails as one of the most common rock types within the Emerson of the study area. While clasts range from .1 to 6 cm in length, coarse intraclasts prevail. Micritic lime surrounds rounded, elongated, and flattened lime fragments. Micritic lime dominates, with a scant amount of sparry calcite.

The Emerson Formation contains fossil remains of Middle and Upper Cambrian in age (Lochman, 1950). Lochman (1950) confirmed the age of fauna at the type section in Lodgepole Creek in the Little Rocky Mountains. The upper part includes no fauna of Lower Ordovician Series. Lochman realized the time equivalence of the Emerson Formation with units to the west, the Wolsey, the Meagher, the Park, and the Pilgrim Formations. On the other hand, other authors noted the occurrence of Middle and Upper Cambrian in the Little Rockies as equivalent to the Deadwood Formation of the Black Hills (Greis, 1952). Knechtel (1956) later defined the type section on Emerson Gulch of Lodgepole Creek as the Emerson Formation. Knechtel recognized that even though the ages were comparable to either the western or eastern counterparts, the
changes in rock type between Western Montana and Western South Dakota were sufficient to warrant a new unit name, hence the Emerson Formation.

**Upper Ordovician Series**

**Bighorn Formation.** The Bighorn dolomite of the northern Little Rocky Mountains spans a thickness of 84 m (Knechtel, 1959). The Bighorn Formation typically weathers to greyish or bluish white resistant outcrops. Exposures exhibit pitted surfaces of a massive dolomite. Cherty nodules and lenses resist weathering more than the surrounding thin- to medium-bedded carbonate (3-15 cm). Commonly the Bighorn contains coarse and fine dolomite grains with cross-cutting coarsely crystalline calcite veins. This extremely fossiliferous unit exudes a fetid odor when broken.

**Devonian System**

**Jefferson Formation.** Resistant outcrops of the Jefferson limestone of Devonian age weather blue-grey, and pinkish grey. The texture varies from micrite to sparry calcite. Freshly fractured rocks emit a fetid odor. Commonly veins of sparry calcite cut the micrite. Differential weathering produces a pitted surface. Very thinly to thinly bedded limestone and limey siltstone combine to form what resembles wavy bedding and lenticular bedding (1-5 cm), though many areas are thinly to medium bedded (5-15 cm) or massive. In the northern Little Rockies the stratigraphic thickness of the Jefferson limestone measures 128 m (Knechtel, 1959).
The Jefferson limestone contains copious amounts of fossils and fossil fragments. Exposed bedding surfaces show worm burrows, while cross-sections reveal colonies of stromatoporoids. Throughout the unit chert nodules and lenses occur.

**Lower Mississippian Series**

**Lodgepole Formation.** The Lodgepole Formation that forms the flat-irons along the rim of the Little Rocky Mountains, occurs at one locale in the study area. This Lower Mississippian unit exists not in the normal stratigraphic sequence, but rather as an isolated outcrop in the midst of the intrusive rock. As typical for limestones in a semi-arid environment, the Lodgepole limestone forms white to grey resistant outcrops. The Lodgepole in the study area consists of a highly fossiliferous micrite. This very thinly to medium bedded unit (2-12 cm) commonly contains lenses and nodules of chert.
Sample locations were determined by the configuration of drainages in the study area. Stream sediments just below the surface accumulation were collected from drainages, many of which contain intermittent streams. Two samples from each site (2 m apart) were air-dried in Kraft paper collection bags.

Duplicate samples were mixed and representative samples were pulverized with an agate mortar and pestel before igniting them in platinum crucibles.

Splits of samples of different sieve fractions were analyzed. Though there was little difference between them, the 1 mm sieve fraction gave the best results, and was used for the rest of the analyses.

The 1 mm sieve fraction contains a lower amount of elements absorbed onto clays than the more common -80 mesh, for example. This, and the similarity between element concentrations in rocks and stream sediments suggests that the nature of the sediments closely resembles the nature of the rocks. That is, there has been little chemical concentration of elements in the stream sediments that were analyzed.

Further sample preparation was done according to Shapiro and Brannock's method for silicate analysis (Shapiro and Brannock, 1962). One-half gram of sample and 15 ml of Solution B in a covered Teflon beaker were heated in a sandbath overnight. The uncovered beaker was allowed to fume until the volume had decreased by about one-half. After transferring the solution to a Pyrex beaker, four drops of the HClO₄-HNO₃ mixture were added and it was heated to give off strong fumes. After cooling,
3-4 ml of H₂O, 5 ml of HNO₃, and 1 ml of hydrazine sulfate solution were added and boiled again. Finally, cooled samples were diluted to 25 ml.

Chemical analyses were performed on a Varian Techtron Atomic Absorption Spectrophotometer, Model AA-6. A gold standard was purchased from Fischer Scientific Company.

The final results for gold seemed much too high, possibly due to an unknown error in sample preparation. As a check, five samples, including one duplicate were sent for atomic absorption analysis at TSL Laboratories in Opportunity, Washington. Their results differ, but show a direct relationship with the first set of values. Thus, the first values were corrected proportionally to the TSL values which appear more realistic.
Table 2. Gold Concentrations of Stream Sediment Samples

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Gold (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>0.127</td>
</tr>
<tr>
<td>78</td>
<td>0.107</td>
</tr>
<tr>
<td>85</td>
<td>0.145</td>
</tr>
<tr>
<td>89a</td>
<td>0.115</td>
</tr>
<tr>
<td>90</td>
<td>0.127</td>
</tr>
<tr>
<td>92b</td>
<td>0.133</td>
</tr>
<tr>
<td>94b</td>
<td>0.107</td>
</tr>
<tr>
<td>95</td>
<td>0.145</td>
</tr>
<tr>
<td>96</td>
<td>0.115</td>
</tr>
<tr>
<td>100</td>
<td>0.118</td>
</tr>
<tr>
<td>104</td>
<td>0.133</td>
</tr>
<tr>
<td>108</td>
<td>0.124</td>
</tr>
<tr>
<td>114</td>
<td>0.133</td>
</tr>
<tr>
<td>116</td>
<td>0.157</td>
</tr>
<tr>
<td>116a</td>
<td>0.145</td>
</tr>
<tr>
<td>119</td>
<td>0.127</td>
</tr>
<tr>
<td>126</td>
<td>0.139</td>
</tr>
<tr>
<td>134</td>
<td>0.127</td>
</tr>
<tr>
<td>137</td>
<td>0.121</td>
</tr>
<tr>
<td>140</td>
<td>0.127</td>
</tr>
<tr>
<td>142</td>
<td>0.139</td>
</tr>
<tr>
<td>144a</td>
<td>0.130</td>
</tr>
<tr>
<td>151a</td>
<td>0.139</td>
</tr>
<tr>
<td>153</td>
<td>0.151</td>
</tr>
<tr>
<td>162</td>
<td>0.133</td>
</tr>
<tr>
<td>166</td>
<td>0.127</td>
</tr>
<tr>
<td>170a</td>
<td>0.114</td>
</tr>
<tr>
<td>171a</td>
<td>0.136</td>
</tr>
<tr>
<td>172</td>
<td>0.157</td>
</tr>
<tr>
<td>174</td>
<td>0.127</td>
</tr>
<tr>
<td>183</td>
<td>0.148</td>
</tr>
<tr>
<td>187</td>
<td>0.127</td>
</tr>
<tr>
<td>196c</td>
<td>0.164</td>
</tr>
<tr>
<td>213c</td>
<td>0.130</td>
</tr>
</tbody>
</table>

-a Soil samples.

-b Whole rock sample.

-c Stream sediment sample from Bear Gulch, Little Rocky Mountains.
Figure 14. Spatial distribution of gold concentrations in stream sediment, soil, and rock samples.
STATISTICAL PROCEDURES

Geochemical data were analyzed statistically to determine the local background of gold, and if an anomalous population exists in the White Cow drainages.

For valid use of statistical methods, the geochemical stream sediment survey was designed to approach randomness so that conclusions about the samples could be applied confidently to the entire population of stream sediments. To approach a random homogeneous sample, two sediment samples per site were mixed, and only samples from drainages on the White Cow unit were analyzed statistically.

The first step in using statistical methods was to determine how the geochemical data are distributed. Typically values of trace elements, such as gold are lognormally distributed with a positive skew, meaning the logarithms are distributed by the normal or Gaussian law (Lepeltier, 1969; Ahrens, 1957; Tennant and White, 1959; Levinson, 1980, p. 569). The histogram of geochemical data from the White Cow area shows a positively skewed frequency in Figure 12a. The gold distribution is asymmetrical about its mean, and its mode is less than its median. This suggests that a logarithmic transformation might be appropriate. Further, the histogram of logarithms of gold values approximates a normal distribution by being symmetrical about its mean, and its mode is similar to its median (Fig. 12b). Thus, the histograms suggest that gold is lognormally distributed.
The second step in the statistical analysis was to plot the cumulative frequencies for gold (Fig. 13). The procedure for constructing a cumulative frequency plot, as outlined by Lepeltier (1969), was used to cumulate values from highest to lowest on logarithmic probability graph paper, so that the lowest values correspond to 100% frequency which is impossible to plot. This procedure was followed because the high values are more interesting geologically than the low values. Thus, it is better to disregard the lowest values at 100% frequency.

Once cumulative frequencies were plotted the procedure of linear regression was used to draw lines of best fit (Wonnacott and Wonnacott, 1977, p. 320-326). The result was a single straight line for gold which suggests a lognormally distributed population.

The result of the gold cumulative frequency plot is relatively simple: the population, shown by a single straight line suggests that there is only one lognormal population for gold. This is interpreted as the background concentrations for gold in the White Cow Intrusion.
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