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FINAL TECHNICAL REPORT

Closeout of Grant NAG 9-68
An Archean Suture Zone in the Tobacco Root Mountains? (1984)
Evolution of Archean Continental Crust, SW Montana (1985)

Awarded to: David W. Mogk
Dept of Earth Sciences
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Final Technical Report

The following specific accomplishments were achieved during the granting period. A list of abstracts, papers in review or accepted, and papers in preparation follows.

1. Mapping and geochemical sampling of the Lake Plateau area, Beartooth Mountains, Montana. This work serves to tie together the earlier investigations of Mogk in the North Snowy Block (to the west) and Mueller and Wooden in the eastern Beartooth Mountains. Results have been reported in 2 abstracts and 2 papers in preparation.

2. The allochthonous nature of the Stillwater Complex has been investigated. The results have been reported in 2 abstracts, one paper accepted for publication and one paper in preparation.

3. The North Snowy Block, Beartooth Mountains, has been re-interpreted as a Cordilleran-style continental margin. This paper is in review.

4. The metamorphic and tectonic history of the Beartooth Mountains has been addressed in 3 abstracts, one paper accepted for publication, and one paper in preparation.

5. The Archean geology of the Spanish Peaks area, northern Madison Range has been addressed in 2 abstracts and one paper in preparation. A voluminous granulite terrain of supracrustal origin has been identified, as well as a heretofore unknown Archean batholithic complex.

6. Mapping, petrologic, and geochemical investigations of the Blacktail Mountains, on the western margin of the Wyoming Province, are completed. Two abstracts have been presented and the manuwscript is in preparation.

7. Mapping at a scale of 1:24000 in the Archean rocks of the Gravelly Range is near completion. This sequence is dominantly of stable-platform origin. Samples have been collected for geothermometric/barometric analysis and for U-Pb zircon age dating. Mineral analyses are waiting for access (and funding) to do further microprobe work.

8. Similar reconaissance studies are in progress for stable-platform derived metaseimentary rocks in the Tobacco Root Mountains (mapping, structural analysis, geothermometry/barometry, and goechronology). Preliminary mineral analyses indicate temperatures in excess of 700°C and Pressures in excess of 7 Kbars for this terrain.

9. Our field studies of these numerous areas have provided the basis for additional geochemical and geochronologic studies by Paul Mueller and Joe Wooden. At this time there is not an adequate geochronologic framework for the Archean basement of SW Montana. Our field studies have allowed rocks to be dated in a systemmatic manner, and in a geologically reasonable context.

10. These numerous independent lines of evidence have allowed us to present a model for the tectonic and geochemical evolution of the Archean basement of SW Montana (one manuscript is accepted and others are in preparation).

Papers Submitted

Mogk, D. W., Mueller, P. A., and Wooden, J. L., Tectonic Aspects of Archean Continental Development in the North Snowy Block, Beartooth Mountains, Montana (in review, Geology)

** Geissman, J. W., and Mogk, D. W., Late Archean Tectonic Emplacement of the Stillwater Complex along Reactivated Basement Structures, Northern Beartooth Mountains, Southern Montana, USA, (in review, Proceedings VI International Basement Tectonic Symposium)

**Mogk, D. W., and Henry, D. J., Metamorphic Petrology of the Northern Archean Wyoming Province, SW Montana: Evidence for Archean Collisional Tectonics (invited paper for Rubey Colloquium VII) (in review)

**Wooden, J. L., Mueller, P. W., and Mogk, D. W., A review of the geochemistry and geochronology of the northern Archean Wyoming Province (invited paper for Rubey Colloquium VII, in review)

** Accepted for Publication

Papers in Preparation:

Two Occurrences of Magmatic Epidote in the Archean Basement of SW Montana (with Richmond, Salt, Mueller, Wooden, and Henry)

Latest Archean Tectonic Emplacement of the Stillwater Complex (with J. Geissman)

Metamorphic Petrology of the Beartooth Mountains, Montana (with Darrel Henry)

Archean Geology of the Spanish Peaks Area, northern Madison Range, Montana (with Ken Salt)

Archean Geology of the Lake Plateau Area, Beartooth Mountains, Montana. I. Petrology and Structure. (with Doug Richmond)

Archean Geology of the Lake Plateau Area, Beartooth Mountains, Montana. II. Geochemistry and Geochronology. (with D. Richmond and P. Mueller).

Archean Geology of the Blacktail Mountains, Montana. (with Mike Clark)

Metamorphic Petrology of the northern Gallatin Range, Montana. (with Karen May).

Tectonic Evolution of the North Snowy Block, Beartooth Mountains, Montana.

ABSTRACTS

Mogk, D., Mueller, P., and Wooden, J., 1984, Secular variation in ARchean tectonic style, Beartooth Mountains, Montana: EOS volume 65, (transactions of the American Geophysical Union).

Mogk, D., and Geissman, J., 1984, The Stillwater Complex is allochthonous: Geol. Soc. Amer. Ann. Meet. Progr. w. Abstr, Reno.

Mueller, P., Mogk, D. W., WOoden, J., Henry, D., Bowes, D., 1984, Archean metasedimentary rocks from the Bearooth Mountains: evidence for an accreted terrane? Geol. Soc. Amer. Ann. Meet. Progr. w. Abstr., Reno.

Salt, K., and Mogk, D., 1985 Archean geology of the Spanish Peaks area, southwestern Montana: Geol. Soc. Amer. Rocky Mtn Section, Boise.

Richmond, D., and Mogk, D., 1985, Archean Geology of the Lake Plateau area, Beartooth Mountains, Montana: Geol. Soc. Amer. Rocky Mtn Section, Boise.

Clark, M., and Mogk, D., 1985, Development and significance of the Blacktail Mountians metamorphic complex, Beaverhead County, Montana. Geol. Soc. Amer. Rocky Mtn. Section, Boise.

Mogk, D., Richmond, D., Salt, K., Clark, M., Mueller, P., Lafrenze, D., Wooden, J., Henry, D., Archean collisional tectonics in SW Montana: Geol. Soc. Amer. Ann. Meet. Progr. w. Abstr., Orlando.

Geissman, J., and Mogk, D. W., 1985, Reactivated latest Archean structures, NE flank, Beartooth Mountains, Montana, and the Tectonic emplacement of the Stillwater Complex: 6th International Conference on Basement Tectonics, Santa Fe.

Mogk, D., 1985, A review of the Archean basement of SW Montana, Tobacco Root Geological Society, Bozeman.

Clark, M., and Mogk, D., Tectonic setting of the Blacktail Mountains Archean supracrustal sequence, SW Montana 1986 Geol. Soc. AMer. Rocky Mtn Section.

Salt, K., and Mogk, D., 1986 Archean allochthonous terranes in the Spanish Peaks Area, SW Montana: Geol. Soc. Amer. Rocky Mtn Section.

Secular Variation in Archean Tectonic Style, Beartooth Mountains, Montana

D. W. Mogk (Dept. Earth Sciences, Montana State University, Bozeman, Montana 59717)
P. A. Mueller (Dept. of Geology, University of Florida, Gainsville, Florida 32611)
J. L. Wooden (USGS, Menlo Park, CA 94025)

Archean rocks of the Beartooth Mountains, Montana show evidence of at least three distinct stages of crustal evolution: 1) generation of trondhjemitic continental crust, 2) deposition of thick supracrustal sequences, 3) generation of rocks and structures similar to Cordilleran-type orogens.

In the NW Beartooth Mountains there is a trondhjemitic gneiss-amphibolite unit, with apparent age of 3.6 Ga. REE geochemistry indicates the trondhjemite was derived by partial melting of an amphibolite source. Between 3.4 and 3.2 Ga numerous supracrustal sequences were deposited in either ensialic basins or at contintental margins. Closure of these basins resulted in granulite grade (P=6 Kbar, T=800`C) metamorphism or migmatization. The burial mechanism is interpreted as tectonic thickening during compression. Late Archean tectonothermal events include 1) generation of a 3.0 Ga old andesitic suite, 2) regional amphibolite-grade metamorphism at 2850 Ma, which culminated in 3) generation of voluminous calc-alkaline granitoids at 2800 Ma, 4) tectonic thickening of the crust in an early stage of transcurrent faulting followed by emplacement of two major thrust sheets.

This terrane contains a variety of Archean rock types and structures, characteristic of different crustal levels; this allows documentation of the thermal history and attendant igneous and tectonic processes responsible for the evolution of this continental crust.

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THE STILLWATER COMPLEX IS ALLOCHTHONOUS

MOGK, David W., Department of Earth Sciences, Mont. State University, Bozeman, MT 59717; and GEISSMAN, John W., Department of Geology, Colorado School of Mines, Golden, CO 80401

№ 30313

Field relations and petrologic and paleomagnetic studies indicate that the Stillwater Complex and associated hornfels aureole are tectonically emplaced against the Archean basement of the Beartooth Mountains, Mont. The Archean basement consists of 2.8 Ga granitic gneiss and biotite schist. The metamorphism is of Buchan type; characteristic minerals include subsets of the assemblage bio-gar-staur-plag-anth-cord. A well-developed transposed foliation is axial planar to pervasive isoclinal folds. Metasedimentary rocks of the contact aureole are typically fine-grained clastics with interlayered banded iron formation. Primary cross bedding and graded bedding are locally present; relict minerals and structures that would indicate an earlier metamorphic cycle are not preserved. Contact metamorphism formed cord-anth or cord-opx assemblages; pressure estimates are about 2 kb, based on hornfels assemblages and igneous phase equilibria for the depth of emplacement of the complex. The Stillwater Complex has an age of 2700-2720 m.y. and is not affected by high grade regional metamorphism. The Mouat quartz monzonite cross cuts both the complex and basement rocks and has an age of circa 2700 m.y. Intrusion of the Stillwater Complex and tectonic emplacement must have occurred in rapid succession. After correction for local tilt of igneous layering, paleomagnetic data which reflect the initial cooling of the Stillwater Complex are not coincident with those from undeformed, nearly time-equivalent units in the Superior Province. Much of the 25-35° discrepancy in directions may reflect the allochthonous nature of the Stillwater Complex. Emplacement of the complex probably occurred along a wrench fault, possibly associated with the Nye-Bowler lineament.

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№ 48289

ARCHEAN METASEDIMENTARY ROCKS FROM THE BEARTOOTH MOUNTAINS: EVIDENCE FOR AN ACCRETED TERRANE?

MUELLER, P. A., Dept. of Geology, Univ. of Florida, Gainesville, FL 32611; MOGK, D. W., Dept. of Earth Science, Montana St. Univ., Bozeman, MT 59717; WOODEN, J. L., U.S. Geol. Survey, Menlo Park, CA 94025; HENRY, D. J., ARCO Oil and Gas, 2300 Plano Pkwy, Plano, TX 75075; and BOWES, D. R., Dept. of Geology, Univ. of Glasgow, Glasgow, Scotland

The Beartooth Mountains contain several metamorphosed supracrustal assemblages with metasedimentary members that were derived from source regions that formed at least 3.1-3.4 Ga ago. A section in the eastern Beartooth Mountains (EBT) contains ironstones, quartzites, wackes and volcanic rocks that were metamorphosed to granulite facies ~3.4 Ga ago. The North Snowy Block (NSB) contains two sequences now at amphibolite grade, one dominated by metabasalt, marble, and quartzite and the other by quartzite, amphibolite, and metapelite. The contact aureole of the Stillwater Complex (SCA) contains hornblende and pyroxene hornfels that were pelites, wackes, quartzites and ironstones.

Despite their relatively high metamorphic grade, these rocks display chemical features suggestive of separate provenances. All clastic rocks have transition metal contents higher than average post-Archean crust, e.g., Cr contents ranging from ~50 ppm in EBT quartzites to ~300 ppm in SCA quartzites. REE patterns of the EBT clastic rocks (La = 100x, $(La/Yb)_n$ = 7-15) are clearly different from those of the NSB (La = 50x, $(La/Yb)_n$ = 4-7). Other differences include Ba contents, accessory mineral suites, and Nd and Sr isotopic systematics. These observations, in conjunction with the lithologic variety and differences in metamorphic history, suggest that these metasedimentary suites did not evolve in their present geographic positions. It seems more reasonable that they evolved in widely separated areas and were juxtaposed ~2800 Ma ago as a result of processes similar to those producing modern accreted terranes.

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ARCHEAN GEOLOGY OF THE SPANISH PEAKS AREA, SOUTHWESTERN MONTANA

SALT,KJ,and MOGK,David W,Dept.of Earth Sciences, Montana State University,Bozeman,MT 59717

The Spanish Peaks area of SW Montana contains two distinct suites of Archean rocks including a large volume of high-grade meta-supracrustal rocks and a batholithic complex consisting of at least 4 distinct intrusive phases. Supracrustal rocks include biotite quartzofeldspathic gneiss, metapelites (biot-gnt-ky-sill-musc-qtz;biot-anth-ky-plag-qtz) and amphibolites (gnt-diop-hbld-plag). The rocks are isoclinally folded on a cm- to m-scale with displacement common on small-scale nappes.Crystallization foliation is well-developed and is axial planar to the isoclinal folds.

The intrusive phases include trondhjemite, hornblende monzodiorite, granodiorite and granite. The trondhjemite and hornblende monzodiorite are intruded by the granodiorite;all 3 are moderately to well foliated. Late-stage, unfoliated granites and associated pegmatites cut all of the above units. Amphibolitized dikes and sills occur throughout the area and are folded and boudinaged. A northeast trending mylonite zone divides the area into predominantly supracrustal rocks to the northwest and granitic rocks to the southeast;mylonitization occurred under epidote stable conditions.

The abundance of clastic supracrustal rocks in the Spanish Peaks contrasts sharply with the dominantly granitic Archean rocks of the Beartooth Mountains to the east. The high grade of metamorphism and structural style requires deep burial of these sediments; the preferred burial mechanism is tectonic overloading. The subsequent formation of calc-alkaline intrusives suggests that this area may be part of a late Archean,Cordilleran-type continental margin.

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№ 69398

ARCHEAN GEOLOGY OF THE LAKE PLATEAU AREA, BEARTOOTH MOUNTAINS, MONTANA

RICHMOND, Douglas P., and MOGK, David W., Dept. of Earth Sciences, Montana State Univ., Bozeman, MT 59717

The Lake Plateau area in the central Beartooth Mountains is comprised of voluminous intrusive rocks ranging from diorite to granite in composition with a variety of supracrustal inclusions. The inclusions range in size from centimeter to kilometer scale and include calc-schists (bio-qtz-hbld-epi-plag), pelitic schists (bio-plag-qtz±gar) and well foliated amphibolites. Some inclusions show small scale isoclinal folds and transposition foliation that is axial planar to these folds.

The intrusive rocks vary in modal mineralogy and texture on a meter scale. In some places they have a foliated augen texture, and in others they have an hypidiomorphic granular texture. Foliation is better developed near inclusions and in most cases is conformable with foliation of the inclusions. Emplacement occurs as lit-par-lit injections; assimimilation of inclusions is common. Pegmatite and aplite veins associated with the intrusive rocks cut across nearly all Archean rocks and comprise 20% of the total rock volume.

Structural trends are north-south and include foliation, broad open kilometer scale folds, and at least two shear zones with mylonitic textures and retrograde metamorphism to chlorite and epidote. Younger rocks include amphibolite dikes and a few Tertiary felsic dikes.

The inclusions at Lake Plateau are similar to the Archean supra-crustal rocks of the North Snowy Block mobile belt to the west, and the intrusives are similar to the 2750 m.y. granites in the eastern Beartooths. This association in the Lake Plateau area marks the boundary between these two Archean terranes.

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DEVELOPMENT AND SIGNIFICANCE OF THE BLACKTAIL MOUNTAINS ARCHEAN METAMORPHIC COMPLEX, BEAVERHEAD COUNTY, MONTANA

№ 69396

CLARK, Michael L. and MOGK, David W., Department of Earth Science, Montana State University; Bozeman, Montana 59717

The southwestern most major exposure of Archean metamorphic rocks in Montana is found in the Blacktail Mountains. Quartzofeldspathic gneisses are predominant with characteristic mineral assemblages of quartz-plag-Kspar±bio±hblnd±garnet. Compositional layering occurs on a centimeter to meter scale and is defined by variations in color index (5 to 40), variation in Kspar/plag and variation in biotite, hornblende and garnet content. A NE-SW striking crystallization foliation, parallel to compositional layering, and SW trending mineral streak lineation are well developed. Interlayered and conformable with these gneisses are discrete amphibolite bodies, meters to tens of meters thick. Layering and foliation have been deformed into tight to isoclinal folds, with wavelengths on a tens of meters scale and with axial plane traces parallel to foliation. Several small bodies of late to post kinematic biotite granite intrude the gneisses. These granites are foliated to non-foliated and are locally injected lit-par-lit. The youngest Precambrian features seen are unfoliated diabase dikes intruded at high angles to foliation and unfoliated granite bodies intruded subparallel to foliation.

The fine scale layering and lack of any relict igneous textures suggest that these interlayered gneisses are a sequence of clastic sediments metamorphosed to at least amphibolite grade. These rocks may represent the southwestern edge of the Archean basin proposed by Vitaliano, et.al.,(1979), wherein the marble bearing sequences in the central Dillon Block are the basin's center and the marble-deficient sequences proximal to the older Beartooth Block are the basin's eastern margin. Alternatively, the Blacktail complex may represent one of several separate sequences accreted eastward onto the Beartooth Block.

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ARCHEAN COLLISIONAL TECTONICS IN SW MONTANA

MOGK, D., RICHMOND, D., SALT, K., CLARK, M., Dept. Earth Sciences, Montana State Univ., Bozeman, MT 59717; MUELLER, P., LAFRENZE, D., Dept. Geol., Univ. Florida, Gainesville, FL 32611; WOODEN, J., USGS MS 937, Menlo Park, CA 94025; HENRY, D., Dept. Geol., Louisiana State Univ., Baton Rouge, LA 70803

The Archean continental crust of SW Montana evolved through alternating cycles of stable platform sedimentation followed by crustal thickening through collisional tectonics. The ancient sialic crust in the Beartooth Mountains served as the nucleus for accretion of younger terranes to the west.

The oldest orogenic cycle recognized in the Beartooth Mountains involves a 3.4 Ga old supracrustal sequence which was metamorphosed in the granulite facies (T=700-800°C, P=6Kb, 35°C/Km); deep burial is interpreted as the result of collisional tectonic thickening. The second orogenic cycle is subduction related and has produced 2.8 Ga old andesites, 2.75 Ga old calc-alkaline intrusives, upper amphibolite grade metamorphism, transcurrent faulting (in the North Snowy Block and Yankee Jim canyon at 2.8 Ga) and nappe emplacement. In the central Beartooths post-orogenic granites intrude pelitic schists (T=600°C, P=8Kb, 25°C/Km).

West of the Beartooths the basement consists of 2.75-2.70 Ga old, tectonically telescoped coarse clastics (Gallatin, Madison Ranges) and stable platform sequences (Gravelly, Tobacco Root, Ruby Ranges). Nappe formation and granulite-migmatite (700-750°C) associations are common, suggesting deep burial through tectonic thickening. A late-kinematic mesozonal (8Kb) qtz diorite-granodiorite batholithic complex is present in the northern Madison Range. Quartzofeldspathic paragneisses in the westernmost Archean basement (Highland, Blacktail Ranges) are derived from either a continental or island arc source.

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REACTIVATED LATEST ARCHEAN STRUCTURES, NE FLANK, BEARTOOTH MOUNTAINS, MONTANA, AND THE TECTONIC EMPLACEMENT OF THE STILLWATER COMPLEX

GEISSMAN, John Wm., Department of Geology, University of New Mexico, Albuquerque, NM 87131, USA; and MOGK, David W., Department of Earth Sciences, Montana State University, Bozeman, MT 59717, USA

A major basement feature in the northern part of the Bighorn Basin, northern Wyoming, is the Nye-Bowler lineament, first described by C.W. Wilson (1936, A.A.P.G. Bull.), running from the Crazy Basin in southern Montana to the northern end of the Bighorn Mountains. Subsurface exploration has indicated that the feature was active many times during the Phanerozoic, especially during Laramide and younger activity. Field relations, petrologic observations, and paleomagnetic and regional geophysical data all indicate that transcurrent faulting along portions of the lineament occurred in the Precambrian. Geochronologic data on rocks along the northeast flank of the Beartooths imply that faulting may have taken place as long ago as in the latest Archean. The Stillwater igneous complex and associated hornfels have been tectonically emplaced against 2.8 Ga basement, consisting of granitic gneiss and biotite schist, along the Mill Creek-Stillwater fault zone. Basement metamorphism is of Buchan type; characteristic minerals include subsets of the assemblage bio-gar-staur-plag-anth-cord. Transposed foliations are axial planar to pervasive isoclinal folds. At the contact, metasedimentary rocks are fine-grained clastics with interlayered banded iron formation. The presence of primary cross- and graded-bedding implies lack of significant penetrative deformation at an earlier time. Contact metamorphism formed cord-anth or cord-opx assemblages yielding pressure estimates of 2 kb. The Stillwater Complex has an age of 2720-2700 Ma and is not affected by high grade regional metamorphism. The Mouat quartz monzonite cross cuts both the complex and basement rocks and has an age of circa 2700 Ma. Intrusion of the Stillwater Complex and tectonic emplacement must have occurred in rapid succession. Paleomagnetic data, after correction for local structure, are not coincident with results from undeformed, nearly time-equivalent units in the Superior Province. Much of the 25-35° of discrepancy in directions may reflect the allochthonous nature of the Stillwater Complex. This portion of the Nye Bowler lineament must have been stabilized in latest Archean time.

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ARCHEAN ALLOCHTHONOUS TERRANES IN THE SPANISH PEAKS, SOUTHWESTERN MONTANA

SALT, K.J., and MOGK, David W., Dept. of Earth Sciences, Montana State University, Bozeman, MT 59717

Two distinct Archean domains are juxtaposed along a NE trending, steeply SE dipping mylonite zone in the Spanish Peaks of SW Montana. These domains are characterized by differences in lithology, metamorphic grade, and structural style.

The southern domain is a batholithic complex intruded into supracrustal gneisses, metapelites and amphibolites with scattered quartzites and metaultramafites. Paragneisses are tonalitic. Orthoamphibole assemblages are common occurences and kyanite is the stable aluminosilicate of this domain. Scattered sequences of layered amphibolite-trondhjemite also occur within this domain. The batholithic phases follow a fractionation path different from most Cordilleran sequences, ranging from older monzodiorite and quartz diorite to younger granodiorite and granite. Peak conditions of metamorphism were 650-700 C at 7-8 kbars.

The northern domain is predominantly metasupracrustal, consisting of gneisses, metapelites, quartzite, and amphibolites. The gneisses are granitic and are less mafic than those of the southern domain. Sillimanite replaces kyanite. Amphibolites have lower granulite facies assemblages. Notably absent are the batholithic phases, the amph-trond sequences, and orthoamphibole assemblages. Metaultramafites are much less abundant. Peak metamorphism occurred at 680-720 C at 6-7 kbars.

Preliminary structural analysis suggests an oblique sense of slip and possibly several periods of motion along the shear zone, resulting in emplacement of a higher P intrusive complex over a lower P metasupracrustal sequence. The last motion occurred under epidote-amphibolite facies conditions. Juxtaposition probably occurred during Archean orogenesis, with renewed activity possibly occuring during a greenschist facies thermal event postulated by Giletti (1966) at 1.6 b.y.

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Tectonic Aspects of Archean Continental Development in the North Snowy Block, Beartooth Mountains, Montana

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ABSTRACT

The North Snowy Block (NSB), Beartooth Mountains, Montana is an Archean terrain that exhibits numerous aspects of Phanerozoic orogens, including sedimentary sequences characteristic of stable platforms, a wide range of metamorphic grades, transcurrent and thrust faulting, and injection of granitic sills. The occurrence of contemporaneous late-Archean andesites and voluminous calc-alkaline granitoids in the central and eastern Beartooth Mountains suggests this terrain may have evolved in response to orogenic forces generated by plate tectonic-like processes. In particular, the local and regional geology appears consistent with development in a Cordilleran-type orogeny.

INTRODUCTION

Many workers have proposed that most of the Earth's continental crust formed during the Archean (e.g. Moorbath, 1977, 1978; Moorbath and Windley, 1981; Taylor and McLellan, 1981) and that this process occurred in environments similar to those of the modern plate tectonic regime (e.g. Windley, 1981; Burke et al., 1976). However, it has proved difficult to develop comprehensive models for the Archean tectonic regime because of the restrictions imposed by the generally limited areal extent and selective preservation of Archean terrains, the later orogenic reworking of this older crust which has generally destroyed the original paleomagnetic record, and the lack of paleontologic/stratigraphic control. In light of these problems, it is important to thoroughly investigate as wide a variety of Archean terrains as possible if we are to clearly understand Archean tectonics and crustal growth. The high relief, excellent exposures and wide variety of rock types in the North Snowy Block (NSB) offer unique

insight into the breadth of Archean tectonic style. In this paper we review the large-scale structures, lithologies and ages of this critical area in the Archean basement of SW Montana.

The NSB defines a zone of tectonic dislocation between two fundamentally distinct terrains in the Archean basement of the northern Wyoming Province (Figure 1). To the east, the Beartooth Mountains and other exposures of Archean rocks are comprised dominantly of late Archean granitoids with inclusions of older supracrustal rocks (Peterman, 1979; Henry et al., 1982; Mueller et al., 1985). The voluminous late-Archean granitoids and associated igneous rocks of the Beartooth Mountains have been interpreted as the products of subduction along a continental margin (Mueller and Wooden, in prep.). The western terrain consists dominantly of 2.75 Ga old (James and Hedge, 1980) high-grade metasedimentary rocks as exposed in the Gallatin (Spencer and Kozak, 1975), Madison (Erslev, 1983), Ruby (Garihan, 1979) and Tobacco Root Mountains (Vitaliano et al., 1979). The metasupracrustal rocks include quartzites, marbles, aluminous schists, banded iron formation, and quartzofeldspathic gneiss that have been interpreted as stable platform associations (Vitaliano et al., 1979). Individually, these lithologic sequences must have evolved in a variety of environments. Collectively, their present configuration suggests later tectonic juxtaposition.

NORTH SNOWY BLOCK

The NSB was first described in detail by Reid et al. (1975). Our current investigations have expanded upon this earlier work and suggest that the NSB is a zone of extensive tectonic mixing of both metaigneous and metasedimentary rocks as a result of transcurrent and thrust faulting. The

NSB consists of four lithologically and metamorphically distinct linear belts separated by faults and overlain by two apparently east-verging thrust sheets (Figure 2). These six units are distinguished by abrupt discontinuities in lithology, metamorphic grade, structural style, and, to a lesser extent, isotopic age. A late open folding event post-dates the faulting events. The following summarizes the characteristics of these units as they occur in an east-west cross section; more complete descriptions can be found in Mogk (1984).

Paragneiss Unit (PG). This unit is a broken formation which is comprised of a wide variety of supracrustal rocks including quartzofeldspathic gneisses, pelitic schists, amphibolites, and banded iron formation. These rocks have been metamorphosed in the upper amphibolite facies and yield garnet-biotite temperatures (Ferry and Spear, 1979) of 650-700°C. Anastomosing shear zones surround meter- to tens-of-meter scale phacoid-shaped pods of the various lithologies; internal tectonic mixing occurred under greenschist or epidote-amphibolite facies. A strong mineral streak lineation lies in the plane of foliation with a small angle of rake. Rocks of similar composition, metamorphic grade, and structural style lie along strike in Yankee Jim Canyon of the South Snowy Block (Burnham, 1983; Figure 1).

Mount Cowen Augen Gneiss (MCA). This granitic augen gneiss occurs as sill-like bodies which have been injected parallel to the regional NE strike. It is characterized by an anastomosing foliation defined by biotite and chlorite around K-spar porphyroclasts. Late to post-kinematic emplacement of the granitic protolith occurred along a postulated fault between the Davis Creek Schist and the PG. Local contact metamorphism of

the Davis Creek Schist produced static growth of biotite and indicates that the MCA is the youngest major rock unit in the NSB.

Whole-rock Rb-Sr isotopic data suggest the MCA is 2737 +/- 52 Ma old with an initial Sr isotopic ratio of 0.7023 +/- 20 (Figure 3). The age and initial ratio of this unit are indistinguishable from those of the igneous rocks of the eastern and central Beartooth Mountains (Wooden et al., 1982; unpubl.).

Davis Creek Schist (DCS). The DCS is a phyllitic metapelite with subordinate layers of quartzite. The dominant metamorphic assemblage is chlorite-muscovite-albite-quartz (greenschist facies). The DCS is structurally below and in tectonic contact with the trondhjemitic gneiss-amphibolite complex (see below) as evidenced by their strongly mylonitic contact. This contact also shows wispy intercalations in map view and cannot readily be reconciled as either imbricate slices or intrusive contacts. A weakly developed quartz rodding lineation lies in the plane of foliation with a subhorizontal plunge direction. Rare intrafolial isoclinal folds are overprinted by asymmetric kink folds.

Trondhjemite-amphibolite complex (TGA). This unit consists of trondhjemitic gneisses interlayered with a series of conformable, but discontinuous, amphibolites. The amphibolites range from fine-grained, well-lineated, basaltic varieties, to coarse-grained metamorphosed gabbros and anorthositic gabbros. Cross-cutting relationships are rare, but where present indicate that portions of the trondhjemitic gneiss are younger than at least some of the amphibolites. The entire unit has experienced pervasive ductile shearing (Mogk, 1982) during metamorphism in the epidote-oligoclase facies (≈500°C based on coexisting neoblasts of albite and

oligoclase). It characteristically exhibits blastomylonitic texture, passive flow folding, and a mineral streak lineation lies in the plane of foliation with an average orientation of 15°S48°W. Discrete amphibolite layers are rotated into conformity with the shear foliation. The ductile shearing that is characteristic of this unit is not recorded in the overlying Pine Creek Nappe Complex.

Age relations in this highly sheared complex are difficult to define. Rb-Sr whole-rock measurements yield scattered data that lie mostly along a 3400 Ma reference line (Figure 4). Several samples appear to have lost Rb, probably as a result of shearing, and lie above the reference isochron. Sm-Nd whole-rock determinations yield chondritic model ages of 3.26 and 3.59 Ga (Table I). Initial zircon studies (Mueller et al., unpubl.) also suggest ages in the range 3.1-3.4 Ga. Together these data suggest that this unit may be composed of a variety of quartzofeldspathic components as old as 3.4 Ga.

Pine Creek Nappe Complex (PCN). Structurally overlying the TGA is the Pine Creek Nappe Complex (Reid et el., 1975; Mogk, 1984; Figure 2). This is an isoclinally folded thrust-nappe structure (Mogk, 1981). The regional isoclinal structure consists of an amphibolite core with symmetrically disposed marble and quartzite. Closure of this isoclinal structure is observed in the NE corner of the map area. The lower limb of the nappe complex is strongly attenuated indicating that this is a detached antiformal structure. Mylonites are well-developed in quartzites only along the lower contact with the TGA. Isoclinal folding occurs on all scales in this complex and fold axis lineations display an average orientation of 20°N40°E. Metamorphism is in the middle to upper amphibolite facies with

garnet biotite temperatures in the range of 600-650°C. A strong crystallization schistosity is developed along the axial surfaces of the isoclinal folds. A single Sm-Nd chondritic model age (Table I) on a sample of the amphibolite in the core of the nappe suggests a protolith age of approximately 3.2 Ga for this supracrustal sequence.

Heterogeneous Gneiss and Quartzite-Amphibolite Units (HG and Q-A).

A second major thrust fault has emplaced the migmatitic HG and associated high-grade supracrustal rocks of the Q-A units over the PCN (Mogk, 1982). The occurrence of the Q-A unit is restricted to the upper section of this thrust sheet (Figure 2). Metamorphism is in the upper amphibolite facies; subordinate pelitic layers in the Q-A unit record garnet-biotite temperatures up to 700°C. A synkinematic transposition foliation is axial planar to small-scale isoclinal folds. In the lower section of the thrust sheet the HG consists of lit-par-lit injections of granite to tonalite in the metasupracrustal sequence. Locally, foliation in the supracrustal rocks is truncated by the intrusive rocks and partial assimilation of the supracrustal rocks is common.

These observations supplement those of Reid et al. (1975) and have resulted in a different tectonic interpretation of this area than that proposed in this earlier work. The wide variety of rock types and the abrupt discontinuities in metamorphic grade, structural style, and isotopic ages (Table II) discussed above suggest significant tectonic displacements. Although it is not possible to determine the original orientations of the major faults because of lack of control over later block rotations, the style and timing of the original tectonic juxtaposition are constrained by the following observations. 1) All units in the NSB have recorded unique

metamorphic and deformational histories. Each unit exhibits the same metamorphic grade along strike; the breaks in metamorphic grade between units can only be rationalized in terms of tectonic juxtaposition. 2) Within the PG the phacoidal form of individual lithologic pods, separated by anastomosing shear zones, and the subhorizontal mineral streak lineation suggests that intraformational tectonic mixing occurred during transcurrent faulting rather than imbricate thrusting. The greenschist-grade DCS also displays a subhorizontal lineation and is separated from the amphibolite-grade PG by a thin sill-like body of MCA which produced clear evidence of contact metamorphism in the DCS. Juxtaposition of the DCS and PG units is interpreted as the result of transcurrent faulting and must have occurred prior to the injection of the MCA at a time of 2735 Ma ago. 3) The contacts between the DCS and the TGA are strongly mylonitic, both units also show subhorizontal lineation and the wispy intercalations of these two units in map view (stylistically represented in Figure 2) suggest that these units were also emplaced along a transcurrent fault. 4) The age relations between the TGA and the PCN preclude the possibility that the trondhjemite was injected into the nappe complex as was originally suggested by Reid et al (1975). In addition, the ductile shearing in the trondhjemitic gneiss must have occurred prior to the emplacement of the PCN. 5) Emplacement of the two thrust sheets marks a major change in tectonic style during the evolution of the NSB. The metamorphic grade increases discontinuously up section from the TGA through the PCN to the HG. The PCN structure formed synkinematically during amphibolite grade metamorphism; its current structural position requires post-metamorphic tectonic emplacement. The overall isoclinal structure of the nappe complex and the strong attenuation of the

lower limb indicates that this unit was emplaced along a thrust fault. The overlying migmatites of the HG must represent a deeper crustal process that occurred prior to the emplacement of this unit. In addition, the HG now appears to occupy an older-over-younger structural position suggesting that this unit also was emplaced along a thrust fault.

TECTONIC EVOLUTION OF THE NSB

The North Snowy Block is an aggregation of discrete lithologic associations that evolved over a period of approximately 600 million years. These associations developed in a variety of tectonic environments and are present now as allochthonous units in the NSB. The tectonic evolution of the NSB, therefore, must be interpreted not only in terms of the geologic history of the individual lithologic associations, but also in terms of the history of adjoining Archean terrains. Taken as a whole, the NSB and adjacent terrains exhibit many features consistent with development in a late-Archean Cordilleran-style orogeny. These features are:

1) There are remnants of relatively thick (½20 km), continental crust of at least 3.4 Ga age preserved in the eastern Beartooth Mountains (Henry et al., 1982). In the NSB, at least portions of the TGA appear to be of equivalent age and may be part of the same ancient continent. This continental mass served as the nucleus for both magmatic and tectonic continental growth in the latest Archean.

2) Voluminous, late-Archean, calc-alkaline granitoids and associated igneous rocks, including andesites, were emplaced into the older continental nucleus about 2.75 Ga ago (Mueller and Wooden, in prep.; Richmond and Mogk, 1985). The chemical and isotopic compositions of these rocks have been interpreted to indicate derivation as a result of subduction-related

processes (Mueller and Wooden, in prep.). These rocks represent the major magmatic aspect of this late-Archean orogeny.

3) The association of quartzites and marbles in the Pine Creek Nappe Complex suggests that these rocks were originally deposited in a stable platform environment. This sequence was probably deposited during a period of tectonic quiescence on a continental margin or in an ensialic basin. The similarity between these rocks and other platformal rocks in the Archean of southwestern Montana, as well as the closure of the nappe structure, suggests that original deposition occurred west of the NSB.

4) The final tectonic juxtaposition of the lithologic associations in the NSB probably occurred prior to, or contemporaneous with, the development of the late-Archean magmatic complex in the Beartooth Mountains based on the similarity of ages of the Mount Cowen Augen Gneiss and the magmatism in other portions of the Beartooth Mountains.

DISCUSSION

The NSB has experienced a complex history of tectonic juxtaposition of dissimilar units probably by means of both transcurrent and thrust faulting. It is difficult to demonstrate the magnitude and original orientation of of these displacements because Archean exposures in this region are locally limited to Laramide uplifts. However, immediately adjacent Archean lithologic associations exposed to the east (Wooden et al., 1982), south (Erslev, 1983; Casella et al., 1982), and west (Spencer and Kozak, 1975; Salt and Mogk, 1985) are not readily comparable to the main units in the NSB. When considered in light of the adjacent and contemporaneously developed magmatic terrane of the eastern Beartooth Mountains (Wooden et

al., 1981, 1982; Mueller and Wooden, in prep.) and the dichotomy between this magmatic terrane and the metasedimentary terrains of SW Montana, it appears that the NSB lies along a late-Archean continental margin (Mueller et al., 1985; Mogk and Henry, in review; Wooden and Mueller, in press) that was involved in a complex orogenic episode 2700-2800 Ma ago.

This orogenic event involved the addition of segments of continental crust to an older Archean continent via mechanical and magmatic processes. The spatial and temporal association of andesitic and calc-alkaline magmatism in the Beartooth Mountains and the tectonic juxtaposition of widely disparate in the NSB is analogous on a small-scale with the tectonic features described for the Cordillera of western North America (e.g. Burchfiel and Davis, 1972; Coney et al., 1980). If this analogy is valid, it suggests that all of southwestern Montana is a collage of allochthonous terrains that were aggregated in a Cordilleran-style orogeny during late Archean time. The existence of such orogenic zones has not been clearly demonstrated for the Archean, althogh allusion to their existence has been made (Windley and Smith, 1976; Dewey and Windley, 1981; Dickinson, 1981). Documenting the existence of these zones and the orogenic processes that produced them remains an important, yet unresolved, aspect of Archean geology that has important implications for understanding the relative importance of mechanical versus magmatic aggregation of continents.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Figure 1: Index map of the northern portion of the Archean Wyoming Province showing the location of the North Snowy Block mobile belt, igneous and metaigneous rocks to the east, and dominantly metasupracrustal rocks to the west.

Figure 2a: Sketch map showing part of the North Snowy Block mobile belt. The linear belts of the trondhjemitic gneiss-amphibolite complex, Davis Creek Schist, Mount Cowen Augen Gneiss, and Paragneiss Units are overlain by the thrust sheets of the Pine Creek Nappe Complex and Heterogeneous Gneiss.

Figure 2b: Schematic cross section across strike of the North Snowy Block mobile belt (units denoted as in Figure 2a).

Figure 3: Rb-Sr whole rock isochron for the Mount Cowen Augen Gneiss.

Figure 4: Rb-Sr whole rock isochron for the trondhjemitic gneiss. This unit is strongly sheared and all samples may have lost some Rb; open circles denote samples that appear to have lost substantial amounts of Rb.

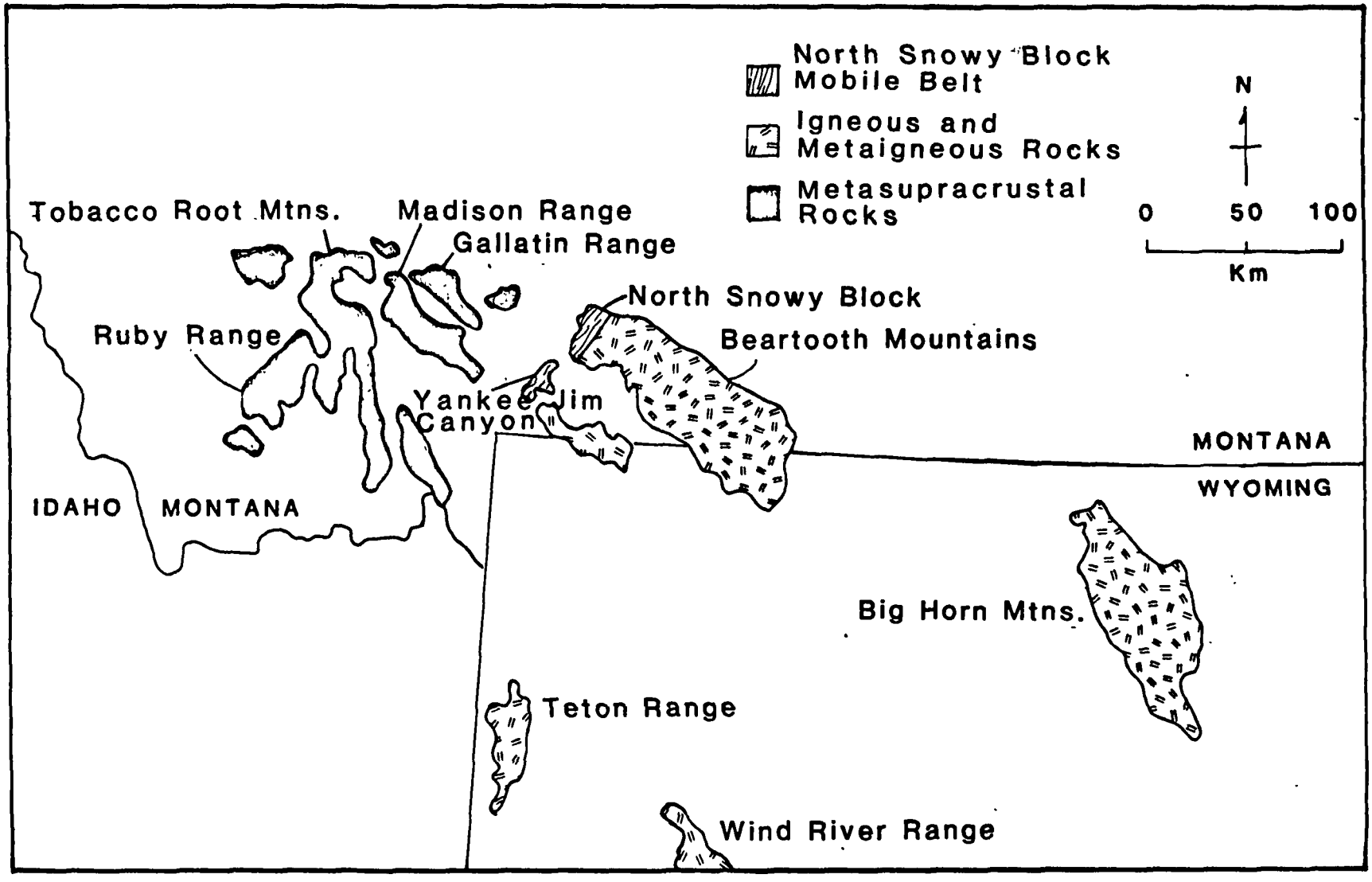
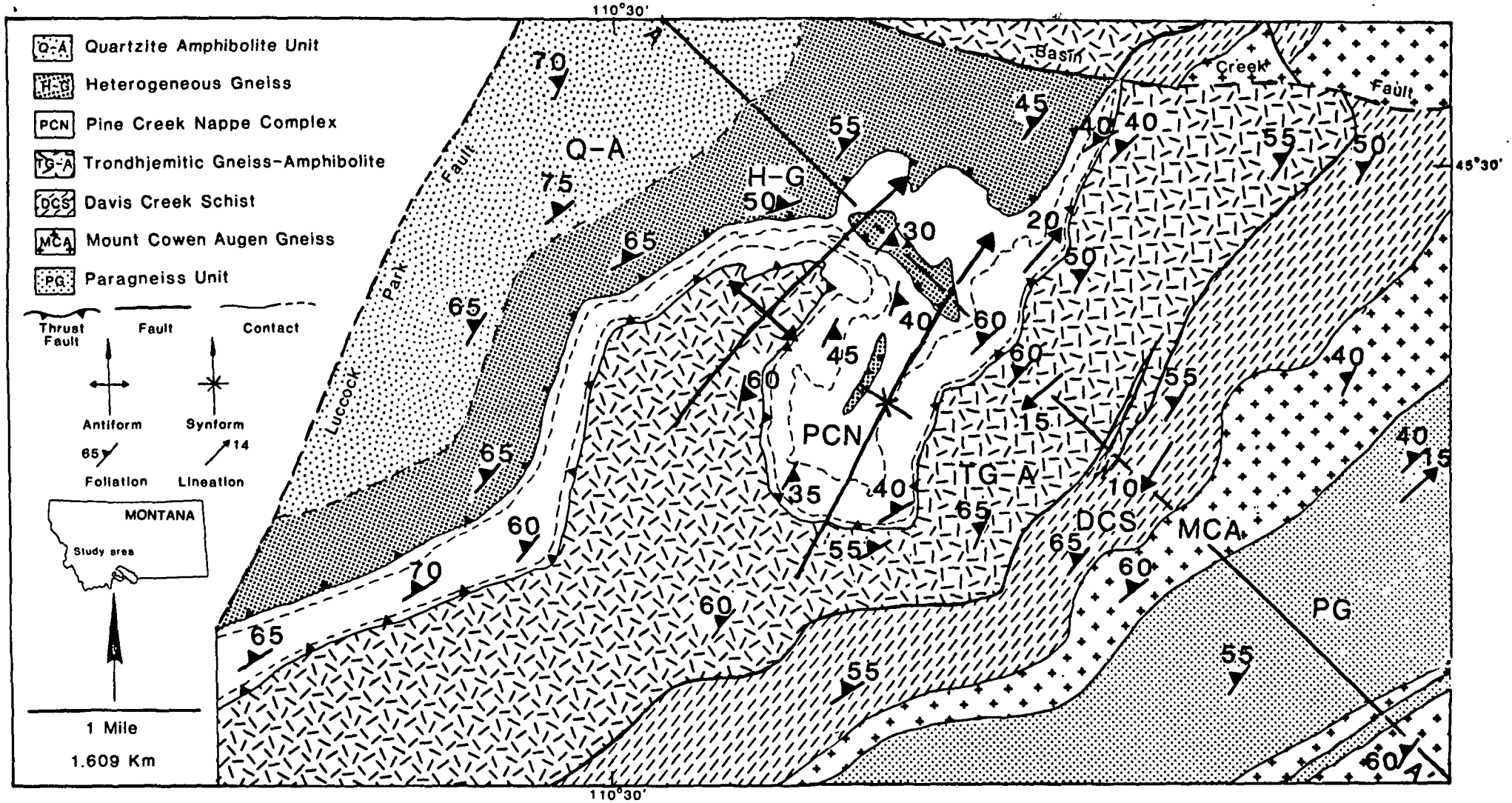

North Snowy Block Mobile Belt
Igneous and Metaigneous Rocks
Metasupracrustal Rocks
N
0
50
100
Km
Tobacco Root Mtns.
Madison Range
Gallatin Range
North Snowy Block
Beartooth Mountains
Ruby Range
Yankee Jim Canyon
MONTANA
WYOMING
IDAHO
MONTANA
Big Horn Mtns.
Teton Range
Wind River Range

Figure 1



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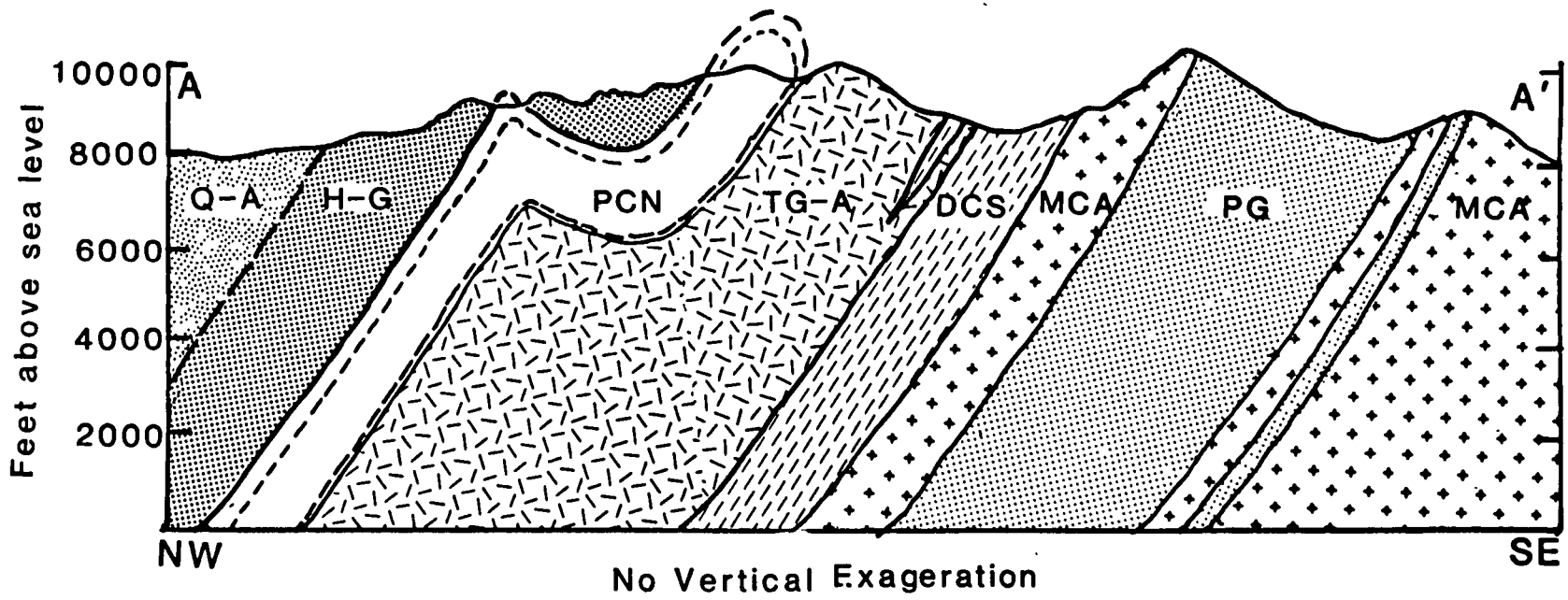
10000
8000
6000
4000
2000
Feet above sea level
A
A'
Q-A
H-G
PCN
TG-A
DCS
MCA
PG
MCA
NW
SE
No Vertical Exageration

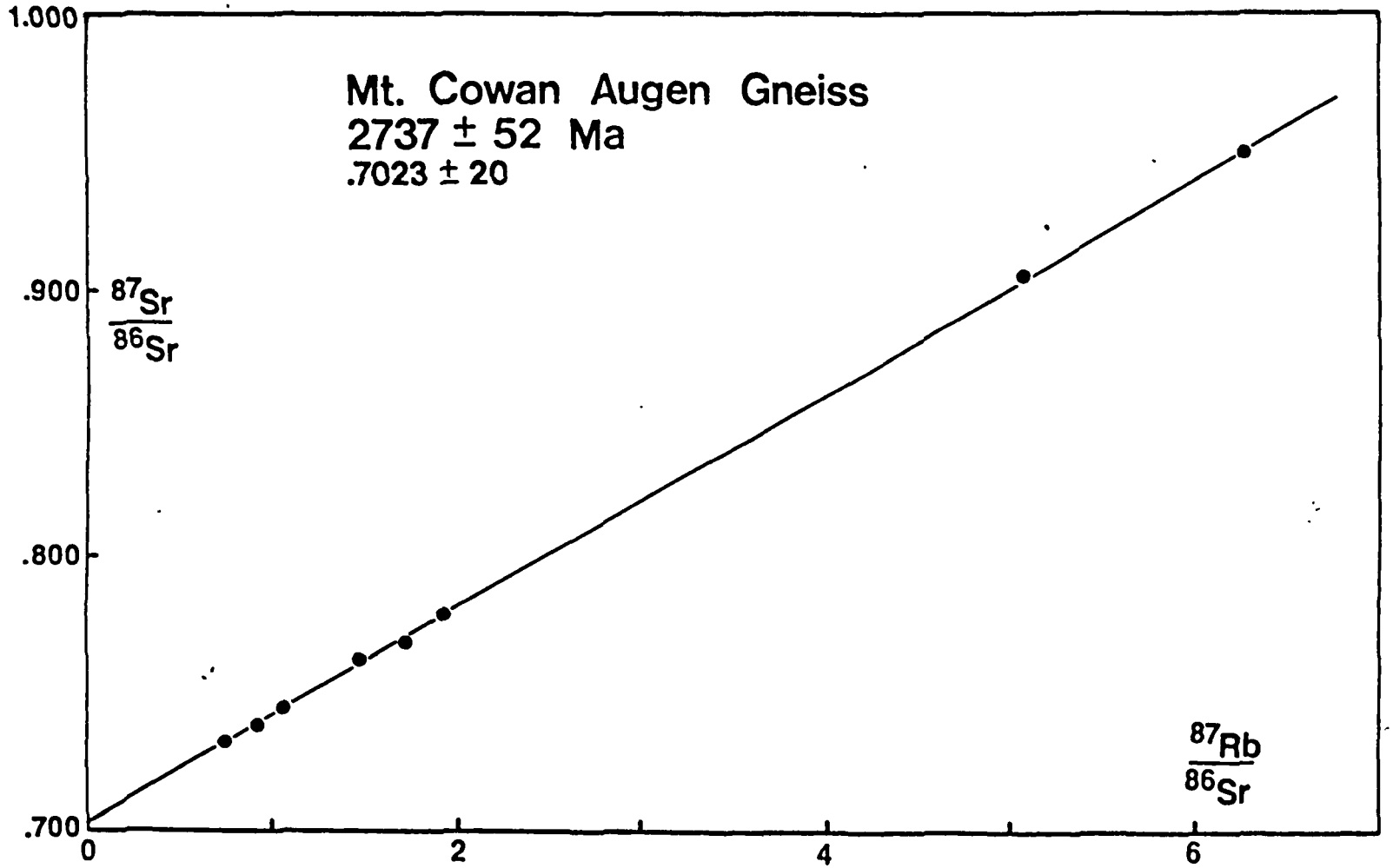
Mt. Cowan Augen Gneiss
2737 ± 52 Ma
.7023 ± 20
1.000
.900
.800
.700
87Sr/86Sr
87Rb/86Sr
0
2
4
6

Figure 3

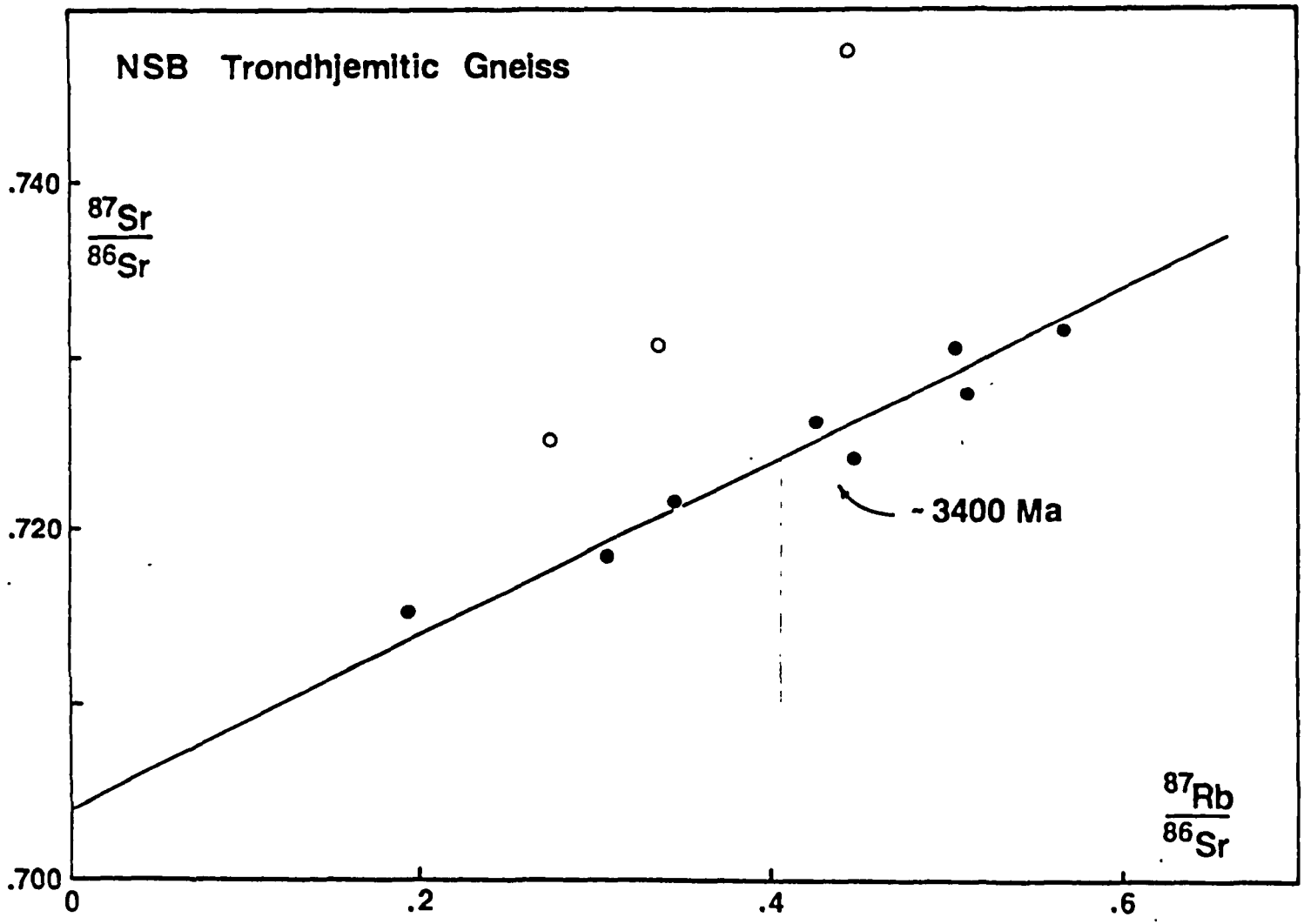
NSB Trondhjemitic Gneiss
.740
.720
.700
87Sr/86Sr
~3400 Ma
87Rb/86Sr
0
.2
.4
.6

Figure 4

Table I. Sm-Nd Chondritic Model Ages in the North Snowy Block

	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Chondritic Model Age
BCA-1 Barney Creek Amphibolite	6.97	32.74	.1288	.510495±27	3.20 Ga
243 Trondhjemitic Gneiss	2.63	15.08	.1056	.509791±36	3.55 Ga
161 Trondhjemitic Gneiss	1.94	14.88	.0790	.509393±29	3.26 Ga

Table II: Characteristics of the Lithologic Units of the North Snowy Block

Unit	Metamorphic Grade	Structural Style	Isotopic Ages
Heterogeneous Gneiss	Upper amphibolite 650-700°C(gar-bio)	Transposition foliation, intrafolial isoclinal folds	3.4 Ga Rb-Sr whole rock on injected migmatites
Pine Creek Nappe Complex	Mid- Upper-Amphibolite 600-650°C (gar-bio)	Isoclinal folding on all scales,	3.2 Ga Sm-Nd chondritic model age on amphibolite
Trondhjemite-Amphibolite Complex	Epidote-oligoclase zone 500°C, coexisting albite-oligoclase	Ductile shear zone, blastomylonitic, passive flow folds	3.55 and 3.26 Ga Sm-Nd chondritic model age ≈3.4 Ga Rb-Sr whole rock
Davis Creek Schist	Greenschsit Facies chlor-musc-albite-qtz	Phyllitic, local isoclinal fold late-stage kinks	
Mount Cowen Augen Gneiss	Greenschist Facies	Granitic augen gneiss	2.74 Ga Rb-Sr whole-rock isochron
Paragneiss	Upper amphibolite 700°C (gar-bio)	Anastomosing shear zones, high degree of internal tectonic mixing	≈2.8 Ga on quartzo-feldspathic gneiss in Yankee Jim Canyon

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LATE ARCHEAN TECTONIC EMPLACEMENT OF THE STILLWATER COMPLEX ALONG REACTIVATED BASEMENT STRUCTURES, NORTHERN BEARTOOTH MOUNTAINS, SOUTHERN MONTANA, U.S.A.

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ABSTRACT

A major basement feature of the northern Bighorn Basin, northern Wyoming, is the Nye-Bowler Lineament (NBL). Field relations, petrologic observations, and paleomagnetic and regional geophysical data all indicate that transcurrent faulting occurred along strands of the NBL in latest Archean time. Structures along the northern flank of the Beartooth Range and isopach data indicate the NBL to have been active as recently as Laramide time. The Mill Creek-Stillwater fault zone, a probable splay of the NBL, tectonically juxtaposes a portion of the Stillwater Complex and its thick hornfels aureole against Beartooth massif schists and granitoids. Hornfels rocks contain opx-cord and anth-cord assemblages, with $T \approx 800°C$ and $P_T \approx 2-3Kb$. Penetrative deformation fabrics are absent and sedimentary structures are often preserved. Regional metamorphism of the schists, however, formed subsets of the assemblage bio-gar-staur-anth-cord-sill and $T \approx 600°C$ and $P_T \approx 7-8Kb$. The Stillwater Complex (Ca. 2700 Ma) is not affected by high grade regional metamorphism. It, as well as basement rocks, is cut by the Mouat Quartz Monzonite (MQM), whose age is also Ca. 2700 Ma. Tectonic emplacement of the complex and hornfels occurred soon after intrusion and differentiation. Paleomagnetic data from Banded Series units are discordant with respect to nearly age-equivalent results of the Superior Province. Data from latest Archean dikes, units thermally reset by the MQM, and Middle Proterozoic dikes are, after partial correction for Phanerozoic deformation alone, coincident with those of respective age from the Superior Province and also support a pre-MQM age of dismemberment. Significant gravity and magnetic anomalies southwest of Billings (the "Fromdorf High") may signify the buried remainder of the complex.

INTRODUCTION

The Stillwater Complex, a Late Archean stratiform mafic-ultramafic intrusive, is exposed along the northern flank of the Beartooth Mountains, Montana, in the Archean Wyoming Province (e.g., Condie, 1976) of the western Cordillera. It has been the topic of extensive petrologic and geochemical studies (Jones and others, 1960; Hess, 1960; Jackson, 1961; Page, 1977, 1979; McCallum and others, 1980; Raedeke and McCallum, 1984). Much recent work is summarized in Czamanski and Zeintek (1985). The nature, significance, and origin of the tectonic setting of the Complex have been relatively overlooked; the most comprehensive discussions are by Page (1977) and Page and Zeintek (1985). Its layered nature at least suggests that the Stillwater Complex might serve as a chronologic structural marker of Archean tectonism in the northern Wyoming Province. Our recent field, petrologic and paleomagnetic studies provide strong evidence for Page's (1977) suggestion that the Stillwater Complex was tectonically emplaced against the main Beartooth massif initially in the latest Archean, and that structures responsible for emplacement were reactivated at least once, during Laramide uplift of the Beartooth Mountains.

GEOLOGIC SETTING

The Stillwater Complex and associated hornfels rocks comprise one of four Archean structural/lithologic blocks in the Beartooth Mountains (Figure 1a), as defined by J. T. Wilson (1936). To the west is the North Snowy Block, a mobile belt consisting of tectonically juxtaposed metaigneous and metasupracrustal rocks (Mogk, 1984).

The main Beartooth massif (Granite Range Block), consists of voluminous calc-alkaline granitoids with inclusions of high-grade metasupracrustal rocks (Mueller and others, 1985; Henry and others, 1982; Mogk and others, 1985, unpublished data). The South Snowy Block also consists of schists and gneisses and is separated from the main Beartooth massif by unconformably overlying Phanerozoic strata. At its eastern end, the Mill Creek-Stillwater Fault Zone (MCSFZ) (J.T. Wilson, 1936) juxtaposes the Stillwater Complex and hornfels aureole with the main Beartooth massif. Where it intersects the northeastern front of the range, the MCSFZ delineates a marked change in Laramide structures, as described below. Latest Archean quartz monzonite plutons (e.g., the Mouat Quartz Monzonite in the Stillwater River area) intrude both the Stillwater Complex and schists and gneisses of the Beartooth massif.

The Stillwater Complex is continuous in outcrop for almost 50 km along the northern margin of the Beartooth Mountains, is approximately 6 km in maximum thickness, and dips steeply to the north-northeast. The original size and shape of the complex are unknown (Page, 1977). Hess (1960) recognized that approximately 3 km of the upper zone, gabbroic-composition stratigraphy is missing. Furthermore, the eastern margin of the complex is truncated by a splay of the MCSFZ. The underlying hornfels aureole is up to 10 km thick (Vaniman and others, 1980; Page and Zientek, 1985) (Figure 1b) and has been tectonically juxtaposed against the main Beartooth massif. West of the main Boulder River the hornfelses are in tectonic contact with high-grade schists along a proposed splay of the MCSFZ. These schists are part of a large pendant in Archean granitoid rocks.

Phanerozoic sedimentary rocks unconformably overly the Stillwater Complex. The entire Beartooth Range is a Laramide foreland uplift block

(Foose and others, 1961), and numerous faults of Laramide and younger age cut all older rock units (Jones and others, 1960; Page, 1977, J.T. Wilson, 1936). Laramide structures and associated igneous activity along the northeast front of the Beartooth Range have been described by J.T. Wilson (1936), C.W. Wilson (1936), and Foose and others, (1961). East of the intersection of the MCSFZ with the front (Figure 1b) to beyond Red Lodge, the front is marked by overthrusting of basement units and Paleozoic strata into the northern Bighorn Basin. West of the West Fork of the Stillwater River, the front is characterized by asymmetrical folds and small reverse faults.

TECTONIC EMPLACEMENT OF THE STILLWATER COMPLEX

The Stillwater Complex and associated hornfelses and the Archean basement of the Beartooth Mountains represent two fundamentally different terraines. Differences in their geologic histories can best be documented by the composition, metamorphic grade, and structural style of their metasedimentary rocks. Butler (1969) suggested that the hornfelsic aureole of the Stillwater Complex merely overprinted the regional metamorphism recorded by the high-grade schists and gneisses of the main Beartooth massif. Page (1977) and more recently Page and Zientek (1985), however, recognized that the hornfelsic aureole and the high-grade schists and gneisses experienced distinct geologic histories. Our current investigations further support the latter hypothesis.

Observations on the Metasedimentary Hornfelses

Composition

Metasedimentary rocks of the Stillwater hornfelsic aureole include fine-grained pelites with locally well-preserved sedimentary structures, banded iron formation, a blue metaquartzite, and a diamictite unit (Page,

1977; Page and Zeintek, 1985). Whole-rock analyses of the pelitic hornfelses are presented in Table 7 of Page (1977). These rocks are somewhat unusual in their relatively high MgO and FeO and low Na_2O and K_2O contents. Pelites also show unusally high Cr (up to 1400 ppm) and Ni (up to 1000 ppm) values. Page (1977) has recognized the chemical similarities between these pelites and the Fig Tree Group, South Africa, and has postulated an ultramafic or mafic source area for these sediments.

The high-grade schists of the Beartooth massif, on the other hand, occur as pendants and screens on a meter- to kilometer-scale within voluminous granitoids. The most abundant rock type is hornblende schist, similar to the andesitic amphibolites described by Mueller and others (1985) in the eastern Beartooth Mountains. Pelitic to psammitic schists occur in pendants on the south side of the West Fork of the Stillwater River, southwest of Mount Douglas, and on both sides of the main Boulder River north of the MCSFZ (Figure 1b). Representative chemical analyses of these rocks are presented in Table 1. Chemical variation diagrams (Figure 2) illustrate the diagnostic compositional differences between schists and Stillwater hornfelses. We propose that the two protolith sequences were derived from very different source areas.

Metamorphism

Metamorphism of the pelitic Stillwater hornfelses is characterized by the assemblage orthopyroxene-cordierite-biotite; in the distal portions of the aureole anthophyllite occurs in place of orthopyroxene (Page, 1977; Page and Zientek, 1985). In the banded iron formation the dominant assemblage is quartz-magnetite-orthopyroxene +/- grunerite. Vaniman and others (1980) and Labotka (1985) have estimated metamorphic conditions to have been approximately 800°C and most importantly, 2-3 Kb total pressure. This pressure

estimate is consistent with a shallow emplacement level of the Complex inferred from magmatic fractionation trends (McCallum and others, 1980).

Metamorphism of the Beartooth massif schists is of the Barrovian style. The dominant assemblage in pelitic schists is biotite-garnet-plagioclase-quartz +/- sillimanite and cordierite. Weeks (1980) and Labotka (1985) also report staurolite in the Boulder River area. The hornblende schists contain the assemblage hornblende-biotite-plagioclase-quartz +/- epidote. Garnet-biotite geothermometry (Ferry and Spear, 1978) of the pelitic schists yields temperatures in the range 650-700°C. Pressure estimates of 7-8 kbar have been calculated based on the garnet-cordierite-sillimanite-quartz geobarometer (Newton, 1983). Pressures during metamorphism of the granitic gneisses exceeded 4 Kb, based on the association of primary muscovite and quartz, and may have been as high as 8 Kb based on the presence of magmatic epidote (Richmond and Mogk, 1985).

Structural Style

Hornfels textures are usually granoblastic, while a strong recrystallization foliation is developed in the schists. There is no relict penetrative fabric in the hornfelses, nor are there relict garnet or staurolite porphyroblasts or Al-rich domains which would imply contact metamorphic overprinting of existing regionally metamorphosed rocks.

Primary sedimentary structures, including graded bedding, cross bedding, and cut-and-fill structures, are well-preserved in hornfelses. The metasedimentary rocks underwent a complex folding history prior to contact metamorphism; however, the only penetrative structural element developed is an incipient axial planar cleavage associated with mesoscopic folds (Page, 1977; Page and Zeintek, 1985). Rare intrafolial isoclinal folds appear to predate the first major folding event, and may be the result of soft sediment

deformation. The first major fold generation includes closed to open, similar to isoclinal folds. These folds have been overprinted by open, large wavelength folds (Page and Zientek, 1985).

The regional schists exhibit a strong foliation defined by compositional layering and preferred orientation of micas. This foliation is transposed and is axial planar to intrafolial isoclinal folds. Large-scale isoclinal folds, plunging gently to the north, have been recognized in the granitic gneisses in the Cathedral Peak area (Butler, 1969) and in the Lakes Plateau area (Richmond and Mogk, 1985).

Age Dates and Time of Tectonic Emplacement

The discontinuities in metamorphic grade, structural style, and geochemistry documented above indicate that the Stillwater Complex and its thermal aureole are allochthonous with respect to rocks of the Beartooth massif. The age of tectonic emplacement is constrained by the age of intrusion of the Mouat Quartz Monzonite, which cross cuts both the Archean schists and gneisses and the basal zone of the Stillwater Complex.

A summary of radiometric determinations for Beartooth Mountains rocks is given in Table 2. The age of the gneisses is not well-known. Based on work in the eastern Beartooth massif (Mueller and others, 1985) amphibolite grade metamorphism took place at approximately 2800 Ma. Granitic plutons which cut schists and gneisses in the Beartooth massif and North Snowy Block were intruded between 2750-2735 Ma, (Mueller, and others, 1985; Mogk and others, 1985, unpublished data). Most attempts to date the Stillwater Complex and its hornfels aureole indicate an age of emplacement of approximately 2700 Ma. Dates on the Mouat Quartz Monzonite range from 2760 to 2690 Ma.

Based on field relations, the Stillwater Complex must have been tectonically juxtaposed against the Beartooth massif prior to intrusion of the Mouat Quartz Monzonite. The isotopic ages of the Stillwater Complex and the Mouat Quartz Monzonite are almost identical, requiring that in the Late Archean the Stillwater Complex was intruded and crystallized and then, along with at least some of its contact aureole, faulted, in rapid succession, into its approximate position with respect to the Beartooth massif and North Snowy Block.

Sense and Mechanism of Displacement

The concept that the Stillwater Complex is allochthonous with respect to the schists and gneisses of the rest of the Beartooths has been previously offered by Page (1977) and Bonini (1982). It has long been recognized that the exposed stratigraphy of the Stillwater Complex is compositionally incomplete in comparison to similar layered intrusives such as the Bushveld Complex. Based on mass balance calculations, Hess (1960) estimated that between 27 and 50% of the Stillwater Complex section is presently unexposed or missing. That the eastern end of the complex is truncated by faults of the MCSFZ suggests that the original lateral extent of the complex was significantly greater than present strike length.

The most logical structure along which dislocation of the Stillwater Complex occurred is the MCSFZ and an eastern extension (Figure 1a), as suggested by Page (1977). Tectonic emplacement was suggested to have occurred by wrench faulting and such motion could have involved both tilting and more complicated rotations, about axes nearly perpendicular to igneous layering. The sense and magnitude of overall displacement may be inferred from regional

structural and geophysical data. The MCSFZ is probably a splay of a much larger regional structure, originally described as the Nye-Bowler Lineament by C.J. Wilson (1936), which strikes northwest from the northern Bighorn Basin to Livingston, Montana (Figure 1a). Regional gravity data (Bonini, 1982; Bonini and others, 1969) for the area including this structure reveal a prominent anomaly north of the Nye-Bowler Lineament extending to the northwest end of the Pryor Mountains (Figure 1a). We agree with Bonini's (1982) suggestion that a probable location for buried portions of the complex is northeast and east of present exposures (Figure 1) rather than directly to the north-northeast, as suggested by Kleinkopf (1985). If the Nye-Bowler Lineament was indeed responsible for the tectonic emplacement of the Stillwater Complex, it probably was a large, Late Archean wrench fault with a minimum of 100 km dextral displacement.

We discount the possibility of major sinistral motion emplacing the Stillwater Complex, even though Proterozoic sinistral motion along numerous northwest-trending faults has been well-documented by Schmidt (1985) in the Tobacco Root Mountains. The remaining portion of the complex would be located northwest of the Beartooth Mountains, and neither geologic nor geophysical evidence support this location. The original position of the entire complex would have coincided with the northern extension of the North Snowy Block, which exposes compressional structures active just prior to complex emplacement. Little is known of the few exposures of Archean rocks northwest of the Beartooth Mountains.

PALEOMAGNETIC DATA AND IMPLICATIONS FOR POST-EMPLACEMENT TECTONIC DISRUPTION

Paleomagnetic data from Banded Series rocks of the Stillwater Complex allow the possibility of significant structural disruption since intrusion.

Early investigations by Bergh (1968, 1970) and renewed work by one of us (JWG) and graduate students has identified a magnetization component which in all likelihood is a thermoremanent magnetization (TRM) acquired during initial cooling of the complex. Evidence for an early age for this magnetization (Geissman and others, 1985, unpublished data) is briefly reviewed here. The in-situ magnetization characteristic of the Banded Series units is of northeast to southeast declination and usually moderate to steep negative inclination. This direction is not one we can readily associate with any portion of Phanerozoic time. The magnetization is of high coercivities and narrow, high laboratory unblocking temperatures (Figure 3) and is carried by low-titanium magnetite inclusions in cumulus plagioclase grains. We are not aware of any one particular, or series of, geologic events affecting the Stillwater Complex which could have led to remagnetization, which would require temperatures exceeding 530°C, of this magnetization after initial cooling.

On a small scale, the TRM exhibits considerable directional variability which most likely reflects rapid, short-term Archean field behavior. The data do not support a hypothesis calling for deep burial and later, slow uplift/cooling (∿5°C/Ma) of the complex in latest Archean and younger time. Finally, magnetization data from cross-cutting plutons of latest Archean (?), Proterozoic, and Laramide age are statistically distinct from the magnetization characteristic of the Banded Series (Figure 4a).

Unfortunately, no other magnetization of comparable age has been identified in rocks of any portion of the Wyoming Province. Several investigations have been conducted on Late Archean and earliest Proterozoic rocks of the Superior and Slave Provinces (Interior Laurentia). These results

form a sizeable and temporally appropriate data base with which to compare Stillwater magnetizations.

Figure 4a shows data from several localities in Banded Series units across the strike length of the complex. The results have been corrected for attitudes of igneous layering, assuming simple local tilting of originally horizontal or sub-horizontal layering. The correction does not take into consideration additional, undetectable deformation such as a regional plunge of the complex. The corrected locality mean directions may be compared with Interior Laurentia data (Figure 4b) calculated from paleomagnetic pole positions (e.g., Irving, 1979). Our calculations assume an axial geocentric dipole for the time-averaged Archean geomagnetic field and paleomagnetically insignificant motion of the entire Wyoming Province following Stillwater intrusion. The latter assumption is difficult to evaluate (e.g., Green and others, 1985). The Stillwater magnetization is statistically distinct from Superior Province magnetizations of latest Archean to earliest Proterozoic age (Figure 4b). Superior Province data define a track of directions from east southeasterly, and shallow negative inclination, to northerly (and their antipodes) of moderate positive inclination. Comparing Banded Series data with those of latest Archean (?) Superior Province Matachewan dikes (Figure 4b) results in a discrepancy (T, Figure 5), largely in inclination, of at least 30°, which could possibly be resolved by assuming that igneous layering originally dipped moderately southwards and therefore that our tilt correction is incorrect. Alternatively, the age of the Banded Series magnetization may predate that of Matachewan dikes by several tens of millions of years. In this case, comparing the Stillwater data with Abitibi Subprovince metavolcanic and western Superior Province pluton data also results in a significant discrepancy (R, Figure 5) but now a possible explanation, involving rotation

of the complex about an axis nearly perpendicular to layering, is geologically more reasonable.

Earliest Proterozoic dikes and a large xenolith of metamorphosed diabase in the Mouat Quartz Monzonite give data, corrected for full tilt of igneous layering, which are similar to latest Archean directions (Figure 4a). Results from weakly to unmetamorphosed diabase dikes of probable Middle Proterozoic age are, however, discordant with expected Superior Province directions acquired during early-post and post-Hudsonian uplift (Figure 4b). Discordancy between corrected Middle Proterozoic dike and Superior Province data suggests that this portion of the Stillwater Complex must have been deformed prior to emplacement of Middle Proterozoic dikes; the structural correction most likely exceeds the total deformation following dike emplacement. Page (1977) documents an early, pre-Cambrian deformation of the Complex, resulting in a 10-30° angular unconformity with Cambrian strata. Paleomagnetic data suggest that this deformation occurred well-after tectonic emplacement of the complex in latest Archean time and specifically prior to intrusion of the unmetamorphosed mafic dikes. We are currently dating several of the dikes studied for their paleomagnetism to better refine the age of this phase of Proterozoic deformation. The data suggest that deformation included simple tilting of the complex about a near-horizontal axis.

TECTONIC SETTING FOR STILLWATER COMPLEX INTRUSION AND DISMEMBERING

In Figure 6 we offer a model describing the tectonic history of the Stillwater Complex and associated units which is consistent with geochronologic data and geologic relations (Figures 1b, 6a). Injection of a 7+ km thick layered mafic-ultramafic pluton requires thick continental crust,

probably within a tensional, yet generally stable tectonic environment (e.g., Weiblen and Morley, 1980). A period of tectonic quiescence of on the order of 3×10^5 years must be allowed for emplacement and large scale chemical differentiation of the complex (e.g, Irvine, 1970), even though there is evidence of small-scale deformation at some partially crystallized levels.

Formation of thick continental crust within the Beartooth Mountains area prior to Stillwater intrusion is depicted in Figures 6b, c. A trondhjemitic gneiss-amphibolite complex in the North Snowy Block (Mogk, 1984) has yielded a Nd-Sm chondritic model age of 3.55 Ga and Rb-Sr whole rock ages in excess of 3.4 Ga (Mogk and others, in review). Metasupracrustal inclusions in the Quad Creek and Hellroaring Plateau sections of the eastern Beartooth Mountains were metamorphosed in the granulite facies (T = 700-800°C, P = 6Kb) (Henry and others, 1982) at 3.4 Ga (Mueller and others, 1985). Burial of sedimentary protoliths to depths of 20 km occurred in the very early history of this terrane.

Extended periods of tectonic stability must also have been common to the northern Wyoming Province prior to Stillwater intrusion. Metasupracrustal rocks of the eastern Beartooth massif and the North Snowy Block contain quartzite-pelite +/- marble associations. These sequences are interpreted as stable platform or continental margin deposits (Mogk, 1984). By the latest Archean (ca. 2700 Ma), thick, stable continental crust must have evolved throughout this portion of the Wyoming Province.

We propose that the tensional tectonic environment existing during emplacement of the Stillwater Complex was established in direct response to a Late Archean compressional orogeny experienced throughout southwest Montana (Figure 6c) (Mueller and others, 1985; Mogk and others, in review). In the Beartooth Mountains, generation of voluminous andesitic magmas occurred at

about 2.8 Ga (Mueller and others, 1985), and was followed by 2.75 Ga emplacement of calc-alkaline granitic rocks. Geochemical and isotopic data indicate that these rocks reflect subduction-related processes (Mueller and others, 1985). Contemporaneous tectonic mobilization in the North Snowy Block involved early transcurrent faulting and later eastward-verging nappe emplacement (Mogk, 1984) (Figure 6c). West of the Beartooth Mountains the Archean basement appears to have been deformed over a period of somewhat younger tectonic mobilization, in the range of 2.75-2.70 Ga (James and Hedge, 1980). Several workers have reported high-grade supracrustal rocks, metamorphosed in the upper amphibolite to granulite facies, and isoclinally folded, east-verging nappe structures, throughout the Madison, Gallatin, Tobacco Root, and Ruby Ranges.

The deep burial of supracrustal rocks and the prevalent compressional structural styles suggest wholesale thickening of continental crust through collisional tectonics (Mogk and others, 1985, unpublished data). A tensional tectonic environment leading to emplacement of the Stillwater Complex possibly occurred during wrench faulting within the continental interior (Figure 6d) while contraction continued to the west. Modern analogues of rift graben formation along wrench faults include the Rhine Graben and Lake Baikal (Molnar and Tapponier, 1975). If the Stillwater Complex was emplaced along a wrench fault, recurrent movement can account for minor deformation of the igneous stratigraphy. Large-scale dextral motion along an ancestral Mill Creek-Stillwater-Nye-Bowler fault system shortly after crystallization of the Stillwater Complex (Figure 6e) dismembered and juxtaposed the exposed portion of the complex and associated hornfelses with the Beartooth massif in approximately their present position. The youngest deformation event recognized in the North Snowy Block is the intrusion of the Mount Cowen Augen

Gneiss, a granitic sill, at 2734 Ma (Mogk and others, 1985, unpublished data). Other granitic bodies in the Lakes Plateau area were intruded at this time; the Stillwater Complex was emplaced against the Beartooth massif and North Snowy Block after compressional deformation. After emplacement of the Mouat Quartz Monzonite (Figure 6f), the MCSFZ experienced relatively little tectonic activity throughout much of the Proterozoic. The Mill Creek-Stillwater and Nye-Bowler fault zones may have been reactivated during Proterozoic development of the southern margin of the Belt Basin, as discussed by Reynolds (1984). Minor northward tilting of the complex in Middle Proterozoic time may have reflected motion along the MCSFZ. Reactivation of the MCSFZ and Nye-Bowler zone occurred during Laramide uplift of the Beartooth Range (Figure 6g). The eastern portion of the MCSFZ, as well as structures along the front of the Beartooth Range farther to the east, were reactivated as a series of high-angle reverse faults (Figure 6g).

SUMMARY

Geologic and geophysical evidence suggest that the Stillwater Complex and associated hornfelses were tectonically emplaced against the Archean basement of the Beartooth Mountains. That the Mouat Quartz Monzonite intrudes both the Stillwater Complex and regional gneisses and schists requires that juxtaposition must have occurred shortly after crystallization of the complex, prior to about 2700 Ma. We are currently determining the age of recrystallization of a diabase xenolith within the Mouat Quartz Monzonite to more accurately date the intrusion. Paleomagnetic data corroborate the field observations indicating that regional, pre-Cambrian tilting of the complex occurred by Middle Proterozic time. Initial injection of the Stillwater magmas required thick continental crust in a tensional, but largely quiescent, tectonic environment. This environment was created in response to a Late Archean 2800-2750 Ma collisional orogeny that stabilized the northwestern portion of the Wyoming Province.

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FIGURE CAPTIONS

Figure 1. (a) Generalized geologic map of the Beartooth Mountains and vicinity, showing major structural/lithologic "blocks" of Precambrian rocks comprising the range and regional Bouger gravity anomaly data for its northern flank and the northern Bighorn Basin. Modified from Bonini (1982), Page (1977), and J.T. Wilson (1936). SC, Stillwater Complex; GRB, Granite Range Block; NSB, North Snowy Block; SSB, South Snowy Block; MCSFZ, Mill Creek-Stillwater Fault Zone; NBL, Nye-Bowler-Lineament; B, Billings; RL Red Lodge; L, Livingston. (b) Simplified geologic map of the Stillwater Complex area, showing important structural relations among the complex, associated hornfelses, and schists and gneisses of the Beartooth Massif (GRB), North Snowy Block (NSB), and Mouat Quartz Monzonite (MQM). Both regionally metamorphosed schists and hornfelses occur north of the MCSFZ; we propose the existence of a fault zone (dotted) north, and probably a strand, of the MCSFZ, separating the Stillwater Complex (SC) and hornfels (H) from schists (RS) and gneisses to the south. Our own observations indicate the validity of the fault zone, although it is not accurately located. The fault zone is required to allow the emplacement of the complex and hornfelses without creating westward-verging structures in older units.

Figure 2. Chemical variation diagrams showing compositional differences between Stillwater hornfelses and regionally metamorphosed schists. Hornfels data are from Page (1977).

Figure 3. Representative paleomagnetic results. Orthogonal demagnetization diagram of the end-point of the natural remanent magnetization (NRM) projected onto the horizontal (closed) and vertical (open symbols) planes (geographic coordinates). Temperatures of each demagnetization step are along the vertical projections. Demagnetization of plagioclase-clinopyroxene cumulate (gabbro), west side, Stillwater River Valley. In this case, a single magnetization (most likely a TRM) is removed in demagnetization.

Figure 4. Equal area stereographic projections of (a) paleomagnetic data from Stillwater Complex and associated units and (b) approximately age-equivalent units of Interior Laurentia. In (a), for Banded Series units (circles), we show locality mean directions, determined from the means of several individual sites/locality. For Proterozoic dikes (inverted triangles) and Tertiary intrusives, each mean refers to a single pluton. In (b) magnetizations are described by approximate age. Most data are referenced by Irving (1979). The directions enclosed by dots are predominantly of Late Archean (ca. 2700 Ma) age. Those enclosed by dashes are of latest Archean to earliest Proterozoic (ca. 2650 to 2500 Ma) age. MD1 and MD2 refer to data from independent studies of Matachewan dikes. Middle Proterozoic (inverted triangles) and Tertiary (upright triangles) directions are from Irving (1979). Closed (open) symbols refer to lower (upper) hemisphere projections.

Figure 5. Possible mechanisms to account for discrepancies between structurally corrected Stillwater (Fig. 4a) and Superior Province data, as explained in the text. R refers to rotation (about a near-vertical axis), with respect to Late Archean data. T refers to tilting (about a near-horizontal axis), with respect to latest-Archean-earliest Proterozoic data.

Figure 6. Sketch maps of the northwestern Wyoming Province illustrating a sequence of tectonic events associated with and following the emplacement and disruption of the Stillwater Complex. Regional geologic relations taken from Mueller and others (1985), Mogk (1984), and Mogk and others (1985, unpublished data).

Table 1. Whole Rock Chemical Analyses, Lakes Plateau Pelites.

Table 2. Summary of Radiometric Age Data, Stillwater Complex and Surrounding Beartooth Mountains Rocks.

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Unit	Lithology	Location	Age (Ma)	Method
Stillwater Complex	Ultramafic Series, pegmatite	Mountain View Mine	2540 - 2640	K-Ar, phlogopite
	Banded Series, Gabbro	West Fork Adit	2701 ± 8	Sm-Nd, mineral sep.
		Scattered	2896 ± 34	Sm-Nd, whole rock
			2742 ± 34	Sm-Nd, mineral sep.
			2793 ± 21	Sm-Nd, mineral sep.
			2683 ± 87	U-Pb, Zircon
			2667 ± 3	U-Pb, Zircon
	Basal Series, Norite	Scattered	2710	U-Pb, Zircon
			2713 ± 3	U-Pb, Zircon
	Hornfels	Stillwater River Valley	2672 ± 150	Rb-Sr, whole rock
			2692 ± 45	Rb-Sr, whole rock
			3100	U-Pb, Zircon
			3140	U-Pb, Zircon
			2719 ± 76	Rb-Sr, whole rock
		Chrome Mountain	2822 ± 23	Rb-Sr, whole rock
		Boulder River	2573 ± 29	Rb-Sr, whole rock
	Mouat Quartz Monzonite	Stillwater River Valley	2750	U-Pb, Zircon
	Mouat Quartz Monzonite, Aplite	Stillwater River Valley	2690	U-Pb, Zircon
	Ultramafic and Banded Series, Combined	Scattered localities	2662 ± 12	Pb-Pb, whole rock

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Table 2. (cont.)

Unit	Lithology	Location	Age (Ma)	Method
Dikes	Metamorphosed diabase	Stillwater Complex	2650	Sm-Nd, mineral
		Beartooth Massif	2562 ± 126	Rb-Sr and K-Ar, whole rock
		Picket Pin Mtn.	2441	K-Ar, whole rock
	Unmetamorphosed diabase	Picket Pin Mtn.	1640	K-Ar, whole rock
	Unmetamorphosed diabase	Beartooth Massif	1500 - 1800	Rb-Sr and K-Ar, whole rock
	Metamorphosed, tholeiitic, picritic noritic	Eastern Beartooth Mountains	2500 - 2800	Rb-Sr, whole rock
	Unmetamorphosed, olivine-normative	Eastern Beartooth Mountains	1370	K-Ar, whole rock
	Unmetamorphosed, quartz-normative	Eastern Beartooth Mountains	740	K-Ar, whole rock
Regional Gneisses	Mount Cowen Augen Gneiss	North Snowy Block	2734 ± 72	Rb-Sr, whole rock
	Trondhjemite amphibolites	North Snowy Block	3190 - 3390	Sm-Nd, whole rock
			3100 - 3400	U-Pb, Zircon
	Quartzofeldspathic	Stillwater River Valley, Beartooth Massif	2750 ± 150	Rb-Sr, K-Ar, mineral

Table 2. (cont.)

Unit	Lithology	Location	Age (Ma)	Method
Regional Supracrustal rocks	Quartzofeldspathic gneiss, metasedimentary and metaigneous rocks	Eastern Beartooth Mountains	3390 ± 55	Rb-Sr, whole rock
	Quartzofeldspathic gneiss, metasedimentary and metaigneous rocks	Eastern Beartooth Mountains	2900 ± 3550	Sm-Nd, whole rock
	Metafelsites	Eastern Beartooth Mountains	2831 ± 128	Rb-Sr, whole rock
	Amphibolites	Eastern Beartooth Mountains	2750 ± 75	Rb-Sr, whole rock
Granitoids	Unfoliated quartz monzonite (?)	Eastern Beartooth Mountains, Long Lake	2800 ± 45	Rb-Sr, whole rock
	Foliated granodiorite	Eastern Beartooth Mountains, Long Lake	2750 ± 80	Rb-Sr, whole rock
	Granitoids combined with amphibolites	Eastern Beartooth Mountains, Long Lake	2790 ± 35	Rb-Sr, whole rock

Specific references for data presented here may be found in Lambert and others (1985), Mogk and others (in review), Mueller and others (1985), and Page (1977).

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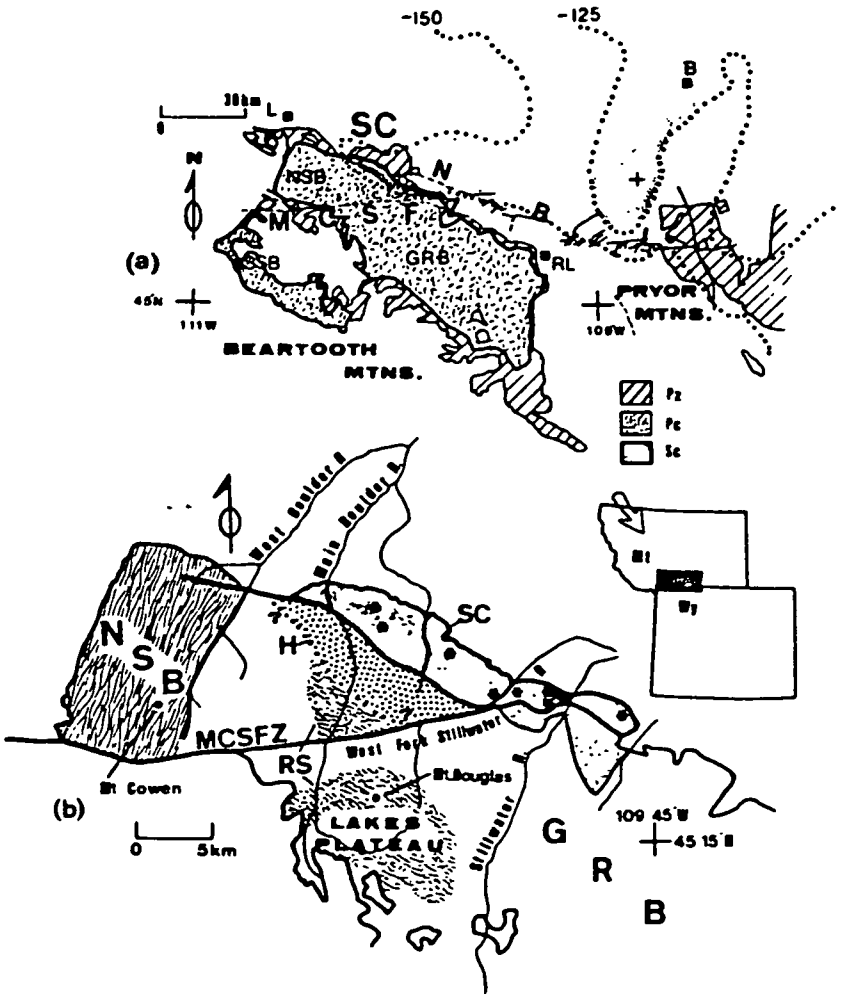

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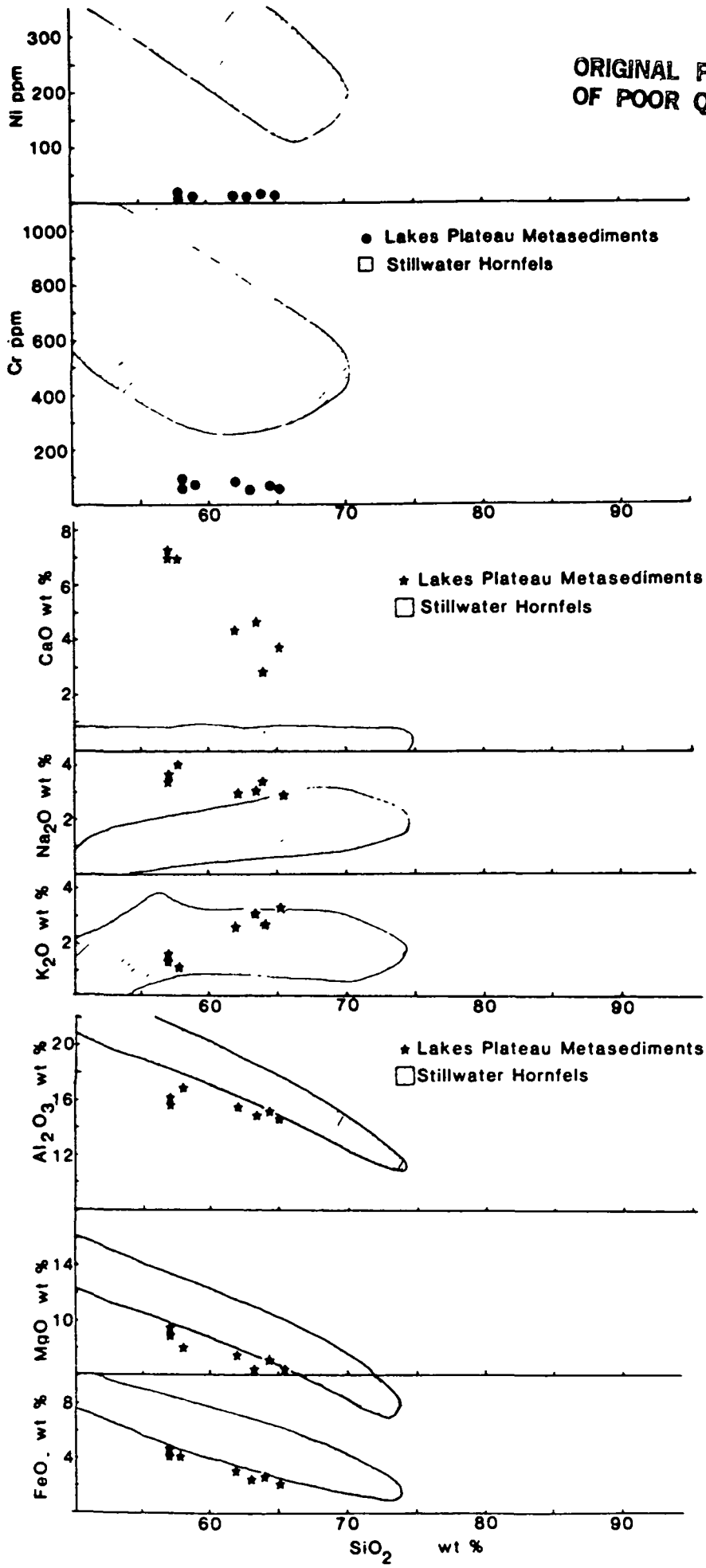

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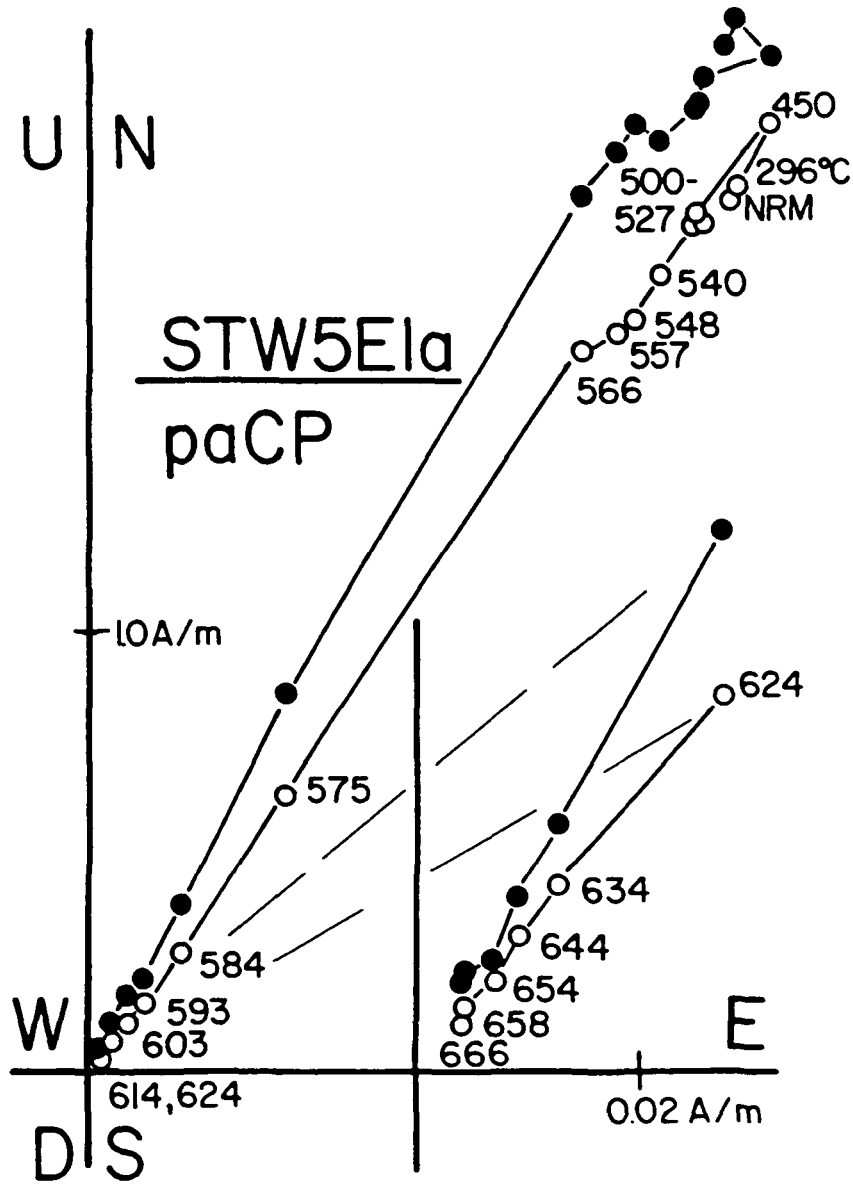
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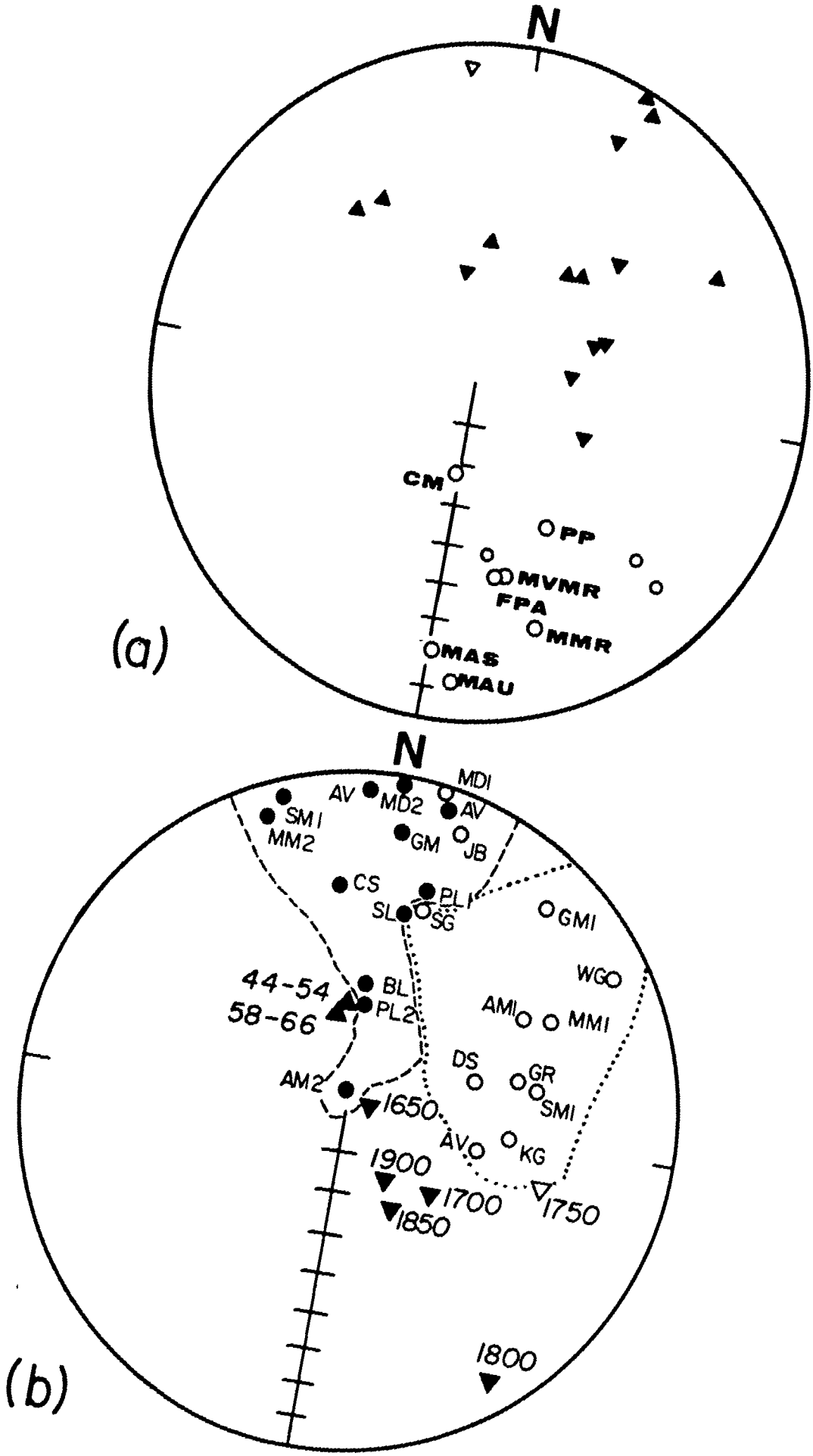
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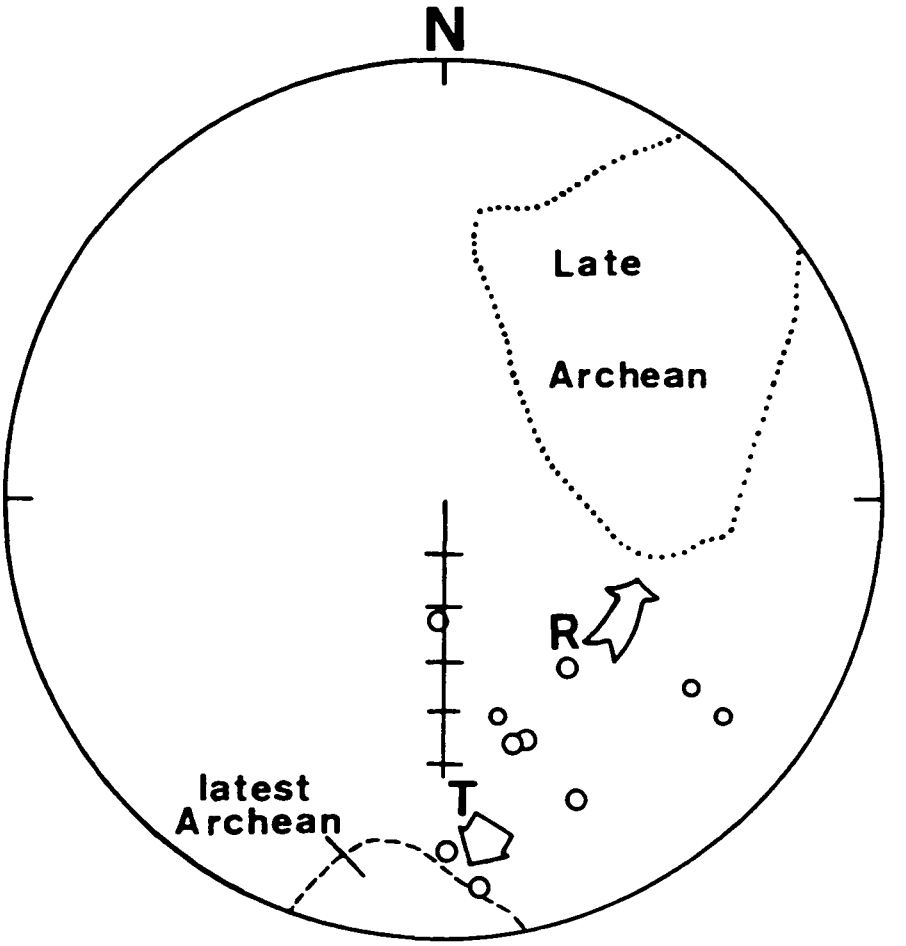

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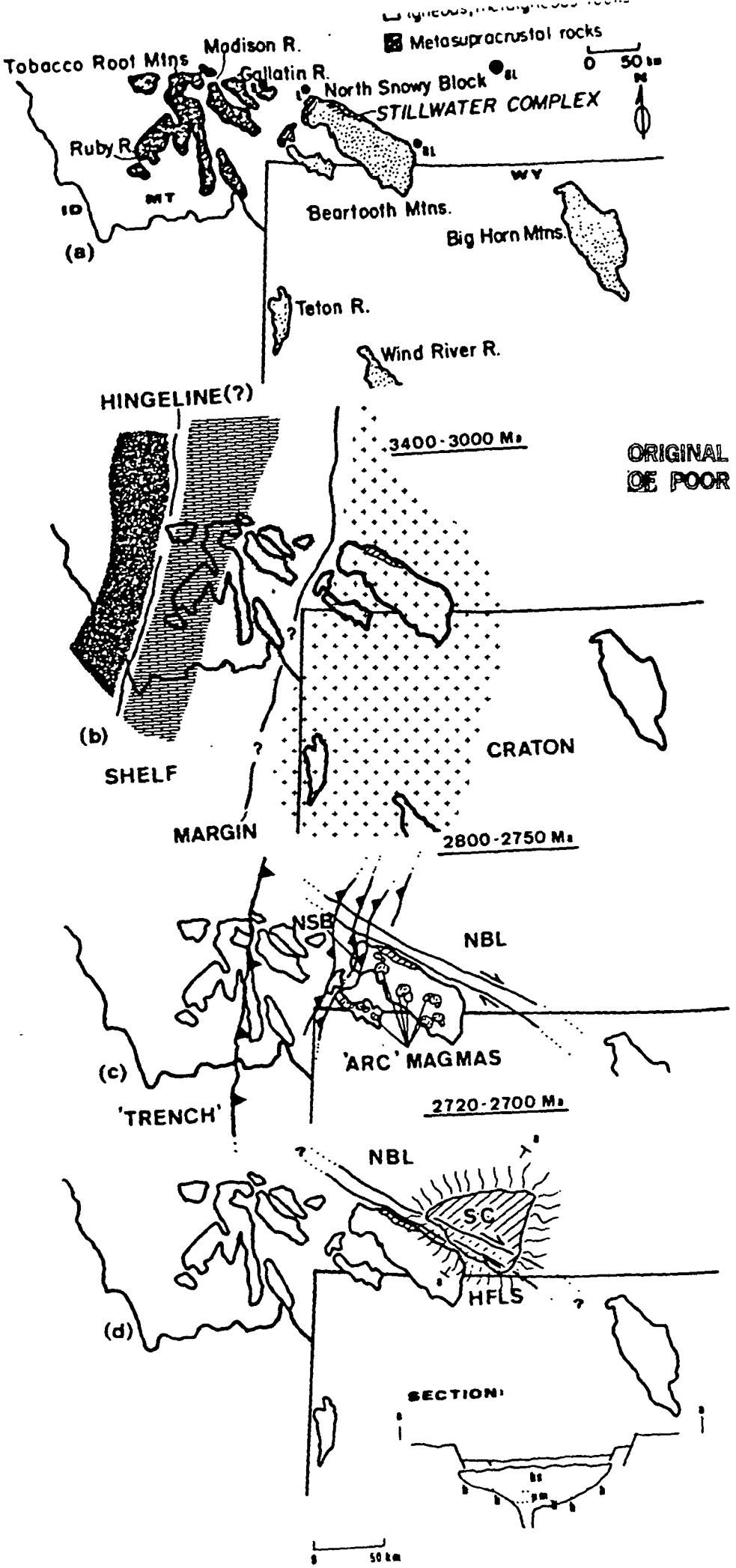

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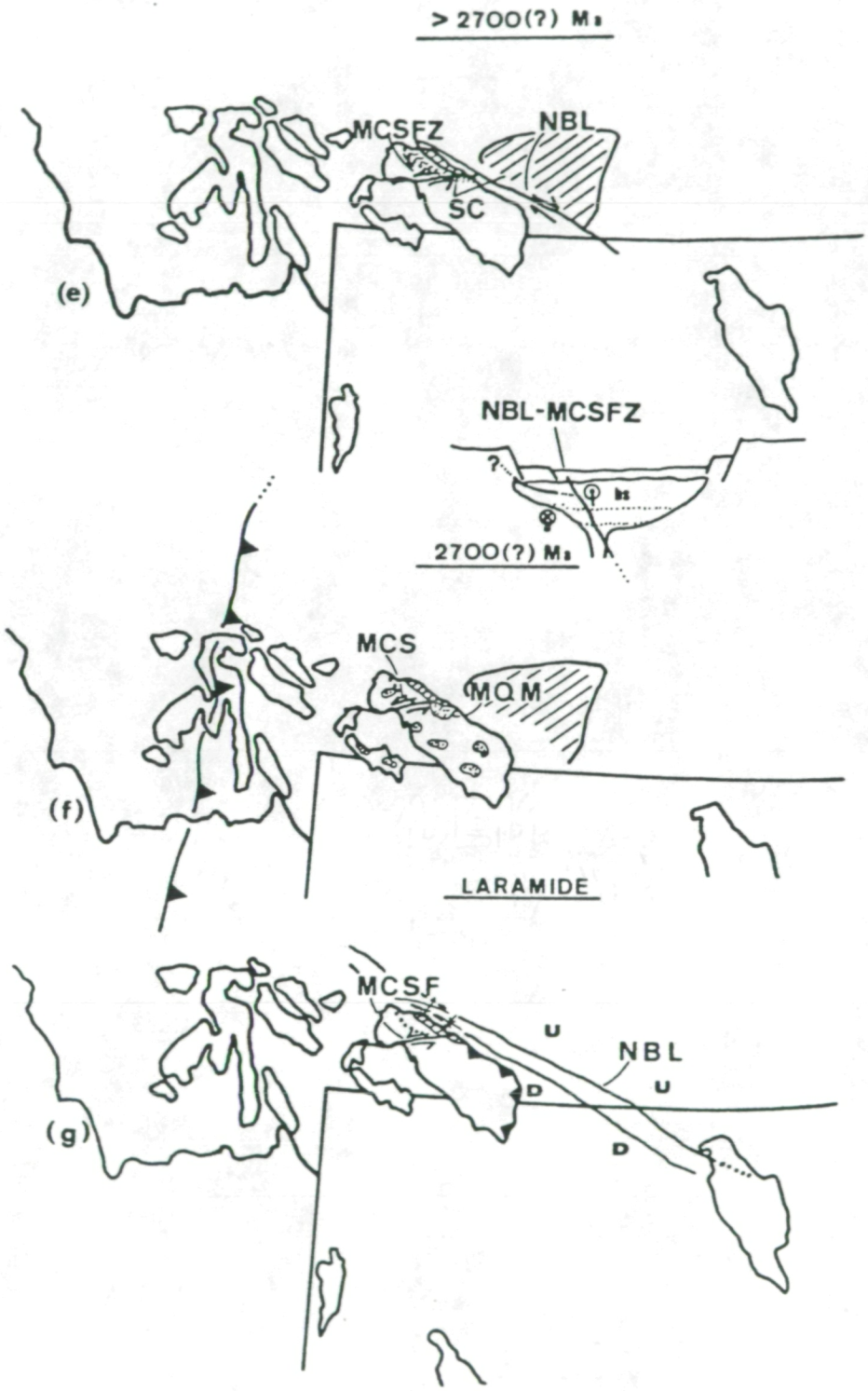
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A REVIEW OF THE GEOCHEMISTRY AND GEOCHRONOLOGY OF THE ARCHEAN ROCKS OF THE NORTHERN PART OF THE WYOMING PROVINCE

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ABSTRACT

The major exposures of Archean rocks in the western U.S. are found in what is called the Wyoming Province which encompasses Wyoming, Montana, and parts of Idaho, Utah, and South Dakota. Archean exposures are confined to crustal blocks uplifted during Laramide time and therefore represent only a small fraction of the surface area of this region. This lack of continuous exposure prevents widespread correlations and means that the exposed rocks are not necessarily representative of the province as a whole. The major exposures in the northern part of the Wyoming Province consist of the Beartooth, Bighorn, Owl Creek, and Tobacco Root Mountains, and the Gallatin, Madison, and Ruby Ranges.

The Beartooth Mountains have been more extensively studied than the other areas and can be divided into several distinct terranes that have general counterparts in other areas. The eastern and central Beartooth Mtns. are dominated by a late Archean suite of andesitic amphibolites and granitoids that have ages in the range 2.79-2.74 Ga. A period of deformation and middle amphibolite grade metamophism occurred in the earlier part of this range. Many of the foliated granitoids in the Bighorn Mtns. have a similar age and were synkinematically emplaced. Thus the eastern Beartooth and Bighorn Mtns. may represent a major, late Archean, magmatic arc. In both areas the late Archean suites intruded older rocks. In the Bighorn Mtns. these rocks are a trondhjemitic, tonalitic, and amphibolitic gneiss suite that is 2.9-3.1 Ga old. A suite of mafic amphibolites and dacitic gneisses similar in age and composition to the older Bighorn Mtn. suite is present in the Owl Creek Mtns. This Owl Creek suite is the nearest equivalent to a greenstone belt type assemblage in this part of the Wyoming Province. In the eastern Beartooth Mtns. the older rocks appear to be a varied supracrustal suite that is 3.2-3.4 Ga old. Supracrustal rocks 2.9-3.1 Ga old are present in the southwestern Beartooth Mtns. and immediately south of the 2.70 Ga old Stillwater Complex in the northcentral Beartooth Mtns.

The northwestern Beartooth Mtns. represent a different type of terrane. This area seems to have been assembled from as many as six different crustal segments by tectonic processes like those that operated in the Cordilleran orogeny. Some of the crustal segments in this terrane may be as old as 3.4 Ga (a trondhjemitic and amphibolitic gneiss complex) while others are late Archean in age. The late Archean event that formed this terrane may be the same one that was responsible for the 2.8 Ga old magmatic arc to the east or a somewhat younger event. The northern part of the southern Madison Range is also cored by a 3.4 Ga old tonalitic gneiss complex that is intruded by late Archean, gneissic granitoids. Thus the oldest rocks presently recognized in the northern Wyoming Province are found in a limited area formed by the Beartooth Mtns. and the southern Madison Range.

The northern Madison and Gallatin Ranges are a transitonal area composed dominately of strongly deformed, high grade quartzofeldspathic gneisses that were intruded by a late Archean granitoid suite. This area lies between the terranes to the east that contain early Archean rocks and/or are dominated by late Archean granitoids and the terranes to the west that contain rocks of a definite continental shelf affinity and seem to be only late Archean in age. Thus the region from the Ruby Range and Tobacco Root Mtns. on the west to the northwestern Beartooth Mtns. on the east may represent a late Archean continental margin that was shaped by tectonic processes like those operating in the Phanerozoic that produce areas of strong defomation and high metamorphic grade, juxtaposition of terranes, and magmatic arcs. The number of discrete events that formed this margin is not resolved at this time.

INTRODUCTION

There are two major exposures of Archean rocks in the United States. These are the southern extension of the Superior Province into Minnesota, northern Michigan, and Wisconsin and the Wyoming Province of Wyoming, southwestern Montana, and minor parts Idaho, Utah, and western South Dakota. This paper will concentrate on the northern part of the Wyoming Province where the authors have done most of their work and are most familiar with the work of other researchers. The reader is refered to the papers of Peterman (1979) and Condie (1976) for more comprehensive reviews of the geology and geochronology of the Wyoming Province.

The exposures of Archean rocks in the Wyoming Province (Fig. 1) differ from those of most other shield areas in that they consist of discrete blocks uplifted during the Larimide orogeny. Unlike the Superior Province where there is little relief and continuous exposures except where they are covered by glacial deposits, the Archean rocks of the Wyoming Province are characterized by over a km of topographic relief and as much as 10 km of structural relief. In the Wyoming Province Archean rocks form less than a third of the exposures. The wide separation of these exposures poses a major problem for interpretation of the Archean history. It prevents widespread correlation of structural or lithologic trends and probably makes it impossible to ever know if the area is divisible into subprovinces such as those that are distinguished for the Superior Province. The general lithologic character of the province is also impossible to know. As presently exposed the province would seem to be dominated by gneissic and granitoid rocks with only minor exposures of greenstone belt type rocks. Peterman (p.c.) has pointed out by superposing a map of the Wyoming Province exposure pattern on the Superior Province that the distribution of lithologic types in the Wyoming Province could easily come from an area with alternating greenstone-granite and granite-gneiss terranes such as those seen in the Superior Province.

In spite of the fairly small area of Archean rocks in the Wyoming Province, these rocks have not been extensively studied. Archean

shields in other parts of the world have received more extensive study for two major reasons. The first of these is economic deposits which in Archean rocks are concentrated in greenstone-volcanic belts. The previously mentioned paucity of exposed greenstone belt like rocks in the Wyoming Province can be directly related to the minor occurence of major economic deposits in the Archean rocks of the area. The second reason for major interest in a particular Archean area is the presence of early Archean rocks which provide us with what little information there is available about the earliest geologic history of the earth. Although there is growing evidence, as will be discussed later, that rocks 3.4 Ga or older must exist in the Wyoming Province, the oldest unambiguously dated rocks in the Wyoming Province are only 3.2 Ga old.

The northern part of the Wyoming Province that will be discussed in detail in this paper consists of the Beartooth, Bighorn, Owl Creek, Teton, Madison, Gallatin, Ruby, and Tobacco Root Mountains. The geochemistry and geochronology of each area will be discussed separately. Special emphasis will go to the Beartooth Mountains because of the authors' research experience there, because this area has been studied in greater detail than others in the region, and because the rocks there cover a greater range of ages and lithologies than is presently known elsewhere. Many of the problems of geologic interpretation that are detailed for the Beartooth Mtns. are valid for the other areas discussed and Archean terranes in general. The reader is refered to Mogk and Henry (this vol.) for a complimentary study of the metamorphic petrology and tectonic evolution of the Archean rocks of southwestern Montana.

BEARTOOTH MOUNTAINS

The Beartooth Mountains of Montana and Wyoming (Fig. 2) lie immediately north of Yellowstone National Park and are a roughly WNW trending block that contains over 5000 km^2 of Archean rocks. The Beartooth block can be divided into four areas: 1) the late Archean granitoid rocks of the eastern area that contain km size inclusions of older supracrustal rocks (Mueller and others, 1982a,b, 1985; Wooden and others, 1982; Mueller and Wooden, 1982), 2) the metasedimentary rocks of the northcentral area into which the Stillwater Igneous Complex was intruded (Page, 1977) and associated granitoid rocks, 3) the metasedimentary plus minor granitoid rocks of the southwestern area (Casella and others, 1982), and 4) the metamorphosed supracrustal and igneous rocks of the northwestern area that have been tectonically interleaved by thrusting (Reid and others, 1975; Mogk, 1982,1984; Mogk and others, 1986). Because the geology of each area is significantly different, individual areas will be discussed separately. It is not clear at this time what the relationship of individual areas are to each other, and it is possible that fundamentally different areas were tectonically juxatosed in the late Archean.

EASTERN BEARTOOTH MOUNTAINS

The eastern Beartooth Mountains were studied in detail in the late 1950's and early 1960's by Arie Poldervaart and his students

(Eckelman and Poldervaart, 1957; Harris, 1959; Larsen and others, 1966; and Casella, 1969). The dominate granitic rocks of this area along with the minor associated metasedimentary rocks were explained originally as the result of the granitization of a sequence of folded sedimentary rocks. Later models from this group recognized the probable role of igneous processes and multiple deformation and metamorphism. Work during the last ten years by Mueller, Wooden, Bowes, and coworkers (see Mueller and others, 1985 for a summary) has lead to a model involving the intrusion of a suite of late Archean rocks into a middle to early Archean supracrustal sequence parts of which had experienced a granulite facies metamorphic event (Henry and others, 1982).

Geochemistry of Late Archean Rocks

There are at least three distinctive compositional members of the late Archean suite (Fig. 3). These three groups have been given the following informal names - andesitic amphibolite, Long Lake granodiorite, and Long Lake granite. Field relationships indicate that the andesitic amphibolite is the oldest member of this group and that these rocks experienced an amphibolite grade metamorphism before the other members of the suite were emplaced. The present mineralogy of these amphibolites is biotite, hornblende, plagioclase, and quartz. The andesitic amphibolite is found as meter to km size inclusions in the younger granitoid rocks. The Long Lake granodiorite is intermediate in age being found in some places as weakly foliated inclusions in the Long Lake granite. The Long Lake granodiorite is compositionally distinctive but very difficult to distinguish in the field from the Long Lake granite. Both these rocks are leucocratic, medium to coarse grained, two feldspar and quartz rocks with biotite as the only mafic mineral (Wooden and others, 1982; Warner and others, 1982). It is difficult, therefore, to estimate the relative abundance of the granodiorite vs the granite in the field. Geochemical sampling indicates, however, that the granite is much more abundant.

The major element composition of the andesitic amphibolites is restricted to the andesitic or dioritic field (Fig. 3). There is, however, a good deal of variety in major element abundances in this group, and several subgroups can be distinguished within which there are regular elemental changes that may be related to fractionation processes. According to the classification developed by Gill (1981) for modern orogenic andesites, the andesitic amphibolites have major element compositions that fall into both the calc-alkaline and tholeiitic field. The calc-alkaline types dominate and are found over a wide geographic area in the eastern and central Beartooth Mountains. The tholeiitic types seem to be restricted to the eastern Beartooth Mountains. Because these rocks have been recrystalized in the middle amphibolite facies, it is not possible to reliably classify them according to their alkali contents. The major element compositions of the andesitic amphibolites are not unusual with respect to modern or Archean andesites (Gill, 1981; Condie, 1976, 1982).

The trace element concentrations of the andesitic amphibolites deserve special mention. While the range and abundance of the compatible trace elements in these rocks is within the normal range found in andesitic rocks, that of the incompatible trace elements is not. Sr concentrations range from 200-1000 ppm, Zr from 40-300 ppm, Ce from 20-300ppm, and Ba 200-1500 ppm. In addition the abundances of these incompatible elements are well correlated with each other (Fig. 3). This is particularly unusual for Sr which typically shows little variation within an andesitic suite even when fractionation has produced obvious variations in other elements. The best explanation for these chemical characteristics is a model that involves the interaction of an incompatible element rich fluid with a partial melting process (Mueller and others, 1983). Variable degrees of partial melting can explain the range of major element compositions and some of the trace element variation. An incompatible element rich fluid is needed to produce the unusually high concentrations of these elements in many of the rocks. Since Sr acts as an incompatible element, these processes must be occurring in a plagioclase free environment, possibly the mantle.

The Long Lake granodiorite has the major element composition (Fig. 3) of a typical calc-alkaline granodiorite (63-70 % SiO_2). Although it overlaps the Long Lake granite in SiO_2 content, it maintains a lower Na_2O concentration. In keeping with its lower SiO_2 contents, the granodiorite is generally a more mafic rock than the granite with higher FeO, MgO, and CaO concentrations. It is the trace element contents of the granodiorite that really distinguish it from the granite. The granodiorite has higher Sr, Ba, and REE concentrations than the granite. The REE pattern of the granodiorite is particularly distinctive being higher in both the LREE and HREE and having a noticeable negative Eu anomally (Fig. 3). The high incompatible trace elements of the granodiorite suggest that it also could have had a trace element fluid involved in its genesis. The negative Eu anomally, however, indicates that plagioclase was important as either a source or fractionating mineral and therefore that at least part of this rock's genesis was accomplished at crustal P and T.

The Long Lake granite is the volumetrically dominant rock type in the eastern Beartooth Mountains. It is divisible into at least two subgroups on the basis of Na_2O vs SiO_2 relationships (Fig. 3). The high Na group is volumetrically more important and compositionally more coherent than the low Na group. Although the silica content of the granite suite is restricted, the variation in Na_2O and K_2O concentrations (and modal plagioclase and K feldspar) mean that the rock types vary from high silica tonalite to average granite. The negative correlation between Na and Si in both subgroups is unusual in modern calc-alkaline rocks but is typical of Archean tonalite and trondhjemite suites. The genesis of tonalite and trondhjemite suites is best explained as the result of partial melting and/or fractionation of a basaltic parent. The lack of sodic suite rocks with intemediate

compositions strongly favors an origin by partial melting of a mafic source (basaltic and/or mafic andesite) that contained garnet, amphibole, or clinopyroxene to hold the HREE concentrations at 4X chondrites or lower. The strong LREE vs HREE fractionation seen in these rocks, along with the relatively low Sr and Rb contents, the low Rb/Sr ratios, and the high average K/Rb ratio of 350 with respect to other granitic rocks, all are compatible with an origin from a mafic source.

Geochronology and Isotopic Systematics Late Archean Rocks

A range of isotopic data is now available for the late Archean rocks of the eastern Beartooth Mountains. Recently obtained U-Pb zircon data (Mueller and others, in prep.) provide the best chronologic information for this group. These data are in agreement with the previously discussed field relationships and give the following ages: andesitic amphibolite, 2789 +/- 5 Ma; Long Lake granodiorite, 2782 +/- 3 Ma; Long Lake granite, 2748 +/- 41 Ma. The imprecise age of the Long Lake granite results from these zircons being at least 60% dicordant. Within confidence limits this suite of rocks covers a time period of 10 to 90 Ma. Previously available Rb-Sr whole rock data (Wooden and others,1982) gave a composite isochron for all three major groups of 2790 +/- 45 Ma (Fig. 4). The initial Sr ratio of this isochron is 0.7022 +/- 2. Common Pb isotopic data (Fig. 5) for whole rocks and feldspars from the same three groups give an age of 2780 +/- 100 Ma (Mueller And Wooden, in prep.). The feldspar separates provide a good estimate of the initial Pb isotopic ratio in these rocks at the time of their formation. These ratios are 13.86 for 206Pb/204Pb, 14.97 for 207Pb/204Pb, and 34.15 for 208Pb/204Pb (avr. of 3). Sm-Nd chondritic model ages (Fig. 4) vary from 2.88 to 3.02 Ga, and initial epsilon Nd values calculated for an age of 2.78 Ga range from -1.5 to -3.1 for five samples.

The chronologic and isotopic data for the late Archean suite clearly show that they are restricted to a small time interval and are remarkably homogeneous in their initial Sr, Nd, and Pb isotopic ratios. A time interval of 10-50 Ma for andesitic volcanism, deformation, and metamorphism, and additional major plutonism is not remarkable for the Archean or the Phanerozoic. It is unusual that such a compositionally diverse suite of rocks would have the same initial isotopic ratios. These ratios are not what would be expected for new crust that was forming from primitive or depleted mantle. Initial Sr, Nd, and Pb ratios in this case would be approximately 0.7010, epsilon of 0 to +2, and 6/4 = 13.40, 7/4 = 14.58, 8/4 = 33.16 respectively. The difference between these values and those observed in the late Archean suite suggest either an enriched mantle source or contamination of the suite by older Archean crust. The very high Pb ratios strongly favor the involvement of Archean crust in whatever process was responsible because it is only in crustal environments that the necessary high U/Pb could be produced to allow the Pb 6/4 and 7/4 to grow as high as needed. If crustal contamination occurred during emplacement of the late Archean

suite into an older crust, then it is hard to understand how the necessary homogeneity was acheived. It seems most probable that a portion of the mantle itself was contaminated possibly by introduction of crustal material through subduction, dewatering of the slab, and penetration of the overlying mantle wedge by fluids carrying Pb, Sr, and Nd with a crustal signature (Mueller and Wooden, in prep.). Crust made from this contaminated mantle would then have the necessary isotopic values and be isotopically homogeneous across a whole spectrum of compositional types especially if the crust forming cycle was confined to a short time period that limited further radiogenic growth.

Geochemistry of the Older Archean Rocks

Enclosed in the late Archean rocks of the eastern Beartooth Mountains are meter to several km sized inclusions of metamorphised supracrustal rocks. At least some of these rocks have experienced both a granulite grade metamorhpic event (Henry and others, 1982) and the late Archean amphibolite grade event discussed above. This granulite event was characterized by temperatures of about 800^{0}C and pressures of about 6 kb which suggest a geothermal gradient similar to those of modern orogenic zones (about 40-45^{0}C/km). These rocks are strongly deformed and isoclinally folded and many lithologic layers exist only as boudins of various lengths. The metamorphic equivalents of ironstones, basalts and ultramafic rocks, pelites, wackes, quartzites, and felsic volcanics can all be found in the supracrustal assemblages. At present no older plutonic rocks have been unequivocally identified.

In spite of the deformation and metamorphism that has affected these rocks, they appear to have largely retained their original bulk chemistries. The variation diagrams shown in Fig. 6 have no unusual features. If the obvious samples with strongly fractionated sedimentary compositions are not considered (high Si quartzites, low Na pelites, high Fe ironstones), the remaining samples show the expected compositional variations of an igneous calc-alkaline sequence. Most of this sequence has moderate K_2O contents (2% or less), and K_2O/Na_2O less than 1. Only the samples with SiO_2 in the mid 70's have K_2O/Na_2O of about 1.

Specific compositional features of some of the rock types in the older Archean sequence are worth emphasizing. The basaltic amphibolites are close to average basalt in composition and show little to only moderate Fe enrichment. Rare earth patterns are generally unfractionated and less than 20X chondrites, Sr contents are about 100 ppm, and Cr and Ni contents are about 250 and 100 ppm respectively. The samples with SiO_2 contents between 65 and 73 weight % are comparable to moderate K dacites. These samples have strongly fractionated REE patterns and no Eu anomalies. There is a group of rhyolitic composition rocks with K_2O/Na_2O = 1 that have fractionated REE patterns and strong negative Eu anomalies. The quartzites range in SiO_2 from 80 to 97 %, are locally fuchsitic and contain up to 100 ppm Cr, and contain obvious detrital zircons. Iron-rich rocks vary in SiO_2

from 47 to 61 % and in total Fe as FeO from 30 to 40 %. Their compositional characteristics favor a continental shelf rather than a eugeoclinal depositional environment. Pelitic rocks in the section have SiO2 contents in the low 60's, and very low CaO and NaO2 contents. The combination of quartzites, iron rich rocks, and pelitic rocks strongly indicate that at least part of the history of this sequence involved a continental shelf environment.

Geochronology of the older Archean rocks

The age of the older Archean sequence is problematical and will remain so until new U-Pb zircon studies are completed. The zircon data that is available now (Mueller and others, 1982) indicate a minimum age (207Pb/206Pb age) of 3295 Ma for a quartzite and 3220 Ma for a granitic migmatite from Hellroaring Plateau. This data was produced by acid leaching of zircons that fell on a discordia line that intersected concordia at about 3100 Ma. The 3100 Ma age may have no geological meaning because it may be a point along an episodic cord between the true age of the zircons and the time of new zircon growth and/or Pb loss. The lower end of this episodic cord is represented by clear, acicular zircons with an age of about 2800 Ma. The 2800 Ma age is consistent with the amphibolite metamorphic event that is recorded by the andesitic amhibolites although it could also repesent an event that preceded the crystalization of the igneous precusors of the andesitic amphibolites at 2790 Ma.

Rb-Sr, Sm-Nd, and common Pb data also provide information about the age of the older Archean rocks. A Rb-Sr isochron for the granitic migmatite discussed above gives an age of 2830 $\pm$ 130 Ma and an initial ratio of 0.738 $\pm$ 7. The high initial ratio of the isochron clearly shows that it represents the time at which a much older rock had its Rb-Sr system reset. A model age based on the average Rb and Sr contents and Sr isotopic values of this rock is approximately 3500 Ma if an initial Sr ratio of 0.700 is used. Rb-Sr data for other rocks in the older complex also indicate an early Archean age. Henry and others (1982) reported data for many of the lithologic types discussed above that fall along a 3350 Ma reference isochron with an initial ratio of 0.700 (Fig. 4). Additional work (Mueller and Wooden, unpub.) continues to confirm this trend. These data do not define an isochron because samples scatter both above and below the reference line. This scatter may be caused by many factors related to the complicated geologic history of these rocks. Possibilities include Rb or 87Sr loss during high grade metamorphism, Rb addition during metamorphism or later plutonism, mixing of different age rocks during plutonism or deformation, or improper identification of younger rocks included in the older complex. Although the lower Rb/Sr samples could represent mixing between late and early Archean materials, the high Rb/Sr's of some of the rocks on the reference line provide clear evidence that some early Archean material must be present.

The implication for ages of 3.3 Ga from the Rb-Sr system is

supported by Sm-Nd and Pb-Pb data. Four samples have Sm-Nd chondritic model ages between 3.3 and 3.5 Ga (Fig. 4). Three other samples have model ages between 3.1 and 3.2 Ga. Common Pb studies just started show that the same samples that have high Rb-Sr and Sm-Nd model ages have very radiogenic Pb compositions that are consistent with a minimum age of 3.3 Ga and very high U/Pb ratios (Fig. 5). The high initial Pb ratios of the late Archean suite (see above) also require the presence of older Archean material. Therefore there is strong inferencial along with reasonable direct evidence that rocks at least 3.3 Ga old exist in the eastern Beartooth Mountains. Further studies are needed to provide details of their complex history.

NORTHCENTRAL BEARTOOTH MOUNTAINS

The area surrounding the Stillwater Complex has been of special interest to geologists studing the origin of this famous layered mafic igneous complex. Unfortunately the field relationships in this area are complicated by major faults that separate the Stillwater Complex and the metasedimentary rocks it intrudes from the main exposures of Archean rocks in the rest of the Beartooth Mountains. Butler (1966) was one of the first studies to consider the transition from the Stillwater Complex and its contact metamorphosed border rocks into the dominately crystalline Archean rocks that lie to the south. Page (1977), Wooden and others (1982), and Czemanske and Zientek (1985) contain the best recently published information on the area. The following discussion also utilizes unpublished data from ongoing studies by Wooden, Mueller, and Mogk and students.

The Stillwater Complex intruded a sequence of metasedimentary rocks (Page, 1977; Page and Zientek, 1985) 2700 Ma ago (DePaolo and Wasserburg, 1979; Mueller and Wooden, 1976). These metasedimentary rocks are variable in composition with SiO_2 ranging between 45 and 80 percent. Low Na and Ca contents across this range indicate that all these rocks went through a strong weathering cycle. High Fe, Mg, Cr, and Ni contents throughout this range indicate that these rocks formed by mixing between quartz rich and high Mg sources. Nunes and Tilton (1971) reported U-Pb zircon ages for these rocks of 3060 and 3090 Ma (Fig. 8). DePaolo and Wasserburg (1979) reported a single chondritic model age of 3130 Ma for a hornfels sample. These rocks are therefore well dated at about 3100 Ma. At present there is no compositional and geochronological equivalent to these rocks known in the rest of the Beartooth Mtns.

These metasedimentary rocks are separated from the crystalline rocks of the Beartooths by faults. This crystalline complex is similar in many ways to the late Archean complex of the eastern Beartooth Mtns. The granitoid rocks are dominated by high SiO_2 members that have variable NaO_2/K_2O ratios (Fig. 7). These rocks contain numerous inclusions of amphibolitic and schistose rocks that have dioritic/andesitic bulk compositions. The style of intusion for the granitic rocks seems to be one of numerous thin sheets that can produce a lit-par-lit appearance. Pegmatite and

aplite veins are the latest intusions and account for about 20% of the volume. A composite Rb-Sr isochron for the granitoid rocks gives an age of 2700 ± 100 Ma with an initial Sr ratio of 0.7023 (Fig. 7) . A U-Pb zircon age for one of the granitoids is 2752 ± 14 Ma. Thus the presently available data suggest that these rocks are roughly equivalent to those of the eastern Beartooth Mtns in both age and composition.

There is a small body of coarse grained granite that occurs at the boundary between the Stillwater Complex and the meatsedimentary rocks. This granite may be a member of a major suite of medium grained granitoids (Page and others,1972). Nunes and Tilton (1971) obtained a zircon age of 2700 Ma on the coarse grained granite (Fig. 8). This is the youngest reliable age for granitoids in the Beartooth Mtns.

SOUTHWESTERN BEARTOOTH MOUNTAINS

The Archean geology of the southwestern Beartooth Mtns. is known from the work of C. J. Casella and students and is reported in detail in Casella and others (1982). Metasedimentary rocks are the dominate rock type here. These metasedimentary rocks are intruded by a variety of granitoids, and the synkinematic intrusion of these rocks produced migmatitic zones. The metasedimentary rocks occur as thinly bedded units of schist, quartzite, meta-conglomerate, and rare iron formation. Sedimentary structures including graded bedding, cross-bedding, and channel cut and fill have been preserved in spite of the multiple periods of deformation and metamorphism that these rocks suffered. The major period of deformation produced isoclinal folds and was accompanied by amphibolite grade metamorphism. A second period of amphibolite grade metamorphism is associated with only minor deformation and the intrusion of two mica granites. These granites have a minimum Rb-Sr age of 2740 Ma and a high initial Sr ratio indicating that they are partial melts of upper crustal rocks (Wooden, 1979). Bulk compositional data for the metasedimentary rocks suggest that they were originally mostly graywackes with a minor shale component. The age of the metasedimentary sequence is uncertain but seems to be in the range of 2.9-3.1 Ga based on model Rb-Sr data and a single model Sm-Nd age (Montgomery and Lytwyn, 1984; Wooden, unpub.).

The metasedimentary sequence is intruded along the eastern edge of its exposure by granitoids. The earliest of these granitoids is a quartz-hornblende diorite that seems to be the equivalent of the andesitic amphibolites of the eastern Beartooth Mtns. Intrusive into these rocks is a composite batholith with phases varying from tonalite to granite but with granodiorite dominating. The bulk compositions of some of these rocks are similar to the granitoids of the eastern Beartooth Mtns. However the majority of these rocks have higher K_2O/Na_2O ratios at the same SiO_2 level, and a greater number of the samples have wt.% SiO_2 contents in the 60's in keeping with their granodioritic modal classification. Rb-Sr and U-Pb zircon data (Montgomery, 1982; Montgomery and Lytwyn, 1984; Wooden, 1979) are consistent

with these rocks being the same age as the granitoids of the eastern Beartooth Mtns., but a significant reheating of this area in the Proterozoic has complicated the Rb-Sr systematics of these rocks.

NORTHWESTERN BEARTOOTH MOUNTAINS

The northwestern part of the Beartooth Mtns. is commonly referred to as the North Snowy block. This area was first described in detail by Reid and others (1975). Subsequent work by Mogk (1982, 1984) has added to the structural and geochemical knowledge of the area and allowed for new interpretations. Mogk and others (1986) can now show that this area is a series of lithologically and metamorphically distinct packages that have been juxtaposed by tectonic processes. There are six major units which can be defined from east to west (Fig. 9).

1) A paragneiss unit that contains a heterogeneous assemblage of supracrustal rocks including quartzofeldspathic gneisses, pelitic schists, amphibolites, and banded iron formation.

2) The Mount Cowen augen gneiss (Fig. 10) is a granitic, sill-like body. Unlike the granitic rocks of the east and central Beartooth Mtns., this unit has Na_2O/K_2O ratios less than one and higher Rb/Sr ratios. A Rb-Sr isochron for this rock gives an age of 2740 $\pm$ 50 Ma and an initial ratio of 0.7023 both of which are within error of the data for the eastern and central granitoids.

3) The Davis Creek schist is a phyllitic metapelite with minor layers of quartzite.

4) A trondhjemite-amphibolite complex that consists of trondhjemitic gneisses interlayered with a variety of amphibolites that range in composition from basaltic to anorthositic gabbroic. The trondhjemitic gneisses are like those found in Archean terranes elsewhere. They are high in SiO_2 (68-76%) and Na_2O (8-4%), low in K_2O (<2.5%), total Fe (<2%), and MgO (<1%). Unfortunately these rocks are in a ductile shear zone metamorphosed in the epidote-oligiclase facies. This probably explains why the Rb-Sr whole rock data for these rocks is scattered (Fig. 9). The majority of the data lie close to a 3.4 Ga reference line but a significant number of samples lie to the left of this line indicating immpossibly old ages. An early Archean age for this unit is supported by two Sm-Nd chondritic model ages of 3.26 and 3.59 Ga.

5) The Pine Creek nappe complex is cored by amphibolite that has symmetrically disposed quartzite and marble outside it. The amphibolite has an andesitic bulk composition. A single chondritic Sm-Nd model age of 3.2 Ga is the only chronologic information available for this unit.

6) The heterogeneous gneiss consists of a supracrustal package with quartzites, amphibolites, and minor schists that contains gneisses of granitic to tonalitic composition that appear to have been injected into the supracrustal rocks. Rb-Sr whole rock data for gneissic samples indicate that these rocks are approximately 3.4 Ga old. The data lie along the reference isochron for the trondhjemitic gneiss discussed above and there are compositional similarities between some members of the heterogeneous gneiss and

the trondhjemitic gneiss.

SOUTHERN MADISON RANGE

The southern Madison Range (Fig. 11) lies southwest of the Beartooth Mountains and has been studied in detail recently by Erslev (1981, 1982,, 1983). The field oriented studies of Erslev are now being extended by chronologic studies involving Erslev, P. Mueller, and J. Sutter, and the ages used in this section should be considered preliminary because these studies are not complete and not formally published. The major features of this range are a northern gneissic and migmatitic terrane. This terrane is separated from a southern sequence of meta-pelitic to psammitic schists and marbles called the Cherry Creek metamorphic suite (Erslev, 1983) by a thick sequence of mylonites called the Madison mylonite zone (Erslev, 1982).

Two units in the northern terrane have been analyzed by the Rb-Sr whole rock technique. A tonalitic gneiss has a limited spread in Rb/Sr ratios and somewhat disturbed systematics but the data for this unit clearly fall along a 3400 Ma reference isochron (Fig. 11). This age is similar to that of the trondhjemitic gneiss of the northwestern Beartooth Mtns. and the supracrustal sequence of the eastern Beartooth Mtns. The composition of the tonalitic gneiss is distinct from any member of these other units since it is a typical calc-alkaline tonalite with SiO2 in the low to middle 60's. The other unit examined is a granitic augen gneiss that is the main phase of a gneiss dome that penetrated the tonalitic gneiss. Limited Rb-Sr data for this unit indicate that it is approximately 2700 Ma old and support the observations of Erslev (1983) that the tonalitic gneiss is older than the granitic gneiss. The granitic gneiss is richer in K and Rb and has higher Rb/Sr ratios than the typical granitoid of the eastern and central Beartooth Mtns. The preliminary similarity in age between this part of the southern Madison Range and the Beartooth Mtns. is intriguing and will be examined in detail as more data become availabe.

The only chronologic data available for the southern terrane is limited Rb-Sr and U-Pb zircon data that indicates an age of about 2500 Ma for a granodioritic augen gneiss. This gneiss was syntectonically intruded into the metasedimentary sequence and provides a minimum age for the last deformation in this area and the deposition age of the sediments. This age is distinctly younger than those presently known from other parts of the northern Wyoming Province. The younger age, the lithologic distinction of this supracrustal sequence from those in the Beartooth Mtns., and the supracrustal vs. orthogneiss contrast between northern and southern terranes suggest that the Madison mylonite zone represents a significant crustal discontinuity.

NORTHERN MADISON AND GALLATIN RANGES

Earlier work in the the northern Madison Range by Spencer and Kozak (1975) described an extensive terrane of quartzofeldspathic

gneiss that had been multiply deformed and metamorphosed in the amphibolite facies. This work is currently being extended by D. Mogk and students. Salt and Mogk (1985, unpub.) have recognized three distinctive terranes. The first is a granulite and migmatite association in the Gallatin and Madison River valleys. A previously unrecognized batholitic complex that contains quartz-diorite, monzodiorite, granodiorite, and granite comprises the second terrane. The third terrane consists of metasupracrustal rocks in the upper amphibolite to granulite facies. The northern Gallatin Range appears to be an extension of the granulite and migmatite terrane mentioned above (May and Mogk, unpub.). No detailed geochemical or geochronologic data are available from this area at this time. James and Hedge (1980) included three samples from this area in their regional Rb-Sr study that produced a composite isochron age of about 2750 Ma for the Ruby, Tobacco Root, and northern Gallatin ranges. Additional data for this area will be important because it represents a transition between the metamorphosed shelf sequences to the west and the granitoid and older supracrustal sequences to the east.

TOBACCO ROOT AND RUBY RANGES

Vitaliano and others (1979) and Garihan (1979) provide the geologic framework for the Tobacco Root and Ruby Ranges, respectively. These two areas are similar and consist of a heterogeneous assemblage of quartzofeldspathic and mafic gneiss, para- and orthoamphibolite, metamorphosed ultramafic rock, marble, quartzite, pelitic schist, and iron formation. These areas have experienced at least one period of deformation that resulted in isoclinal folds. Two periods of metamorphism are possible with an amphibolite facies event overprinting a granulite facies event. Notable for these areas is the major metasedimentary component that is indicative of a continental shelf environment - marble, quartzite, schist, and iron formation.

Two Rb-Sr whole rock studies supply the only geochronologic information for these areas. Mueller and Cordua (1976) obtained an age of 2670 Ma for quartzofeldspathic gneisses for the Horse Creek area in the southern Tobacco Root Mtns. An initial ratio of about 0.704 indicates that these metamorphic rocks could not have had a long history before this time. James and Hedge (1980) analyzed a suite of quartzofeldspathic gneisses from the Tobacco Root, Ruby, and Gallatin Ranges. These samples gave an age of 2760 $\pm$ 115 Ma by themselves or an age of 2730 $\pm$ 85 Ma when combined with the data of Mueller and Cordua (1976). No comprehensive geochemical data are available for these samples but their Rb and Sr contents and Rb/Sr ratios are consistent with evolved granitic rocks or arkosic sediments. There is no evidence from either of these studies that this area had a history before approximately 2800 Ma; however, the existing database is small and only quartzofeldspathic samples have been examined.

BIGHORN MOUNTAINS

The Bighorn Mountains are located in north-central Wyoming (Fig. 1), west-southwest of the Beartooth Mtns, and contain major exposures of Archean rocks (about 2800 sq. km). The Bighorn Mtns. (Fig. 12) can be divided into a northern terrane of granitoids ranging in composition from tonalite to granite and a southern terrane consisting of orthogneisses and foliated granitoids (Heimlich and others, 1972; Barker and others, 1979). K-Ar dating throughout the range (Heimlich and Banks,1968; Condie and Heimlich,1969; Heimlich and Armstrong, 1972) showed that all the country rocks were Archean, and a careful K-Ar biotite age study (Heimlich and Armstrong, 1972) showed that ages in the northern terrane averaged 2.73 Ga while those in the southern terrane averaged 2.51 Ga. The reasons for the difference in age are unclear, but it serves to show that the two areas have more than lithologic differences. U-Pb studies in the northern terrane gave ages between 2840 and 2865 Ma while those in the southern terrane gave ages in the range 2890 to 2905 Ma with one younger age of 2710 Ma (Heimlich and Banks, 1968; Banks and Heimlich, 1976). A Rb-Sr whole rock study of granitoids and gneisses from both terranes gave an age of 2805 $\pm$ 60 Ma (Steuber and Heimlich, 1977).

The only intergrated field, geochemical, and geochronologic study in the Bighorn Mtns. is that of Barker and others (1979) and Arth and others (1980) in the Lake Helen area of the southern terrane. These studies established that two generations of rocks are present - an older E-1 and a younger E-2. The older E-1 assemblage consists of trondhjemitic and tonalitic gneiss, basaltic amphibolite, and hornblende - biotite gneiss. The sequence of events is intusion of trondhjemitic magmas, deformation and metamorphism, synkinematic intrusion of tonalitic magmas, and very late synkinematic intrusion of andesitic (hornblendé - biotite gneiss) magmas. The basaltic amphibolites are associated with the trondhjemitic rocks and may represent inclusions or later dikes of mafic compositions. These trondhjemitic and tonalitic rocks (Fig. 12) have similar major element contents with SiO2 69-72 wt.%, Al2O3 15-16 wt.%, and NaO2/K2O ratios between 3 and 4. REE patterns are strongly fractionated with minimal Eu anomalies and moderate LREE abundances (30-80X chrondrites) and low HREE abundances (1-4X). The amphibolites show a range of basaltic compositions for both major and trace elements. A composite Rb-Sr whole rock isochron (Fig. 13) for trondhjemitic, tonalitic, and amphibolitic samples gave an age of 3007 $\pm$ 68 Ma (ISR = 0.7001 $\pm$ 1), and a U-Pb zircon age for the trondhjemitic - tonalitic gneisses was 2947 $\pm$ 100 Ma. The compositions of these rocks are similar to those of the trondhjemitic - amphibolitic complex of the western Beartooth Mtns. but apparently they are distinct in age. The andesitic gneisses of the Bighorn Mtns. are so similar in major and trace element contents to those of the andesitic amphibolites of the eastern and central Beartooth Mtns. that some genetic relationship must exist (Mueller and others,1983). The age of the Bighorn andesitic rocks is unknown.

The younger E-2 event in the Lake Helen area starts with the synkinematic intrusion of a trondhjemitic to leucogranodioritic pluton that sharply cuts the structures of the E-1 rocks. This pluton was followed by additional synkinematic intrusions of hornblende-biotite tonalite, biotite tonalite, biotite granodiorite, and biotite granite. The trondhjemitic rocks are similar to the older E-1 trondhjemitic - tonalitic rocks (Fig. 12) in all respects except for slightly higher LREE contents. Compositional data for the later intrusions is not published except for information that these rocks range in SiO2 from 57 to more than 75 wt.% and are typically calc-alkaline. A Rb-Sr whole rock isochron (Fig. 13) that includes samples from all the E-2 rock types gave an age of 2801 ± 62 Ma with an initial ratio of 0.7015 ± 2.

OWL CREEK MOUNTAINS

The Owl Creek Mountains are located in central Wyoming and represent several small areas of exposure. The work that has been done there is concentrated in Wind River Canyon which transects one of the areas of exposure. This area has been described by Condie (1967), Granath (1975), Mueller and others (1985), and Stuckless and others, (?). The rocks exposed in the canyon represent a multiplely folded, amphibolite grade, supracrustal sequence that consists of interlayered gneiss, amphibolite, and minor schist. The supracrustal sequence is cut by a potassic granite of late Archean age.

Mueller and others (1985) have shown that the supracrustal sequence is largely of igneous origin. As presently exposed the sequence is composed mostly of two types of amphibolite - one with tholeiitic basaltic compositions and flat REE patterns and another with basaltic andesitic compositions and LREE enriched REE patterns. A gneiss with dacitic compositions is found interlayered with the tholeiitic amphibolites. These dacitic rocks have SiO2 between 66-72 wt.%, average K2O/Na2O = 0.65, and strongly fractionated REE patterns (La = 100X and HREE = 3X). A U-Pb zircon age (Fig. 14) for a dacitic sample is 2905 ± 25 Ma and is interpreted as the time of crystalization. A Rb-Sr isochron (Fig. 14) for dacitic samples gives an age of 2755 ± 96 Ma and is interpreted as the time of metamorphism. Samples of basaltic andesite fall on this isochron but tholeiitic samples fall slightly below suggesting that there is some genetic link between the dacitic and basaltic andesitic samples. Model initial Sr ratios in the range 0.702-0.704 for the dacitic - basaltic andesitic rocks between 2.75 and 2.90 Ga indicate that the genesis of these rocks involved the crust in some way.

SYNTHESIS

This review should make it clear to the reader that a reasonable amount of information is available about the geochemistry and geochronology of the northern part of the Wyoming Province and that some first order hypotheses about the origin of this area

can be made. The authors wish to make it clear that the data available for this area is really very fragmentary, even in the better studied areas such as the Beartooth and Bighorn Mtns. We expect that the ideas presented here about the Archean history of this area will change a great deal as more information becomes available. We hope that this review will convince readers that the Archean terranes of the western U.S. have much to tell us about early crustal evolution and are worthy of much additional study.

There is a growing body of data that strongly suggest that there are rocks 3.3 Ga old and older in the northern Wyoming Province. Rb-Sr data from the eastern and northwestern Beartooth Mtns. and the southern Madison Range indicate ages of 3.3-3.4 Ga. Sm-Nd and Pb-Pb data support these ages in the Beartooth Mtns. Unfortunately the meager zircon data available for these rocks tend to provide only minimum ages of about 3.1 Ga, but the data contain obvious indications of complex systematics and modern analytical techniques should be able to yield more information for these systems. These older rocks are trondhjemites and tonalites in the southern Madison Range and northwestern Beartooth Mtns. This type of rock is known to be the most common component of early Archean terranes (Barker and Peterman, 1974; Wooden and others, 1980). However the older rocks of the eastern Beartooth Mtns. are dominately potassic gneisses and a lithologically varied supracrustal sequence. Trace element and common Pb isotopic data support the evolved nature of these rocks. The early Archean rocks of the eastern Beartooth Mtns. indicate that crustal processing of the more "primitive", low K rocks suites most common in the early Archean did take place.

Middle Archean rocks (2.9-3.1 Ga old) are common in the northern Wyoming Province. Supracrustal rocks of a dominately sedimentary origin in the northcentral and southwestern Beartooth Mtns. and trondhjemitic, dacitic, and basaltic amphibolitic suites in the Bighorn and Owl Creek Mtns. are all in this age range. It is perhaps significant that the low K suites of this age are common in the areas where there is no present evidence of older Archean crust.

It seems likely that these middle Archean rocks experienced at least an amphibolite grade metamorphic event before they became involved in major late Archean events. Both the eastern and central Beartooth Mtns. and the Bighorn Mtns. contain major suites of magmatic rocks that are 2.75-2.80 Ga old. In the Beartooth Mtns. the earliest members of this suite are andesitic amphibolites that record a middle amphibolite grade metamorphic event. This period of metamorphism preceded the intrusion of a dominantly high silica and sodic granitoid suite. Activity in the Bighorn Mtns. started with trondhjemitic rocks that are intruded by a synkinematic calcalkaline suite. The geology of both these areas is consistent with the development of a major magmatic arc like those associated with modern day convergent plate tectonics.

The northwestern Beartooth Mtns. and the area west of it represent a very different late Archean environment (Mogk and Henry, this vol.). There is evidence for plutonic activity only in the northern and southern Madison Ranges and the northwestern Beartooth Mtns. The plutonic rocks are subordinate to sequences of quartzofeldspathic gneisses and/or supracrustal rocks containing quartzites and carbonates. The rock associations in the Tobacco Root Mtns. and the Ruby Range are particularly indicative of a continental shelf environment. Many of the rocks in this western area have high amphibolite or granulite grade metamorphic assemblages that could be produced in crustal doubling events (Newton and Perkins, 1982). A good case can be made that the northwestern Beartooth Mtns. are an assemblage of at least six terranes that were tectonically juxtaposed during the late Archean. Thus this area seems to be experiencing major tectonic activity like that seen along continental margins undergoing convergent plate tectonics while the area inboard of it was developing a magmatic arc. The major activity in the magmatic arc seems limited to about 50 Ma but chronologic constraints are not available for this western area. Its history may involve several distinct events.

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METAMORPHIC PETROLOGY OF THE NORTHERN ARCHEAN WYOMING PROVINCE, SW MONTANA: EVIDENCE FOR ARCHEAN COLLISIONAL TECTONICS

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Introduction

The Archean basement of southwest Montana comprises the northern part of the Wyoming Province as defined by Condie (1976). Archean rocks are currently exposed in a series of foreland block uplifts across this terrain (e.g. Foose et al., 1961). A major discontinuity in the nature of this Archean continental crust is defined by a mobile belt in the North Snowy Block, western Beartooth Mountains (Mogk et al., in review; Figure 1). To the east of the North Snowy Block mobile belt the central and eastern Beartooth Mountains, Bighorn Mountains, and deep-drill samples of Archean rocks are comprised dominantly of late Archean granitoids with inclusions of older supracrustal rocks (Barker et al., 1979, Peterman, 1981; Henry et al., 1982; Timm, 1982; Mueller et al., 1985). To the west the North Snowy Block mobile belt the Archean terrains consist dominantly of 2.75 Ga old (James and Hedge, 1980) high-grade metasedimentary rocks as exposed in the Gallatin (Spencer and Kozak, 1975), Madison (Erslev, 1983), Ruby (Garihan, 1979), and Tobacco Root Mountains (Vitaliano et al., 1979). These rocks have been isoclinally folded and emplaced as nappes, and have attained upper amphibolite to granulite grades of metamorphism.

The metamorphic history of each of these areas provides an important framework in the understanding of the tectonic evolution of this Archean continental crust. The determination of the physical conditions of metamorphism, using heterogeneous phase equilibria and mineralogical geothermobarometers, provides the basis for construction of P-T trajectories, allows the interpretation of tectonic and geochemical processes, and aids in the recognition of

allochthonous units. Specific areas in the Beartooth Mountains and adjacent ranges will be described in detail to characterize their lithologic associations, metamorphic grade, and structural style. This information will be combined with geochemical and geochronological information (Wooden et al., this volume) to present a working model for the evolution of this continental crust.

BEARTOOTH MOUNTAINS

The Beartooth Mountains have been divided into four distinct domains, including the central Beartooth Block, the Stillwater Block, the North Snowy Block, and South Snowy Block (Wilson, 1936) (Figure 2). A major project conducted by Arie Poldervaart and his students in the eastern and central Beartooth Mountains provided the first field and petrologic studies (Eckelmann and Poldervaart, 1957; Spencer, 1959; Harris, 1959; Casella, 1964, 1969; Prinz, 1964; Butler, 1966, 1969; Larsen et al., 1966; Bentley, 1967; and Skinner et al., 1969). Their initial interpretation of this area called for granitization of a sequence of openly-folded supracrustal rocks. Recent petrologic, geochemical, and geochronologic studies (Mueller et al., 1985 and references therein) have demonstrated that the Beartooth Mountains consist predominantly of voluminous late-Archean granitoids with inclusions of supracrustal rocks which exhibit a wide range in composition, metamorphic grade and isotopic ages. The following sections describe those areas in the Beartooth Mountains where detailed petrologic studies have been done.

A. Quad Creek and Hellroaring Plateau, central Beartooth Block

The easternmost portion of the central Beartooth Mountains is composed predominantly of granitic to tonalitic granitoids, gneisses and migmatites whose Rb-Sr isotopic systematics indicate an age of formation of 2.8 Ga. (Wooden et al., this volume). Within these felsic rocks there are inclusions of various supracrustal lithologies ranging in size from a few centimeters to several kilometers. These earlier lithologies include quartzite, felsic gneiss, pyribolite, amphibolite, iron formation, pelitic schist and ultramafite. Similar to many high-grade terrains in the Archean (Windley, 1977) this assemblage of lithologies is more reminiscent of a shelf environment rather than a eugeoclinal or typical greenstone-belt setting. This is supported by bulk compositions and REE abundances of the lithologic units (Mueller et al., 1982, 1985).

The structural features of the rocks of the eastern Beartooth Mountains are dominated by two phases of deformation. The first major phase of deformation is characterized by a series of SSW-plunging isoclinal and intrafolial folds formed during the passive flow folding of a high grade metamorphic event (Rowan, 1969). The second major deformational phase is characterized by upright, typically nonisoclinal folds which form about SSW- to S-plunging axes and in which flexure is the dominant fold style. The common large antiformal and synformal structures with wavelengths of several kilometers are a manifestation of the second deformation. There are some minor subsequent deformations that produced broad, symmetric, open folds and relatively minor development of mineral lineations parallel to the

axial planes of the folds (Skinner et al., 1969; Rowan and Mueller, 1971). The supracrustal lithologic units are commonly boudin-shaped and separated by mylonitic zones and probably underwent a significant amount of tectonic thinning. Isoclinal and intrafolial folding are common in these units indicating their involvement in the first deformation.

Most of these earlier lithologies display mineral assemblages that are indicative of granulite grade metamorphism [M1] (Table 1; Figure 3,4). Application of a series of geothermometers and geobarometers (Ferry and Spear, 1978; Ellis and Green, 1979; and Newton and Perkins, 1982) yield temperatures of 750 - 800`C and pressures of 5 - 6 kbar (Henry et al., 1982). Some of these lithologies are partially-to-completely reset by a subsequent amphibolite grade metamorphism [M2] (Table 1; Figure 5). In the pelitic schists, coexisting sillimanite and muscovite are locally stable placing the stability field for M2 below the muscovite breakdown curve (Figure 3). Application of geothermobarometers (Ferry and Spear, 1978; Plyusnina, 1982) to those assemblages showing amphibolite grade reequilibration indicate this metamorphism developed at temperatures of 575 - 625` C and pressures of 3 - 5 kbar. The degree of retrogression of a given lithology is related to the size and rock type (the quartzites and ironstones being the least subject to retrogression). The Rb-Sr isotopic systematics of the supracrustal rocks are very different than those of the felsic intrusive rocks involved in the 2.8 Ga. event. Most samples define a 3.4 Ga. isochron

that is interpreted as the approximate time of granulite grade metamorphism with a few samples partially reset toward a 2.8 Ga. isochron (Wooden et al., this volume).

It is currently believed that the granulite grade supracrustal lithologies are restricted to the eastern portion of the central Beartooth Block. Consequently, this is a site of deposition of a series of platform-type supracrustal rocks that suffered large scale horizontal shortening and deep burial to about 20 kilometers at 3.4 Ga. A continent-continent collisional mechanism can most easily explain such deep burial of supracrustal rocks and implies that this early Archean crust locally doubled to at least 40 kilometers thickness (Newton, 1983; Mueller et al., 1985).

B. Long Lake and Broadwater River areas, central Beartooth Block

The Long Lake portion of the central Beartooth Block is also dominated by granitoid plutons, gneisses and migmatites. The most voluminous rock type is a tonalitic-to-granitic plutonic rock (the Long Lake granite (LLG)) that is weakly foliated, retains its igneous texture and surrounds the rest of the major rock units (Warner et al., 1982; Wooden et al., this volume). The LLG intrudes a ubiquitous, strongly-lineated granitoid gneiss (LLGd). Both of these units include blocks (1 m - 1 km) of a strongly-lineated and foliated amphibolite of basaltic andesite to andesitic composition (termed the andesitic amphibolite (AA)). This amphibolite shows no evidence of having previously reached granulite grade metamorphism. There are also minor amounts of quartz-microcline pegmatites that cut all of these units. The structural features that affect this area are similar to those of the eastern Beartooth Mountains (Harris, 1959; Casella, 1969; Khoury and Ghaly, 1973).

The typical mineral assemblages of these lithologies are given in Table 2. Although there are no well calibrated geothermobarometers for these mineral assemblages some indication of the P-T conditions can be obtained from the hornblende-plagioclase relations (Spear, 1980; Plyusnina, 1982; Nabelek and Lindsley, 1985). In the amphibolites, temperatures of 550-600 C are obtained. The geobarometric calibration of Plyusnina (1982) yields pressures of 4.5-6 kbars. However, the high tetrahedral Al in the hornblende may indicate metamorphism of even higher pressures (Spear, 1981). The minor amount of pegmatitic dikes suggest a relatively low P H_2O.

Rb-Sr and Sm-Nd isotopic systematics of these units suggest that the AA and possibly LLGd were formed and underwent metamorphism during the period 3.0-2.8 Ga. Finally, Rb-Sr systematics were disturbed and at least partially reset at 2.8 Ga. during emplacement of the LLG.

In addition to these units, minor amounts of supracrustal xenoliths (including pelitic schist, quartzite and iron formation) are found to the west of Long Lake in the Lonesome Mountain and Broadwater River areas (Larsen et al., 1966; Timm, 1982). Unlike the Quad Creek area, these supracrustal lithologies contain assemblages of medium-to-upper amphibolite grade metamorphism with some indications of an earlier lower P-T metamorphism (Timm, 1982). Preliminary U-Pb analyses of zircons from some of the metasedimentary xenoliths suggest that the source region for the sediment was about 3.1 Ga old (Montgomery et al., 1984).

These data are interpreted as signalling a major crust-forming event (3.0-2.8 Ga.) that began with the development of large amounts of andesitic magma as extrusive or shallow intrusive rocks in a convergent plate margin (Mueller et al., 1985). It is suggested that a compressional regime continued until about 2.8 Ga. culminating in an episode of amphibolite grade metamorphism and development of voluminous granitoid magmatism that also entrapped metasedimentary units that were derived from a 3.1 Ga old source terrain.

C. Lake Plateau Area

The Lake Plateau area is similar in many respects to the central Beartooth Mountains; however, it does appear to have formed at much deeper crustal levels. Regional mapping was originally done by Page et al., 1973 a and b) and Butler (1966) and detailed petrologic studies of this area have been reported by Richmond and Mogk (1985). Large volumes of pegmatite-rich granite-granodiorite have been intruded as sheet like bodies into a series of metasupracrustal rocks (Wooden et al., this volume). To the east the inclusions are dominantly andesitic amphibolites, similar to those reported by Butler (1966, 1969) in the Cathedral Peak area and also the Long Lake area (as described above). The west side of the area has meter- to kilometer- sized inclusions of pelitic and psammitic schists. Both types of inclusions have a strong crystallization schistosity developed parallel to the axial surfaces of isoclinal folds. Injection of the granites appears to be in lit-par-lit fashion into this earlier schistosity.

Metamorphism of the supracrustal inclusions pre-dates intrusion of the granites and is in the amphibolite facies. The dominant assemblage in the pelitic schist is: garnet-biotite-plagioclase-quartz+/-cordierite+/-sillimanite; staurolite is present in the Boulder River area. Application of the garnet-biotite geothermometer (Ferry and Spear, 1978) yields temperatures in the range of 570-620°C. The garnet-cordierite-sillimanite-quartz barometer (Thompson, 1976; Lonker, 1981; Newton, 1983) yields pressures of 7-8 Kbars (assuming $P_{H2O} = P_{total}$) and the garnet-plagioclase-sillimanite-quartz barometer

(Ghent, 1979; Newton, 1983) yields similar pressure estimates. The andesitic amphibolites contain the assemblage hornblende-plagioclase-biotite-quartz+/-epidote.

The granites of the Lake Plateau are similar in many respects to Caledonian-type granites as described by Pitcher (1982). They have a restricted range of compositions, from granite to granodiorite (tonalite is conspicuously absent). Rb-Sr whole rock systematics indicate an age of 2698+/-86 Ma and a U-Pb zircon age Of 2748+/-20 Ma has been determined (Wooden et al., this volume). These granites are pegmatite rich and contain magmatic muscovite (wt % TiO_2 > 0.7) (Speer, 1984) suggesting P_{H_2O} in excess of 4 Kbars. The occurrence of magmatic epidote (euhedral grains with straight grain boundaries against hornblende and biotite) indicates that P_{H_2O} may be as high as 8 Kbars (Zen and Hammarstrom, 1984), which is consistent with the pressure estimates based on the pelitic assemblages. The granites were emplaced into amphibolite-grade supracrustal rocks at the culmination of this late-Archean orogenic cycle. Generation of the Lake Plateau granites is interpreted as the result of post-collisional, adiabatic melting (Richmond and Mogk, 1985; Wooden et al., this volume).

D. North Snowy Block

The North Snowy Block (NSB) is an Archean mobile belt characterized by tectonic juxtaposition of both metaigneous and metasedimentary rocks. The NSB consists of four lithologically and metamorphically distinct linear belts separated by transcurrent faults and overlain by two east-verging thrust sheets (Mogk, 1984)(Figure 6). These six units are distinguished by abrupt discontinuities in

metamorphic grade, structural style, and isotopic age. The evolution of this continental crust is dominated by tectonic thickening as opposed to the magmatic thickening which occurred in the main Beartooth massif. The following summarizes the characteristics of these units as they occur in an east-west cross section (Table III).

1. The Paragneiss Unit consists of a wide variety of quartzo-feldspathic gneisses, pelitic schists and amphibolites. Anastomosing shear zones are responsible for abrupt discontinuities of lithology on a meter- to tens-of meter scale and a strong subhorizontal lineation is defined by mineral streak lineations. Metamorphism is generally upper amphibolite facies with garnet-biotite pairs yielding temperatures of 700`C; tectonic mixing of the individual units occurred under epidote amphibolite or greenschist facies conditions.

2. The Mount Cowen Augen Gneiss is a late- to post-kinematic, sill-like granitic body which has been emplaced along a postulated fault between the Paragneiss Unit and the Davis Creek Schist. The augen texture is defined by an anastomosing foliation, defined by ragged chlorite and muscovite, which wraps around microcline porphyroclasts. The presence of epidote and chlorite suggest recrystallization in the greenschist facies. The Mount Cowen Augen Gneiss is the youngest major rock unit in the NSB (2737+/-52 Ma).

3. The Davis Creek Schist is a phyllitic metapelite with subordinate quartzite layers. The dominant metamorphic assemblage is chlorite-muscovite-albite-quartz. Rare intrafolial isoclinal folds are overprinted by asymmetric kink folds. Contacts with the overlying

Trondhjemitic Gneiss-Amphibolite Complex are strongly mylonitic and occur as wispy intercalations.

4. The Trondhjemitic Gneiss-Amphibolite Complex is a ductile shear zone characterized by blastomylonitic texture, passive flow-folding and subhorizontal mineral streak lineation in the trondhjemitic gneiss. The amphibolites occur as rigid bodies that have been rotated into conformity with the ductile shear foliation in the trondhjemitic gneiss. They include fine-grained well-lineated varieties as well as coarse-grained metagabbros and anorthositic gabbros metamorphosed in the epidote-bearing and epidote-free amphibolite facies. Hornblende-plagioclase relations (Spear, 1980) are consistent with recrystallization in the lower to middle amphibolite facies. Individual amphibolite layers yield a variety of P-T conditions (e.g. 520-540`C, 6-7 Kbar; 560-580`C, 4-6 Kbar; 620-650`C, 4-5 Kbar; using the phase relations of Plyusnina, 1982) suggesting tectonic mixing of different levels of mafic crust during ductile shearing. Dynamic recrystallization of both albite and oligoclase neoblasts around oligoclase porphyroclasts in the trondhjemitic gneiss indicates ductile shearing ocurred at less than 500`C (below the crest of the peristerite solvus), and post-dates the peak amphibolite metamorphism recorded in the amphibolites.

5. The Pine Creek Nappe Complex is an isoclinally folded thrust-nappe consisting of amphibolite (core), with symmetrically disposed marble and quartzite on the upper and lower limbs. The lower limb is strongly attenuated and mylonites are well-developed in the quartzite at the lower contact. Isoclinal folding occurs on all scales and is

contemporaneous with a crystallization schistosity which is parallel to the axial surfaces. Metamorphism is in the middle to upper amphibolite facies as indicated by hornblende-plagioclase relations in the amphibolites (Spear, 1980) with average temperatures of 580`C-620`C and pressures of 4-6 Kbars (Plyusnina, 1982), garnet-biotite temperatures of 600-650`C in rare pelitic layers in the quartzite, and calcite-dolomite-diopside-phlogopite-retrograde tremolite assemblages in the marble.

6. The Heterogeneous Gneiss unit consists of a migmatitic complex associated with a high grade metasupracrustal sequence which have been thrust over the Pine Creek Nappe Complex. In the lower part of the thrust sheet lit-par-lit injections of granite to tonalite invade the country rock. Locally, foliation is truncated and partial assimilation of the supracrustal rocks is common. Higher in the thrust sheet the igneous rocks are absent and the supracrustal assemblage includes orthoquartzite, feldspathic quartzite, amphibolite, and minor pelite. Metamorphism at the base of the thrust sheet is in the upper amphibolite facies as demonstrated by the occurrence of sillimanite in pelitic rocks, hornblende-plagioclase relations and garnet-biotite temperatures in the range 650-700`C.

Within the North Snowy Block the wide variety of rock types and the abrupt discontinuities in metamorphic grade, structural style and isotopic ages suggest significant tectonic displacements. The Paragneiss Unit, Davis Creek Schist and Tronhjemitic Gneiss-Amphibolite Complex probably were emplaced along transcurrent faults as evidenced by their subhorizontal lineations. These units cannot be readily restored to a pre-faulting stratigraphy, as would be expected

if they currently represent a series of stacked thrust faults. In addition, the Paragneiss Unit is a chaotic mixture of tectonically juxtaposed, diverse rock types; the style of deformation of this unit is analogous to the tectonic mixing associated with wrench faults rather than thrust faults. The minimum age for the transcurrent faulting is 2.75 Ga based on the age of the protolith of the Mount Cowen Augen Gneiss. The emplacement of the two thrust sheets marks a significant change in the tectonic style of the NSB and appears to post-date the transcurrent faulting. The ductile shearing observed in the Trondhjemitic Gneiss is absent in the overlying thrust sheets. It is also significant to note that the metamorphic grade increases discontinuously up-section from the Trondhjemitic Gneiss through the overlying thrust sheets. The age of the protolith of the amphibolite in the Pine Creek Nappe is 3.2 Ga, which precludes the possibility of intrusion of the Trondhjemitic Gneiss as suggested by Reid et al. (1975), and the Heterogeneous Gneiss is older than the Pine Creek Nappe requiring tectonic juxtaposition to achieve the observed older-over-younger stacking sequence.

E. Yankee Jim Canyon

The Yankee Jim Canyon area is a ductile shear zone (Burnham, 1982) which is similar in all respects to the Paragneiss Unit in the North Snowy Block. A wide variety of lithologies, including quartzo-feldspathic gneisses, quartzite, pelites, amphibolites and ultramafites are tectonically mixed on a meter to tens-of-meters scale. Common assemblages include:

K-spar-plag-qtz-bio+/-musc (quartzofeldspathic gneisses)

bio-gar-sill-plag-qtz (pelitic rocks)

hornblende-plagioclase-quartz+/-Biotite (metabasites)

opx-hornblende (ultramafites)

Although diagnostic index minerals are rare, these assemblages indicate peak metamorphism is in the upper amphibolite facies. Garnet-biotite temperatures are in the range of 680-740`C. Retrograde minerals occur in anastomosing shear zones in this area and include chlorite, epidote, actinolite, and sericite. Calculated rim temperatures on garnet-biotite pairs of 480-520`C reflect retrograde metamorphic temperatures. The age of metamorphism is about 2.8 Ga (Rb-Sr whole rock age by Paul Mueller, unpubl. data) and there is some evidence of zircons as old as 3.6 Ga in some of the units (Guy and Sinha, 1985). The mixture of lithologies, metamorphic grade, and structural style of the Yankee Jim Canyon area are similar to those observed in the Paragneiss Unit of the North Snowy Block.

F. Jardine-South Snowy Block

The Jardine area is characterized by a sequence of fine-grained detrital sediments and associated iron formation. Included in this sequence are quartz-biotite schists, chlorite-muscovite schists, and grunerite-bearing ironstones (Hallager, 1984). This sequence is interpreted as the distal fan sediments associated with a rifted continental margin (Thurston, 1986). Sedimentary structures such as graded bedding and cut-and-fill channel structures are locally preserved; penetrative deformation is conspicuously absent. Towards

the margins of this sequence the grade apparently increases as evidenced by the occurrence of andalusite, garnet, and staurolite in the pelitic units. These low-grade metasediments are rare in the Archean basement of southwestern Montana. The Jardine sequence is tectonically-juxtaposed along ductile shear zones in the Yankee Jim Canyon area on the west and Broadwater River area to the east. 2.6 Ga. old quartz monzonite stocks have been emplaced in this sequence.

The bulk of the South Snowy Block consists of an extensive metasedimentary sequence which is intruded by late-Archean granites (Casella et al., 1982). The dominant rock type is biotite schist with varying modal abundances of quartz, plagioclase, muscovite, garnet, staurolite, and andalusite. Grunerite-bearing ironstones are also present in this area. On the eastern margin the schists are upgraded to upper amphibolite facies indicated by the presence of sillimanite and injection-type migmatites. Isoclinal folding accompanies amphibolite grade metamorphism and a second open folding event is also recorded.

G. Stillwater Complex Hornfels Aureole

The Stillwater Complex aureole has been described by Page (1977), Vaniman et al. (1980), Page and Zientek (1985) and Labotka (1985). The aureole consists of layered, fine-grained clastic sediments, iron formation, blue quartzite and diamictite. Sedimentary structures such as cross bedding, graded bedding, and cut and fill structures are locally preserved. The diagnostic assemblages in pelitic rocks are orthopyroxene-cordierite and anthophyllite-cordierite with associated quartz, plagioclase, spinel, biotite,

ilmenite, and sulfide minerals. The iron formation contains the assemblage: quartz-magnetite-orthopyroxene-grunerite; clinopyroxene, olivine and chlorite are locally present. The estimated conditions of metamorphism are P = 2-3 Kbars based on the composition of pigeonite in the iron formations (Vaniman et al., 1980) and T = 710°C (garnet-biotite) to 825°C (minimum temperature of pigeonite stability at 3 Kbars) (Labotka, 1985). The hornfels aureole is truncated by a splay of the Mill Creek-Stillwater Fault Zone (Figure 7) (Geissman and Mogk, in review). Metasediments in the Boulder River area (Weeks, 1981), on the south side of this fault, have mineral assemblages, penetrative deformation, calculated pressures and temperatures, and whole-rock chemistries more characteristic of the regionally metamorphosed schists described in the Lake Plateau area. Labotka (1985) has recently reported fine-grained garnet, staurolite, and chlorite in this area. The Stillwater Complex and its associated aureole have been tectonically emplaced against the Beartooth Mountains shortly after the time of crystallization of the complex (2700-2720 Ma) and prior to the emplacement of the 2700 Ma old Mouat Quartz Monzonite (Mogk and Geissman, 1984; Geissman and Mogk, in review).

Summary of the Archean Geology of the Beartooth Mountains

The Beartooth Mountains have evolved through at least two orogenic cycles separated by long periods of tectonic quiescence during the mid to late Archean (Mogk et al., 1984; Mueller et al., 1985). Platform-type sediments in the Quad Creek and Hellroaring Plateau areas which have been metamorphosed to granulite grade are the only remnants of the first cycle, recorded at 3.4 Ga. Deep burial of

these sediments is interpreted as the result of deep burial by continental collision. A second orogenic cycle involved both magmatic and tectonic thickening of the crust. Generation of andesitic rocks occurred at about 2.8 Ga and voluminous granitoids were emplaced at 2.75 Ga in the central Beartooth Mountains. These rocks are interpreted to be subduction-related (Mueller et al., 1985). Tectonic thickening in the North Snowy Block is roughly contemporaneous with the magmatic activity of the central Beartooth Mountains. The metasupracrustal rocks of the Beartooth Mountains exhibit a broad range of metamorphic grade, structural style, and whole-rock chemistry, suggesting that they were derived from a variety of source areas and experienced independent geologic histories (Mueller et al., 1984; Mogk et al., in review).

OVERVIEW OF THE WESTERN WYOMING PROVINCE

The mobile belt in the North Snowy Block marks a major discontinuity in the nature of the Archean continental crust of the northern Wyoming Province (Figure 1). Rocks to the west of this mobile belt include vast expanses of quartzofeldspathic gneiss with interlayered mafic granulite and extensive platform-type sediments. Metamorphism is dominantly in the upper amphibolite to granulite facies. Isoclinal folding on all scales and nappe emplacement characterize the regional structural style. Recognizable plutonic rocks are restricted to one narrow belt in the Spanish Peaks area. Rocks with oceanic affinity are also absent in the northern Wyoming Province; there are no greenstone belt associations similar to those observed in the southern Wyoming Province and the sediments are

distinctly of platform-type as opposed to an eugeoclinal assemblage. A model is proposed that calls for early development of a rift-bounded ensialic basin, or Tethyan-type basin with only limited generation of oceanic crust, followed by deep burial of sediments by means of tectonic thickening (A-type subduction). The following summarizes the major features of the exposures of Archean basement in an east-west cross progression.

A. Northern Gallatin Range

The northern Gallatin Range consists dominantly of a variety of quartzofeldspathic gneisses, with subordinate layers of orthoquartzite and pelitic schists, and meter-scale boudins of mafic granulite. Compositional layering on a centimeter scale is defined by wide variations of modal abundances of microcline and plagioclase and color index. This fine-scale layering and the association of quartzites and pelites strongly suggests that these rocks are derived from supracrustal assemblages. Metamorphism is in the upper amphibolite facies to hornblende granulite facies. The dominant assemblage in mafic layers is: clinopyroxene-garnet-hornblende-plagioclase-quartz+/-scapolite. Garnet-clinopyroxene temperatures in mafic granulites (Ellis and Green, 1979; Dahl 1980) yield temperatures of 700-750`C. Orthopyroxene is also recognized in centimeter-scale mafic layers in the quartzofeldspathic gneisses. Garnet-biotite temperatures in the gneissic and schistose layers also yield temperatures of 700-750`C. Within the quartzofeldspathic gneisses there are numerous layers of both concordant and discordant remobilized granitic leucosome. These are interpreted as anatectic melts, produced in response to vapor-absent melting during granulite facies metamorphism. The granulite facies assemblages are overprinted

by amphibolite facies assemblages; no new structural elements are recognized in this area so the amphibolite event is interpreted as part of the retrograde path of this metamorphic cycle.

B. Spanish Peaks Area, Northern Madison Range

The Spanish Peaks area has many of the same components recognized in the Gallatin Range. Migmatitic gneiss-granulite associations are present in both the Gallatin and Madison River Canyons. The lithologic sequence, metamorphic grade, and structural style observed in these areas are identical to those reported above. However, in addition, a mesozonal batholithic complex is present in the central part of the range (Salt and Mogk, 1985). The batholithic terrain is separated from the high-grade metasupracrustal terrains by NE-trending ductile shear zones. The intrusive phases follow a differentiation trend from gabbro- quartz diorite-monzodiorite-granodiorite-granite; only the late-stage granites are unfoliated. Magmatic epidote has been observed suggesting intrusion of these plutonic rocks under 8 Kbars P_{H2O}. The host rock is dominantly tonalitic gneisses with subordinate pelitic layers and mafic granulites. The pelitic gneisses are kyanite bearing; garnet-biotite and clinopyroxene-garnet geothermometry yields temperatures of 650-700`C and garnet-plagioclase-quartz-kyanite geobarometry indicates pressures in the range of 7-8 Kbar.

West of the batholithic terrane the paragneisses are characteristically K-rich. In the pelitic rocks sillimanite replaces kyanite as the stable aluminosilicate polymorph, and amphibolite assemblages replace the mafic granulites. Calculated temperatures are somewhat higher in this terrane, in the range of 680-750`C and

pressures are lower, in the range of 6-7 Kbars. There is a conspicuous absence of plutonic phases in this terrane, as well. The apparent break in metamorphic grade, and lithologic sequences suggests large scale displacements along the ductile shear zones; dominant down-dip lineations suggest that juxtaposition occurred along thrust faults.

C. Tobacco Root and Ruby Ranges

Extensive platform-type metasedimentary rocks, including, marble, pelitic schists, banded iron formation, and orthoquartzites, are exposed in these ranges. Quartzofeldspathic gneisses are still the most abundant rocks, with both plagioclase- and K-spar rich varieties, and mafic granulites and metaultramafites are also present (e.g. Cordua, 1973; Vitaliano et al., 1979; Garihan, 1979; Desmairais, 1980). Isoclinal folding is present on all scales, and detachment along attenuated limbs has resulted in nappe emplacement. This sequence has also attained upper amphibolite to granulite facies grade metamorphism. Diagnostic assemblages include:

olivine-diopside-scapolite-phlogopite-calcite-dolomite (marble)

garnet-biotite-kyanite-sillimanite-plagioclase (pelitic schist)

garnet-orthopyroxene-quartz-magnetite-retrograde grunerite (BIF)

olivine-orthopyroxene-spinel (ultramafites)

garnet-clinopyroxene-plagioclase-hornblende (metabasites)

Garnet biotite temperatures are in the range of 700-800`C (Mogk, unpubl data) as are garnet - clinopyroxene temperatures (Dahl, 1979, 1980). Pressure estimates based on the garnet-aluminosilicate-quartz-plagioclase barometer are on the order of 7 Kbars.

D. Blacktail Range

West of the above platform-type assemblages the dominant rock type is again quartzofeldspathic gneiss with a wide range of plagioclase/K-spar ratios and color index. These gneisses characteristically have attained a granoblastic texture and the following mineral assemblages have been recognized in discrete centimeter-scale layers:

plag-k-spar - qtz

biotite-garnet-k-spar-quartz

biotite-cordierite-sillimanite-plagioclase-qtz

hbld-cpx-plagioclase-qtz-garnet+/-orthopyroxene

These gneisses are interpreted as a supracrustal sequence originally comprised of arkoses, graywackes, mafic sills or flows, and possibly felsic volcaniclastic sediments (Clark and Mogk, 1985 and 1986).

Evolution of the western Wyoming Province

To the west of the Beartooth Mountains, during the interval 2.75-2.70, crustal evolution was dominantly through tectonic thickening. A working model for the evolution of this terrane includes early formation of a rift-bounded ensialic basin, with possible formation of a small amount of oceanic crust, followed by collapse of this basin and ultimate deep burial through stacking of nappes. The quartzofeldspathic gneisses have been interpreted as paragneisses based on fine-scale compositional layering and the intimate interlayering of pelitic and quartzitic units. It is significant to note that these are the oldest K-rich gneisses (sediments) recognized

in this area. Presumably they were once arkoses derived from an orogenic terrain similar to those found in the Beartooth Mountains, rich in late-Archean silicic volcanic and plutonic rocks. The mafic rocks have been interpreted as continental quartz tholeiites (e.g. Hanley, 1976) and probably occurred originally as flows or sills in the supracrustal pile. The platform-sediments must have been deposited in the basin during a long period of quiescence. The structural style and high metamorphic grade now observed in these rocks requires large scale horizontal shortening and deep burial of these supracrustal rocks. Continental collision is the most reasonable process, as suggested by Newton and Perkins (1982). No direct evidence of ancient oceanic crust is preserved in the northern Wyoming Province. There is a distinct lack of large volumes of mafic rocks or eugeoclinal sediments preserved in this area (in contrast to characteristic greenstone belt assemblages). However, the batholithic rocks in the Spanish Peaks area may be a remnant of a magmatic arc generated in response to consumption of a small oceanic basin. The absence of platform sediments in the ranges to the far west of the Wyoming Province (and dominance of quartzofeldspathic gneisses) suggests that there was another sialic clastic source to the west which we do not now recognize. This phantom sialic source area could simply represent the western margin of the basin, another colliding continental mass (in a Tethyan-type setting), or a colliding island arc (e.g. Cheyenne Belt, Wyoming; Karlstrom and Houston, 1985). Figure 9 presents a schematic east-west cross section of the northern Wyoming Province, highlighting the salient properties of each of the major ranges.

SUMMARY

Within the Archean basement of southwestern Montana crustal evolution has occurred by means of both tectonic and magmatic processes. Discrete metamorphic/deformational cycles have been followed by long periods of quiescence and deposition of platform-type sediments. The best documented orogenic events recorded in the Archean basement of southwestern Montana include:

1) Granulite grade metamorphism of platform-type sediments at a time of 3.4 Ga in the Quad Creek and Hellroaring Plateau areas of the Beartooth Mountains; deep burial of these sediments is interpreted as the result of tectonic thickening.

2) Generation of 2.8 Ga old andesites and voluminous 2.75 Ga granitoids in the eastern and central Beartooth Mountains, and contemporaneous tectonic thickening by means of thrust and transcurrent faulting in the North Snowy Block.

3) Deposition of thick supracrustal sequences in the western Wyoming Province, followed by large-scale crustal shortening and granulite-grade metamorphism of platform-type sediments in the latest Archean (ca. 2.70-2.75 Ga); this style of orogeny is interpreted to be the result of continental collision.

Based on these observation, we propose that in the latest Archean that continental growth occurred through processes analogous with those of contemporary-style plate tectonics. The ancient rocks recognized in the Beartooth Mountains, incuding the 3.6 Ga old trondhjemitic gneiss in the North Snowy Block and the 3.4 Ga old metasupracrustal sequences in the Quad Creek and Hellroaring Plateau

areas, are remnants of the oldest continental material recognized in the Wyoming Province. The orogeny that occurred between 2.8 Ga and 2.75 Ga in the Beartooth Mountains produced large volumes of igneous rocks through subduction-related processes (Mueller et al., 1985) and the North Snowy Block has many aspects of a modern Cordilleran-type continental margin (Mogk et al., in review). Orogenesis continued to the west of the Beartooth Mountains in the latest Archean and continental collision is believed to be the culminating event in this cycle. The evolution of the continental crust of the Northern Wyoming Province has occurred through late Archean magmatic and tectonic accretion to an ancient sialic continental nucleus.

The metamorphic petrology and structural relations observed in the northern Wyoming Province have implications for the nature of the Archean continental crust in general. The pressures and temperatures calculated in the granulite-grade mineral assemblages in supracrustal rocks requires deep burial of these rocks on the order of 20-25 Km as far back as 3.4 Ga in the Earth's history. This requires that thick, continental crust must have been developed, at least locally, early in the geologic record. The widespread occurrence of platform-type sediments in these high-grade terrains requires long periods of tectonic quiescence, calling into question the concept of the Archean "permobile" tectonic regime. Finally, the temperatures and pressures of metamorphism recorded in these Archean rocks are similar to those observed in modern orogens, suggesting that the mechanism for dissipation of the Earth's internal heat has been fundamentally the same throughout the history of the Earth.

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Table 1

Typical granulite and amphibolite (retrogressed) mineral assemblag
of the supracrustal lithologies

Lithology	Granulite assemblage	Amphibolite assemblage
Quartzite	Qz+biot+opx+plag(1) Qz+biot+cord+sill	Qz+biot+hb+plag
Pelitic schist	Qz+biot+plag+ksp+sill Qz+biot+gar+cord+sill+plag Qz+biot+plag+sill+cord	Qz+biot+plag+mu+sill
Pyribolite	Qz+biot+plag+hb+gar+opx+cpx Qz+biot+plag+hb+opx Qz+biot+plag+cord+opx	
Amphibolite		Qz+biot+hb+plag Hb+plag Qz+biot+plag+cord+ant
Iron formation	Qz+mt+gar+opx+cpx+hb Qz+mt+gar+opx	Qz+mt+grun
Ultramafite	Hb+opx+gr sp Ol+opx+hb+gr sp	Anth+biot+hb

(1) Abbreviations used: anth = anthophyllite/ biot = biotite/ cord
cordierite/ cpx = clinopyroxene/ gar = garnet/ gr sp = gre
spinel/ grun = grunerite/ hb = hornblende/ ksp = K feldspar/
= magnetite/ mu = muscovite/ ol = olivine /opx = orthopyroxen
plag = plagioclase/ Qz = quartz/ sill = sillimanite

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Table 2

Mineral assemblages of the lithologic units of the Long Lake area

Unit	Mineral assemblage
Long Lake granite	Qz+biot+plag+mt+ksp
Long Lake granodiorite	Qz+biot+plag+mt+/-ksp
Andesitic amphibolite	Hb+plag+qz+biot+mt+epid+sph+/-ksp
Pegmatite	Qz+ksp+/-plag+/-mu

Abbreviations used: biot = biotite/ epid = epidote/ hb
hornblende / ksp = K feldspar / mt = magnetite/ mu = muscovit
plag = plagioclase/ qz = quartz / sph = sphene

Table 3 Characteristics of the Lithologic Units of the North Snowy Block

Unit	Metamorphic Grade	Structural Style	Isotopic Ages
Heterogeneous Gneiss	Upper amphibolite 650-700°C(gar-bio)	Transposition foliation, intrafolial isoclinal folds	3.4 Ga Rb-Sr whole rock on injected migmatites
Pine Creek Nappe Complex	Mid- Upper-Amphibolite 600-650°C (gar-bio)	Isoclinal folding on all scales,	3.2 Ga Sm-Nd chondritic model age on amphibolite
Trondhjemite-Amphibolite Complex	Epidote-oligoclase zone 500°C, coexisting albite-oligoclase	Ductile shear zone, blastomylonitic, passive flow folds	3.55 and 3.26 Ga Sm-Nd chondritic model age ≈3.4 Ga Rb-Sr whole rock
Davis Creek Schist	Greenschsit Facies chlor-musc-albite-qtz	Phyllitic, local isoclinal fold late-stage kinks	
Mount Cowen Augen Gneiss	Greenschist Facies	Granitic augen gneiss	2.74 Ga Rb-Sr whole-rock isochron
Paragneiss	Upper amphibolite 700°C (gar-bio)	Anastomosing shear zones, high degree of internal tectonic mixing	≈2.8 Ga on quartzo-feldspathic gneiss in Yankee Jim Canyon

Figure Captions

Figure 1: Sketch map of the northern Wyoming Province showing major exposures of Archean rocks. The North Snowy Block mobile belt delineates a major discontinuity in the nature of the contnental crust in this area, with dominantly rocks of igneous origin to the east and rocks of supracrustal origin to the west.

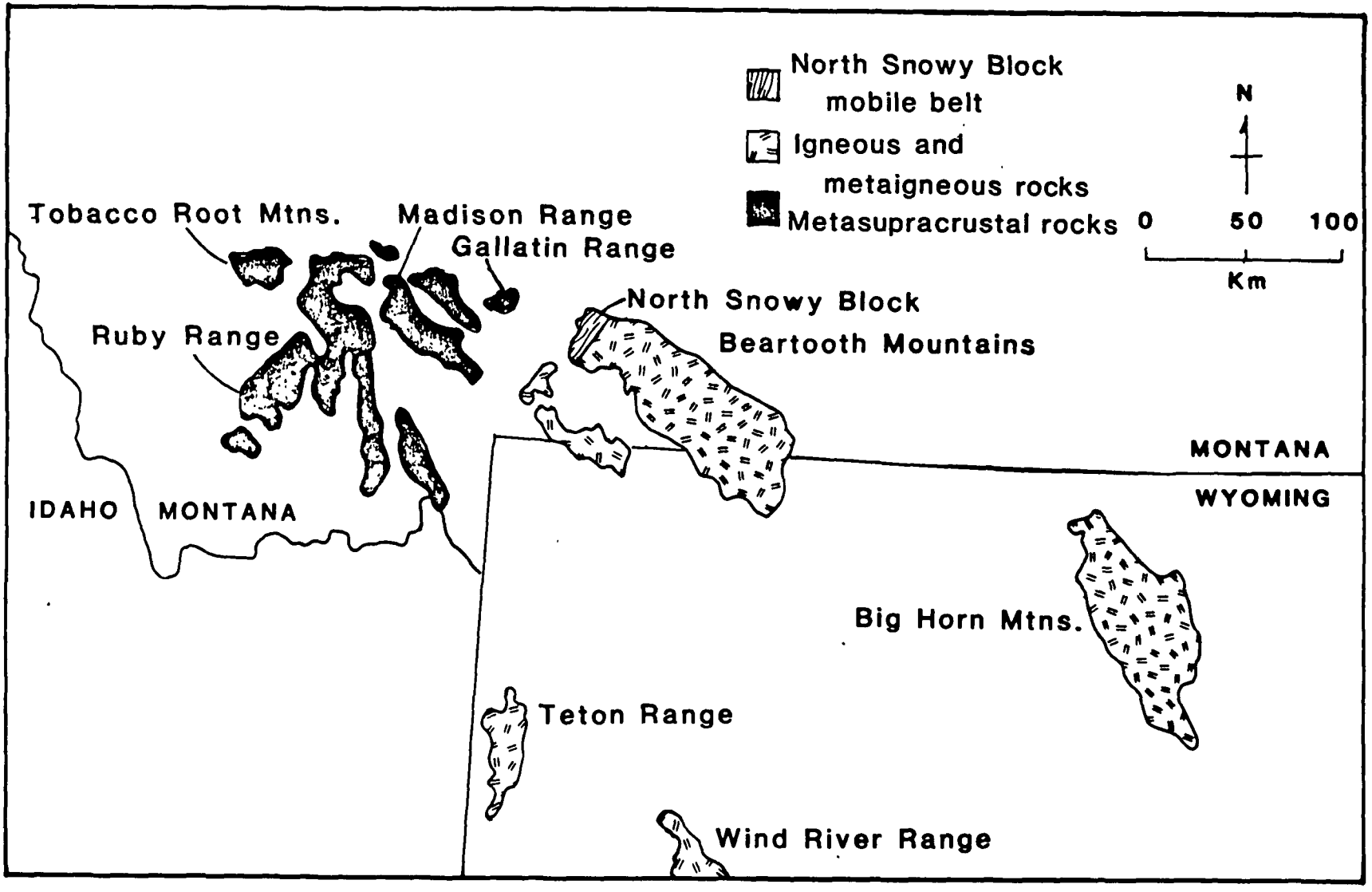
Figure 2: Sketch map of the Archean rocks of the Beartooth Mountains, showing the location of the areas discussed in the text: QC--Quad Creek, HP--Hellroaring Plateau, LL--Long Lake, BR--Broadwater River, LP--Lake Plateau, SH--Stillwater hornfels aureole, NSB--North Snowy Block, YJ--Yankee Jim Canyon, J--Jardine, SSB--South Snowy Block.

Figure 3: P-T diagram showing stability fields for M1 and M2 metamorphism based on several geothermobarometers. Reference reaction curves are shown for aluminosilicates (Holdaway, 1971), muscovite breakdown (Chatterjee and Johannes, 1975), granite melting (Thompson and Algor, 1971), Mg-chlorite and Mg-cordierite breakdown (Evans, 1977).

Figure 4: Photomicrograph of a mafic granulite with the assemblage garnet-orthopyroxene-clinopyroxene-hornblende-plagioclase-quartz-biotite-magnetite.

Figure 5: Photomicrograph of hornblende partially replacing orthopyroxene during the M2 metamorphic event.

Figure 6: Sketch map of part of the North Snowy Block, showing distribution of major units: 1) heterogeneous gneiss, 2)Pine Creek nappe complex, 3)trondhjemitic gneiss-amphibolite complex, 4) Davis Creek Schist, 5) Mount Cowen Augen Gneiss, 6) paragneiss.


North Snowy Block mobile belt
Igneous and metaigneous rocks
Metasupracrustal rocks
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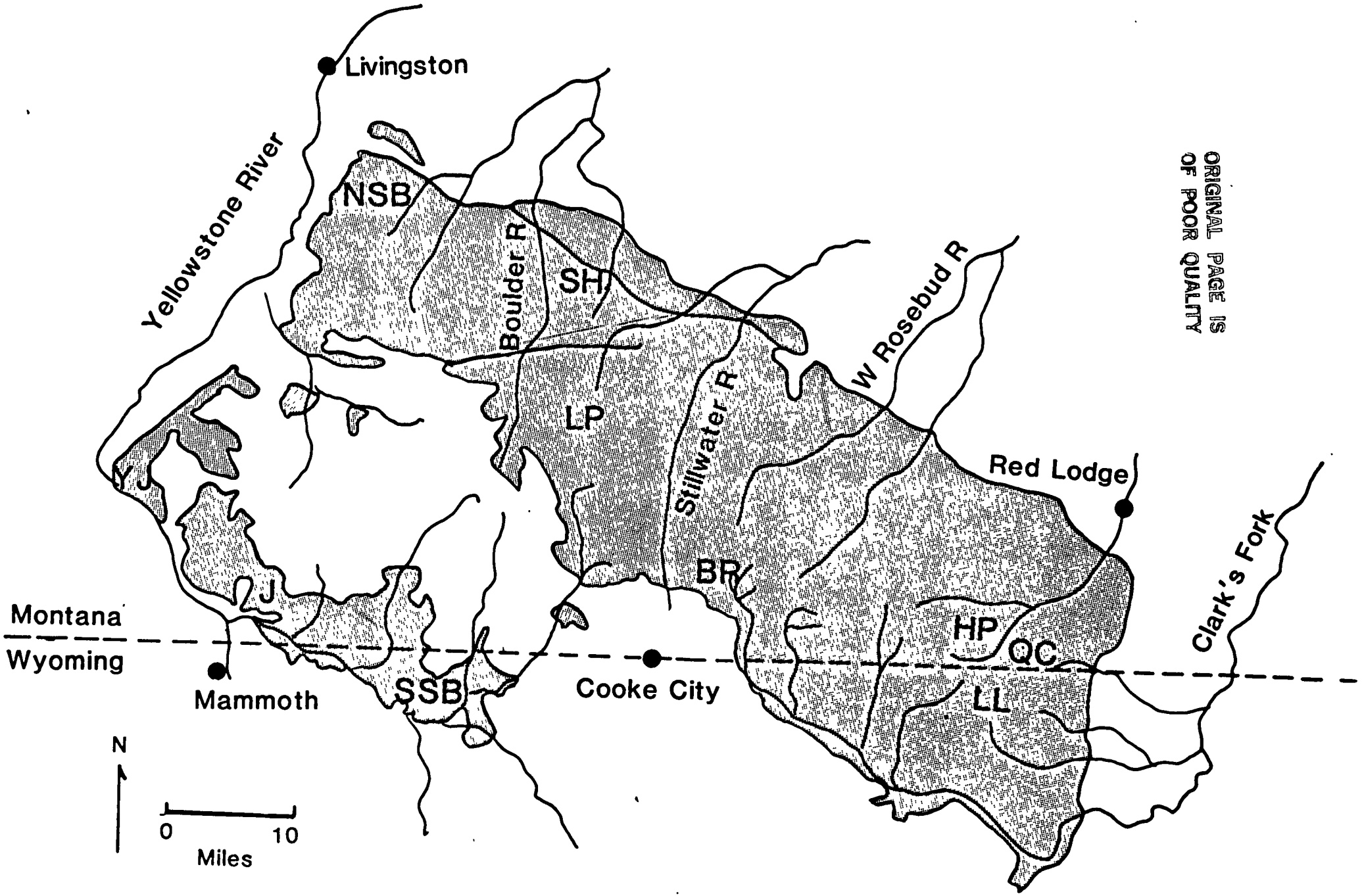
Madison Range
Gallatin Range
Ruby Range
North Snowy Block
Beartooth Mountains
IDAHO
MONTANA
MONTANA
WYOMING
Big Horn Mtns.
Teton Range
Wind River Range



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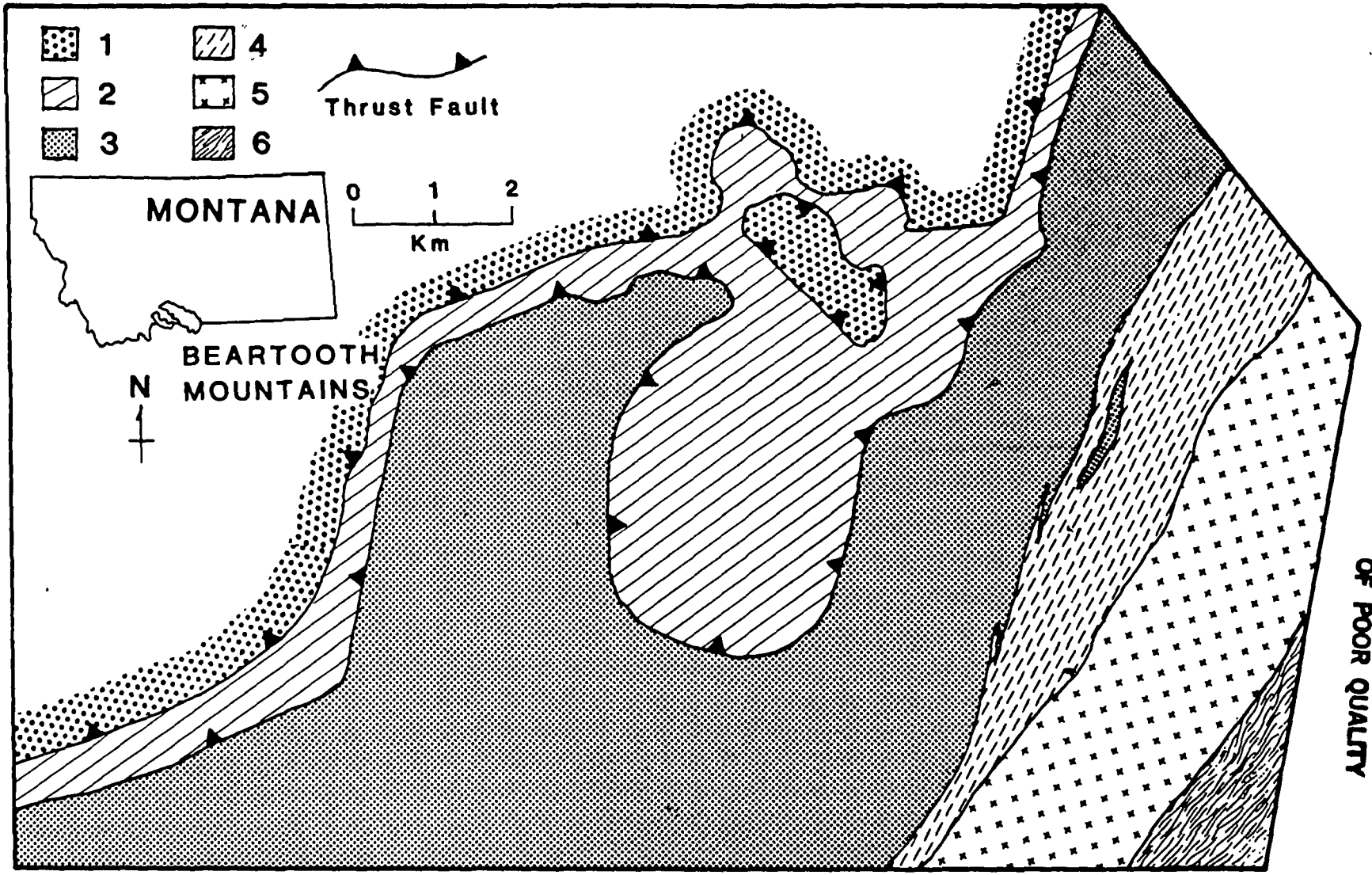

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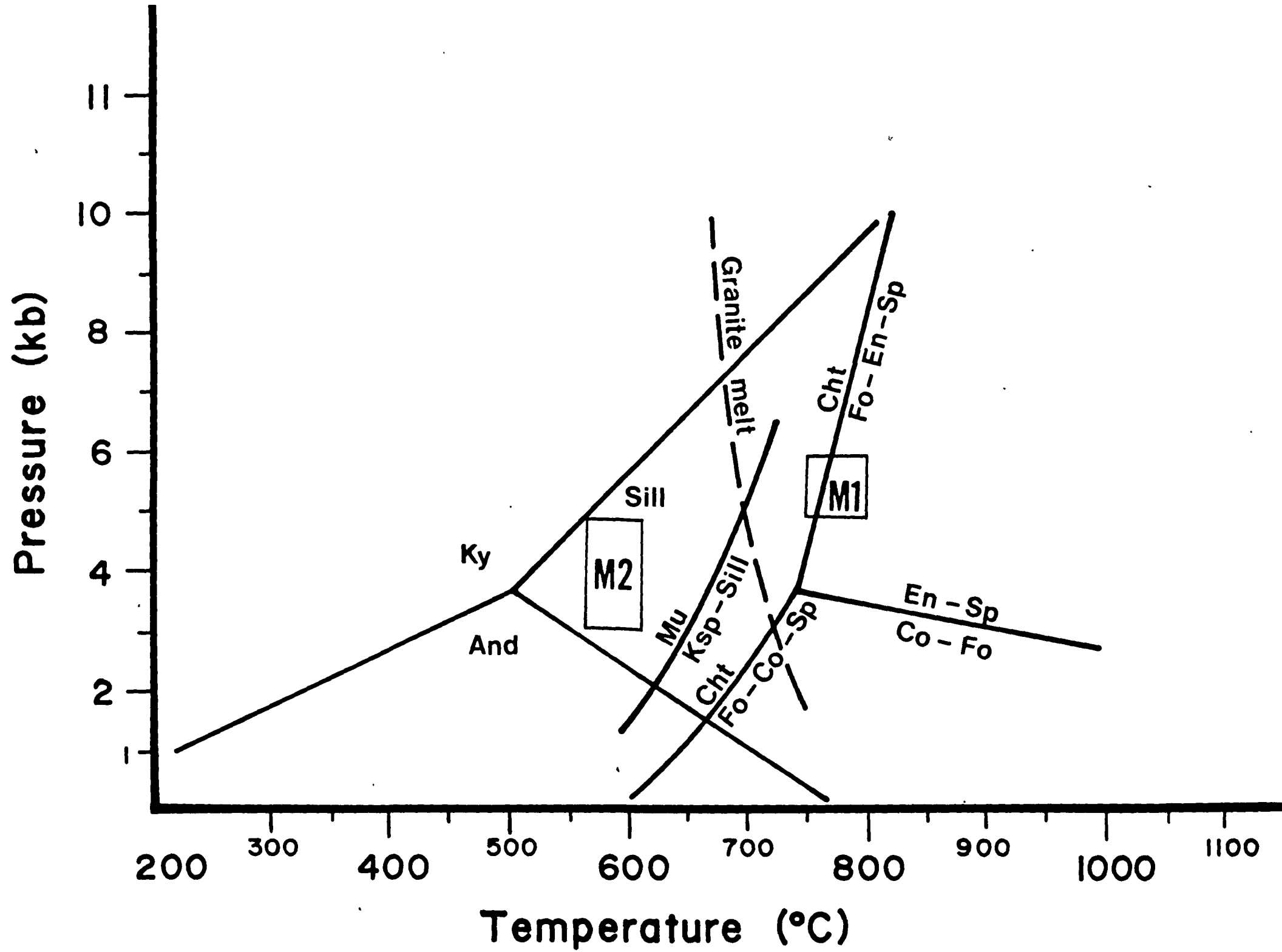
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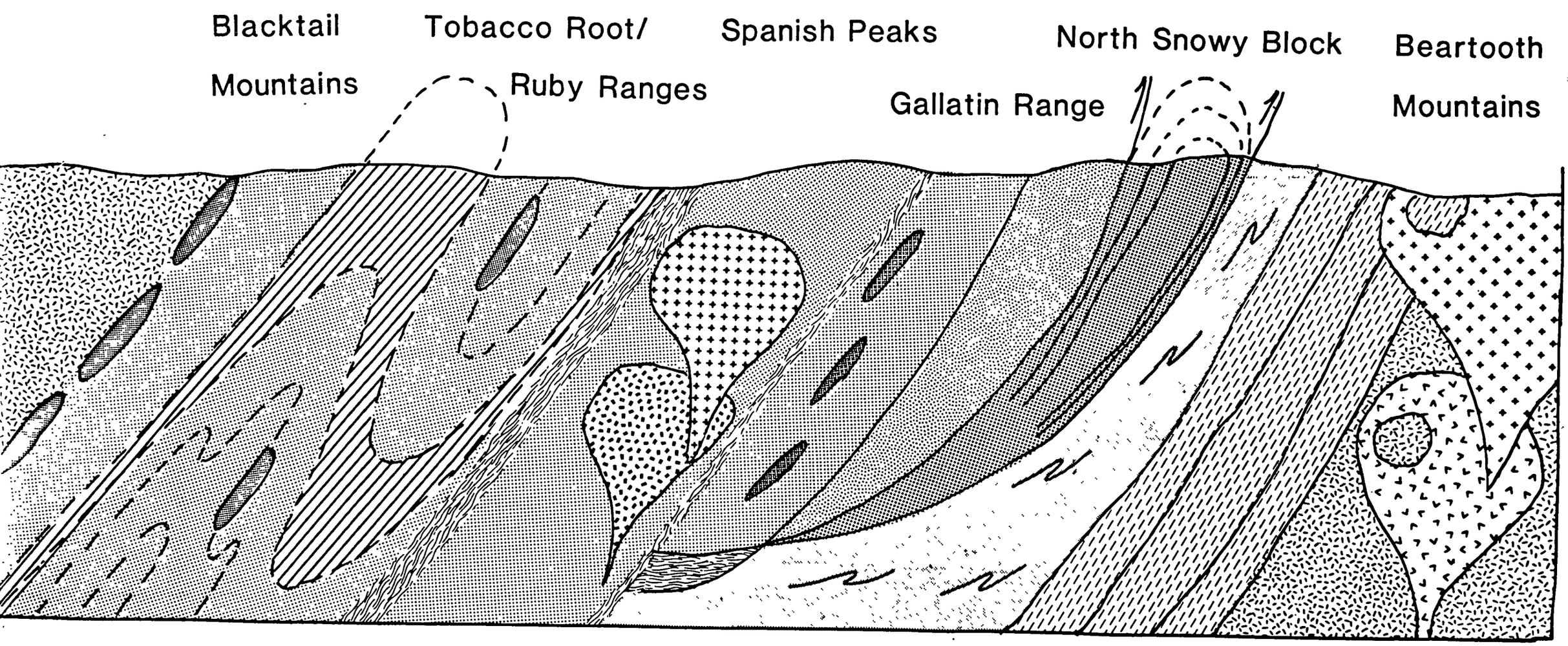

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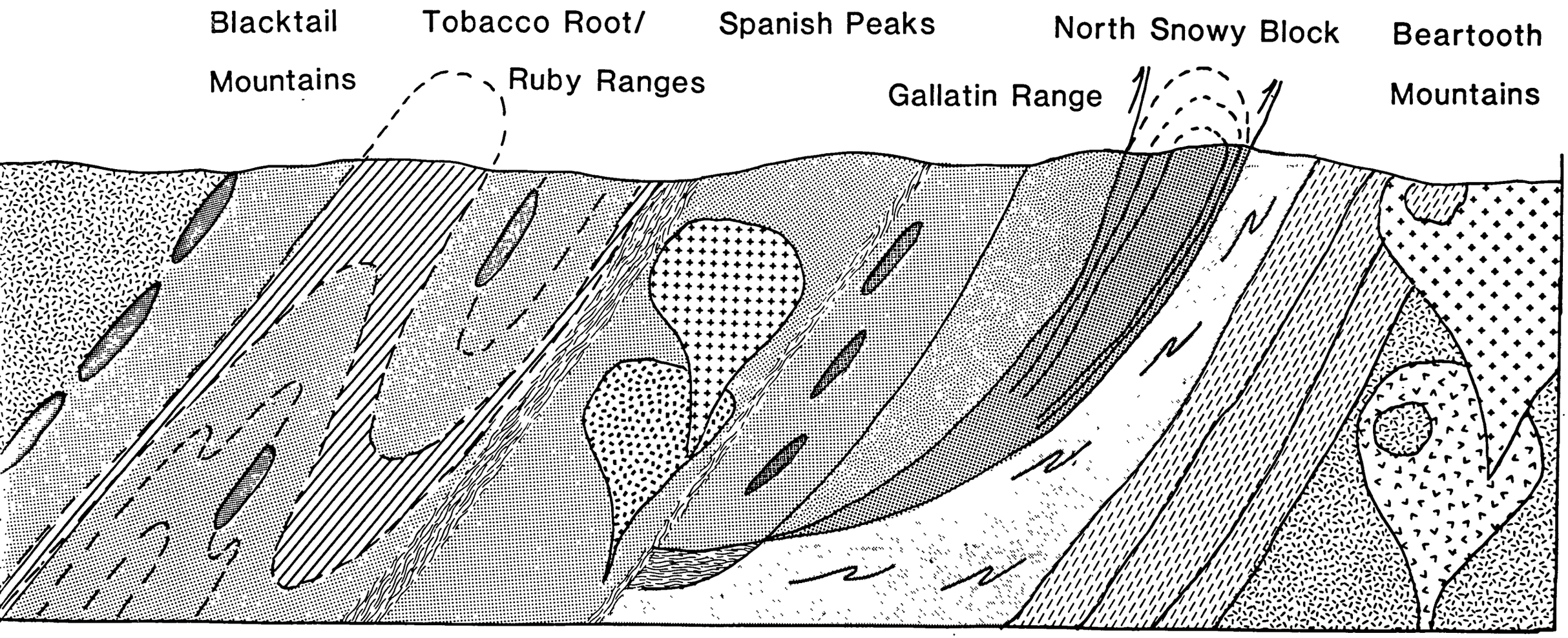
Blacktail
Mountains
Tobacco Root/
Ruby Ranges
Spanish Peaks
Gallatin Range
North Snowy Block
Beartooth
Mountains

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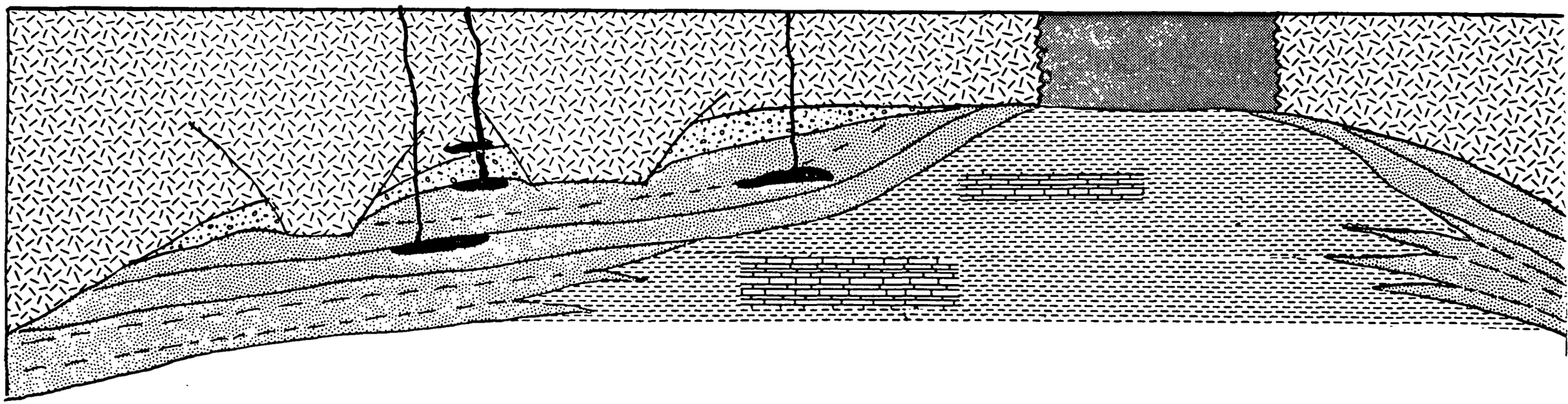
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