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PRECAMBRIAN BASEMENT GEOLOGIC MAP OF MONTANA—AN INTERPRETATION OF AEROMAGNETIC ANOMALIES

By
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SCALE 1:1 000 000

Lambert conformal conic projection
1927 North American datum

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DESCRIPTION OF MAP UNITS

COVER ROCKS

Volcanic rocks (Cenozoic)

MESOPROTEROZOIC SEDIMENTARY ROCKS

Belt Supergroup (Mesoproterozoic)—Area containing major bodies patterned

Yellowjacket Formation and associated metasedimentary rocks (Mesoproterozoic)—Area containing major bodies patterned

TRANS-HUDSON OROGEN

Volcanic-plutonic arc complexes (Paleoproterozoic)—Includes Archean gneisses

TRANS-MONTANA OROGEN (ACCRETED TERRANES)

Wallace terrane (Paleoproterozoic)—Covered

Biotite-quartz-feldspar gneiss and amphibolite of Wallace terrane (Paleoproterozoic)—Exposed in Bitterroot Range

Granite, diorite, and gneiss (Paleoproterozoic)—Crops out in Little Belt Mountains. U-Pb zircon age of 1,860–1,880 Ma (Mueller and others, 2002)

Medicine Hat block (Archean)—Covered

CONTINENTAL-MARGIN ASSEMBLAGE (FOLD-AND-THRUST BELT)

Imbricately intercalated rocks (Paleoproterozoic and Archean)—Covered

Meta-sandstone, shale, iron-formation, and graphitic shale intruded by gabbro dikes (Paleoproterozoic)—Crops out in Gravelly Range. Interpreted as foreland basin deposit

Marble, quartzite, and schist (Paleoproterozoic)—Inferred to have formed on a rifted, passive margin (about 2.0 Ga). Formerly regarded as Archean

Massive to weakly foliated granite to granodiorite (Late Archean)

Foliated and gneissic granitoid rocks (Late Archean)—About 2.74–2.79 Ga (Wooden and others, 1988)
Mafic to ultramafic rocks in Spanish Peaks area and Tobacco Root Mountains (Archean)
WYOMING PROVINCE (CRATON)
Stillwater Complex (Late Archean)—2.7 Ga (Wooden and others, 1988). Exposed
Foliated and gneissic granitoid rocks (Late Archean)—About 2.74–2.79 Ga (Wooden and others, 1988). Exposed
Granitic rocks, undivided (Archean)—Magmatic domain. Covered
Gneissic rocks, undivided (Archean)—Gneiss domain. Covered
Supracrustal (metasedimentary and metavolcanic) rocks (Middle to Early Archean)
Tectonically shortened rocks on margins of Wyoming province (Archean)

Contact—Dashed where approximately located
Strike-slip fault—Dashed where inferred. Opposed arrows show direction of displacement where known
Thrust fault (Laramide)
Thrust fault (Sevier)
Thrust fault (Paleoproterozoic)—Dashed where approximately located
Strike and dip direction of foliation
Trend of foliation
Drill hole to basement rocks

INTRODUCTION

Newly updated aeromagnetic data of Montana, in conjunction with the known geologic framework of basement rocks in the State, have been combined to produce a new interpretive Precambrian basement map of Montana. Crystalline rocks of Precambrian age underlie the entire State, but are exposed only in the cores of Laramide-age mountain ranges in southwestern Montana (fig. 1). A thick clastic succession, the Belt Supergroup (1.47–1.40 Ga; Evans and others, 2000), blankets the crystalline rocks in western Montana (Winston, 1986; Winston and Link, 1993) and Phanerozoic strata cover the basement in eastern Montana. The Belt Supergroup and equivalent rocks of Proterozoic age are not included as part of the Precambrian basement on the geologic map.

This report confirms and extends the hypothesis of O'Neill (1999) that the Great Falls tectonic zone, delineated mainly from tectonic features and igneous activity in overlying Phanerozoic rocks (O'Neill and Lopez, 1985), reflects an early Proterozoic collisional orogen. The updated aeromagnetic map of North America (North American Magnetic Anomaly Group, 2002) provides a means to refine structures in the basement rocks that were expressed more diffusely on the earlier magnetic map prepared for the Decade of North America Geology (Committee for the magnetic anomaly map, 1987) and to decipher the known geologic data into a more regimented framework, analogous to better exposed and known Paleoproterozoic orogens in the Canadian Shield (Hoffman, 1987, 1988).

Principal features deduced from the aeromagnetic anomaly map (fig. 2, North American Magnetic Anomaly Group, 2002) are: (1) the prominent northeast-trending, 300-km-wide zone of magnetic anomalies, extending from southwestern Montana to the Canadian border, which reflect structures developed during suturing of accreted northern terranes to the Archean Wyoming province during the Paleoproterozoic; (2) subtle northwest- and west-trending negative anomalies, mainly in western Montana, which represent ductile strike-slip faults of early Mesoproterozoic age; and (3) north-northwest-trending magnetic lows in extreme eastern Montana, which reflect the Paleoproterozoic Trans-Hudson orogen. The structures, developed in Paleoproterozoic and Mesoproterozoic time, have provided zones of crustal weakness that have been reactivated repeatedly during Phanerozoic tectonic and igneous activity.

In this report, precise isotopic ages are reported in millions of years (Ma) and generalized ages are given in billions of years (Ga). The subdivision of Precambrian rocks is the time classification recommended by the International Union of Geological Sciences (Plumb, 1991).

TERMINOLOGY

We introduce the term “Trans-Montana orogeny” in this report for the orogenesis accompanying assembly of the Precambrian terranes in the northwestern United States during Paleoproterozoic time. The orogeny is defined as the deformation associated with the collision of an outboard Paleoproterozoic ocean-arc terrane and conjoined Archean continental blocks with the northwest margin of the Archean Wyoming craton during the approximate interval 1.9–1.8 Ga. The collisional tectonics involved the reworking of the craton margin as well as deformation of the accreted terranes. The orogeny is similar in magnitude and scope, and of the same approximate age, as the Penokean orogeny along the southern margin of the Superior province (Sims, 1996). Both orogenies had important roles in the amalgamation of the North American (Laurentian) continent.
The term “Great Falls tectonic zone” is retained informally as a general descriptor of the highly disturbed tectonic zone between the respective plates of the Trans-Montana orogen. Because the tectonic zone was delineated from structures in outcropping Phanerozoic rocks, which resulted mainly from reactivation of basement structures, and does not encompass the internides (accreted terranes) of the orogeny, we do not use it in a formal sense. The term includes several newly defined structures shown on the geologic map, namely, from north to south, the Great Falls shear zone, the Dillon suture (shear) zone, the Madison mylonite zone, and intervening thrust faults between it and the Dillon suture zone. These structures were formed during the collisional phase of the Trans-Montana orogeny.

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MAP COMPILATION

The basement geologic map is a product of interpretation of the aeromagnetic anomaly map of Montana (McCafferty and others, 1998), using mostly published geologic and isotopic data. The aeromagnetic map provides a major tool for interpreting basement geology in the vast region where the basement rocks are covered by thick sequences of younger sedimentary rocks, which are essentially nonmagnetic. Magnetic anomalies are caused mainly by different intensities of magnetization of the crystalline basement rocks and the structures that penetrate and transect the basement. In northwestern Montana, the thick (15–20 km) sedimentary succession of the Belt Supergroup largely obscures the magnetic fabric of the underlying crystalline rocks. Accordingly, the basement geologic fabric in this part of the State is mainly based on interpretation of the isostatic gravity map of the State (McCafferty and others, 1998). The magnetic anomalies mainly result from induced magnetism, which varies with the amount of magnetite and other iron oxides in the rocks.

GENERAL GEOLOGY OF CRYSTALLINE BASEMENT

The basement geologic framework of Montana is complex, recording a history of at least 3 billion years of time. Archean granite-granodiorite intrusions and granitic gneiss containing mixed orthogneiss, paragneiss, and schist of amphibolite and (or) granulite grade make up most of the Archean Wyoming craton (or province), which underlies the southern and eastern parts of the State (Wooden and others, 1988). The craton is bounded on the northwest by rocks of the Paleoproterozoic Trans-Montana orogen. The Trans-Montana orogen comprises the zone of tectonism and crustal suturing of the Paleoproterozoic Wallace ocean-arc terrane and attached Archean Medicine Hat block to the Wyoming craton. The buried Dillon shear zone is interpreted to be the primary suture; it formed at 1.9–1.8 Ga (O'Neill, 1999; Mueller and others, 2002). The Trans-Hudson orogen, which is not exposed but is inferred to exist beneath cover in the State, adjoins the Wyoming craton on the east (Sims and others, 1990). Geophysical anomaly data (McCafferty and others, 1998) are interpreted to indicate that the Trans-Hudson orogen truncates the Trans-Montana orogen. The Trans-Hudson orogen is not discussed herein.

The assembled Precambrian crystalline basement rocks were disturbed by (1) strike-slip wrench faults, a major component of the Mesoproterozoic northwest-trending Trans-Rocky Mountains fault system (Sims, 2002; Sims, unpub. data, 2003); (2) the Late Cretaceous–early Tertiary Laramide and Sevier orogenies; and (3) block faulting during Neogene time that formed Basin and Range structures (Reynolds, 1979). The younger tectonic episodes modified but did not obscure the earlier Precambrian framework; in many places older structures were reactivated during Cretaceous-Tertiary tectonic and igneous activity (Schmidt and Garihan, 1983; O'Neill and others, 1986; McBride and others, 1992).

Transtension along the Trans-Rocky Mountains fault system in Mesoproterozoic time produced structural basins, which were Mesoproterozoic depocenters for sediments of the Belt Supergroup, as previously recognized by Winston (1986) and O'Neill (1995). Winston (1986) and other investigators, however, did not recognize that these structures were the northern part of a vast systematic transcurrent fault system that transgressed the Western United States. Determination of the broad regional pattern of the fault system and its systematics (Sims, unpub. data, 2003) was made possible by recently updated aeromagnetic anomaly (North American Magnetic Anomaly Group, 2002) and other geophysical maps prepared by the U.S. Geological Survey. In addition to the aeromagnetic map of Montana (McCafferty and others, 1998), noteworthy examples are the updated aeromagnetic maps of Wyoming (Kucks and Hill, 2000) and Colorado (Oshetski and Kucks, 2000).

The Late Cretaceous–early Tertiary Laramide orogeny produced the basement-cored uplifts in southwestern Montana, which are a part of the northern Rocky Mountains; the essentially contemporaneous Sevier orogeny produced the mostly (but not entirely) thin-skinned, north-south trending, east-vergent Sevier fold and thrust belt, as discussed by Kulik and Schmidt (1988). In general, the Laramide deformation in southwestern Montana preceded late-stage Sevier thrusting; basement-cored uplifts that formed during the Laramide orogeny acted as buttresses, producing the southwestern Montana reentrant (fig. 1; Schmidt and others, 1988). Recognition and delineation of Sevier versus Laramide structures are essential for determining the origin and evolution of post-Precambrian thermal and tectonic events in the region, especially the emplacement of Late Cretaceous–early Tertiary granitic plutons and associated epigenetic metallic mineral deposits. The Late Cretaceous–Eocene intrusions are spatially related to Sevier structures (Schmidt and others, 1990; Kalakey and others, 2001), and presumably owe their origin to Sevier orogenesis.

Basin and Range structures were formed in extreme southwestern Montana by extensional deformation during the Neogene (Reynolds, 1979). This faulting is still active locally, as indicated by the Hebgen Lake earthquake in Montana and the 1983 Borah Peak earthquake in adjacent Idaho (Stickney and Bartholomew, 1987). As was the case for Sevier and Laramide deformation, Neogene deformation was influenced by structures formed during development of the Mesoproterozoic Trans-Rocky Mountains fault system, which provided ancestral zones of weakness (Schmidt and Garihan, 1983; O'Neill and others, 1986).

RELATION OF MAGNETIC PATTERNS TO BASEMENT GEOLOGY

Magnetic patterns visible on the aeromagnetic anomaly map of Montana (fig. 2; McCafferty and others, 1998) that greatly enhance interpretation of the basement geology include: (1) the contrasting magnetism of major Archean rock units of the Wyoming province in southeastern Montana, which permits gross delineation of predominantly granitoid rocks from predominantly metasedimentary-metavolcanic units; (2) the prominent northeast-trending belt of linear anomalies across the central part of the State, caused by major ductile shear zones within the Paleoproterozoic Trans-Montana orogen; (3) the conspicuous northwest- to west-trending negative anomalies expressed mainly in the western part of the State, caused by ductile-brittle faults of the Mesoproterozoic strike-slip fault system; and (4) the north-northwest-trending zone of negative anomalies in extreme northeastern Montana, caused by predominantly ocean-arc rocks within the Paleoproterozoic Trans-Hudson orogen.

The grossly ovoid magnetic patterns over Archean rocks in the inner part of the Wyoming province, together with the curvilinear magnetic patterns in Wyoming, clearly indicate that the primary regional structural fabric of the Wyoming province has a crudely oval configuration (see Sims and others, 2001, for discussion).

The pronounced northeast-trending magnetic fabric (fig. 2) across central Montana is attributed to ductile shear zones that were developed during the Trans-Montana orogeny. Major structures include the Dillon suture zone, several subparallel shear zones in the foreland, and similarly oriented shear zones in the outboard (hinterland) sector. The foreland shear zones shown on the basement have been mapped in the mountain ranges of southwestern Montana, and are extended laterally into covered areas by means of derived linear magnetic anomalies; they include, from north to south, the Mirror Lake shear zone (Kellogg and Williams, 2000) and the Madison mylonite zone (Erslev, 1983). The Dillon suture juxtaposes magmatic arc rocks assigned to the Paleoproterozoic Wallace terrane, and locally the Medicine Hat block, with tectonically shortened rocks on the margin of the Wyoming craton (units XAr and Ats). The linear block between the suture zone and the Mirror Lake shear zone consists of imbricated thrust slices of crystalline Archean rocks and presumed Paleoproterozoic passive continental-margin supracrustal rocks (unit Xm, Ruby Range and Tobacco Root Mountains). The innermost block in the foreland fold-and-thrust belt, between the Mirror Lake shear zone and Madison mylonite zone, contains faulted and folded late Paleoproterozoic foreland basin deposits (unit Xfb) structurally beneath the overthrust Paleoproterozoic supracrustal rocks in the Gravelly Range (O'Neill, 1999; O'Neill and Christiansen, 2004). In the accreted terranes of the hinterland, a major linear northeast-trending negative magnetic anomaly, herein named the Joplin structure, is presumed to be a ductile shear zone. This structure coincides with a conspicuous, narrow gravity trough trending N. 60° E. within the Archean Medicine Hat block. The structure is oriented similarly to the Vulcan low, to the north, in adjacent Alberta, Canada (Ross, 2002), and possibly has a similar origin.

Faults of the northwest-trending Mesoproterozoic strike-slip fault system produce generally narrow negative magnetic anomalies and are abundant across western Montana. Major faults associated with these anomalies are plotted on the map; magnetic patterns suggest the presence of many more northwest-trending structures of this system, many of which have been documented on the ground (Schmidt and Garihan, 1983). The northwest-trending faults in this region are the northern component of the Trans-Rocky Mountains fault system (Sims, unpub. data, 2003); they commonly show sinistral shear, but many have had later dextral displacements, such as, for example, the Lewis and Clark tectonic zone (Billingsley and Locke, 1939) of the Coeur d'Alene mining district in adjacent Idaho (Wallace and others, 1960). The two west-trending faults mapped in west-central Montana—the Garnet line (Winston, 1986) and the Perry line (Thom, 1957)—mark the northern and southern boundaries of the Belt basin in the Helena embayment (Winston and Link, 1993). The unique orientation of these two faults, and the fact that they were active in Mesoproterozoic time, suggest that they are tectonically tied to the Trans-Rocky Mountains system. These two faults outline a tectonic pull-apart basin or graben accommodating the subsidence that formed the east-trending Helena embayment of the Belt basin. This "major crustal rift" in west-central Montana was first proposed by Thom (1957) and the southern fault of this rift was described by Harris (1957) as a "line of basement faulting," later called the Perry line by Thom (1957). Winston (1986) proposed a westward continuation of the Garnet line, but this is not evident on the magnetic anomaly map (see McCafferty and others, 1998). The relationship of other fault-bounded blocks in the Belt basin, as depicted by Winston (1986, sheet 1), to the basement faults shown on the map deserves further study.

The magnetic patterns over the buried Archean Medicine Hat block and the northern part of the Paleoproterozoic Wallace terrane in the hinterland of the Trans-Montana orogen, in northwestern Montana, do not clearly indicate internal gross tectonic-stratigraphic trends. Strongly magnetic anomalies over the Medicine Hat block (and drill data) suggest that the terrane consists largely of Archean plutonic rocks, as discussed by Ross (2002). However, the abundant northwest-trending faults that transect the terrane (Lemieux and others, 2000) and a thick cover of Belt rocks mask primary structural elements in the crystalline rocks. The strong positive magnetic signature over the Medicine Hat block contrasts sharply with the generally moderate overall magnetic signature of the Wyoming province, indicating that the two crustal blocks likely represent different basement terranes. The previously unrecognized Wallace terrane in the hinterland, interpreted as a Paleoproterozoic ocean-arc body, has a weak northwest-trending neutral to negative magnetic signature, but has a distinctive northwest-oriented isostatic gravity signature (McCafferty and others, 1998). Evidence for a Paleoproterozoic age of the terrane has been provided by isotopic studies of the Bitterroot lobe of the Idaho batholith in eastern Idaho. Inherited (pre-magmatic) zircons in Late Cretaceous igneous rocks of the lobe have a minimum age of about 1.74 Ga (Mueller and others, 1995), and a large granitic gneiss xenolith with a comparable age within Cretaceous granitic plutons of the lobe (Toth and Stacey, 1992) has a comparable age. Further evidence for the existence of the Paleoproterozoic terrane is given by outcrops of probable pre-Belt biotite-quartz-plagioclase gneiss and amphibolite (unit Xwv) along the western border of Montana, southeast of the Bitterroot lobe (Berg, 1977). Foliations in these rocks strike northwestward, subparallel to magnetic and gravity fabrics. The age range of magmatic rocks within the Wallace terrane is not known, except within broad limits, but as discussed in a following section, we interpret the terrane as having hosted the approximately 1.85 Ga igneous rocks generated during subduction along the Dillon suture zone; accordingly, we presume that the terrane is in part older than 1.85 Ga.

Both the Medicine Hat and Wallace terranes are cut by a pronounced colinear, north-trending negative magnetic anomaly. This continuous anomaly coincides with the approximate location of the southern extension of the Rocky Mountain trench (Bryant and others, 1984). In Canada, the trench has been variously interpreted to represent a major zone of crustal weakness that has accommodated significant transcurrent movement in the Phanerozoic (Price, 1979; Chamberlain and Lambert, 1984).

Thrust and reverse faults active during the Laramide orogeny in the northern Rocky Mountains are deep-seated structures largely inherited from previously formed zones of basement weakness (Sims, unpub. data, 2003). The position of most of these structures clearly mimics the trace of faults of the Mesoproterozoic fault system (for example, Kulik and Schmidt, 1988; O'Neill and others, 1986). Also, some Sevier structures in extreme southwestern Montana definitely involve basement rocks (O'Neill and others, 1990);

these faults clearly follow zones of basement weakness formed during the Paleoproterozoic Trans-Montana orogeny.

Magnetic patterns over rocks deformed by the Eocene and younger extensional deformation are not adequate—at the scale of the geologic map—to accurately delineate basement fabrics. However, this faulting did not grossly modify fabrics in the Precambrian basin the within the study area.

PALEOPROTEROZOIC TRANS-MONTANA OROGEN

The Trans-Montana orogen, as defined herein, evolved along the northern margin of the Archean Wyoming province in Paleoproterozoic time. It comprises a deformed, north-facing, passive continental-margin assemblage overstepped southward by a synorogenic foredeep succession (which overlies imbricated Archean basement rocks) that is juxtaposed with a Paleoproterozoic magmatic arc terrane and a conjoined Archean micro-continent. The Paleoproterozoic magmatic arc is designated here as the Wallace terrane; the attached Archean micro-continent previously has been named the Medicine Hat block. The deformed continental margin is termed the Trans-Montana fold-and-thrust belt. The juncture between the accreted terranes and the Wyoming craton is the Dillon suture zone. Suturing is interpreted to have occurred during the interval 1.9–1.8 Ga (Mueller and others, 2002).

The Trans-Montana orogen contains many features typical of better known Paleoproterozoic convergent terranes that surround Archean cratons in the Canadian shield (Hoffman, 1987, 1988)—major orogen-parallel, craton-vergent, ductile thrust faults and related folds, asymmetric structures indicative of transport direction, imbricate juxtaposition of thrust wedges of Archean and Paleoproterozoic rocks, and stratigraphic assemblages indicative of craton-rifted margins and foredeep deposits that migrate ahead of advancing suture-related thrusting. The fold-and-thrust belt of the Trans-Montana orogen, as discussed in the following, coincides approximately with the Great Falls tectonic zone of O'Neill and Lopez (1985).

TECTONIC MODEL

A conceptual model for evolution of the Trans-Montana orogen is shown in figure 3. Stage 1 of figure 3 represents the rifted margin of the Archean Wyoming craton approaching a north-dipping subduction zone in Paleoproterozoic time. Passive margin deposits, including quartzite and dolomite (unit Xm), accumulate on the rifted continental margin. Stage 2 of figure 3 represents active subduction of the continental margin. Crustal loading by the ensuing fold-and-thrust mass has occurred, generating as a flexural response an actively migrating foredeep (including the weakly metamorphosed sedimentary succession recognized by O'Neill (1999) and O'Neill and Christiansen (2002) in the Gravelly Range; unit Xfb on the continental foreland). The Archean basement, its overlying passive-margin and foredeep deposits, and the accreted volcanic arc rocks (as exposed in the Little Belt Mountains) are involved in the fold-and-thrust deformation (stage 2 of fig. 3). This scenario can account for the imbricate thrusting involving basement and its Proterozoic supracrustal rocks in the foreland of the Trans-Montana orogen.

ACCRETED TERRANES

The two terranes accreted to the northern margin of the Wyoming craton in Montana during the Trans-Montana orogeny are interpreted as having been amalgamated prior to collision along the Dillon suture zone. Impetus for convergence is attributed to closing of the inferred Paleoproterozoic ocean between the accreted terranes and the craton (fig. 3). Correlation of the magmatic arc rocks in central Montana with the Wallace terrane in northwestern Montana is based on similar rock compositions and isotopic ages, and is deserving of further investigation. As stated previously, the rocks in northern Idaho have been dated indirectly at about 1.74 Ga, presumably a minimum age (Mueller and others, 1995); their northwest trend in the hinterland is based on geophysical data. The northeast-striking belt of Wallace terrane rocks along the Dillon shear (suture) zone is more definitive; it is based on scattered exposures of volcanic arc and plutonic rocks in the Little Belt and Pioneer Mountains; recently dated metamorphic and plutonic rocks in the Little Belt Mountains have ages of about 1.85 Ga (Mueller and others, 2002). These authors concluded from geochemical data that these rocks have a convergent arc affinity. The similarities in composition and age of the ocean-arc rocks in the two regions permits tentative correlation of the two assemblages.

The Medicine Hat block is known to be Archean in age; U-Pb zircon dating from drill hole samples indicate 3.28–2.61 Ga crystallization ages (Villeneuve and others, 1993). The Medicine Hat block has distinct northwest-trending magnetic anomalies, interpreted by Lemieux and others (2000) from seismic reflection and potential-field data to be west-dipping thrust faults formed during the continental collision of two Archean domains. Alternatively, we suggest that the imbricate thrust faults in the western part of the Medicine Hat block resulted from arc-continent east-directed collision between the Wallace terrane and the Medicine Hat block in the early Paleoproterozoic. With this interpretation, these inferred west-dipping thrust faults probably comprise a fold-and-thrust belt that predated the Trans-Montana orogeny.

FOLD-AND-THRUST BELT

Although it has been known for several decades that the northwest margin of the Archean Wyoming province was disturbed in the Paleoproterozoic, as indicated by reset K-Ar ages in Archean rocks (Giletti, 1966), the nature, cause, and significance of the disturbance has been poorly understood. As stated previously, O'Neill and Lopez (1985) named the disturbed belt the Great Falls tectonic zone, and O'Neill (1999) proposed that it marked a broad suture zone in the basement between the Archean Medicine Hat block and the Wyoming province. This interpretation as a major suture has subsequently been questioned (Boerner and others, 1998; Lemieux and others, 2000); these authors suggested that the zone is a transcurrent fault rather than a suture. However, we conclude that the reworked northwestern margin of the Wyoming province has resulted from the collision of combined Paleoproterozoic and Archean terranes with the Wyoming province.

Earlier, based on studies of the Madison mylonite zone, Erslev and Sutter (1990, p. 1681) correctly postulated that "The Madison mylonite zone is probably a foreland thrust zone on the margin of a major compressional orogen of Early Proterozoic age that reworked the Archean basement of the northwestern Wyoming province."

PALEOPROTEROZOIC STRATIGRAPHIC ASSEMBLAGES

Paleoproterozoic stratigraphic assemblages within the Trans-Montana fold-and-thrust belt include thick units of metamorphosed (amphibolite and granulite grade) dolomite and quartzite (O'Neill and Christiansen, 2004), interpreted by us as continental-margin deposits, and weakly metamorphosed pelitic rocks and iron-formation, interpreted as foreland basin deposits (O'Neill, 1999). The foreland basin rocks are cut by gabbroic sills, which are relatively unmetamorphosed.

Traditionally, the supracrustal metadolomite and quartzite exposed in the cores of uplifts in southwestern Montana have been considered Archean in age and to have been metamorphosed prior to 2.75 Ga. They are complexly intercalated with thrust slices of gneissic rocks dated as Late Archean (James and Hedge, 1980) and, lacking means to directly date the metasedimentary rocks, they have been interpreted as being approximately of the same age as the Archean gneisses. This conventional view was supported by geologic mapping in the Madison Range (Erslev, 1983); Erslev and Sutter (1990) reported that a granodiorite interpreted as cutting the supracrustal rocks has a 39Ar/40Ar age greater than 2.5 Ga. Several lines of evidence, however, favor a

Proterozoic age for the supracrustal rocks. Gibbs and others (1986) reported that the Montana dolomitic marbles have 87Sr/86Sr values typical of post-Archean rocks. More recently, Roberts and others (2002)—in a broad isotopic study of supracrustal rocks in southwestern Montana—demonstrated that these rocks were metamorphosed between 1.82 and 1.74 Ga and that no evidence exists for a 2.75 Ga thermotectonic event, thus challenging the conventional view that the supracrustal rocks were deposited and metamorphosed before 2.75 Ga.

The above interpretation of the supracrustal rocks is consistent with the geology of the southern margin of the Wyoming province, where Archean Wyoming province rocks are overlain by thick quartzite and metadolomite successions of Paleoproterozoic age, interpreted as having been deposited on a rifted (approximately 2.0 Ga) continental margin (Karlstrom and others, 1983), then subsequently deformed during collision of Colorado orogen arc rocks (Sims and Stein, 2003) along the Cheyenne belt (Duebendorfer and Houston, 1987) at about 1.78 Ga (Chamberlain, 1998).

PALEOPROTEROZOIC TECTONIC STRUCTURES

The major shear zones in the Trans-Montana fold-and-thrust belt are ductile shears, characterized by mylonite. They commonly are 1–5 km thick. Rocks in intervening areas are fractured and metamorphosed and at least locally have a penetrative, mainly northeast-striking schistosity or foliation. Linear negative aeromagnetic anomalies indicate extension of the structures northeastward from exposures in uplifts in southwestern Montana. The belt contains most of the tectonic elements common to Paleoproterozoic convergent terranes surrounding the Archean Superior province in the Canadian shield (Hoffman, 1987, 1988), such as the Penokean orogen (Sims, 1996).

The age of suturing along the Dillon shear zone with the Wyoming province is interpreted as 1.9–1.80 Ga. This age is based mainly on U-Pb zircon dating of rocks exposed in the Little Belt Mountains (Mueller and others, 2002), which they interpret as ocean-arc rocks emplaced in a convergent plate margin.

RELATION OF CRETACEOUS–EARLY TERTIARY GRANITIC INTRUSIONS TO BASEMENT STRUCTURES

Granitic to alkalic plutons of Cretaceous to early Tertiary age were emplaced mainly along basement structures formed in Paleoproterozoic and Mesoproterozoic time. The Late Cretaceous Boulder batholith and the linear array of plutons of the central Montana alkalic province were emplaced along northeast-trending inherited structures between the Great Falls and Dillon shear zones, which formed in Paleoproterozoic time. Except for rather small intrusions of Late Cretaceous age near Phillipsburg, Mont., and in the Tobacco Root Mountains, these granitoids are confined to a 60-km-wide disturbed block between the Great Falls and Dillon zones. The emplacement of the Boulder batholith, in particular, was controlled by northwest-trending and east-trending structures formed in basement rocks in Mesoproterozoic time, where they intersect the older northeast-trending zone (Schmidt and others, 1990). The batholith, rhomboid in shape, terminates against east-trending Mesoproterozoic faults on the north and south, and was interpreted by Schmidt and others (1990) to have been intruded into a slowly opening pull-apart basin whose orientation was controlled by the northeast-trending basement Great Falls shear zone. Reactivation of Mesoproterozoic northwest-trending faults south of the batholith played an especially important role in accommodating differential, east-directed tectonic transport of thrust plates north and south of the batholith, allowing for the opening of a pull-apart during the contractional tectonism that accompanied Sevier thrusting. The Tobacco Root batholith was emplaced within a pull-apart zone that formed along northwest-trending Mesoproterozoic faults coeval with Sevier thrusting.

Kalakey and others (2001) have also demonstrated that granitic rocks of the Pioneer batholith, southwest of the Boulder batholith, were emplaced during Sevier deformation. Thus, the loci for Cretaceous–early Tertiary magma emplacement were controlled by three superposed tectonic-thermal episodes of widely different ages: (1) development of shear zones during accretion of the amalgamated Archean and Proterozoic terranes to the Archean Wyoming craton during the Trans-Montana orogeny in Paleoproterozoic time; (2) development of post-orogen northwest-trending shear zones throughout the entire Rocky Mountain region in Mesoproterozoic time; and (3) magma generation within the Sevier fold-and-thrust belt during Late Cretaceous–early Tertiary time.

Valuable intrusion-related ore deposits, including the world-class Butte mining district (Lund and others, 2002, and references therein), were formed during the Late Cretaceous–Tertiary magmatic episodes (O'Neill and others, 2002). These deposits exhibit a northeast basement control parallel to the Trans-Montana fold-and-thrust belt, similar to that of the northeast-trending Colorado mineral belt (Tweto and Sims, 1963; Wilson and Sims, 2002).

DISCUSSION

The Precambrian rocks of Montana are an integral component of the western sector of Laurentia, essentially the Proterozoic North American continent (fig. 4). Terranes defined in Montana partly continue westward into Idaho. Because geologic events occur recurrently along many of the same structures, knowledge of these Precambrian terranes enhances understanding of younger geologic events in the region, as well as the complex history of amalgamation of the basement terranes.

Assembly of the Precambrian basement terranes in the northwestern United States was essentially contemporaneous with amalgamation of terranes adjacent to the Archean Superior province (Hoffman, 1988) in central North America, such as, for example, the Penokeon orogen (Sims, 1996). Assembly in these regions involved accretion of Paleoproterozoic arc assemblages onto Archean nucleii.

Although knowledge of the major basement terranes in the Western United States has advanced incremently over the past several decades, and currently is the subject of intensive investigation in many areas, especially within the southern Rocky Mountains (for example, Karlstrom and others, 2002), understanding of the important Mesoproterozoic Trans-Rocky Mountains fault system has been meager. Tweto (1980) first described some major segments of this ancient structural system in Colorado, but others (for example, Hamilton, 1988) have disputed significant Phanerozoic reactivation of these structures, and even doubted their existence. Current availability of refined aeromagnetic and derivative maps have provided a means to delineate these region-wide structures and to assist in determining their role in the subsequent tectono-stratigraphic evolution of the Western United States.

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Figure 1. Precambrian-cored uplifts (colored) of Rocky Mountain region.

Figure 2. Aeromagnetic anomaly map of northwestern United States showing major Precambrian terrane boundaries and principal Proterozoic faults and shear zones. CB, Cheyenne belt suture; CF, Cedar Creek fault; CZ, Clearwater zone; DSZ, Dillon shear (suture) zone; GFSZ, Great Falls shear zone; LC, Lewis and Clark fault zone; SF, Snake River fault zone; SR, Snake River Plain volcanic field. Aeromagnetic map prepared by North American Magnetic Anomaly Group (2002).

Figure 3. Model for evolution of the Trans-Montana orogen. Stage 1—Passive margin deposits accumulate on continental edge approaching a north-dipping subduction zone. Stage 2—Active subduction of the continental margin during convergence results in craton-vergent imbricate thrusting of the volcanic and sedimentary rocks and their basement. Modified from Hoffman (1987). Generalized for simplicity.

Figure 4. Generalized Precambrian basement geologic map of northwestern United States. Compiled from Sims and others (2001a—Colorado), Sims and others (2001b—Wyoming), and unpublished data, (2003). CB, Cheyenne belt suture; CF, Cedar Creek fault; CZ, Clearwater zone; DSZ, Dillon shear (suture) zone; GFSZ, Great Falls shear zone; LC, Lewis and Clark fault zone; SF, Snake River fault zone; SR, Snake River Plain volcanic field.