MAP I-2452

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC MAP OF PRECAMBRIAN ROCKS OF THE SIERRA MADRE, CARBON COUNTY, WYOMING, AND JACKSON AND ROUTT COUNTIES, COLORADO

By R.S. Houston and P.J. Graff

MISCELLANEOUS INVESTIGATIONS SERIES
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INTRODUCTION

The purpose of this pamphlet is to assist the reader interpret the map. In the pamphlet we discuss the geology and structure of the southern Sierra Madre and the relationship between Precambrian, Laramide, and Tertiary structure of the Sierra Madre, which have not been discussed in recent literature.

The Precambrian geology of the northern Sierra Madre has been reviewed in detail in recent reports and will not be covered here. Key summary reports on northern Sierra Madre Precambrian geology are Graff (1978), Karlstrom and others (1981), Duebendorfer and Houston (1990), and Houston (1993). Divis (1976) presented a review of the general geology and geochemistry of the southern Sierra Madre, and Duebendorfer and Houston (1990) and Houston (1993) gave brief discussions of this part of the range. In the discussion to follow, we will first present an overview of the Precambrian geology of southern Wyoming with emphasis on the structural geology of the southern Sierra Madre. This will be followed by a section on the Laramide structure of the Medicine Bow Mountains and Sierra Madre that emphasizes Laramide reactivation of Precambrian fault systems. The next part of the report will cover late Tertiary extensional faulting that was controlled by both Precambrian and Laramide faults, and the final section will be a discussion of specific fault systems within the Sierra Madre.

OVERVIEW OF PRECAMBRIAN GEOLOGY OF SOUTHERN WYOMING

The margin of the Archean Wyoming Province is exposed in the Medicine Bow Mountains and Sierra Madre of southern Wyoming (Houston and others, 1992; fig. 1). North of the margin, Archean gneissic basement is overlain by Late Archean and Early Proterozoic metavolcanic and metasedimentary rocks. South of the margin, there is no Archean basement and dominant rock types are Early Proterozoic metavolcanic rocks and graywacke (fig. 1). The geology along the margin of the Wyoming Province is best defined in the Medicine Bow Mountains where the margin is not disrupted by later faulting as in the Sierra Madre (Duebendorfer and Houston, 1990).

MEDICINE BOW MOUNTAINS

The Archean basement of the Medicine Bow Mountains is overlain by or in fault contact with four metasedimentary and metavolcanic successions; the oldest is the Late Archean Phantom Lake Metamorphic Suite, followed successively by the Early Proterozoic Deep Lake Group, the Early Proterozoic lower part of the Libby Creek Group, and the Early Proterozoic upper part of the Libby Creek Group (fig. 2). The Late Archean Phantom Lake Suite is a mixed succession of metavolcanic and metasedimentary rocks that is transitional in character between Archean greenstone successions and Early Proterozoic miogeoclinal successions. The Deep Lake Group is fluvial metaconglomerate and quartzite interpreted as rift related deposits (Karlstrom and others, 1981). The lower Libby Creek Group consists of glaciomarine deposits and marine quartzite and schist deposited in a northeast-striking trough that developed as a hypothetical Archean plate separated from the Wyoming Province during the Early Proterozoic (Karlstrom, Flurkey, and Houston, 1983). The upper Libby Creek Group includes a lower stromatolitic dolomite thought to be part of a Proterozoic carbonate bank and it also includes an upper marine volcanic succession and black graphitic slate that developed in a foredeep basin during arc-continent collision (Houston and Karlstrom, 1992; Houston, 1993).

In the Medicine Bow Mountains, the margin of the Wyoming Archean Province ends abruptly at a northeast-striking fault system, the Cheyenne Belt of Houston and others (1979). This fault system consists of three fault blocks separated by zones of intense mylonitization (Duebendorfer and Houston, 1987; 1990; fig. 1). A study of the isotopic compositions of Precambrian rocks within and adjacent to the Cheyenne Belt indicates that fault blocks within the Cheyenne Belt include slivers of Archean crust and slices of paragneiss interpreted as intermixed sedimentary detritus from both Archean and Proterozoic sources (Ball and Farmer, 1991). However, Proterozoic crust south of the Cheyenne Belt contains no crustal material derived from Archean sources (Ball and Farmer, 1991, p. 360).

Proterozoic rocks south of the Cheyenne Belt are mixed metavolcanic and metasedimentary successions and associated intrusive suites thought to be remnants of island arcs exposed at different crustal levels (Houston, 1993).

The Cheyenne Belt is considered a classic example of a Proterozoic suture where island arcs collided with a trailing (Atlantic type) continental margin (Hills and Houston, 1979; Karlstrom and Houston, 1984; Duebendorfer and Houston, 1987).

SIERRA MADRE

The Precambrian geology of the Sierra Madre is similar to that of the Medicine Bow Mountains, and the various metavolcanic and metasedimentary successions north of the Cheyenne Belt can be correlated from one area to the other (fig. 2). However, the metasedimentary successions of the Snowy Pass Group of the Sierra Madre are a more distal facies than their equivalents in the Medicine Bow Mountains (fig. 2).

The Cheyenne Belt of the Medicine Bow Mountains extends into the east-central Sierra Madre where it has an east-northeast strike (Duebendorfer and Houston, 1990; fig. 1; see map). About 4 mi west of the area where the Cheyenne

Belt enters the Sierra Madre it is disrupted by a north-vergent, thrust-tear system that cuts across the suture zone (see map). Two major northwest-striking, cataclastic, dextral strike-slip faults (Quimby Park and Billie Creek faults; see map) in the southeast Sierra Madre merge with cataclastic thrust faults of the central Sierra Madre (Hidden Treasure and Quartzite Peak thrust faults; see map). A major east-west system of cataclastic faults (the Battle Creek fault zone, see map) is also considered part of this thrust fault system, but it is invaded by granite and it is difficult to determine its relationship to the northwest-striking tear faults (Duebendorfer and Houston, 1990). This cataclastic thrust-tear system truncates the Cheyenne Belt, spreads pieces and blocks of mylonite (including mylonite of the Battle Creek fault zone) of the Cheyenne Belt along its trace, and transports much of the southern and southwestern Sierra Madre to the north. The Snowy Pass Group of the north-central Sierra Madre is severely deformed by this cataclastic event and there are probably a number of additional unmapped north-vergent thrust faults that create additional problems in stratigraphic reconstruction.

The amount of displacement on this thrust-tear system is unknown, but the fact that the Snowy Pass Group is a distal facies of Medicine Bow equivalents suggests that it may have been substantial. In addition, there is a significant contrast in the lithology of volcanic successions of the south-central and southwestern Sierra Madre with that of the southern Medicine Bow Mountains and the southeastern Sierra Madre (see map).

UNCONFORMITIES

Stratigraphy is difficult to establish in a mixed succession of metavolcanic and metasedimentary rocks, especially in the area south of the Cheyenne Belt.

NORTH OF THE CHEYENNE BELT

North of the Cheyenne Belt, where tops of bedding are more easily determined than in the south and where metavolcanic rocks are uncommon in the miogeoclinal succession, the stratigraphy has been well established by previous workers (Blackwelder, 1926; Karlstrom and others, 1981). Two major unconformities have been defined north of the Cheyenne Belt in the Medicine Bow Mountains that we believe are present in the Sierra Madre. The Late Archean Overland Creek Gneiss of the Medicine Bow Mountains (fig. 1), which is equivalent to the Vulcan Mountain metavolcanics of the Sierra Madre, is unconformably overlain by the Phantom Lake Metamorphic Suite (Karlstrom and others, 1981; Houston and others, 1992). The Overland Creek Gneiss is higher metamorphic rank than the Phantom Lake Metamorphic Suite, shows evidence of deformational episodes not recorded in the Phantom Lake Metamorphic Suite, and conglomerate of the Phantom Lake Metamorphic Suite contains clasts of felsic gneiss that may have been derived from the Overland Creek Gneiss. This unconformity has been recognized in the Sierra Madre where the basal Jack Creek Quartzite of the Phantom Lake Metamorphic Suite lies unconformably on the quartzo-feldspathic gneiss unit and Vulcan Mountain Metavolcanics. The basal conglomerate member of the Jack Creek Quartzite contains clasts of felsic gneiss and feldspar (derived from the underlying quartzo-feldspathic gneiss unit) where it is exposed in the northwestern Sierra Madre (Houston and others, 1992). In this same area a sericite schist at the base of the Jack Creek Quartzite may be a metamorphosed regolith.

The second major unconformity north of the Cheyenne Belt is between the Early Proterozoic Deep Lake Group and underlying Archean units. The basal conglomerate of the Magnolia Formation of the Deep Lake Group overlaps different rock types of the Phantom Lake Metamorphic Suite in the northeastern Medicine Bow Mountains and contains clasts of granite gneiss derived from the Overland Creek Gneiss. In addition, angular unconformities between rocks of the Phantom Lake Metamorphic Suite and the Magnolia Formation have been observed at two localities in the Medicine Bow Mountains (Houston and others, 1968; Karlstrom and others, 1981).

In the eastern and central Sierra Madre, the Magnolia Formation is either separated from the underlying Phantom Lake Metamorphic Suite by mafic intrusions that occupy the contact or is in conformable contact with rocks of the Phantom Lake Metamorphic Suite. In the northwest Sierra Madre, however, an angular nonconformity is present between the Magnolia Formation and rocks of the Phantom Lake Metamorphic Suite that we correlate with the unconformity in the Medicine Bow Mountains (Karlstrom and others, 1981).

We suspect that an unconformity existed between the Vulcan Mountain Metavolcanics and the quartzo-feldspathic gneiss unit of the northern Sierra Madre. The Vulcan Mountain Metavolcanics are interpreted as remnants of a greenstone belt infolded with the quartzo-feldspathic gneiss and present as inclusions within the Spring Lake Granodiorite. We believe that the Vulcan Mountain Metavolcanics once lay unconformably on the quartzo-feldspathic gneiss, but most contacts are either conformable or gradational. Rare conglomerate layers within the Vulcan Mountain Metavolcanics contain clasts that may have been derived from the quartzo-feldspathic gneiss unit, but these clasts could have come from other sources.

SOUTH OF THE CHEYENNE BELT

We believe that there are two unconformities between units of the southern Sierra Madre, but we emphasize that stratigraphic relationships are difficult to establish in this area that is dominated by metavolcanic rocks and was subject to several episodes of deformation. The sillimanite gneiss unit is exposed in the southeast corner of the Sierra Madre (see map) in a crescent-shaped syncline that shows the effects of superposed folds. The western contact between the sillimanite gneiss unit and the "underlying" mixed gneiss units is structurally discordant (see map). This relationship plus the major change in lithology from metavolcanic rocks, diopside gneiss, marble, and quartzite to aluminous rocks suggests that an unconformity may exist between these units.

The Green Mountain Formation of Divis (1976) is the least deformed and metamorphosed of any unit of the southern Sierra Madre. It occupies a syncline (Green Mountain syncline; see map) that has a crescent shape similar to that of the sillimanite gneiss unit. The rocks of the Green Mountain Formation are not in contact with various metavolcanic and metasedimentary rocks labeled as Xbm, Xbf, Xbs, Xbmg, Xbc in the southeastern and south-central Sierra Madre (see map). The Sierra Madre Granite is present as a screen between the units Xbm, Xbf, Xbs, Xbmg, and Xbc and the Green Mountain Formation. We suggest that prior to the deformational event that resulted in the crescent shape of the Green Mountain syncline, units Xbm, Xbf, Xbs, Xbmg, and Xbc may have been structurally under the syncline and thus a possible basement succession. The complex structure of the southern Sierra Madre succession makes this interpretation highly conjectural, but we suspect that rocks of the Green Mountain Formation were deposited unconformably on a basement of Xbm, Xbf, Xbs, Xbmg, and Xbc rocks and that the Green Mountain rocks were preserved in a syncline that was later refolded. Units Xbm, Xbf, Xbs, Xbmg, and Xbc are of distinctly higher metamorphic rank than rocks of the Green Mountain Formation and they are more highly deformed. Neither higher metamorphic rank nor intensity of deformation can be taken as proof of age, but the Xbm, Xbf, Xbs, Xbmg, and Xbc units retain evidence of an episode of isoclinal recumbent folding that is not recorded in the Green Mountain Formation.

GEOCHRONOLOGY

Limits on the age of various successions in the Sierra Madre and Medicine Bow Mountains have been established by Hills and others (1968), Divis (1976), Hills and Houston (1979), and by Premo and Van Schmus (1989). A detailed discussion of geochronology is in Premo and Van Schmus (1989) and Houston (1993).

The Archean quartzo-feldspathic gneiss unit and Vulcan Mountain Metavolcanics are intruded by a red-pink orthogneiss dated as 2683±6 Ma and the Spring Lake Granodiorite dated as 2710±6 Ma by the uranium/lead zircon method (Premo and Van Schmus, 1989). The Jack Creek Quartzite of the Phantom Lake Metamorphic Suite is intruded by the Spring Lake Granodiorite, and the Silver Lake Metavolcanics of the Phantom Lake Metamorphic Suite are intruded by undated granodiorite correlated with the Spring Lake (Houston and others, 1992). The Phantom Lake Metamorphic Suite is considered Archean but, as noted by Houston and others (1992), only the lower part is dated.

The Magnolia Formation of the Sierra Madre has a radioactive quartz-pebble conglomerate at its base that contains euhedral zircons that are morphologically homogenous and are thought by Premo and Van Schmus (1989, p. 23) to be derived from a single source. These zircons have been dated by the uranium/lead method by Premo and Van Schmus (1989) as 2471±9 Ma; they suggest that this age represents a maximum age limit for deposition of the Magnolia Formation. A pegmatitic phase of a mafic body that intrudes the Cascade Quartzite of the Sierra Madre was dated by the uranium/lead zircon method as 2092±9 Ma (Premo and Van Schmus, 1989). These dates indicate that the Magnolia Formation, Singer Peak Formation, and Cascade Quartzite of the lower Snowy Pass Group were deposited between about 2471 and 2100 Ma and are Early Proterozoic. There are no internal dates on the upper part of the Snowy Pass Group of the Sierra Madre, although map relations show that the Slaughterhouse Formation is intruded by the Sierra Madre Granite dated as about 1744–1763 Ma by the uranium/lead zircon method (Premo and Van Schmus, 1989).

In the Medicine Bow Mountains, the Sugarloaf Quartzite of the lower Libby Creek Group is intruded by the Gaps Intrusion that has been dated as 2100–2150 Ma by the Rb/Sr method (C.E. Hedge in Houston and others, 1992), provided the intrusion is a differentiate of a mafic body as suggested by field relationships. We suggest that the lower part of the Snowy Pass Group of the Sierra Madre is older than 2100 Ma and is Early Proterozoic.

There are no internal dates on either the upper part of the Snowy Pass Group of the Sierra Madre or the upper part of the Libby Creek Group of the Medicine Bow Mountains; however, geologic evidence suggests that the Nash Fork Formation of the Libby Creek Group and Slaughterhouse Formation of the Snowy Pass Group are different facies of a carbonate platform deposited on a trailing margin (Houston and Karlstrom, 1992). Hills and Houston (1979) suggested that the collapse of this platform took place as island arcs approached the continental margin from the south and that this collapse promoted the deposition of marine volcanics of the Towner Greenstone and black graphitic slate of the French Slate in a foredeep basin. If the upper part of the Libby Creek Group does represent parts of a foredeep basin, an internal date on volcanics of the Towner Greenstone might date this event.

Attempts to date volcanics of the Towner Greenstone have failed, but geologists (Blackwelder, 1926; Houston and others, 1979) have suggested that the upper Libby Creek Group of the Medicine Bow Mountains may correlate with the Marquette Range Supergroup of the Lake Superior Region and that the Towner Greenstone may correlate with

1950 Ma Hemlock Formation of the Marquette Range Supergroup (fig. 2). If geochronology eventually supports this correlation, the upper Libby Creek Group may be older than 1950 Ma (see Houston and others, 1992; and Houston, 1993).

The single reliable date on volcanic rocks south of the Cheyenne Belt is the uranium/lead zircon date of 1792±15 Ma on a metadacite porphyry from the Green Mountain Formation (Premo and Van Schmus, 1989). So far, no rocks older than about 1800 Ma have been identified south of the Cheyenne Belt. If none of the volcano-sedimentary successions south of the Cheyenne Belt exceed about 1800 Ma, the concept of the foredeep basin is not tenable because a collision with a volcanic arc would have taken place prior to formation of the arc. Houston (1993) has suggested that some of the volcanic rocks south of the Cheyenne Belt in the Medicine Bow Mountains (Centennial Ridge area) may be older than 1800 Ma and that an earlier collision may have taken place in this area. As noted, structural evidence indicates that rocks of the southeastern Sierra Madre may be older than the Green Mountain Formation, but there is no geochronological evidence to support this assumption.

The quartzo-feldspathic gneiss, Vulcan Mountain Metavolcanics, and, at least the lower part of the Phantom Lake Metamorphic Suite are Archean (>2700 Ma). The lower Libby Creek Group of the Medicine Bow Mountains and equivalent facies of the Sierra Madre are Early Proterozoic (>2100–2150 Ma). The age of the upper Libby Creek Group of the Medicine Bow Mountains and equivalent facies of the Sierra Madre is not well established although these rocks are older than about 1750 Ma. Geologic evidence suggests that the upper Libby Creek Group is older than the about 1800 Ma Green Mountain Formation of the southern Sierra Madre, but this assumption has not been confirmed.

SOUTHERN SIERRA MADRE

East of the northwest-striking strike-slip faults of the southeastern Sierra Madre, lithology and structure of the southern Sierra Madre is similar to that of the southern Medicine Bow Mountains. This is an area of amphibolite facies metavolcanic and metasedimentary rocks and associated intrusive rocks that exhibit more than one deformation and that are invaded by syntectonic and post-tectonic granite (Houston and others, 1968; Houston, 1993).

The south-central Sierra Madre is dominated by a large, fine- and coarse-textured amphibolite body (see map). The coarse-textured amphibolite is probably intrusive, but some of the fine-grained amphibolite retains pillow structure (Condie and Shadel, 1984), and other fine-grained bodies have a fragmental texture that may indicate an origin as tuff (Houston, 1992). This amphibolite complex is interpreted as a possible center of basaltic volcanism on the basis of lithology and chemistry (Ware, 1982). On the northeast, the amphibolite complex interfingers with and grades into biotite gneiss whose progenitor was probably metagraywacke. To the west and southeast the amphibolite complex interfingers with and grades into felsic and mafic gneiss and schist that locally contain bodies of calc-schist and marble. These rocks are probably a mixed suite of metavolcanic and metasedimentary rocks. Some felsic gneisses east of the amphibolite complex are more massive (less foliated) than other gneisses and may be orthogneiss. The amphibolite and associated gneisses and schists are amphibolite facies metamorphic rock.

It has not been possible to establish a stratigraphy or to locate mappable units that can be traced for any distance in the amphibolite complex. However, two bits of evidence suggest superimposed folds. The gneiss and schist west of the amphibolite complex exhibit both large-and small-scale recumbent folds that are probably an indication of an early deformational episode because these recumbent folds are wrapped around the amphibolite complex. In addition, plots of foliation in the amphibolite complex and flanking metamorphic rocks suggest large-scale interference folds which indicate more than one episode of deformation (Houston, 1993). The same situation has been observed by Snyder (1980) in metamorphic rocks of the northernmost Park Range adjacent to this area.

The major structure of the south-central and southwestern Sierra Madre is a folded syncline of metavolcanic rocks of the Green Mountain Formation of Divis (1976). The Green Mountain Formation (Xgmm, Xgmf, Xgmw, Xgmx, and Xgms; see map) is a bimodal volcanic suite that has mafic to felsic volcanic cycles (Schmidt, 1983; Houston and others, 1984). It is calc-alkaline and is chemically similar to island arc volcanics (Condie and Shadel, 1984; Schmidt, 1983). In the Fletcher Park (T. 13 N., R. 86 W.) and Green Mountain (T. 13 N., R. 85 W.) areas, rocks of the Green Mountain Formation are less deformed and of lower metamorphic rank than elsewhere. Here graded bedding can be recognized in metatuffs and metagraywacke and this topping criteria has been used to define the Green Mountain syncline (see map). The axis of the Green Mountain syncline strikes northwest in secs. 8 and 17, T. 13 N., R. 84 W., where the fold is thought to plunge northwest. It is partially engulfed by granite in this area and in secs. 16 and 21, T. 13 N., R. 84 W., it is disrupted by a set of northeast-striking folds and faults (see map). In the Green Mountain area (secs. 1, 2, 11, and 12, T. 13 N., R. 85 W., and secs. 12 and 13, T. 13 N., R. 86 W.) the syncline is bisected by the Encampment River Granodiorite and Sierra Madre Granite. The north limb of the syncline reappears in the Fletcher Park area where it is cut by a series of strike faults that are probably south-dipping thrusts. South of Fletcher Park, the Green Mountain syncline is thought to be disrupted by a major thrust fault, the Roaring Fork fault, that transported the south limb of the syncline north and west (see map), but this fault trace is now mostly occupied by granite and granodiorite, so this interpretation is conjectural. South of the Roaring Fork fault, rocks of the Green Mountain Formation increase in metamorphic rank to amphibolite facies, and preserved features that could be used to determine tops of bedding are uncommon. In addition, the proportion of metasedimentary rocks and marine volcanics (pillow lava) increases in the south (Swift, 1982). The axis of the Green Mountain syncline has not been accurately located in the southwest Sierra Madre, but tops in pillow lavas indicate that the axis is at the western margin of the Sierra Madre Precambrian outcrops and that it must strike northwest.

CRITERIA USED TO ESTABLISH AGE OF CATACLASTIC FAULTS

In the section to follow we discuss Laramide reactivation of Precambrian fault systems, so it is critical that we establish a Precambrian age for the cataclastic tear faults and thrust faults that disrupt the Cheyenne Belt. The northwest-striking tear faults are well exposed in a number of areas of the southeast Sierra Madre. These faults contain cataclastic fault zones as much as 40 m wide that are locally silicified and are marked by hematite-limonite alteration. Some areas within the cataclastic faults are mineralized (copper and minor gold). Rare subhorizontal chlorite and epidote fibers are within the cataclasites (Duebendorfer and Houston, 1990). This suggests that these faults developed at deeper levels than present surface exposures of Laramide faults where the fault traces are usually indicated by breccia and fault gouge. Inasmuch as there is no record of base-metal mineralization that is post-Precambrian in this immediate area, a Precambrian age was inferred for these faults by Duebendorfer and Houston (1990).

In secs. 1 and 2, T. 13 N., R. 84 W., the Sierra Madre Granite (dated as 1750–1760 Ma by U/Pb zircon; Premo and Van Schmus, 1989) exists as sills within the northwest-striking fault systems, but the granite is also marked by zones of cataclasis. This relationship suggests that some of the cataclastic faults preceded the emplacement of the granite, but that deformation continued after its emplacement.

Thrust faults and related cataclastic zones of the central Sierra Madre contain 66-ft-thick subvertical cataclastic zones that overprint mylonite foliation and that have features in common with the cataclastic tear faults, such as base-metal mineralization. The Battle Lake fault zone is best exposed in the west-central Sierra Madre south of the Lost Creek and Haskins Creek campgrounds and northeast of the Rambler Guard station (see map). The Battle Lake fault zone is a mixture of mylonitic rock and cataclastic faults in which the cataclastic faults are superimposed on an earlier mylonitic fault system. The mylonitic rocks are interpreted as pieces of the Cheyenne Belt brought into this area by late thrust faults (Duebendorfer and Houston, 1990). The cataclastic faults of the Battle Lake fault zone not only disrupt mylonite but these faults cut undeformed rocks as well (Duebendorfer and Houston, 1990). Cataclasites within this fault zone are sheared, altered to hematite and limonite, and mineralized. Shear surfaces that dip south at shallow angles and that crosscut regional foliation contain south-plunging step-like epidote and quartz fiber lineation that suggests top-to-the-north shear (Duebendorfer and Houston, 1990). This shear sense suggests that these faults are thrust faults, and, if so, the faults developed before emplacement of the Sierra Madre Granite that invades the Battle Lake fault zone in a number of areas (see map).

Indirect evidence for a Precambrian age for major faults of the southern Sierra Madre is the possible thrust-tear system, the Roaring Fork fault. Inasmuch as the Roaring Fork fault trace is believed to be occupied by granite, at least 1750 Ma, it must be Precambrian.

We suggest that many of the cataclastic faults are Precambrian, but we emphasize that other similar faults may be much younger.

LARAMIDE STRUCTURE

Laramide uplifts of southern Wyoming strike northerly and are typically bordered by major thrust faults on one or both margins (Blackstone, 1953). The Medicine Bow Mountains and Sierra Madre are part of a major north-striking uplift bordered on the east by west-dipping thrust faults (fig. 3). The Sierra Madre is separated from the Medicine Bow Mountains by a northwest-striking half graben (down on the west side) filled with late Tertiary sediment (fig. 3).

The Laramide faults on the east side of the Medicine Bow Mountains strike north and dip 17–30° west. Some Laramide faults of the southern Medicine Bow Mountains strike northwest and dip southwest (fig. 3). The northwest thrusts displace earlier north-striking thrusts (fig. 3). A major thrust fault, Independence Mountain thrust, at the northern limit of the North Park basin of Colorado, strikes generally east-west, dips north, and overrides the northern end of the North Park basin and its north-striking Laramide folds (Blackstone, 1977). These Laramide fault systems are believed to be related, and their orientation partially controlled by Precambrian faults (Blackstone, 1953).

Laramide thrust faults on the east side of Elk and Pennock Mountains in the northwest Medicine Bow Mountains strike north but curve southwest and northeast at their extremities so that they have a concave west form (fig. 3). These curved faults override Cretaceous and lower Tertiary rocks along most of their traces (fig. 3); the north-striking segment is thrust to the east, the northwest-striking segment to the northeast, and the southwest-striking segment to the southeast (fig. 3). Elk and Pennock Mountains are fault blocks uplifted and thrust to the east, southeast, and northeast on curved faults and, so far as is known, show no relationship to Precambrian structures.

The major faults of the northeastern Medicine Bow Mountains are the Arlington and Corner Mountain thrust faults, which are most recently described by Blackstone (1987) and by Houston and Karlstrom (1992). These faults are also curved but they do not override Phanerozoic sedimentary rocks at their southern limit where they strike northeast (fig. 3). These faults have a pivot point or hinge northwest of Arlington (Arlington fault) and south of Arlington (Copper Mountain fault; fig. 3). They rotate counterclockwise and break out of northeast-striking tear faults (north of Centennial) that are controlled by northeast-striking Precambrian fault systems of the Cheyenne Belt (Houston and others, 1968; Blackstone, 1987; Houston and Karlstrom, 1992). If this block rotation concept is correct, strain exerted on the northeast-striking tear faults should result in the development of northwest-dipping thrusts, especially at the southwest extremity of the blocks. Instead, the prominent northwest-striking Precambrian faults of the Sierra Madre were reactivated, which resulted in movement on the Independence Mountain thrust (fig. 3). The Independence Mountain thrust is also a rotational fault. It has a pivot point on the east and shows increasing displacement to the west where it encounters northwest-striking faults of Precambrian age (Blackstone, 1977). The northwest-striking thrusts of the southern Medicine Bow Mountains may also be related to this system. Strain may have caused northeast-directed movement on these northwest-striking thrust faults, which have pivot points in the northwest and show increasing displacement to the southeast (Houston and others, 1968; fig. 3).

The timing implications of this concept are that these Laramide uplifts developed from an east-west compression that resulted in north-striking folds and faults, but that subsequent breakup of individual blocks, partially controlled by preexisting faults of Precambrian age, resulted in block rotation and the development of later, more complex fault systems.

LATE TERTIARY EXTENSIONAL FAULTING

The Saratoga Valley east of the Sierra Madre is a basin filled with Oligocene and Miocene sediment of the Browns Park Formation (Montagne, 1991). Paleozoic and Mesozoic sedimentary rocks crop out at the north end of the basin near Saratoga and south of the Colorado-Wyoming State line at the northern extremity of the North Park basin of Colorado (Houston and others, 1968; Tweto, 1979; Montagne, 1991; fig. 3). According to Montagne (1991), deposition of sedimentary rocks in the Saratoga Valley may have begun as early as Paleocene, the age of the lower part of the Coalmont Formation, which he has tentatively identified in the southwestern Saratoga Valley. The bulk of the Tertiary sediment in the Saratoga Valley is Neogene and its deposition may be related to extensional faulting that took place in Neogene time.

A major episode of Neogene extensional faulting is recorded in the Rio Grande rift of New Mexico, which extends through Colorado to the Colorado-Wyoming Border (Tweto, 1979). In Colorado, the majority of these faults strike north-northwest and northwest, and many are reactivated faults of Laramide, late Paleozoic, or Precambrian age (Tweto, 1979). Our recent mapping in the Sierra Madre, along with earlier work of Montagne (1955) and Houston and others (1968), suggests that this extensional faulting extended into the Saratoga Valley and that many of the Tertiary normal faults are reactivated Laramide and Precambrian faults.

The eastern margin of the Sierra Madre is characterized by northwest-striking normal faults that preserve Tertiary sediment of Neogene age on their down-dropped, eastern side (Montagne, 1991). Although these faults displace sediment of the Browns Park Formation (Oligocene and Miocene) in some areas, the episode of faulting probably began during and continued after deposition of the Browns Park. There are very few normal faults on the east side of the Saratoga Valley, but these include a minor set of faults near Pennock Mountain (Montagne, 1955; Houston and others, 1968; fig. 3) which are also down-dropped on their east side. Normally, the Tertiary sediment is in depositional contact with older rocks on the east side of the valley.

Neogene sediment (Browns Park Formation) is preserved in a number of parks in the southern Sierra Madre (see map). In each case, the Neogene sediment is preserved in half grabens. Hog Park, in the southwest Sierra Madre, has a northwest-striking normal fault on its southwest margin that is down-dropped on the east (see map). This fault does not appear to have a Precambrian ancestry but it passes into a Laramide thrust in Colorado (Snyder, 1980) and it may be a reactivated Laramide structure. Big Creek Park, in the southeastern Sierra Madre, has two normal faults on its eastern side, the Billie Creek fault of Montagne (1955) and this report and the Quimby Park fault (see map). These northwest-striking faults are down-dropped on the west and have both a Precambrian and Laramide ancestry. They are the best documented evidence for long-term fault reactivation in southern Wyoming. Cunningham Park, in the southeastern Sierra Madre, is bordered on its east margin by a northwest-striking normal fault, the Cunningham fault of Montagne (1955). This fault is a reactivated Precambrian fault, but no movement has been documented during the Laramide.

ALTERNATIVE INTERPRETATIONS

In the discussion of Laramide structure, emphasis was placed on Laramide reactivation of northwest-striking tear faults to generate offset on the Independence Mountain fault. It is possible that this right-lateral movement also reactivated east-west thrust faults in the central Sierra Madre that have been interpreted here as Precambrian. The Hidden Treasure thrust fault of Precambrian age may be such an example of Laramide reactivation. The Hidden Treasure fault is offset in a left-lateral sense in sec. 27, T. 14 N., R. 87 W., near Haskins Creek campground (see map) by a fault that can be traced southwest to an area (secs. 23, 24, 25, and 26, T. 13 N., R. 87 W.) where Mesozoic sedimentary rocks are displaced in a left-lateral sense by a fault (Ritzma, 1949). If the east-striking Hidden Treasure fault was reactivated during the Laramide, showing an opposite sense of movement with respect to the Independence Mountain fault, the left-lateral fault may be a tear fault of Laramide age that is related to the reactivation. Could movement on the Hidden Treasure fault be entirely Laramide? We do not accept this possibility because the Laramide displacement (Ritzma, 1949) is much less than that indicated in sec. 27 where the Hidden Treasure overrides the Quartzite Peak fault (see map).

If the concept of Laramide reactivation is accepted, how much of the right-lateral movement on the Quimby Park and Billie Creek faults is Precambrian and how much is Laramide? As noted, the Precambrian geology of the south-central and southwestern Sierra Madre is exotic as compared with the southern Medicine Bow Mountains, and even rocks of the Snowy Pass Group of the Sierra Madre are a distal facies of Medicine Bow equivalents. This suggests major displacement but does not indicate actual displacement. The apparent horizontal displacement on the Independence Mountain thrust at its western limit has been estimated by Blackstone (1977) as a maximum of 22,000 ft. The apparent right-lateral displacement on the Quimby Park and Billie Creek faults is over twice this amount. However, Laramide reactivation of the Hidden Treasure and possible related faults could explain some of this difference. There is a possibility that these fault systems have had greater displacement in the Laramide than in the Precambrian.

Is the Laramide right-lateral offset on the Quimby Park and Billie Creek faults relieved by southward thrusting on the Independence Mountain fault and northward thrusting on the reactivated Hidden Treasure and other similar faults, or is this strain relieved by movement on the Savery Creek fault of the northwest Sierra Madre?

The strike of the Savery Creek fault is parallel with tear faults of the southeast Sierra Madre (see map). It is a major fault that exhibits left-lateral offset as shown by the displacement of the Divide Peak syncline (see map). The Savery Creek fault has been reactivated at a relatively recent date as shown by offset of an upper Tertiary or Quaternary conglomerate bed in T. 16 N., R. 88 W. (Vine and Prichard, 1959, plate 14). This Tertiary fault movement is down on the southwest.

Inasmuch as the Savery Creek fault is covered over its entire trace, the only movement that can be timed is the late Tertiary or Quaternary normal fault. The left-lateral movement is probably Precambrian and may have preceded the Precambrian thrust-tear system. Is there significant right-lateral movement on the Savery Creek fault during the Laramide? If the Savery Creek fault extends to the northwest, much of it is covered with late Tertiary and Quaternary sedimentary rocks (Love and Christiansen, 1985). However, there is a bend in the Cretaceous section in T. 17 N., R. 91 W., that may have resulted from right-lateral movement on the Savery Creek fault (Love and Christiansen, 1985). Our current thinking is that the Savery Creek fault did indeed move in a right-lateral sense during the Laramide.

We have described the increasing displacement from the eastern end to the western end of the Independence Mountain fault, which can be accounted for by right-lateral movement on the Quimby Park and Billie Creek faults. However, thrust faults west of the Independence Mountain fault appear to be displaced to the west and southwest (Snyder, 1980; fig. 3). The Independence Mountain fault may also exhibit an element of westward thrusting. Perhaps the faults that exhibit displacement to the west are early and have been overridden by the Independence Mountain fault, or the westward and southward displacement on these faults may have been nearly simultaneous.

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