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Precambrian Tectonics and Metallogeny of the Hartville Uplift, Wyoming

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PROTEROZOIC STRUCTURAL EVOLUTION OF HARTVILLE UPLIFT, SOUTHEASTERN WYOMING

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SUMMARY

The Hartville uplift is located on the southeast margin of the Archean Wyoming craton and exposes Late Archean granite and gneiss and Late Archean or Early Proterozoic supracrustal rocks that were deformed during three, and possibly four, major compressional events in Early Proterozoic time, extending from ~2.1 Ga to 1.76 Ga. The recognized events are (1) inversion of the supracrustal succession (D_1), at least in parts of the uplift, as a result of probable fold nappe formation; (2) folding of rocks on east-west axes (D_2)in southern part of uplift; folds are open to tight, generally plunge westward, and verge southward; (3) west-vergent folding on northeast-trending axes and associated thick-skinned thrusting (dominant deformation, D_3) in central and northern parts of uplift, with concomitant prograde metamorphism; and (4) local recumbent folds in southernmost part of uplift.

The inverted succession probably constitutes the lower limb of a fold nappe (or nappes) that could have formed as an early phase of deformation D_2. Deformation D_2 produced similar folds having a north-dipping axial planar cleavage; S_0-S_2 intersections (L_2) plunge parallel to F_2. Deformation D_2 deformed the supracrustal rocks and the Archean basement in the southern part of the uplift, and D_2 folds are preserved in the area south of the village of Hartville. D_2 deformation developed prior to mafic dike emplacement at ~2.0 Ga. In the area north of Hartville, F_3 folds a foliation, which developed early in D_3 deformation as a ductile structure. The main deformation in the uplift (D_3 at ~1.82 Ga) constitutes a west-vergent fold-and-thrust belt on the western continental margin of the Trans-Hudson orogen; the continent-arc suture is not exposed but is inferred to lie a few kilometers to the east of the uplift. The youngest recognized significant deformation (D_4), represented by scattered, small-scale recumbent folds in the southernmost part of the uplift, possibly resulted from vertical compression caused by imbricate thrusting attributed to collision along the 1.76-Ga Cheyenne belt.

INTRODUCTION

The Hartville uplift, on the southeast margin of the Archean Wyoming craton, is a Laramide anticline that consists of a Precambrian core overlain by gently outward - dipping Paleozoic strata and, locally, by flat-lying Tertiary strata. The core is composed mainly of Late Archean Rawhide Buttes Granite (Snyder, 1980) and associated Archean gneisses and metamorphosed Precambrian supracrustal rocks (Whalen Group; fig. 1). The supracrustal rocks are intruded by the 1.98-Ga Flattop Butte Granite and by younger Twin Hills Diorite (1.74 Ga) and Haystack Range Granite (1.72 Ga) (Snyder, 1993). The 1.72-Ga granite is virtually undeformed but has conspicuously domed the supracrustal rocks. North-striking swarms of Fe-tholeiite dikes, now mainly granular quartz amphibolite, intrude the Archean granite and gneiss and the supracrustal rocks but not the 1.98-Ga Flattop Butte Granite. The dikes are inferred to be ~2 Ga because they similar to those in a 2.0-Ga dike swarm that occurs in the Laramie Mountains (Sims, 1995, pl. 1B).

Detailed structural studies (Day and others, 1994) have shown that the Precambrian rocks in the Hartville uplift were deformed during at least three, and possibly four, major, diversely oriented, compressional events in Early Proterozoic time. Although the main structural features of the uplift resulted from the Trans-Hudson orogeny (~1.82 Ga), an older, previously unrecognized deformation (~2.1 Ga) produced a probable fold nappe that subsequently was folded into east-west-trending, west-plunging, south-vergent structures. A younger deformation--possibly caused by collision along the Cheyenne belt (~1.76 Ga; Premo and Van Schmus, 1989)--produced local, small-scale recumbent folds that are superposed on previously folded supracrustal rocks in the southernmost part of the uplift.

The purpose of this report is to describe the general geology of the Precambrian rocks in the Hartville uplift, with emphasis on the structure, and to relate these structures insofar as possible to specific compressional events along the southern and southeastern margins of the Wyoming craton.

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PRECAMBRIAN TECTONICS AND METALLOGENY OF THE HARTVILLE UPLIFT, WYOMING

Leaders:
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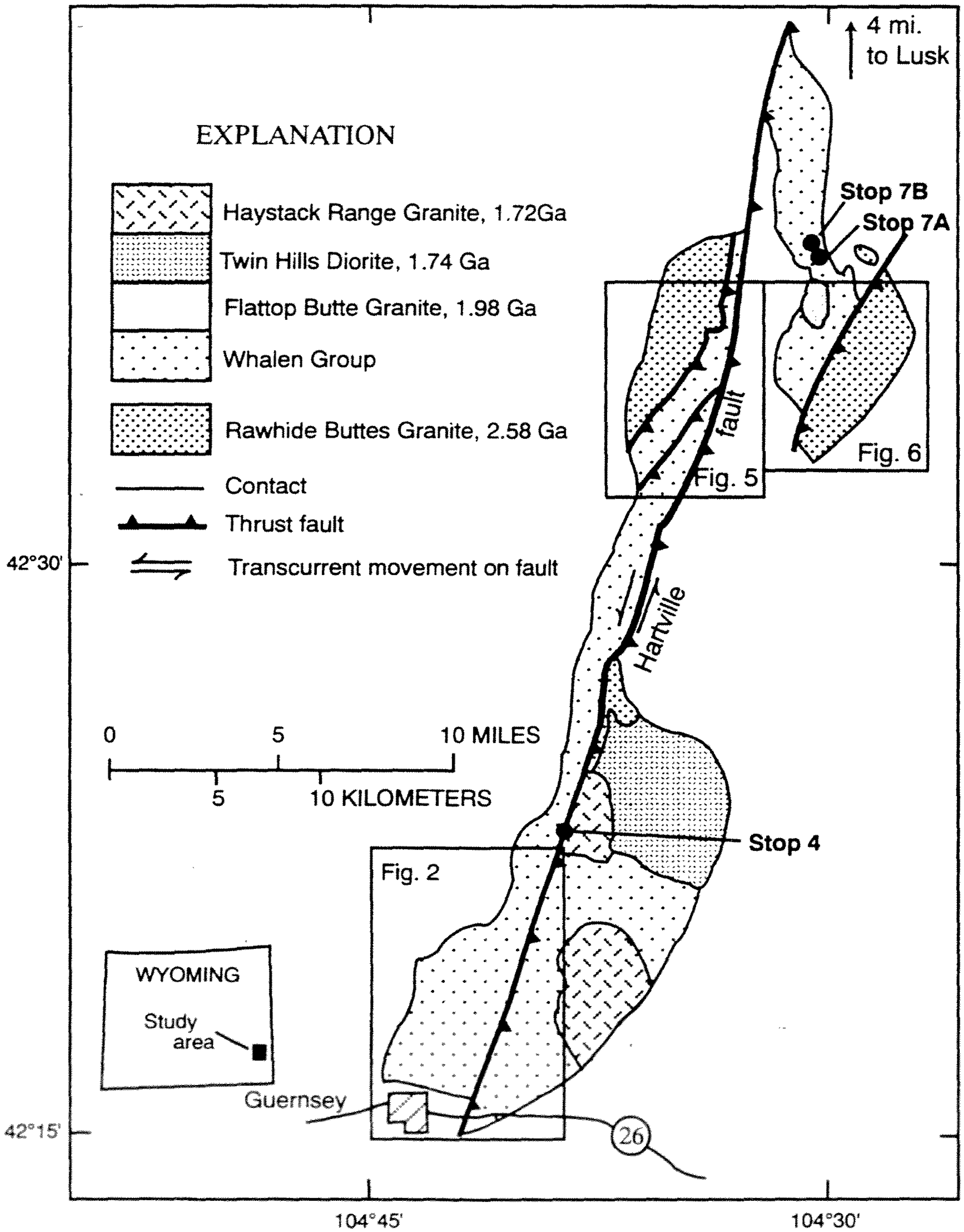


Figure 1. Generalized geologic map of Precambrian rocks ofHartville uplift, southeastern Wyoming. Modified from Snyder (1980).

PRECAMBRIAN ROCK UNITS

The major Precambrian rock units in the Hartville uplift are the Late Archean (2.58 Ga) Rawhide Buttes Granite (Snyder and Peterman, 1982) and associated undated gneisses and a Late Archean or Early Proterozoic supracrustal succession composed mainly of mica schist, metadolomite, and metabasalt units (fig. 2). Less widespread supracrustal rock units are quartzite and banded iron-formation. The supracrustal rocks were assigned to the Whalen Group by Smith (1903). The age of the Whalen Group is equivocal because internal isotopic ages are lacking. Snyder (1980, 1993) considered the Whalen Group to be Late Archean because he interpreted the rocks within it to be intruded by the Late Archean Rawhide Buttes Granite. Our structural studies, however, indicate that the major granite–supracrustal rock contacts are ductile shear zones, and age relationships are uncertain.

The Whalen Group is known to be older than 1.98 Ga because the supracrustal rocks are intruded by the 1.98-Ga Flattop Butte Granite (fig. 1) and probably is entirely older than ~2.0 Ga, the age of the diabasic dikes that locally cut the supracrustal rocks. Strontium isotope compositions of metamorphosed carbonate rocks in the Whalen Group are permissive with an Early Proterozoic rather than a Late Archean age (Zell E. Peterman, U.S. Geological Survey, written communication, 1994). An Early Proterozoic age is also suggested by the presence of Superior-type iron-formation (Gross, 1965; James, 1983) in the Whalen Group, which in the northern hemisphere characteristically is Early Proterozoic in age (Gross, 1980, p. 218). Lacking an internal isotopic age on the rocks, however, we tentatively designate them as either Early Proterozoic or Late Archean.

STRUCTURE

Four episodes of deformation, designated D_1 through D_4, are recognized in the Hartville uplift, as follows: D_1, overturning of Early Proterozoic stratigraphic succession; D_2, folding on east-trending axes, as recorded in the southern part of uplift; D_3, folding on northeast-trending axes, coeval with west-directed thick-skinned thrusting in the central and northern parts of the uplift; D_4, scattered small recumbent folds in the southernmost part of uplift.

D_1 and D_2 Deformations

Deposition of the Whalen Group on a southeast-facing passive margin was followed by formation of a fold nappe (or nappes) (D_1), which could have resulted from an early phase of deformation D_2. An associated axial planar fabric is very weak or absent, suggesting that the fold nappe could have formed by soft sediment deformation. Subsequent erosion has exposed the lower, overturned limb of the nappe (fig. 2).

Following nappe formation, north-south directed compressional deformation folded the supracrustal rocks and apparently also the underlying granite basement. The folds are exposed west of the Hartville fault in the area south of Hartville (fig. 2): they plunge westward and verge southward in the Guernsey domain (southernmost area near Guernsey) (fig. 3); farther north, near the Graves Ranch anticline (a downward-facing anticline; Shackleton, 1958) and the Sunrise syncline (a downward-facing syncline), D_2 structures plunge both east and west (figs. 2 and 3). D_2 folds are similar folds having a north-dipping axial planar cleavage; S_0-S_2 intersections (L_2) plunge parallel to F_2. An undeformed diabasic dike, interpreted as belonging to the 2.0-Ga set, cuts D_2 folds on the hill south of the Graves Ranch anticline, indicating that D_2 deformation preceded ~2.0 Ga.

D_3 Deformation

Deformation D_3, the main structural event recorded in the Hartville uplift, produced northeast-trending folds and thrusts that are longitudinal to the axis of the uplift and span the length of it. F_3 structures fold S_0 and S_2. Folds verge westward and are coeval with west-directed thrusting. The principal thrust, the Hartville fault, follows the axis of the uplift (fig. 1) and juxtaposes middle to upper amphibolite facies rocks on the east with upper greenschist facies rocks on the west. The estimated relative uplift of the eastern block is about 5 km (K. Chamberlain, University of Wyoming, oral communication, 1993). Where exposed 7 km north of the area shown in figure 2, the Hartville fault is a high-angle ductile reverse fault that dips steeply east and has a component of sinistral strike-slip offset. It is presumed either to have been steepened by later movements or to flatten with depth. The thrusts involve Archean granite basement as well as supracrustal rocks.

In the vicinity of Hartville, in the southern part of the uplift, D_3 deformation refolded the easternmost exposed part of the F_2 Sunrise syncline (fig. 2); the original east-trending fold axis (F_2) is warped to a northeast direction. To the north of this warped structure, F_3 folds trend northeast, mainly plunge northeast (fig. 4), and have a weak to moderate axial planar foliation (S_{3b}). The F_3 folds trend subparallel to the Hartville fault and are clearly coeval with it. South of the Sunrise syncline, the east-west structures characteristic of D_2 deformation were not refolded by F_3.

Figures 5 and 6 are representative of areas in the Hartville uplift that are dominated by D_3 Trans-Hudson orogeny (THO) deformation. Figure 5 is mainly located west of the Hartville fault and figure 6 is east of the fault, within the higher grade segment of the foreland of the THO. In the area west of the Hartville fault (fig. 5), two west-vergent thrust faults separate three tectono-stratigraphic terranes (fig. 7): (1) Rawhide Creek terrane,

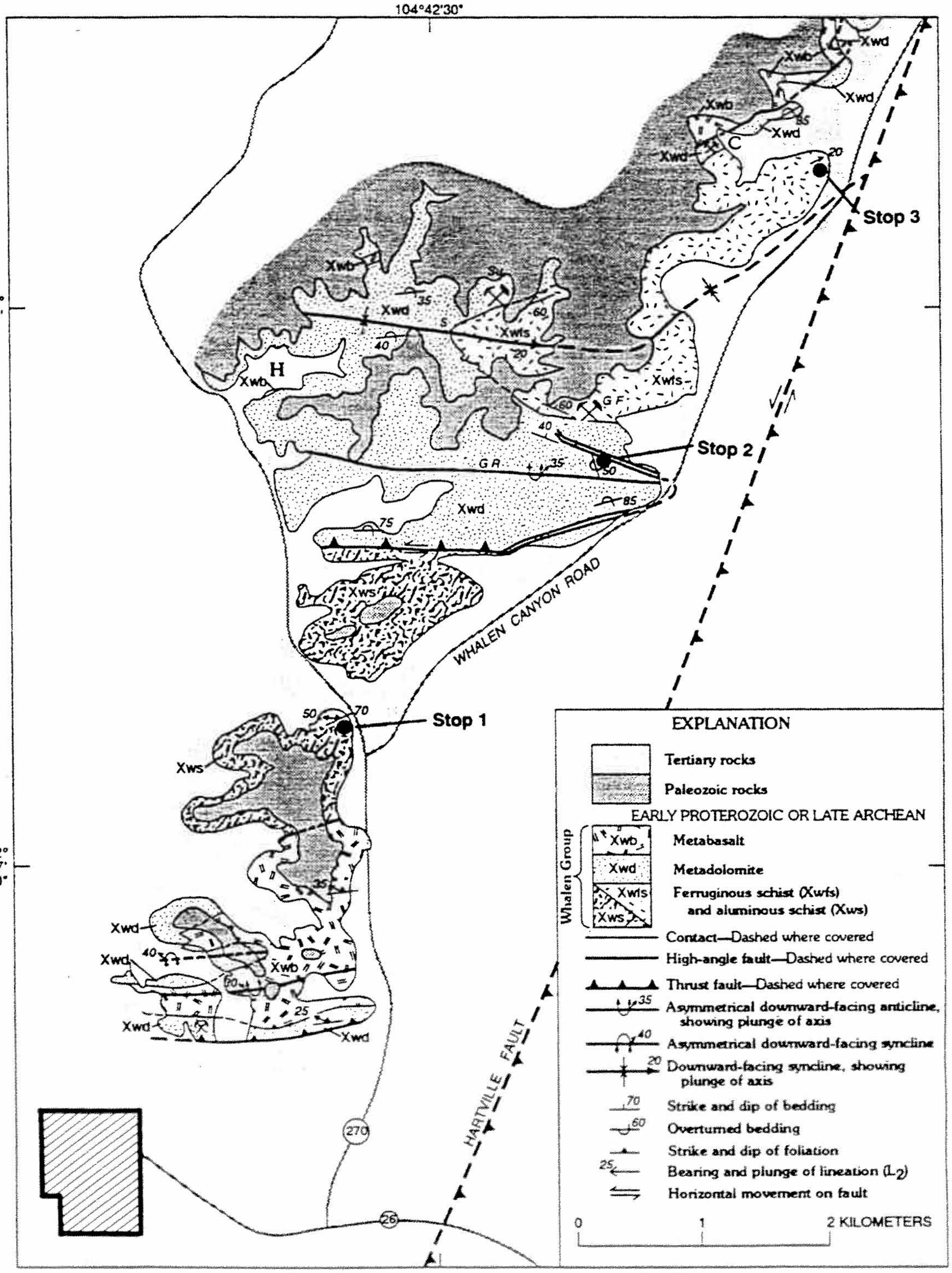


Figure 2. Geologic map of Precambrian rocks in a part of the Guernsey 7 ½-minute quadrangle, Hartville uplift, southeastern Wyoming. C, Chicago mine; H, Hartville; S, Sunrise syncline; GR, Graves Ranch anticline; GF, Good Fortune mine; Su, Sunrise mine. Town of Guernsey is shown by the diagonally-ruled polygon in the lower left corner.

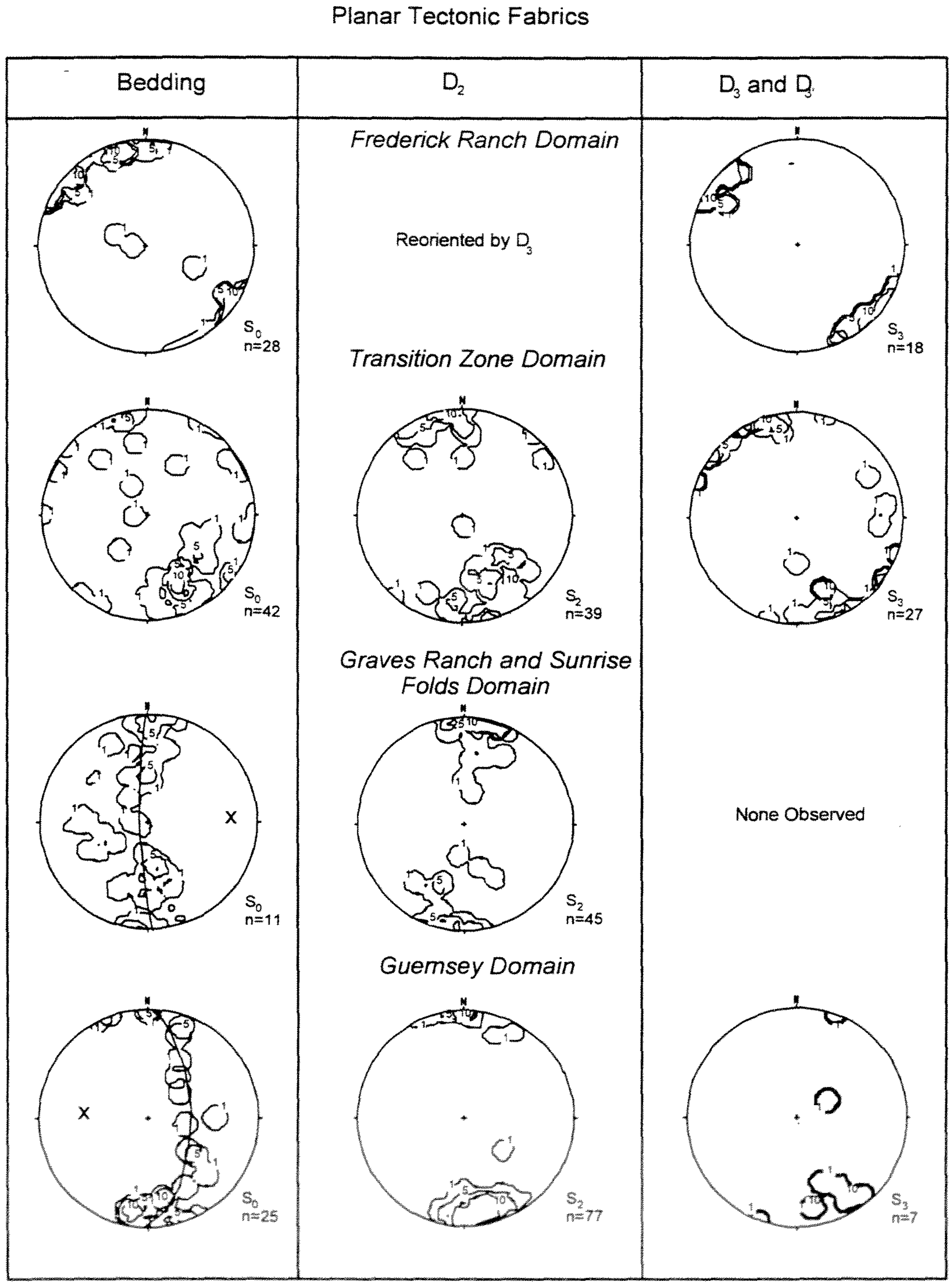
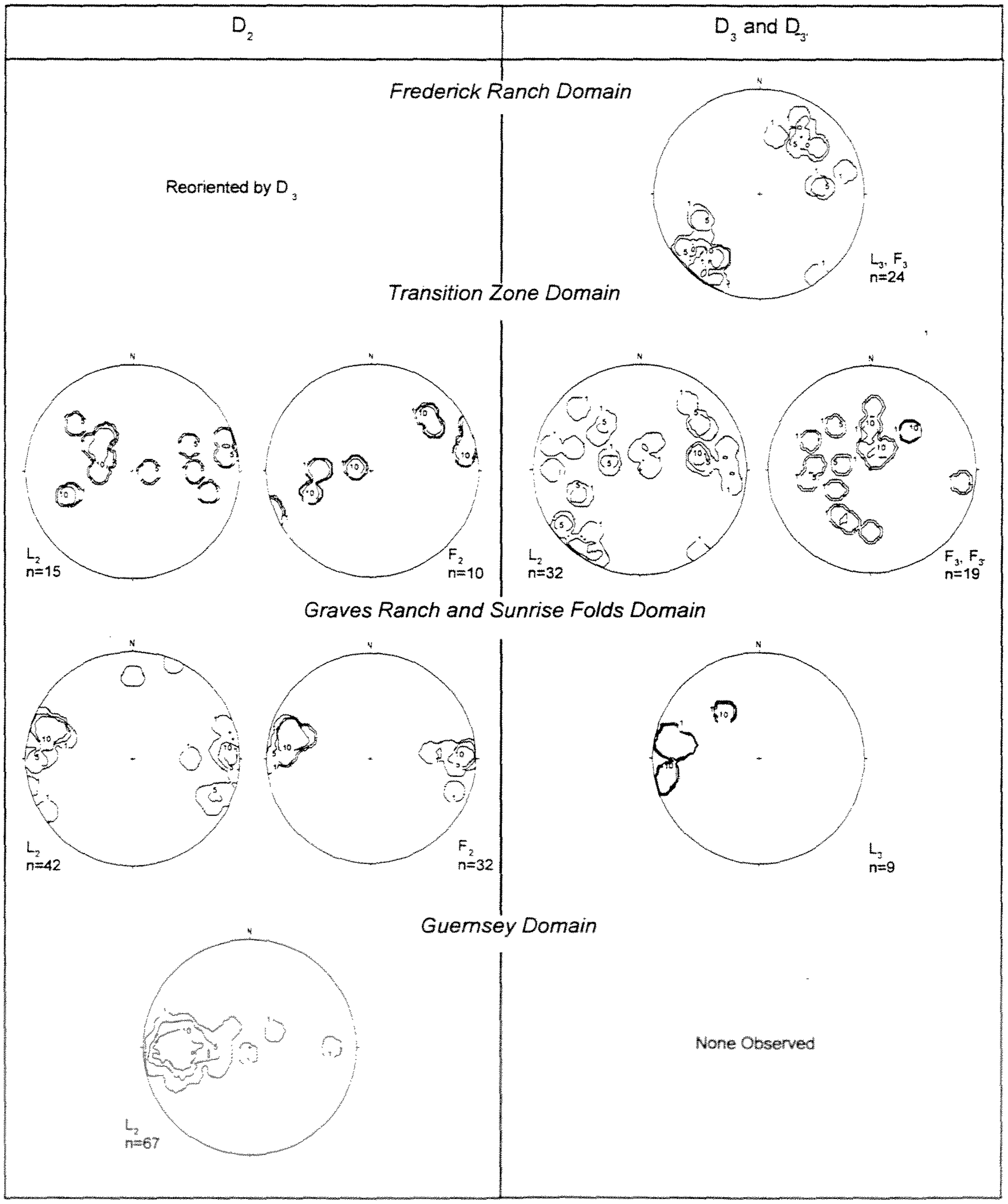


Figure 3. Equal-area projections (lower hemisphere) of structures in western part of Guernsey quadrangle (fig. 2). Planar and linear fabrics are shown for four domains delineated in study area (Sims and others, in press). Guernsey domain is the southern half of area; Frederick Ranch domain is north of Chicago mine (fig. 2); transition zone is northern part of area between Guernsey and Frederick Ranch domains. Planar structures, poles to S surfaces, contoured; linear structures, orientation of plunge of folds and lineations. X, inferred fold axis.

Linear Tectonic Fabrics



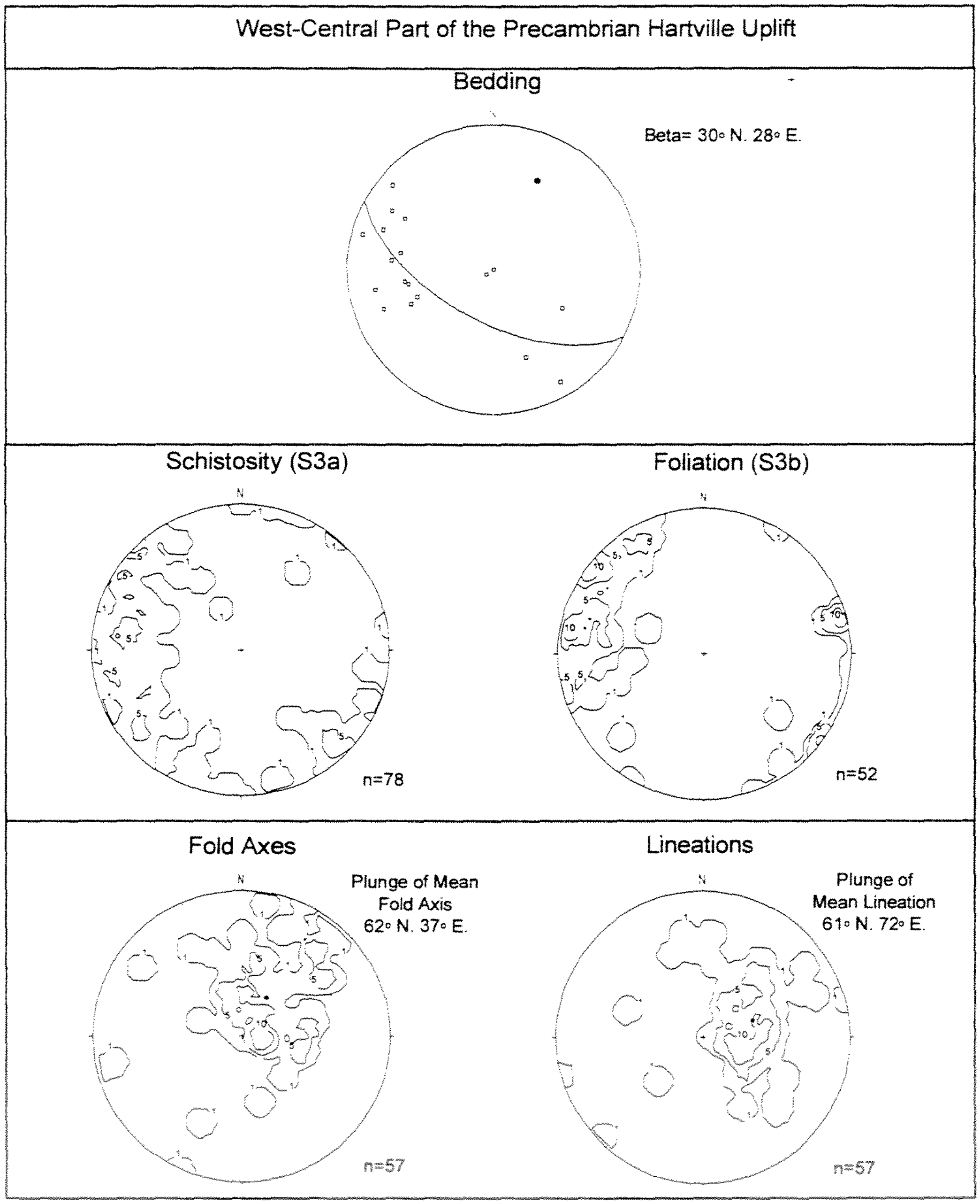


Figure 4. Equal-area projections of D_3 structures and bedding in west-central part of Hartville uplift. Schistosity (S_{3a}) and foliation (S_{3b}) are discussed in text. Fold axes and lineations are D_3 structures. Structures were measured in Frederick Ranch domain and areas to the north, including area of figure 5.

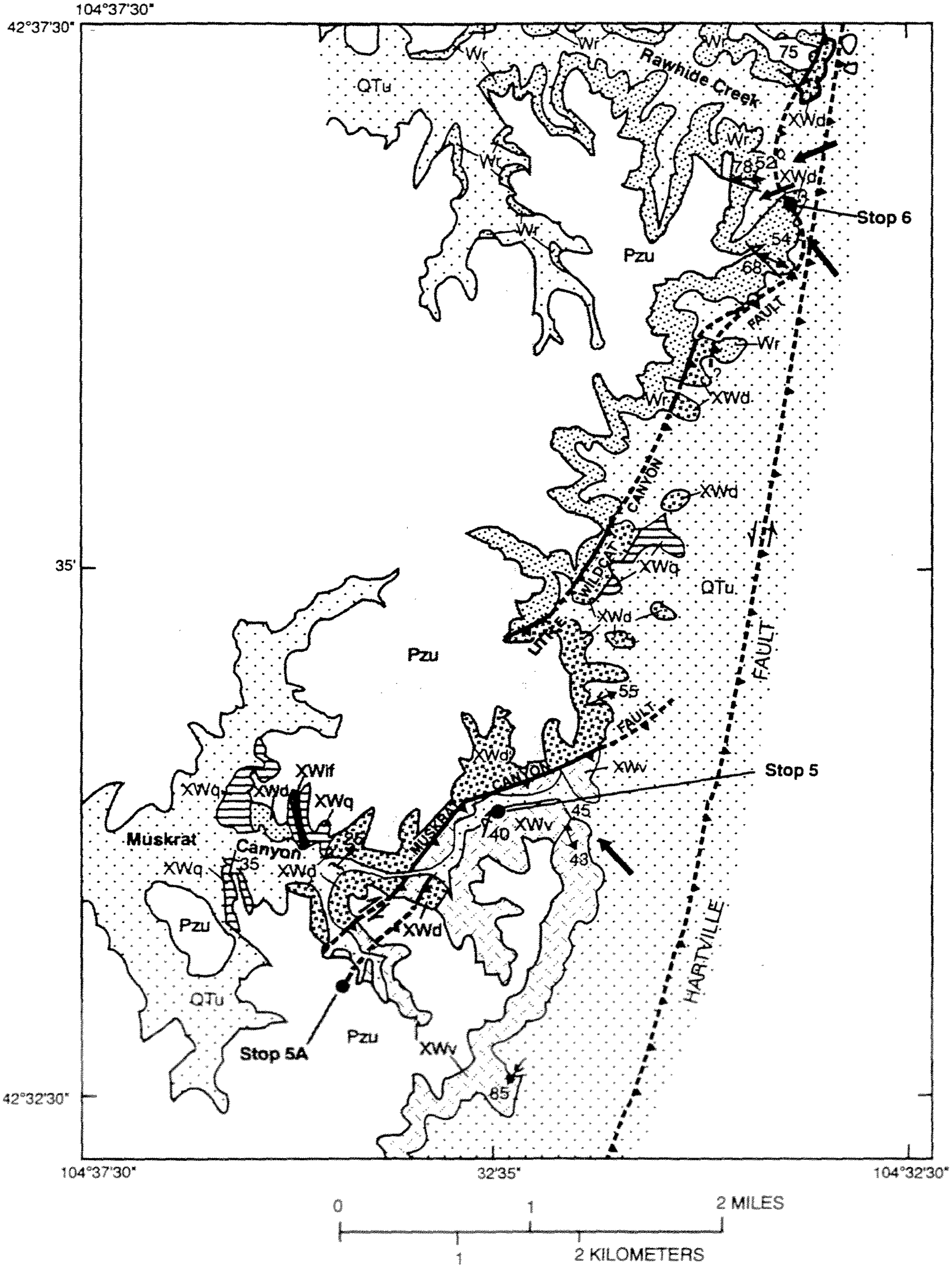


Figure 5. Geologic map of Precambrian rocks in a part of the Rawhide Buttes West 7 ½-minute quadrangle, Hartville uplift, southeastern Wyoming. (legend)

EXPLANATION

QTu	Quaternary and Tertiary sediments
Pzu	Paleozoic rocks
	EARLY PROTEROZOIC OR ARCHEAN
XWv	Mafic metavolcanic rocks
XWd, XWq, XWif	Metadolomite; XWq, quartzite; XWif, banded iron-formation
	ARCHEAN
Wr	Rawhide Buttes Granite; age, 2.58 Ga; includes mylonitic granite
	Contact
	Thrust fault of Early Proterozoic age (Deformation D_3); teeth on hanging wall; dashed where covered; arrows show relative horizontal movement
25	Bearing and plunge of symmetrical folds
55	Bearing and plunge of small-scale syncline
85	Bearing and plunge of small-scale anticline
40	Strike and dip of overturned beds
68, 54	Strike and dip of foliation and bearing and plunge of lineation
	Direction of tectonic transport, as indicated by stretching lineation

NOTE: Early Proterozoic (~2.0 Ga) metadiabase dikes omitted for clarity

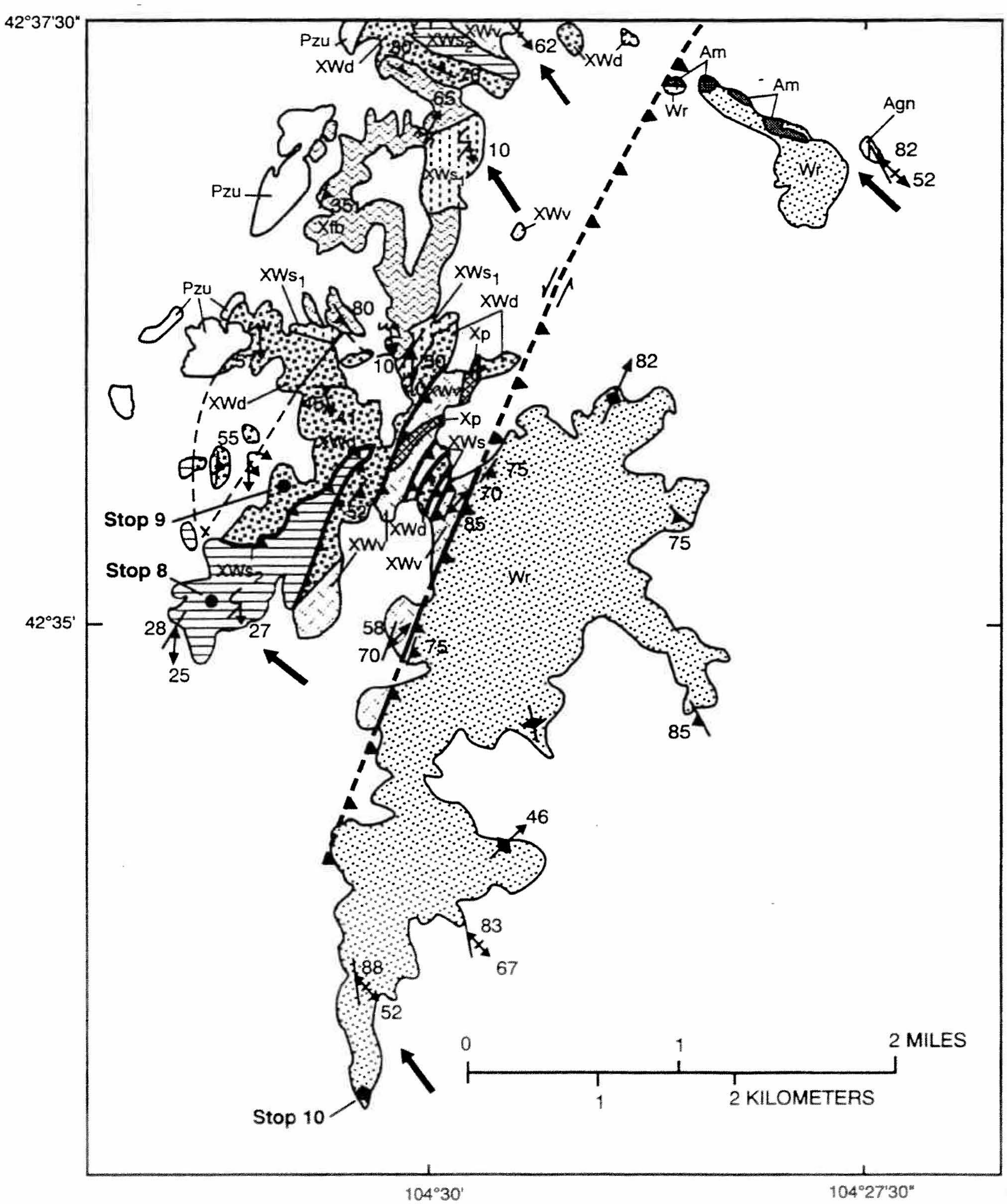


Figure 6. Geologic map of Precambrian rocks in parts of the Rawhide Buttes West and Rawhide Buttes East 7 ½-minute quadrangles, Hartville uplift, southeastern Wyoming. (legend)

EXPLANATION

QTu	Quaternary and Tertiary sediments
Pzu	Paleozoic rocks
	EARLY PROTEROZOIC
Xfb, Xp	Flattop Butte Granite; age, 1.98 Ga; Xp, pegmatite
	EARLY PROTEROZOIC OR LATE ARCHEAN (WHALEN GROUP)
XWv	Mafic volcanic rocks
XWs_2	Biotite-muscovite schist
XWd, XWs	Metadolomite; XWs, pelitic rocks
XWs_1	Biotite schist
	ARCHEAN
Wr	Rawhide Buttes Granite; age, 2.58 Ga
Am	Metasedimentary rocks
Agn	Migmatitic biotite gneiss
	Contact, dashed where inferred
	Thrust fault of Early Proterozoic age (deformation D_3); teeth on upper plate; dashed where covered; arrows show relative horizontal movement
	Asymmetrical anticline showing bearing and plunge of axis
57	Bearing and plunge of symmetrical fold
27	Bearing and plunge of asymmetrical fold
28, 25	Strike and dip of foliation and bearing and plunge of lineation
46	Strike and dip of vertical foliation and bearing and plunge of lineation
62	Bearing and plunge of stretching lineation
	Direction of tectonic transport, as indicated by stretching lineation

NOTE: Early Proterozoic metadiabase dikes omitted for clarity

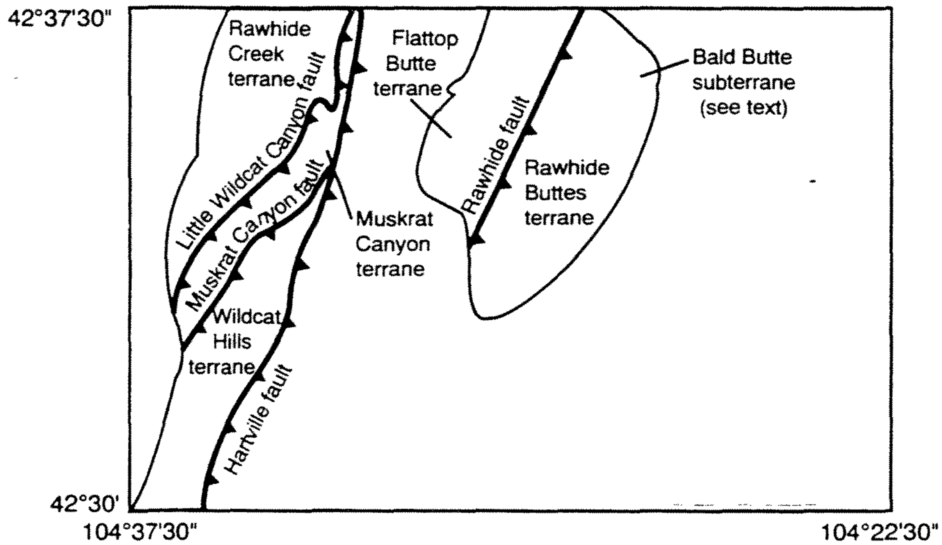


Figure 7. Map showing tectonostratigraphic terranes in Rawhide Buttes West and Rawhide Buttes East 7 ½-minute quadrangles.

which is dominated by the Rawhide Buttes Granite of Snyder (1980); (2) Muskrat Canyon terrane, which is composed mainly of metadolomite and quartzite of the Whalen Group; and (3) Wildcat Hills terrane, which is composed almost entirely of metabasalt of the Whalen Group.

The granite in the Rawhide Creek terrane has a well-developed northwest-striking foliation (interpreted as S_{3a}), and a generally east- or northeast-plunging rodding (stretch) lineation (L_{3c}). Multiple metadiabase dikes are deformed and metamorphosed. Adjacent to the Little Wildcat Canyon fault, S_3 structures in granite are obliterated by a younger $S_{3'}$ foliation (ductile) that is subparallel to the Little Wildcat Canyon fault. The bedded rocks in the Muskrat Canyon terrane are folded on northeast-trending, northeast-plunging axes (F_3). Judging by crossbeds in quartzite near the head of Muskrat Creek, a part or all of the succession in this terrane is overturned. The metabasalt in the Wildcat Hills terrane also is overturned, as indicated by pillow structures exposed in Muskrat Canyon (sec. 19, T. 30 N., R. 64 W.). Folds in these rocks have the prevailing northeast trend characteristic of deformation D_3. A prominent rodding (stretching lineation, L_{3c}) in the metabasalt exposed on the south side of the creek as it exits the canyon plunges 35°-70° S. 45° E. Inasmuch as the rodding represents the X direction of the strain ellipsoid, it indicates that the Wildcat Hills terrane was thrust northwestward and upward over the Muskrat Canyon terrane during deformation D_3. Deformation D_3 definitely involved the basement granite as well as the supracrustal rocks in the areas on both sides of the Hartville fault (fig. 6).

East of the Hartville fault, two terranes are delineated: (1) the Rawhide Buttes terrane, on the east, and (2) the Flattop Butte terrane. A major thrust, the west-vergent Rawhide fault, separates the two terranes. In the area immediately west of the Rawhide fault, narrow slices of supracrustal rocks compose an imbricate thrust belt nearly 1 km wide (fig. 8). The Rawhide Buttes terrane is composed of two subterranes named the Rawhide Buttes and the Bald Buttes. The Rawhide Buttes terrane consists of the Rawhide Buttes Granite, which is cut by abundant deformed and metamorphosed north-trending metadiabase dikes. The granite has a well-developed foliation and two types of lineations, a mineral lineation (L_{3b}) that is subparallel to rare fold axes and a rodding (L_{3c}, stretching) lineation that plunges 65° S. 59° E. (average). The ductile stretching lineation indicates that the Rawhide Buttes terrane (domain) was transported about N. 30° W. and upward relative to the Flattop Butte terrane. The direction of transport was oblique to the Rawhide fault. The Bald Butte subterrane consists of Rawhide Buttes Granite and a fringe of infolded Archean supracrustal rocks on the northeast side of the butte. The granite and supracrustal rocks are folded on northwest-trending axes that are parallel to a conspicuous rodding lineation (L_{3a}) in the granite (55° S. 50° E.). Younger, open folds ($F_{3'}$) that bear S. 40°-50° W. and plunge at 50°-60° deform the supracrustal rocks and the granite. The Flattop Butte terrane is composed of rocks of the Whalen Group that are intruded by the 1.98 Ga Flattop Butte Granite. The bedded rocks as well as the granite were deformed by deformation D_3. S_0 and a well developed foliation, interpreted as S_{3a}, are folded on northeast-trending axes. The major fold is

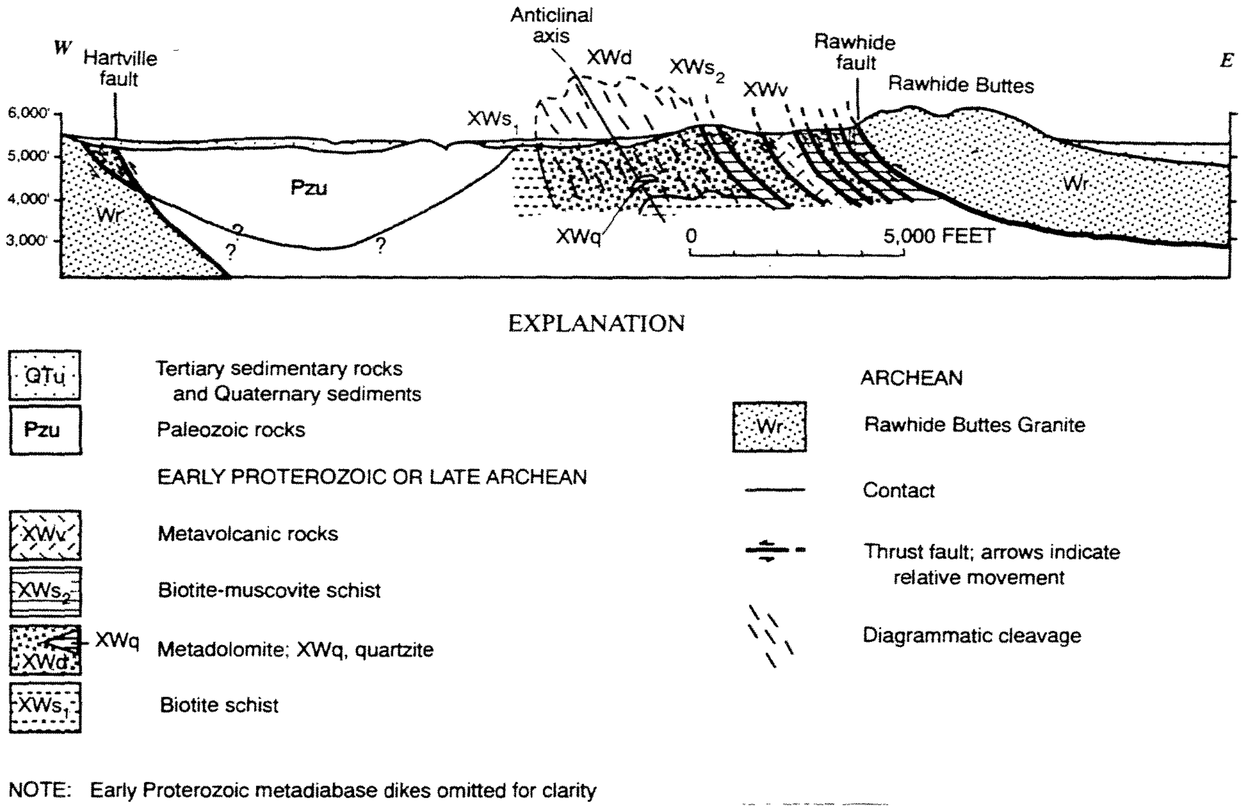


Figure 8. Geologic section showing structures in the foreland fold- and thrust-belt of the Trans-Hudson orogen.

an asymmetrical anticline overturned to the west that plunges southeast, south of the granite body and plunges northeast north of the granite. Scattered stretch lineations that plunge 44° S. 48° E. (average) in the southern part of the terrane and more variably southeast in the northern part indicate tectonic transport to the northwest and upward during deformation D_3.

This transport direction is oblique to the north-trending Hartville fault and can account for the sinistral movement on this thrust, documented in exposures of the fault in the Hell Gap quadrangle to the south.

In summary, deformation D_3 produced a foreland fold-and-thrust belt on the western margin of the Trans-Hudson orogen (fig. 8). The direction of tectonic transport was northwest, but differed slightly in both bearing and angle of plunge from terrane to terrane. Deformation D_3 folded S_0 and a generally prominent S_{3a} ductile foliation.

The culmination of D_3 deformation and metamorphism has not been dated in the Hartville uplift. It is inferred from isotopic studies in the nearby Laramie Mountains (Patel et al., 1991), however, to have taken place at about 1.82 Ga. The 1.82-Ga age is nearly identical to that on metamorphism in the Black Hills (~1.84 Ga; Redden and others, 1990) and in northern Saskatchewan (1.82 Ga; Hoffman, 1989; Weber, 1990)--areas also known to have been deformed as part of the Trans-Hudson orogen.

D_4 Deformation

Small-scale folds having nearly horizontal axial planes and fold axes and that do not appreciably modify previously folded rocks (F_2) are present intermittently in the southernmost part of the area, particularly in biotite schist lithologies. The folds are most intense and abundant in biotite schist immediately south of the Graves Ranch anticline (fig. 2). We suggest that these late flattening structures could have resulted from crustal thickening caused by superposed imbricate thrust sheets related to continent-arc collision along the Cheyenne belt at about 1.76 Ga. The Cheyenne belt is a north-verging mylonite zone (Houston et al., 1993) that superposes island-arc rocks of the Colorado province (Reed et al., 1987) and the Central Plains orogen (Sims and Peterman, 1986) with continental margin rocks of the Wyoming craton.

Associated crenulation and kink folds are superposed on the D_4 flattening structures and D_2 structures in the southern part of the uplift. They are rarely observed north of the Chicago mine (fig. 2). In one area of phyllite (unit XWs, fig. 2) examined in detail (R.L. Bauer, University of Missouri, written communication, 1993), crenulations of S_1 have both S and Z symmetry that occur as a conjugate set. The Z crenulations generally plunge northeast and have northeast-striking axial planes; the S crenulations generally plunge northwest and have northwest-striking axial planes. These crenulations are cut by kink bands that also seem to form a conjugate set. These structures appear to be a result of a west-directed shortening event. Possibly these late structures also are related to collision along the Cheyenne belt. The timing would be consistent with this 1.76-Ga event.

Our interpretation that the late flattening structures in the Hartville uplift probably were produced by stacked thrust sheets caused by collision along the Cheyenne belt is supported by observations of Chamberlain and others (1993) in the Laramie Mountains to the west. They have shown that a 60 km-wide foreland fold-thrust belt, bounded on the north by the Laramie Peak shear zone (Garrett-Fletcher Peak-Cottonwood Park shear zone of fig. 9), exists in the Laramie Mountains north of the Cheyenne belt, although erosion has removed all Early Proterozoic rocks in this belt. The Hartville uplift is estimated to lie well within a range of 60 km from the eastward projection of the Cheyenne belt (fig. 9) and should also have been affected by the 1.76-Ga deformation.

WESTERN CONVERGENT MARGIN OF TRANS-HUDSON OROGEN

The Hartville uplift provides the only exposure of the western continental margin of the Trans-Hudson orogen (THO) in the United States (Sims and others, 1991). The nearest exposures of such continental rocks are 1,400 km to the north, in northern Manitoba and Saskatchewan (Lewry and Collerson, 1990). Arc-related rocks of the THO are exposed in the Black Hills in South Dakota (Redden and others, 1990), where they overlie older miogeoclinal rocks.

In the Hartville uplift, rifting and emplacement of north-trending mafic dikes (~2.0 Ga) in response to opening of the Trans-Hudson (Manikewan) ocean followed deposition of the mainly ferruginous and aluminous sediments, dolomite, minor quartzite, and basalt of the Whalen Group. These supracrustal rocks were deposited before ~2.1 Ga on a south-facing passive continental margin. If sedimentation also took place on the east-facing passive rifted margin exposed in the Hartville uplift after or during dike emplacement, these sedimentary rocks have either been eroded or are covered by Phanerozoic rocks.

Closing of the Trans-Hudson (Manikewan) ocean produced a west-vergent, foreland fold-and-thrust belt (D_3) on the passive, eastern margin of the Wyoming craton. The deformation was thick-skinned because it involved the Late Archean granite and gneiss basement as well as the supracrustal rocks. The culmination of metamorphism is inferred to have taken place at about 1.82 Ga.

Diorite (1.74 Ga) and granite (1.72 Ga) plutons were emplaced in the eastern, higher grade rocks of the Hartville uplift (Snyder, 1980; fig. 1), probably as a consequence of crustal thickening and melting of lower crustal rocks concomitant with collision along the Cheyenne belt (ca. 1.76 Ga; Duebendorfer and Houston, 1987). The Cheyenne belt is the northwest boundary of the Central Plains orogen (fig. 3) (Sims and Peterman, 1986; Sims, 1995). Another probable manifestation of the Cheyenne belt collision in the Hartville uplift is the late, small-scale recumbent structures and the somewhat brittle crenulations and kinks (D_4) that are superposed on the previously folded supracrustal rocks in the southernmost part.

In contrast to the west vergence of the west margin of the Trans-Hudson orogen in the Hartville uplift, two recent deep seismic reflection surveys across the Trans-Hudson orogen indicate symmetrical profiles. A seismic profile by COCORP (Consortium for Continental Reflection Profiling) (Nelson and others, 1993) at latitude 48°30'N. suggests westward subduction of the THO beneath the Wyoming craton (on the west) and eastward subduction of the orogen beneath the Superior craton (on the east). To the west of the west-dipping reflectors (at about longitude 105° W.) within the Wyoming craton, intracrustal reflections in the upper crust dip steeply east, suggesting that the eastern margin of the Wyoming craton was imbricated in an east-over-west sense. This structural scenario appears similar to that seen in outcrop in the Hartville uplift. A similar symmetrical seismic profile across the THO was obtained in Canada, just south of the limit of outcrop of the THO and adjacent cratons, about 700 km north of the United States-Canada border (Lucas and others, 1993).

REGIONAL TECTONIC FRAMEWORK

The Laramide uplifts along the southeast margin of the Wyoming craton lie at the confluence of two major Early Proterozoic orogens, the Trans-Hudson (~1.82 Ga) and the Central Plains (~1.76 Ga) (fig. 9). Mapping in the Hartville uplift has identified another, older orogenic episode along the margin that possibly is related to a pre-Cheyenne belt thrust exposed in the Medicine Bow Mountains. This is the D_2 deformation of the Hartville uplift.

The youngest of the orogens, the Central Plains (Sims and Peterman, 1986), is exposed in the Medicine Bow Mountains, where it is represented by island-arc rocks of the Colorado province (fig. 9) and continental margin sedimentary rocks of the Wyoming craton, which are juxtaposed along the Cheyenne belt, a north-vergent shear zone a maximum of about 12 km-wide (Houston and others, 1992, and references therein). The Cheyenne belt is inferred from geophysical and sparse drill hole data to truncate the Trans-Hudson orogen east of the Laramie Mountains (Sims, 1995) and to extend eastward in the subsurface, passing about 60 km south of the Black Hills (Sims and others, 1991). The eastern extension of the Cheyenne belt is inferred to lie about 15 km south of the southern tip of the Hartville uplift, yet it did not appreciably deform rocks in the uplift. We interpret deformation D_4 as probably having resulted from collision along the Cheyenne belt. It produced recumbent folds, now limited in areal extent to the southernmost part of the uplift, but did not materially affect the distribution or structure of rock units in the uplift. The principal effect of the deformation (~1.76 Ga) along the convergent margin was the generation of the 1.72 Ga granite magma (Haystack Range Granite) and the 1.74 Ga Twin Hills Diorite exposed in the eastern segment of the Hartville uplift. In the same way, a 1.71 Ga (Riley, 1970) granite magma was generated in the Black Hills uplift. These granitic magmas, which form structural domes, can be modeled as being crustal melts generated in a crust thickened by imbricate thrusting during Cheyenne belt deformation.

Exposures in the Hartville uplift mainly constitute a foreland fold-and-thrust belt of the Trans-Hudson orogen. The suture between the continental margin and arc rocks of the hinterland lies east of the uplift and is buried. A major thrust or high-angle reverse fault (Hartville fault) parallels the length of the uplift and separates greenschist-facies metamorphic rocks on the west from amphibolite-facies rocks on the east. The average direction of tectonic transport during deformation D_3 was about N. 45° W., as indicated by stretching lineations. The deformation was oblique to the Hartville fault, resulting in a probably small but unknown amount of sinistral movement on the fault. Where exposed 25 km north of Guernsey, the Hartville fault is a steep southeast-dipping structure. Associated thrust faults are northwest-vergent structures. Mafic dikes that cut the Late Archean (2.58 Ga) granite and the Late Archean or Early Proterozoic supracrustal sedimentary and volcanic rocks are older than the 1.98 Ga Flattop Butte Granite and are presumed to be coeval with the well-dated ~2.0 Ga mafic dike swarm in the Laramie Mountains (G.L. Snyder, oral comm., 1995). The mafic dikes are older than deformation D_3 (Trans-Hudson orogen) and are interpreted as being related to rifting during opening of the Trans-Hudson (Manikewan) ocean. Deformation D_3 has not been dated accurately, but is younger than the 1.98 Ga granite and older than the 1.74 Ga diorite and 1.72 Ga granite in the uplift. Probably the deformation and accompanying metamorphism took place about 1.82-1.84 Ga; this age is in accord with the age of metamorphism in the Black Hills (1.84 Ga; Redden and others, 1990), and is similar to the Pb-Pb ages of apatite (1.82-1.78 Ga) from the Laramie Peak shear zone and areas to the south in the Laramie Mountains (Chamberlain and others, 1993).

In the southernmost part of the Hartville uplift east- west-trending, south-verging folds in the supracrustal rocks clearly are older than deformation D_3 (THO). These structures are assigned to deformation D_2. D_2 was accompanied by the development of fold nappes. In the southern part of the uplift, the foliation is axial planar to F_2 folds. Deformation D_2 pre-dates emplacement of the ~2.0 Ga mafic dikes.

The cause of deformation D_2 is speculative. It is tempting to correlate D_2 with thrusting in the Medicine Bow Mountains that preceded deformation along the Cheyenne belt (1.76 Ga). In the Medicine Bow Mountains, Houston and Karlstrom (1992) recognized a deformation that preceded deformation along the Cheyenne belt (1.76 Ga). They recognized that the north-verging Reservoir Lake fault separated more intensely deformed rocks (Deep Lake Group) on the north from less deformed Early Proterozoic rocks (Libby Creek Group) on the south. They assigned this deformation of rocks north of the Reservoir Lake fault to their F_2 (Karlstrom and others, 1981, fig. 1.9); it preceded intrusion of gabbroic sills in the Deep Lake Group, whose intrusive age is 2,092±4 Ma (Houston and others, 1992, p.39). The Reservoir Lake fault and adjacent rocks were folded later by their deformation F_3 along the 1.76-Ga Cheyenne belt (fig. 9) (Houston and others, 1993).

TECTONOSTRATIGRAPHIC EVOLUTION OF SOUTHEASTERN MARGIN OF THE WYOMING ARCHEAN CRATON

1. Deposition of sedimentary and volcanic rocks of Whalen Group on continental margin, either in Late Archean or Early Proterozoic. Basement in area is predominantly Rawhide Buttes Granite (Snyder, 1980) but includes migmatitic biotite gneiss.

2. Nappe formation, resulting in exposure of lower limbs in Guernsey and Rawhide Buttes West quadrangles (deformation D_1).

3. Deformation D_2--south-vergent folding of supracrustal rocks and possible thrusting involving Archean basement in southern part of Hartville uplift. Deformation metamorphosed gabbro body on hill southeast of Graves Ranch. Deformation D_2 predated emplacement of ~2.0 Ga mafic dikes and is inferred to have occurred at ~2.1 Ga.

4. Rifting on approximate east-west axes and emplacement of ~2.0 Ga diabase dikes. Dikes are older, than 1.98 Ga Flattop Butte Granite (Snyder and Peterman 1982) and, in Laramie Range, are younger than 2.05 Ga granodiorite (Snyder, 1989).

5. Emplacement of Flattop Butte Granite (Snyder, 1980); age 1.98 Ga (Snyder and Peterman, 1982).

6. Deformation D_3--west-directed foreland fold-and-thrust belt developed on west margin of Trans-Hudson orogen; culmination of metamorphism estimated at ~1.82 Ga, based on the age of metamorphism in Laramie Range (Patel and others, 1991). Deformation of Flattop Butte

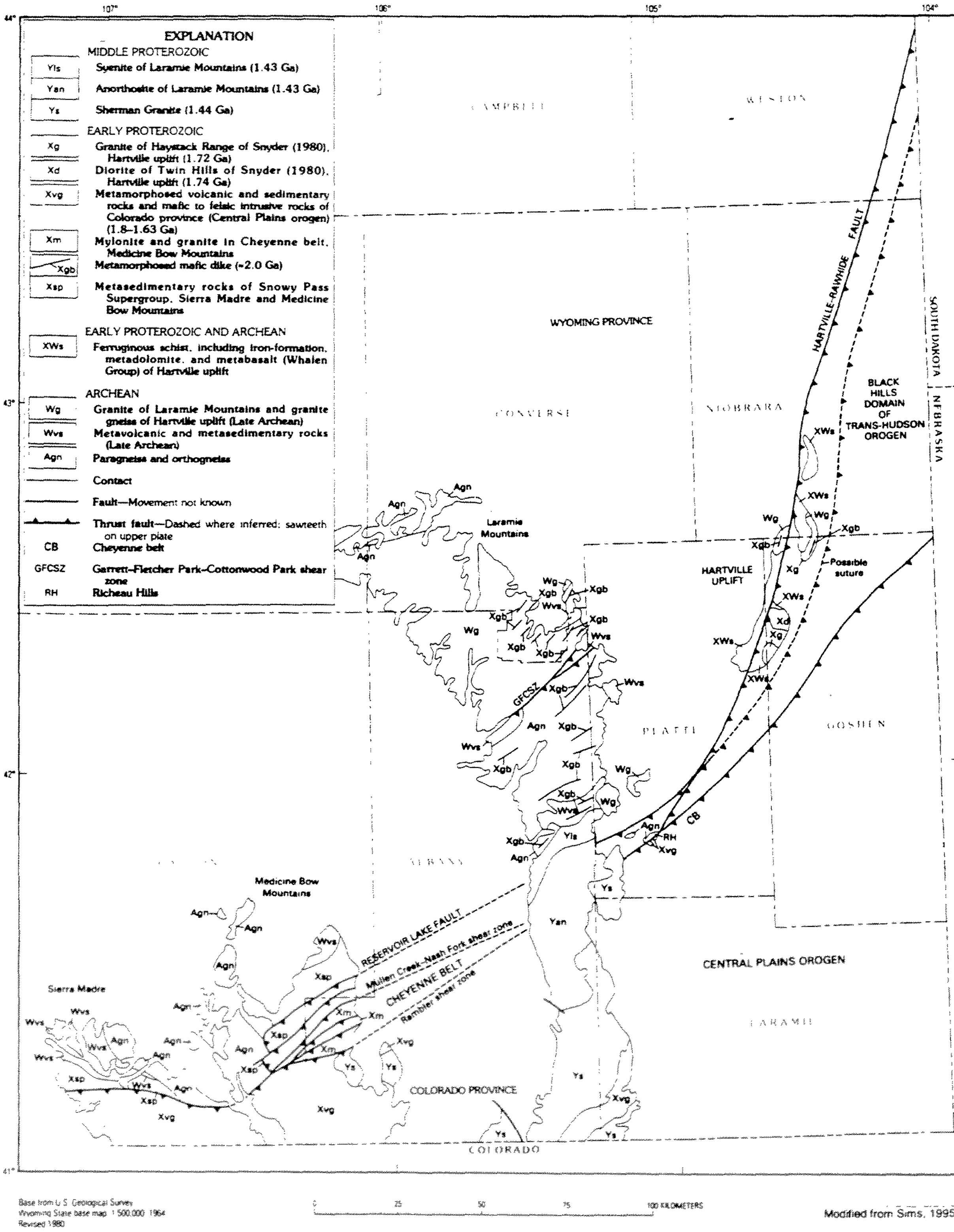


Figure 9. Geologic-tectonic map of Precambrian rocks exposed in Laramide uplifts, southeastern Wyoming.

Granite, as well as supracrustal rocks of Whalen Group and granitic basement (Rawhide Buttes Granite), caused by collision of arc rocks of Trans-Hudson orogen with continental margin.

7. Deformation D_4--small-scale recumbent folds in schist in southern part of uplift; fold D_2 structures. Possibly related to loading by imbricate thrusts developed on continental margin during collision along the Cheyenne belt; age, 1.76 Ga (Premo and Van Schmus, 1989).

8. Emplacement of Twin Hills Diorite (1.74 Ga) in area east of Hartville fault.

9. Emplacement of Haystack Range Granite (1.72 Ga) in southern part of Hartville uplift, east of Hartville fault. The intrusion domed biotite schist country rock.

10. Intrusion of granite pegmatite in schist adjacent to Haystack Range Granite contemporaneous with emplacement of granite. Diorite and granite are interpreted to be related to crustal melting resulting from crust thickened by thrusting along the Cheyenne belt, the paleosuture between Archean continental rocks and arc-related rocks of the Central Plains orogen (Sims and Peterman, 1986).

11. Resetting of U-Pb system in monazite at 1.66 Ga (Krugh and others, 1993), possibly as a result of compressive deformation within the Central Plains orogen. Possibly the ductile deformation (protomylonite) observed in Haystack Range Granite formed at this time.

12. Intrusion of metadiabase dikes with chilled margins; probably 1.4 Ga age (Snyder, 1993).

ACKNOWLEDGMENTS

Our structural study was made possible by the earlier geologic mapping of Precambrian rocks in the Hartville uplift by Snyder (1980). This mapping together with related chemical and geochronologic studies (Snyder and Peterman, 1982) provided the framework needed for our more detailed structural studies.

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Mineral Deposits in the Hartville uplift

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INTRODUCTION

Mineral production began in the Hartville uplift as early as 1880, with the production of copper in the Hartville district in the southern part of the uplift (fig. 2). Shortly after copper production ceased, mining of hematitic iron deposits associated with the copper deposits began and continued for more than 80 years. Volumetrically, the major mineral commodity produced from the uplift has been iron. However, crushed stone from metadolomite (Whalen Group) near Guernsey and granite (Rawhide Buttes Granite) in the northern part of the area (fig. 10) are the only commodities currently being produced; these products will eventually surpass iron in volume. In addition to these commodities, minor amounts of muscovite, gold, silver, and uranium have been produced from the uplift. Most of the mineral production has come from the metasedimentary units of the Whalen Group. Except for the Michigan mine, the locations of iron deposits discussed in this report are shown in figure 2 and the location of copper deposits are shown in figure 10. The Michigan mine is located at the head of Muskrat Canyon (fig. 5).

IRON DEPOSITS

Iron was first produced from the Sunrise mine in the Hartville district in 1898, after the mine was initially developed in the early 1880's for copper (figs. 2 and 10). Three other mines, the Chicago, Central, and the Good Fortune also produced direct-shipping hematite ore for the Colorado Fuel and Iron Corporation open-hearth furnaces in Pueblo, Colorado. At the time mining ceased at the Sunrise mine in 1980, the district had produced about 41 million metric tons of iron ore (Hausel, 1989).

Two distinct types of iron deposits occur in the Hartville uplift: (1) structurally-controlled pods of soft, earthy, massive hematite ore which grades downward to a fibrous, gray, specularite ore (e.g., deposits of the Hartville district), and (2) layers of Lake Superior-type hematite-quartz iron-formation (e.g., Michigan mine, fig. 10). Both types are associated with metapelites in ferruginous schist (Sims and others, in press), immediately below the contact with metadolomite in the Whalen Group.

The distribution of iron deposits in the Hartville district is controlled by east-trending folds related to deformation D_2. All of the large mines in the district are located in the same stratigraphic position relative to the adjacent metadolomite. Along strike, the earthy and fibrous hematitic ore apparently grades into Superior-type iron-formation. The Sunrise ore body is located in a steeply plunging fold that is S-shaped in map view (Osterwald and others, 1966) and extends to a depth of at least 300 m (Ball, 1907a). Oxidation resulting in soft, earthy, hematite ore extends to about 60 m below the surface (Osterwald and others, 1966). The origin of the deposits is problematic. Much of the soft, earthy hematite ore in the upper parts of the deposits was the product of groundwater oxidation of the gray, specularite ore after deposition of the Devonian Guernsey Formation. The fibrous, specularite ore probably is the modification of Superior-type iron-formation by fluids before D_2 folding. However, the source and physical character of the fluids are not known.

In the area of the Michigan mine in Muskrat Canyon (central part of the uplift, figs. 5 and 10), three layers of hematitic iron-formation lie in moderately east-dipping slates within a quartzite unit of the Whalen Group. The western contact of the thickest (western-most) iron-formation with metadolomite is fault-controlled. Iron ore reserves at the mine were estimated to be about 105 million metric tons averaging about 25 percent iron. Copper mineralization is controlled both by the fault zone and the Paleozoic unconformity. Grab samples were reported to contain about 1 percent copper (Hausel, 1989).

COPPER DEPOSITS

Copper was the first mineral commodity mined in the Hartville uplift. During the period 1880-1890, the Sunrise mine produced more than 630 metric tons of copper and more than 70 kg of silver (Hausel, 1989) from

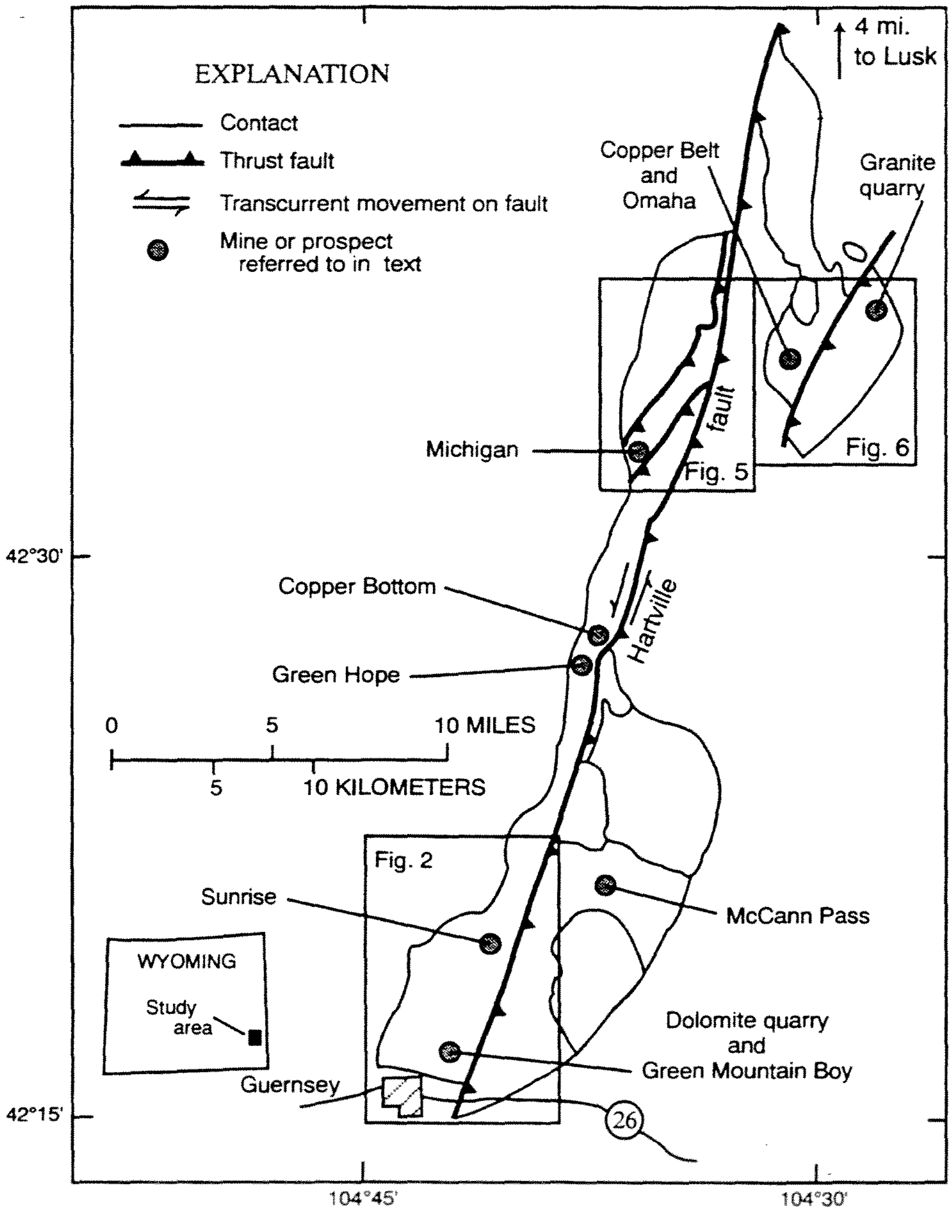

Figure 10. Index map showing locations of mines and prospects referred to in text. Rock units are the same as Figure 1.

oxide and carbonate deposits lying above the hematitic iron ore near the Paleozoic unconformity. In addition, about 100 metric tons of copper was produced from hematitic iron-formation at the Michigan mine (figs. 5 and 10) in Muskrat Canyon (Knight, 1893), about 185 metric tons copper and 8.5 kg silver from a replacement deposit at the Green Mountain Boy mine (figs. 2 and 10), and about 85 metric tons of copper from the Green Hope mine (fig. 10).

Four types of copper deposits are present in the Hartville uplift: (1) Copper sulfides in sediment-hosted massive sulfide deposits (e.g., McCann Pass prospects), (2) disseminated copper sulfide deposits in shear zones (e.g., at the Omaha mine and Copper Bottom prospect and in Muskrat Canyon), (3) copper sulfide deposits associated with iron-formation (e.g., deposits in the Hartville district and the Michigan mine), and (4) copper oxide and carbonate deposits associated with the Paleozoic unconformity (e.g., Green Mountain Boy mine, Green Hope mine). Both gold and silver are associated with shear zone-hosted copper deposits, sediment-hosted massive sulfide deposits, and copper deposits in iron-formation.

Sediment-hosted massive sulfide deposits

Several prominent gossans occur above massive sulfide lenses in the schist unit in the Silver Springs quadrangle, immediately north of figure 5. The zones are typically associated with graphitic intervals and cherts within muscovite schist. In the McCann pass area (fig. 10), several strata-bound lenses are exposed near the west-northwest-trending McCann Pass fault. North of the McCann Pass fault, northeast-striking sulfide lenses are conformable to S_0 in the schist. Along the McCann pass fault, the thickest gossan appears to have been rotated parallel to the northwest-trending fault and may have been tectonically thickened. Chemical analyses of surface samples from the gossan lens, which is about 1,000 m long and 100 m thick, yield values of 20 to 300 ppm copper, 200 to 900 ppm zinc, up to 7,000 ppm arsenic, and 30 to 3,000 ppm boron (Zahoney, 1976). In the northern part of the Hartville uplift, gossans occur in several places, and are similar to those described from McCann Pass. These deposits share many characteristics with Besshi-type massive sulfide deposits, including host-rock lithology (mafic volcanic rocks and pelitic sedimentary rocks), tectonic setting (continental margin), and principal sulfide mineral assemblage (pyrrhotite, pyrite, chalcopyrite)(Slack, 1993). Metal ratios of the deposits in the Hartville uplift.(i.e., Cu/Zn, Zn/Pb) are not known because of the lack of samples from unoxidized parts.

Copper sulfide deposits in shear zones

Copper deposits in the Rawhide Buttes district (Rawhide Buttes West quadrangle; fig. 10) and in several other areas in the uplift are controlled by shear zones in metadolomite. The shears contain copper carbonate and silicates at the surface; below the weathering zone chalcopyrite is the dominant copper mineral. Chalcocite is a locally abundant supergene enrichment product near the water table. Barite is reported to be a common gangue mineral in this district. At the Omaha mine, a thin mineralized schist interval between two metadolomite layers was exploited. In the adjacent Gold Hill mine, a thick quartz vein was mined; ores assayed 6 percent copper with 6.9 g/t gold (Ball, 1907b). The nearby Copper Belt deposit (figs. 6 and 10), which lies along a thrust fault, was extensively developed (more than 1000 m of underground workings) (Osterwald and others, 1966). The mineralized shear zone in the Rawhide Buttes district is a thrust related to D_3 that is characterized by sinistral lateral movement. Thick ore lenses assayed from 2 to 8 percent copper, 1.7 to 20 g/t gold, and from 69 to 170 g/t silver (Ball, 1907b). Graphite-rich rocks and quartz-calcite veins containing secondary disseminated copper minerals occur in several prospects. These deposits resulted from focusing of hydrothermal fluids along regional deformation (D_3) structures. The fluid at these locations differs from fluids in the previous examples in that it was apparently highly reducing. Graphite probably formed by reducing carbonate to carbon; the source of carbonate may have been either from the immediate wall rocks or from carbonate in the hydrothermal fluid.

The structures (D_3) that control these copper and precious-metal deposits in the Hartville uplift are similar to those controlling low-sulfide quartz-Au deposits in metamorphic terranes throughout the world (i.e., reverse/tranpressive regional faults). Faults or shear zones with a reverse sense of tectonic movement are typically the principle controlling structures for epigenetic precious-metal mineralization, at both the regional and local scale (see, Hodgson (1989); Poulsen and Robert (1989)). These faults and shear zones also typically have a component of lateral movement. Within these compressive domains, precious metals are generally localized in tensional environments (dilational zones) produced during deformation and(or) in related secondary structures. Deposition is also favored in lithologies and(or) environments within the shear zones where rocks behave in a brittle or brittle-ductile manner during deformation.

One of the more significant fault-controlled deposits in the Hartville uplift is the Silver Cliff mine near Lusk, Wyoming, which is 15 km north of figure 6. This deposit produced copper, silver, gold, and uraninite from a northeast-trending (N. 15° E.) reverse fault. A small amount of copper, silver, and gold were produced between 1880 and 1884 (Wilmarth and Johnson, 1954). This deposit also produced six carloads of uranium ore (3 percent U_3O_8) between 1918 and 1922. Osterwald (1950) indicated that gold concentrations in some mine samples range up to 17 g/t. Copper concentrations in the near surface workings range from less than 0.02 to 10.88 percent; silver concentrations range from 5.5 to 510 g/t (Wilmarth and Johnson, 1954). Precious metals, uranium minerals (uraninite, uranophane, metatorbernite, and gummite), and secondary copper minerals (chalcocite, native copper, cuprite, azurite, malachite, and chrysacolla) are concentrated in the weathered part of the fault zone and along a basal Paleozoic clastic unit (Guernsey Formation), above and adjacent to the fault along the major Paleozoic unconformity (Wilmarth and Johnson, 1954). A "blanket of copper ore" 6 to 12 m wide, 0.5 to 1.5 m thick, and about 50 m long in the basal Guernsey Formation along the fault was described by Ball (1907a). Copper and silver are enriched in the metamorphic footwall rocks (metapelitic schist) along the fault, but uranium shows no enrichment

(Ball, 1907a). In concert with many other deposits in the uplift, this deposit at Lusk may have had a compound origin, involving both hydrothermal and supergene processes. The uranium and secondary copper and silver deposits in the Silver Cliff mine were formed after the development of the Silver Cliff fault, which is probably a Laramide structure. These shallow deposits were most likely the result of meteoric water migration down the fault zone and into adjacent permeable zones. However, because Laramide faulting quite commonly was controlled by preexisting Precambrian shear zones in the Rocky Mountain foreland, it is possible that the Silver Cliff fault was originally a Precambrian (D_3) structure. The source of uranium is most likely the tuffaceous rocks of the overlying Miocene Arikaree Formation. However, the presence of significant gold in some ore samples from this deposit strongly argues for a hypogene hydrothermal origin. As seen elsewhere in the Hartville uplift, shear zones appear to have controlled hydrothermal base and precious-metal mineralization. The source of the copper and silver in the secondary deposits thus may have been shear zone-hosted deposits of Precambrian age. Alternatively, the source of the base and precious-metals may have been syngenetic sulfide concentrations in the biotite schists of the Silver Spring area which are present in nearby prospects described by Woodfill (1987). Lack of structural data at the Silver Cliff mine does not allow a definitive interpretation of its origin.

Other copper deposits

Much of the early copper production from the Hartville area was from copper oxide and carbonate deposits located near the Paleozoic unconformity at the base of the Guernsey Formation, the deposits occur in both carbonates and the coarse basal conglomerate of the Guernsey Formation and below the unconformity in iron-rich Precambrian rocks. One of the largest deposits in the Guernsey Formation, the Green Mountain Boy mine, was located at the site of the present day dolomite quarry east of Guernsey, Wyoming (see figs. 2 and 10). It consisted of a thick, keel-shaped chalcocite replacement body in the Guernsey Formation (Ball, 1907a). As much as 500 metric tons of high-grade copper ore (37 percent copper and up to 17 g/t silver) possibly was produced from this deposit. At the Green Hope mine (fig. 10), north of Hell Gap (fig. 10), secondary copper minerals occur in the basal Guernsey Formation along the Paleozoic unconformity. The underlying metadolomite of the Whalen Group is characterized by the development of small-scale karst features (Ball, 1907a). Secondary copper deposits also formed in Precambrian hematite-rich rocks below the unconformity in the area near the Sunrise iron mine (figs. 2 and 10). The copper was primarily enriched in permeable zones related to fractures in the iron-rich rocks below the unconformity (Ball, 1907a).

MUSCOVITE DEPOSITS

A small amount of muscovite was produced between 1881 and 1900 from pegmatites of the Haystack Range Granite (fig. 1). The deposits are located near the southern end of the Hartville uplift, south of McCann Pass (fig. 10). These pegmatite bodies are the youngest phases of the Haystack Range Granite (1.72 Ga). In the northern part of the uplift near Silver Springs (immediately north of fig. 5), pegmatite bodies were prospected mainly for beryl (Osterwald and others, 1966). All of the pegmatite bodies in the Hartville uplift are relatively small and poorly to well zoned; most contain minor amounts of tourmaline and beryl (Ball, 1907c). The pegmatites are not conformable to the principal schistosity, which forms a domal pattern (Hanley and others, 1950; Sims and others, in press). They generally are present in discontinuous bodies, ranging from 10 to 100 m in length, in muscovite-rich parts of schists in the Whalen Group.

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ROAD LOG AND STOP DESCRIPTIONS

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This field trip starts in Guernsey, WY, in the early afternoon, ends with stop 10 at the south end of Rawhide Buttes, and is designed as a two day trip. The trip emphasizes the structure of the Archean and Proterozoic rocks in the Hartville uplift as well as the mineral deposits in these rocks. The Whalen Group succession is typical of continental margin platform and rift sequences. The succession is either Late Archean or Early Proterozoic in age.

Day 1

Depart from Bunkhouse Motel in Guernsey, drive east about 1.2 miles to intersection of WY 270, then proceed north on Highway 270 to intersection with the Whalen Canyon road, a distance of about 2.5 miles. Park at intersection and walk northwest onto hill on northernmost part of ridge.

Stop 1

Garnetiferous biotite schist. Structure is typical of D_2 deformation; D_2 structures are overprinted by small-scale crenulations of S_2, which are tentatively considered D_4 structures. S_2, the dominant structure, strikes about N. 70° E. and dips about 70° N. An accompanying lineation plunges about 50° N. 80° W. These structures reflect east-west striking overturned folds that verge south. S_2 is axial planar to the folds; L_2 is given by S_0-S_2 intersections and plunges parallel to F_2.

Return to vehicle. Proceed north on Whalen Canyon road for 2.1 miles, then turn left on unimproved dirt road across field for a distance of about 0.15 mile. Park and walk west-southwest across gulch up hill 5184 (as shown on Guernsey topographic map). Numerous outcrops of stromatolitic metadolomite are present on north slope and crest of the hill.

Stop 2

The metadolomite is on the northern limb of the Graves Ranch anticline (an east-plunging, downward-facing anticline that formed during deformation D_2). On the north limb, overturned bedding strikes northerly and dips 35°-50° E.; on the south limb (not seen during this trip), beds dip about vertical and stratigraphically face south. Thus, the Graves Ranch anticline is an overturned anticline that verges south. We presume from scattered overturned beds elsewhere in the Hartville area, that the supracrustal section throughout the Guernsey quadrangle (west of Hartville fault) is an overturned limb of a nappe. We have designated the overturning as deformation D_1; it could have developed during an early (soft-sediment folding) stage of D_2.

Return to vehicle, and drive back to Whalen Canyon road. Proceed north on this road for 1.9 miles, to the intersection with a secondary road that bears northwest across open range. Park and walk along road for a distance of about 0.2 mile to excellent road cuts at north end of ridge in a biotite schist unit. To the south of this locality, this unit contains beds of banded iron-formation of Lake Superior type.

Stop 3

Excellent open folds (characteristic of deformation D_3) in the biotite schist (metagraywacke) plunge about 20° N. 75° E. The folds (F_3) deform S_0 and S_2 and have an axial planar cleavage (S_3) that is nearly vertical. The outcrops at this locality are at the north edge of a "transition zone", about 1.5 miles wide (north-south direction), between dominantly D_2 structures (like the Graves Ranch anticline) to the south and D_3 structures to the north. North of this locality (to the vicinity of the Frederick Ranch, a distance of 2 miles) F_3 folds plunge both to the northeast and southwest, depending on which D_2 fold limbs F_3 is superposed on. In this northern area, D_2 structures are reoriented by F_3 folds.

Return to Whalen Canyon road, and proceed north. At 2.3 miles, Frederick Ranch on left; at 4.5 miles (cumulative), sharp turn to right; at 5.5 miles, sharp turn to left; at 6.2 miles, junction with secondary road (at sharp bend to right in road). Drive west on this unimproved road across open range to windmill (distance 0.4 mile), take dirt road on left and proceed for 0.5 mile and park. (*Permission must be obtained from E.D. Petersen, who lives atFloyd Damrow Ranch ($SW_{1/4}$, sec. 7, T. 28 N., R. 64 W.)*). Walk up stream valley on left to outcrops of mylonite in the Hartville fault. It is an easy walk up stream valley for a distance of about 0.5 mile. Location of stop is shown on figure 1.

Stop 4

Mylonite in Hartville fault. Foliation in the mylonite (S_3) strikes N.15-20E. and dips 86° W. The protolith is Archean Rawhide Buttes Granite. A stretching lineation plunges essentially down dip. The width of the mylonite zone is 100 meters. S-C structures in the mylonite indicate oblique sinistral movement along the thrust fault. Dolomite of the Whalen Group forms the west wall of the shear zone; a pit exposes graphite hosted in the dolomite. The granite on the east side of the fault has a pronounced vertical foliation and steep lineation that mimics structure in the Hartville fault. Local mylonite zones as much as a foot or so wide can be seen intermittently in the granite gneiss; these zones are parallel to the Hartville fault. As discussed in the accompanying report, the Hartville fault has an estimated vertical displacement of about 5 km, the east side having moved relatively upward.

Return to Whalen Canyon road, and proceed northward toward Lusk. At 4.7 miles, Moore Spring School on east; at 12.8 miles (cumulative), Carl Soderburg Ranch; at approximately 30 miles, junction with U.S. Highway 18-20. Turn right (east) on Highway 18-20 for 1.8 miles. In Lusk, turn left (north) on U.S. Highway 85 to the Covered Wagon Motel.

Day 2

Depart from Lusk via U.S. Highway 18-20 to west. At 1.8 miles, turn left (south) on Silver Springs road and proceed to the Carl Soderburg Ranch. Continue south on Silver Springs road for 0.7 miles. At curve in road, take secondary road toward Muskrat Canyon; proceed for 3.5 miles to Paul Soderburg Ranch (*ask for permission to enter Muskrat Canyon*). Then continue west on secondary road for 0.5 miles, to outcrop of pillowed basalt on the south bank of creek.

Stop 5

Pillowed metabasalt strikes northward and dips 40° E. We interpret the pillows to be overturned. These little-deformed pillows form a small enclave within generally strongly deformed pillowed metabasalt. Metabasalt exposed 0.2 mile east of this stop is strongly deformed, as shown by a conspicuous stretching lineation (L_3) that plunges steeply S. 40°-45° E. This metabasalt lies in the hanging wall of the Muskrat Canyon fault. The fault is a northwest verging thrust that separates metabasalt from metadolomite (on footwall). The metadolomite and associated strata in the footwall also are overturned as indicated by a lenticular bed of quartzite at the westernmost limit of Whalen Group rocks in the canyon.

From stop 5 continue west along the Muskrat Canyon road for approximately 0.6 mi. Park along the road and walk through the gate on the south side of the road and up the prominent north-south-trending ridge to prospects pits. *Be careful of the open shafts and adits.*

Stop 5A

Prospect in graphite-bearing shear zone. This prospect is located in metadolomite of the highly deformed footwall along the Muskrat Canyon fault. Contrast the high degree of ductile deformation here with the low degree observed at the previous stop. Metadolomite west of the prospect is deformed into a distinctive "pencil schist" where minor folds with amplitudes of about 2 cm plunge 62°, S. 20 ° E. Malachite and chrysacolla, associated with iron oxide lenses in quartz veins or as fracture coatings on graphitic rocks or metadolomite, are locally abundant. Quartz and calcite stringers and pods are exposed in the prospect where they are enclosed in an intensely deformed graphite-rich zone that ranges from 0.1 to 0.3 m wide. Locally, crossfiber tremolite veins are generally conformable to the trend of the vein but formed later than minor folds in graphite; these veins indicate high temperature hydrothermal activity. Regionally, exploration drilling along these graphitic zones has encountered zinc and gold concentrations of as much as 1.2 percent and 2.4 g/t, respectively (Woodfill, 1987).

Graphite in the Hartville uplift is common in, although not restricted to, shear zones (e.g., in the prospect pit at Stop 4). The origin of the graphite is problematic. Some of the occurrences in metadolomite and muscovite schist were probably formed from organic-rich layers in the shelf sequence sediments; some are stratiform zones associated with massive sulfide deposits (e.g., near McCann Pass). Other occurrences, such as this one, appear to have formed by highly reducing hydrothermal fluids localized along shear zones where they crosscut metadolomite. The graphite in this case may be derived from the dissolution of carbonate and reduction of dissolved carbonate to carbon.

Return to Whalen Creek Road (here called Silver Springs Road) and proceed northward for a distance of about 5.2 miles to the Ira Lamb Ranch road (to the west) along Rawhide Creek. Turn west on the ranch road and continue for 0.7 mile through cattle guard. At this point turn south on a trail across open range, cross the ford in creek, and drive for 0.4 mile southwestward to rock knob (SW¼SW¼ sec. 33, T. 31N., R.64W.).

Stop 6

Proceed up to the small knob and saddle. This is an excellent exposure of the Little Wildcat Canyon fault, which is a west-vergent, thrust fault that places metadolomite of the Whalen Group over the Archean Rawhide Buttes Granite. The Little Wildcat Canyon fault is associated with the Hartville fault, which lies under the Tertiary and Quaternary cover between the hills seen to the east. This is one of the few outcrops in which the mylonitic structure of the fault is preserved. Therefore, please DO NOT SAMPLE THE OUTCROP--SAVE IT FOR FUTURE

GEOLOGISTS. The Little Wildcat Canyon fault, a D_3 structure, lies in the saddle separating the east-dipping metadolomite in the hanging wall (on the crest of the small knob) from the Archean Rawhide Butte Granite(on the west of the saddle). The fault zone dips steeply to the east and is an ultramylonitic zone with preserved porphyroclasts of Archean granite within a fine-grained matrix of phyllosilicates and remnants of quartz and feldspar. Asymmetric tails on the porphyroclasts indicate a dominantly east-side-up sense of offset. Metadolomite in the hanging wall is folded; F_3 folds plunge 65° N. 50° E., subparallel to L_3 lineation. Within the footwall of the fault, the granite, here an augen gneiss, has strong down-dip stretching lineations that plunge mainly to the southeast. West of the fault, the D_3 foliation within the granite trends northwest and dips to the northeast. Adjacent to the fault zone, however, this D_3 foliation was reoriented parallel to the Little Wildcat Canyon fault, and strikes to the northeast and dips approximately 70^0 to the southeast. Therefore, the Little Wildcat Canyon fault was a northwest-verging, east-side-up compressional fault in which the metadolomite was thrust over the Archean granite.

Silicic and propylitic alteration is common in the footwall along the exposed trace length of the Little Wildcat Canyon fault. Quartz veins up to 10 m thick can be seen along the fault. To the south, on the north wall of Wildcat Canyon, prospect pits were developed in the quartz veins which contain supergene copper minerals, chalcopyrite, and hematite. The quartz vein itself is sheared parallel to the tectonic foliation associated with the fault as are ore minerals within the vein. Thus, silicification and mineralization occurred during deformation and tectonism along the fault zone.

Looking approximately 1.5 miles to the east are hills associated with the high-grade rocks of the Trans-Hudson orogen. The low-lying hills are composed of folded and faulted supracrustal rocks. The higher ridge to the southeast is Rawhide Butte, which is made up of Archean granite that is intruded by abundant 2-Ga Proterozoic amphibolitic diabase dikes. Our mapping indicates that the Rawhide Buttes Granite body in this area is thrust over the high-grade supracrustal rocks, which in turn are internally faulted on west-verging thrust faults. These structures represent the fold-and-thrust belt associated with Trans-Hudson deformation.

The mesa due east in the foreground is the 1.98 Ga Flattop Buttes Granite, a post-D_2 biotite-muscovite granite intrusion that invades the supracrustal sequence. This Proterozoic granite body was intruded into supracrustal rocks that had previously experienced peak metamorphism, as evidenced by assemblages containing sillimanite-biotite-potassium feldspar-muscovite, and, locally, exceeded the second sillimanite isograd. Peak metamorphism was accompanied by development of a strong schistosity (D_3).

Return to Silver Springs road, and turn left (north). Proceed north for about 2.5 miles. Turn northeastward onto the ranch road that ends at windmill. At the windmill proceed approximately 1/5 mile due east to pasture fence line at the NW1/4 SW1/4, sec 23, R31N, T64W.

Stop 7A

Gossan in Silver Springs schist, a local informal stratigraphic name. A narrow shear zone passes through the water gap immediately north of this location, forming the contact between mafic metavolcanics on the west and muscovite-rich units of the Silver Springs schist. Foliation strikes north-south and dips 60° east. The shear zone formed under relatively dry conditions; a few quartz veins and relatively minor alteration occur in the host rocks. East of the shear zone, (S_3, which strikes N. 10-20° W. and dips steeply to the east) is folded by asymmetric minor north-south-trending folds that plunge 52° N. and by symmetrical folds trending N. 70 °E. and plunging 45 °E.

Leave the vehicles for an easy walk of about 220 m in a N. 45° E. direction to the top of the prominent north-south-trending ridge.

Several prospect pits have been located along the easternmost of three gossan layers in the muscovite-rich host rocks of the Silver Springs schist. The contact with a massive, spheroidally weathering, metagraywacke-rich part of the schist, which overlies the micaceous host rock, is about 30 m east of the prospect. The easternmost gossan, which is exposed in this prospect, ranges in thickness from 2 to 6 m. The middle and the westernmost gossan layers are from 1 to 2 m thick. The middle and easternmost gossans can be traced northward for about 600 m, where they pass under a cover of Tertiary sedimentary rocks. These gossans commonly contain silicate breccia clasts in an iron-oxide matrix. These three zones appear to be primary sedimentary layers and are commonly deformed by northeast-plunging D_3 minor which show a left-lateral transport direction. A ground electromagnetic survey over this prospect, using a EM-16 VLF receiver with a less than ideal transmitter geometry, detected a moderate conductor over the easternmost (thickest) layer. These gossans grade laterally into siliceous exhalative layers and iron-formation to the south along this ridge.

These gossans may be similar to gossans in the McCann Pass area in the Haystack Range, which may be weathered sediment-hosted (possibly Besshi-type) massive sulfide deposits. The McCann Pass gossans typically contain silicate breccia clasts and were derived by weathering of the primary sulfides pyrrhotite, pyrite, and chalcopyrite. The McCann Pass gossans grade laterally and vertically into graphitic schists.

Return to vehicle and drive to Silver Springs road. Turn right (north) and proceed for 0.4 miles to water gap that is exposed along the east side of the Silver Springs road.

Stop 7B

Layered amphibolite is exposed in the stream valley floor. Assymetric (F_3) dextral folds (overturned to the west) plunge 35° N. 10° W. (Parallel to mineral alignment (L_{3b})). Folds deform a ductile foliation (S_{3a}) and a stretching lineation (L_{3c}). The amphibolite is strongly hydrothermally altered with several large folded quartz veins and many thin calcite veinlets. This is the northern continuation of the shear zone visited at Stop 7A.

Return to vehicles and drive on Silver Springs road past Mother Featherlegs Cemetery and the road to the Ira Lamb Ranch. From Ira Lamb Ranch road proceed south for 2 miles. Park at edge of road and walk up hill to east, about 0.1 mile, to outcrops of biotite schist. This is an easy walk.

Stop 8

Biotite schist (metagraywacke) is folded by F_3. Asymmetrical folds overturned to northwest (F_{3b}) fold S_0 and S_{3a} (a ductile foliation). F_{3b} folds plunge south and have a weak axial planar foliation (S_{3b}). This structural picture is analogous to that at stop 7B. These folds together with thrusts mapped to the northeast on this ridge are typical of the fold-and-thrust belt on the west margin of the Trans-Hudson orogeny.

Return to vehicle, and drive north on the Silver Springs road for 0.6 mile. Turn right on secondary road and proceed to abandoned marble quarry (0.7 mile).

Stop 9

This stop emphasizes thrust faults and mineralization within the supracrustal rocks. Proceed east from the marble quarry to a small trail in the draw. Walk up the draw to the crest of the ridge toward the Copperbelt mine. You will be traversing upsection through a sequence of east-dipping metadolomite. At the contact with the biotite schist near the top of the ridge, proceed northeastward along the contact for a distance of 750 ft. to an outcrop. Several copper prospects are located at the crest of the ridge farther to the northeast along this metadolomite-biotite schist contact.

The northeast-trending contact between the metadolomite and structurally overlying biotite schist (metagraywacke) is faulted and silicified in this area. Several prospect pits were dug along the contact zone between these two units. Faulting in the footwall metadolomite has caused brecciation, whereas in biotite schist of the hanging wall the schistosity has been intensified. To the southwest, this fault becomes a normal stratigraphic contact, in which the biotite schist overlies the metadolomite. To the northeast, the fault is truncated by another fault that thrusts metadolomite over biotite schist, thus repeating the stratigraphic sequence.

Many of the prospect pits in this package of rocks were developed on copper-bearing quartz veins and silicified and iron-enriched zones of wallrock along a series of faulted contacts. The Copperbelt mine is an example of vein mineralization hosted in the metadolomite adjacent to a steeply dipping D_3 shear zone. This fault-controlled quartz veining and hematitic alteration, which contains D_3 tectonic elements, as well as hydrothermal alteration along the Little Wildcat Canyon fault zone to the west, indicate that metamorphic fluids were expelled along the fault zones during the D_3 tectonism. Therefore, in this area, mineralization processes were intimately involved with the folding, thrusting, and metamorphism associated with the Trans-Hudson (D_3) tectonic event.

Return to Silver Springs road, and drive south to Carl Soderburg Ranch house (distance 3 miles). Take the secondary road to the east across field and stream (0.25 mile) and stop at point on ridge. *Permission must be obtained from Carl Soderburg to use this secondary road*.

Stop 10

Rawhide Buttes Granite. Granite is strongly deformed by D_3 and is gneissic. A prominent foliation (S_{3a}) striking about north-south contains a stretching lineation that plunges 65° S. 59° E. (average). Inasmuch as L_{3c} represents the X axis of the strain ellipsoid, it indicates that this granite terrane moved northwest (N. 59° W.) and upward relative to the metasedimentary rock terrane to the west.

Return to Silver Spring road (at Carl Soderburg Ranch). Proceed south for 0.5 mile to junction with Rawhide Butte road. Turn left (east) on Rawhide Butte road and continue on road to junction with U.S. Highway 85, a distance of about 8 miles. Turn left (north) on Highway 85 and proceed to Lusk, a distance of about 10 miles. Overnight will be at Covered Wagon Motel.