Archean and Early Proterozoic Tectonic Framework of North-Central United States and Adjacent Canada

U.S. GEOLOGICAL SURVEY BULLETIN 1904–T

Chapter T

Archean and Early Proterozoic Tectonic Framework of North-Central United States and Adjacent Canada

By P.K. SIMS

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

P.K. SIMS and L.M.H. CARTER, Editors

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1995

For sale by
U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Sims, P.K. (Paul Kibler), 1918–
Archean and early Proterozoic tectonic framework of North-Central United States and adjacent Canada / by P.K. Sims.
p. cm. — (U.S. Geological Survey bulletin ; 1904–T)
(Contributions to Precambrian geology of Lake Superior region ; ch. T.)
Includes bibliographical references.
Supt. of Docs. no.: I19.3:B1904T
1. Geology, Stratigraphic—Precambrian. 2. Geology, Structural—Middle West. 3. Geology, Structural—Canada. I. Series. II. Series: Contributions to Precambrian geology of Lake Superior region ; ch. T.

QE75.B9 no. 1904–T
[QE653]
557.3 s—dc20
[551.8'2'0977] 94-39033
CIP

CONTENTS

PLATE

[In pocket]

FIGURES

Archean and Early Proterozoic Tectonic Framework of North-Central United States and Adjacent Canada

By P.K. Sims

Abstract

The southern part of the Canadian Shield and the subsurface of the southern interior platform comprise two Archean cratons and three Early Proterozoic collisional orogens. The Middle Proterozoic Midcontinent rift system transects the older rocks in the eastern part of the area. Middle Proterozoic rhyolite-granite complexes overlap these terranes to the south. Anorogenic granite (≈ 1.45 Ga) bodies of the Transcontinental Proterozoic province intrude older rocks in a belt extending from Wyoming northeastward to Lake Huron.

The two Archean cratons, the Superior and Wyoming provinces, are welded by the Early Proterozoic Trans-Hudson orogen. Sm-Nd data together with differences in lithotypes, structure, and geophysical characteristics demonstrate that the two Archean provinces are not correlative as might be expected by simple lateral extension across the Trans-Hudson orogen. The Superior province consists mainly of alternating greenstone-granite and metasedimentary gneiss terranes (subprovinces) formed ≈ 2.7 Ga that are separated from generally older Archean gneiss to the south by the Great Lakes tectonic zone, a major paleosuture. The Wyoming province, on the other hand, consists of Early to Middle Archean crust that formed between 3.8 and 2.8 Ga. Distinct subprovinces such as are present in the Superior province have not yet been identified in the Wyoming province.

The three Early Proterozoic collisional orogens are (1) the Penokean, which extends from the Lake Superior region through the Lake Huron region and in the subsurface from the Lake Superior region to Nebraska, (2) the north-trending Trans-Hudson, and (3) the Central Plains, which truncates the two Archean cratons and the Trans-Hudson and Penokean orogens to the south. The Penokean in the type area (Lake Superior region) consists of a deformed, south-facing, passive continental margin prism (≈ 2.2–1.85 Ga), including foredeep deposits, overlying Archean basement that is juxtaposed to the south with accreted juvenile arc rocks of the Wisconsin magmatic terranes. The suture is the north-verging Niagara fault (or shear) zone. The arc rocks formed during the interval 1.9–1.845 Ga. Collision occurred at ≈ 1.85 Ga. In the Lake Huron area, an older asymmetric succession (Huron Supergroup; 2.5–2.2 Ga) of dominantly metasedimentary rocks lies on the continental margin; this sequence was deformed and metamorphosed prior to 2.2 Ga and again, during the Penokean orogeny, at 1.85 Ga.

The Trans-Hudson orogen is composed mainly of Early Proterozoic arc-related rocks but includes substantial amounts of Archean basement rocks. In the main outcrop area in northern Saskatchewan, the principal igneous and metamorphic events occurred between 1,910 and 1,830 Ma, approximately contemporaneously with rock-forming events within the Penokean orogen. Seismic reflection profiling at latitude 48°30′ N. suggests that both the east and west boundaries of the orogen dip beneath the respective Archean cratons, suggesting subduction beneath the two Archean cratons. Outcrop data in the Hartville uplift, southeastern Wyoming, however, suggest that the west margin of the orogen here is a probable thrust to the west over the Wyoming craton.

The Central Plains orogen, the eastern subsurface extension of the Early Proterozoic foldbelt exposed in the Laramide basement uplifts of Colorado and southeastern Wyoming, is an arcuate belt (convex to north) of arc-related metamorphic and igneous rocks (1.8–1.63 Ga) that truncates the Wyoming and Superior Archean cratons and the Early Proterozoic Trans-Hudson and Penokean orogens on the south. Its northwest margin (suture) is the north-verging Cheyenne belt, exposed in the Medicine Bow Mountains, which formed between 1.78 Ga and 1.75 Ga. Phanerozoic sedimentary rocks cover the north and east margins of the Central Plains orogen.

The south margin of the Wyoming province is a compound passive margin comparable to the compound margin in the Lake Huron region. An older sequence (2.5–2.1 Ga) of dominantly siliciclastic rocks was deformed prior to deposition

of an outboard younger sequence, which in turn was deformed at ≈ 1.78 Ga by collision along the Cheyenne belt.

Several authors have suggested that the dominantly siliciclastic rocks on the south, passive margin of the Wyoming craton are correlative with those on the Lake Huron segment of the Superior province. Although the proposed correlation is appealing because of similarities in lithology and order of succession, the assemblages are homotaxial because they were formed on different cratonic margins and are not necessarily contemporaneous. In the same way, correlation of the younger strata on the Wyoming passive margin with parts of the Marquette Range Supergroup (Early Proterozoic) in Michigan is questionable; these assemblages are also homotaxial because they were deposited on different continental margins and are not necessarily contemporaneous.

INTRODUCTION

Integration of geologic, geophysical, and geochemical data for the southern part of the Canadian Shield and the subsurface of the southern interior platform provides a coherent framework for determining the Precambrian tectonic history of the region. This report describes the regional tectonic elements of the north-central United States and their assembly in the Early Proterozoic. The two Archean cratons in the region, the Superior and Wyoming provinces, are welded by the north-trending Trans-Hudson orogen. The Superior craton is bordered on the south by the northeast-trending Penokean orogen. The arc rocks of both orogens developed nearly contemporaneously during the approximate interval, 1,910–1,830 Ma. The two Early Proterozoic orogens and the intervening Archean cratons are truncated to the south by the younger Central Plains orogen (1.8–1.63 Ga), which was accreted to the North American craton about 1.78 Ga. The Middle Proterozoic Midcontinent rift system (≈ 1.1 Ga) transects the Superior province, the Penokean orogen, and the Central Plains orogen. The Archean and Proterozoic rocks are truncated to the east by the Grenville Front tectonic zone, a Middle Proterozoic northwest-verging zone of thrusting directed toward the interior of the North American craton, known as Laurentia (Hoffman, 1989, and references therein).

The term "province," as used herein, follows Canadian terminology for Archean rocks (>2.5 Ga; Hoffman, 1989). An Archean province is a contiguous area of continental lithosphere bounded by Early Proterozoic orogens inferred to be suture zones. "Subprovinces" have been defined for the Superior province (Card and Ciesielski, 1986; Card, 1990) on the basis of lithologic and tectonic differences within a province, which may include all, or a combination of, structural trends, ages of orogenic units, rock types, metamorphic grade, and geophysical characteristics.

The Early Proterozoic orogens referred to herein are collisional orogenic belts active between 2.0 and 1.75 Ga that welded older cratonic elements.

ARCHEAN CRATONS

Whether the two Archean cratons (pl. 1, view A) are related temporally and physicochemically has been a matter of uncertainty until recently. Abundant new Sm-Nd data (Peterman and Futa, 1988; Frost, 1993) together with differences in lithotypes, structure, and geophysical characteristics have clearly demonstrated that the Superior and Wyoming provinces are not correlative as might be expected by simple lateral extension across the Trans-Hudson orogen (Sims and others, 1991). In addition, the Wyoming province has a higher heat flow than the Superior province (Drury, 1988), indicating that it has a more radiogenic crust. Thus, the Wyoming province is not a rifted segment off the Superior province that was emplaced in its present position during closure of the Trans-Hudson ocean; instead, it is exotic crust relative to the Superior province.

Superior Province

The Superior province is the largest and perhaps most thoroughly studied Archean craton in the world (Card, 1990). It is made up of east-northeast-trending belts of contrasting lithotypes, metamorphic grade, and age, some of which are bounded by major high-angle faults (Southwick, in press). The belts comprise four lithostratigraphic rock assemblages: (1) volcanic-plutonic terranes, which resemble Holocene island arcs, (2) metasedimentary belts, (3) plutonic complexes, and (4) high-grade gneiss complexes. Three juvenile terranes extend from Canada into the United States segment of the province. From north to south, these are the Wabigoon subprovince, a volcanic-plutonic terrane; the Quetico subprovince, a metasedimentary terrane; and the Wawa subprovince, a volcanic-plutonic terrane (Sims and Carter, eds., in press, pl. 2). The southernmost terrane is the Minnesota River Valley subprovince, a high-grade gneiss terrane. The gneiss terrane is 3.6–2.6 Ga, whereas the juvenile terranes are about 2.75–2.68 Ga. The gneiss terrane is juxtaposed with arc rocks of the Wawa subprovince along the Great Lakes tectonic zone (GLTZ), a north-verging structure (Sims, 1991) that has been traced from central South Dakota (Sims and others, 1991) through the Lake Superior and Lake Huron regions to the Grenville front tectonic zone (Sims and others, 1980). In the Lake Huron area, the Murray fault is considered to be the surface expression of the GLTZ.

Sm-Nd model ages (fig. 1) and Rb-Sr data (Sims and Peterman, 1981) indicate that the lithostratigraphic rock assemblages north of the GLTZ constitute juvenile crust that formed mainly at 2.9–2.7 Ga; isotopic evidence is lacking for an older basement, at least in the U.S. segment of the Superior province. The belted nature of the Superior province has been interpreted as resulting mainly from subduction-driven oblique accretion of oceanic and continental volcanic arcs and the additions of accretionary sedimentary prisms and older continental fragments in a convergent margin setting analogous to parts of the Pacific rim (Card, 1990, and references therein).

Rocks in the three subprovinces north of the GLTZ record a coherent regional structural fabric. An early nappe-forming event (D_1) was followed by mostly upright folds (D_2) attributed to regional dextral transpression (Hudleston and others, 1988). This deformation was followed by major dextral faults that are interpreted as later more brittle expressions of this shear regime. The regional extent of the transpressional structures suggests a common cause, and Sims and Day (1992; 1993) have proposed that the transpression could have resulted from oblique collision along the GLTZ, as determined from mapping in the Marquette, Mich., area (Sims, 1991; 1993). In the Marquette area, oblique convergence of the Archean gneiss terrane (Minnesota River Valley subprovince) with the arc terrane (Wawa subprovince) to the north resulted in northward-directed dextral thrust shear along the GLTZ. This dextral thrust shear could have produced transpression across the wide (>250 km) expanse of Archean rocks in the Lake Superior region, United States and adjacent Canada. Such a distance for strain transmittal is consistent with some younger orogens, as for example the Appalachian-Ouachita orogeny (Craddock and van der Pluijm, 1989).

Wyoming Province

The Wyoming province is smaller, less well exposed, and less well studied than the Superior province. Outcrops are limited to the Laramide uplifts in Wyoming (pl. 1, view B) and Montana, which comprise about 10 percent of the

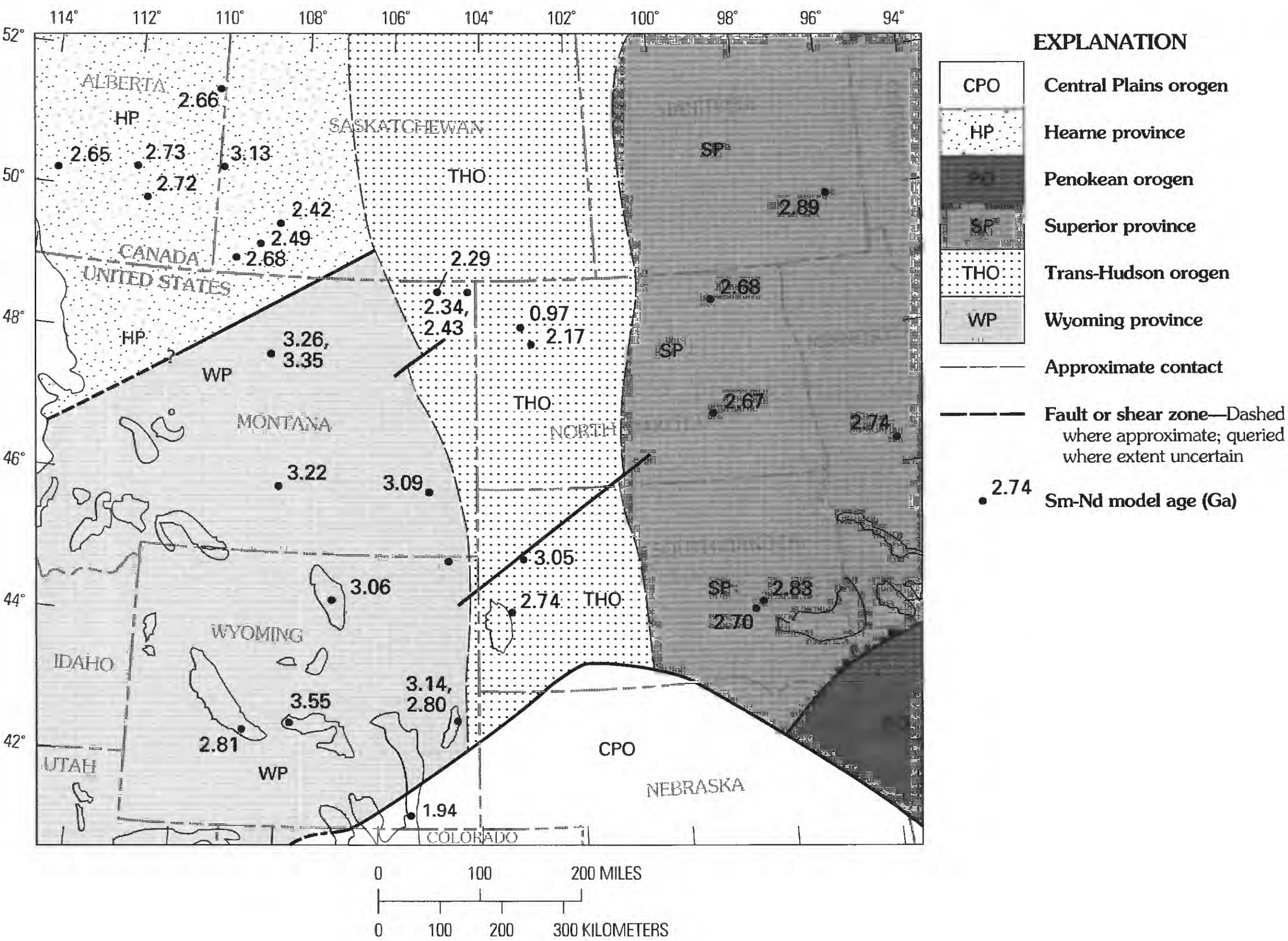

Figure 1. Sm-Nd model ages (depleted mantle model) of Precambrian felsic rocks, north-central United States and adjacent Canada (unpublished compilation by Z.E. Peterman, 1990). Does not include recent data of Frost (1993) for Wyoming province.

province. The Black Hills uplift in western South Dakota is excluded from the Wyoming province inasmuch as it contains arc-related sedimentary and volcanic rocks that were deposited and deformed during the Early Proterozoic Trans-Hudson orogeny (Sims and others, 1991).

The north margin of the Wyoming province, inferred as the Great Falls tectonic zone (O'Neill and Lopez, 1985; Hoffman, 1989, fig. 12), is defined approximately by Sm-Nd model ages of felsic rocks in drill holes (fig. 1). Whereas the Wyoming province is characterized by Sm-Nd model ages of 3.8–2.7 Ga, the Hearne province to the north is characterized by Sm-Nd model ages of 3.1–2.5 Ga and contains abundant juvenile crust. The model ages in the Hearne province are similar to those in the Superior province, including those in the gneiss terrane.

In the well-studied Medicine Bow Mountains and Sierra Madre of southeastern Wyoming (Houston and Karlstrom, 1992), along the south margin of the Wyoming province, quartzofeldspathic gneiss is presumed to be basement underlying metamorphic rocks of the probable Late Archean Phantom Lake Metamorphic Suite (Houston and others, 1992), which includes a thick succession of metavolcanic rocks (fig. 2). The gneiss probably includes both para- and orthogneiss of approximately trondhjemitic composition. The gneiss is Archean, but a precise age has not been determined. The Phantom Lake Metamorphic Suite is overlain unconformably by Early Proterozoic platform sedimentary rocks of the Snowy Pass Supergroup at the south margin of the Wyoming province, adjacent to the Cheyenne belt (Houston and Karlstrom, 1992).

Archean gneiss composes a substantial part of the northern part of the Laramie Mountains (pl. 1, view B), north of the inferred northeastern extension of the Cheyenne belt (Sims and others, 1991, and references therein); it constitutes the major part of the central metamorphic complex of Condie (1969). The gneiss is dominantly granitic gneiss, but includes sillimanite-bearing migmatitic gneiss, amphibolite, and ultramafic rocks. The rocks have Rb-Sr whole-rock ages of 2.9–2.7 Ga (Johnson and Hills, 1976). Greenstone and associated granite crop out sparsely along the northern tip of the Laramie Mountains (Gable, 1987) and in the central Laramie Mountains (Elmers Rock greenstone belt; Graff and others, 1982), immediately north of Middle Proterozoic anorthosite and Sherman Granite (pl. 1, view B). Granite of the Laramie batholith is separated from the older metamorphic rocks to the south by the north-verging Garrett–Fletcher Park–Cottonwood Park (Laramie Peak) shear zone (Chamberlain and others, 1993). The granite has a Rb-Sr whole-rock age of 2.51±0.03 Ga. The Middle Proterozoic anorthosite (1.43 Ga) and the Sherman Granite (1.44 Ga) intrude the central part of the Laramie Mountains, in the vicinity of the inferred position of the Cheyenne belt (pl. 1, view B).

A granitic gneiss (≈ 2.5 Ga)—the granite of Rawhide Buttes of Snyder (1980)—occurs in the Hartville uplift, to the northeast of the Laramie Mountains (pl. 1, view B). It has been interpreted as intruding metamorphic sedimentary and volcanic rocks of the Late Archean Whalen Group (Snyder and Peterman, 1982), but this interpretation is uncertain, as discussed following.

Similarly, Archean para- and orthogneiss of the Wyoming province crop out extensively in the Richeau Hills, east of the Laramie Mountains (Graff and others, 1982; Duebendorfer and Houston, 1987). The rocks are amphibolite facies in metamorphic grade and are cut by mylonite zones, which could be either Archean or Early Proterozoic in age.

Sims and others (1991) suggested on the basis of potential field data that the southeast margin of the Wyoming province (and west margin of the Trans-Hudson orogen) is approximately marked by the Hartville-Rawhide fault (pl. 1, B). Geologic mapping in the Hartville uplift (Snyder, 1980), however, indicates that the craton–Trans-Hudson orogen boundary (suture) lies east of the uplift, and that the Hartville-Rawhide fault is a major west-verging thrust on the continental margin (Day and others, 1994). With this interpretation, the south margin of the Wyoming province is a compound continental margin. (See section on this subject, p. T8.) The possible southwestern extension of the boundary from the vicinity of the Hartville uplift is the Reservoir Lake fault in the Medicine Bow Mountains (Houston and Karlstrom, 1992), a north-verging thrust that predates the younger Cheyenne belt faults, as discussed following.

EARLY PROTEROZOIC COLLISIONAL OROGENS

Three Early Proterozoic collisional orogens have been delineated along the south margin of the North American craton (pl. 1, A): (1) the Penokean, which extends from the Lake Superior region through the Lake Huron region to the Grenville front tectonic zone and in the subsurface from the Lake Superior region to northeast Nebraska; (2) the Trans-Hudson, which welds the Superior and Wyoming cratons; and (3) the Central Plains, which truncates the two Archean cratons and the Trans-Hudson and Penokean orogens, to the south.

Penokean Orogen

The Penokean orogen, where exposed in the Lake Superior region, consists of a deformed, south-facing, passive continental margin prism overlying Superior province Archean basement that is juxtaposed to the south with accreted juvenile rocks of the Wisconsin magmatic terranes (Sims and others, 1989). The suture that juxtaposes the Wisconsin magmatic terranes with the continental margin is the north-verging Niagara fault (or shear) zone. Collision occurred at ≈ 1.85 Ga.

In the Lake Superior region, the continental margin assemblage consists of a lower passive margin sequence mainly composed of quartzite, dolomite, and iron-formation (2.2–1.9 Ga) overstepped northward by a synorogenic foredeep sequence (≈ 1.85 Ga) consisting of iron-formation and graywacke-slate (Southwick and others, 1988; Barovich and others, 1989; Morey, in press). The Early Proterozoic sedimentary-volcanic prism is assigned to the Marquette Range Supergroup in Michigan and Wisconsin and to the Animikie, Mille Lacs, and North Range Groups in Minnesota (Morey, in Sims and Carter, eds., in press).

In northern Michigan and Wisconsin, the Niagara fault (suture) zone trends easterly and overrides the deformed continental margin (pl. 1, A). In Minnesota, to the west of the Middle Proterozoic Midcontinent rift, the presumed equivalent of the Niagara fault zone, the Malmo discontinuity (Southwick and others, 1988; Southwick and Morey, 1991), makes a pronounced oroclinal bend to the south, and is inferred to continue southwestward through northwest Iowa into Nebraska as the Spirit Lake trend (Anderson and Black, 1983). The position of the Malmo discontinuity in south-central Minnesota has been confirmed by recent Nd isotopic data (Hemming and others, 1993). East of the inferred Penokean tectonic front (Malmo discontinuity), Nd model ages are Early Proterozoic (≈ 2.3 Ga), whereas west of the tectonic front Nd model ages are 3.1–2.6 Ga. The subsurface extension of the orogen into Iowa and Nebraska is based mainly on aeromagnetic and sparse drill hole data (Sims, 1990) but is considered moderately accurate. The Penokean orogen is truncated in the subsurface in northeastern Nebraska by the younger Central Plains orogen (pl. 1, A; Sims and Peterman, 1986; Sims, 1990).

Collision of the Wisconsin magmatic terranes along the Niagara suture (and related structures) produced a thick-skinned foreland fold-and-thrust belt north of the suture (Klasner and Sims, 1993) that passes cratonward into parautochthonous Early Proterozoic sedimentary rocks (Gregg, 1993). The deformation includes a 20-km-wide zone of out-of-sequence backthrusting in Michigan (Klasner and Sims, 1993).

The Penokean orogen is truncated by the east arm of the Midcontinent rift in eastern Michigan (pl. 1, A) and reappears again on the north shore of Lake Huron, in southern Ontario (Bennett and others, 1992, and references therein). In the Lake Huron area only the continental margin sequence is exposed. This assemblage, assigned to the Huron Supergroup, is a south-facing sequence (Sims and others, 1981, and references therein; Morey, in Sims and Carter, eds., in press) consisting of four unconformity-bounded, northerly tapering, onlapping clastic wedges; metavolcanic rocks occur near the base. As in the Lake Superior region, this sequence was deposited during Early Proterozoic stretching (and ocean basin formation?) along the south margin of the Superior province. The thickness and facies variations reflect syndepositional down-to-the-basin (south) normal faulting that controlled the accumulation and preservation of the lower three Huron successions. Sediment thickening is most pronounced across the Murray fault zone. These successions are overlapped northward by the youngest succession, an extensive sheet of clastic sedimentary rocks recording post-stretching regional subsidence of the cratonic margin (Zolnai and others, 1984). The Huron Supergroup was deposited in the interval 2,500–2,200 Ma, as bracketed by metavolcanic rocks near the base (2,450±25 Ma; Krogh and others, 1984) and closely associated layered gabbro-anorthosite (2,480±10 Ma and 2,491±5 Ma, U-Pb zircon method) and Nipissing Diabase (2,219±4 Ma; Corfu and Andrews, 1986), which cuts rocks of the Huron Supergroup.

The Huron Supergroup was deformed and metamorphosed during two distinct intervals: (1) prior to emplacement of the 2,200 Ma Nipissing Diabase, and (2) at about 1,900±50 Ma (Fairbairn and others, 1969). The younger deformation was more intense; it compressed the margin of the Superior craton and its cover of Huron rocks as thrusting propagated northward, eventually deforming the 1,850 Ma Sudbury Nickel Irruptive. During the main (second) deformation (penetrative cleavage and peak metamorphism) the thicker, southerly part of the Huron Supergroup was overridden and depressed to mid-crustal depths, presumably because it was overridden by an allochthonous terrane now possibly underlying Lake Huron (pl. 1, A; Zolnai and others, 1984). The postulated allochthonous terrane could be the equivalent of the Wisconsin magmatic terranes. The cause of the pre-2,200 Ma deformation is enigmatic. That it is related to continent-arc collision is unlikely inasmuch as the oldest known arc-related rocks in the Wisconsin magmatic terranes are about 1,890 Ma (Sims and others, 1989), at least 300 m.y. younger than the pre-2,200 Ma collisional event. The pre-2,200 Ma age of the Huron deposits and the documented multiple deformation of the continental-margin rocks (Zolnai and others, 1984) suggest that the Huron segment of the Superior margin is a compound passive margin. Presumably, Huron deposits formed on an older margin prior to 2,200 Ma, then were deformed by 2,200 Ma. Subsequently, these rocks, including the Whitewater Group in the Sudbury area (Morey, in Sims and Carter, eds., in press), as well as the subjacent Archean basement, were deformed again by the north-verging Penokean collision. No record is preserved of either shelf deposits younger than 2,200 Ma or foredeep deposits related to the Penokean collisional orogen.

Trans-Hudson Orogen

The Trans-Hudson orogen (pl. 1, A) has been traced southward in the subsurface from exposures in northern Saskatchewan and Manitoba (Hoffman, 1989, and references therein), mainly by magnetic anomaly maps (Green and others, 1985), but also by gravity patterns (Thomas and others, 1987) and drilling (Bickford and others, 1990). In addition, the position of the North American Central Plains (NACP) conductivity anomaly, which has been traced southward from northern Saskatchewan to just east of the Black Hills (pl. 1, A), then southwestward along the east margin of the Wyoming craton, supports the extension of the Trans-Hudson orogen into the United States (Jones and Savage, 1986, and references therein; Jones and Craven, 1990). Isotopic age data also support the southward extension of the orogen from southern Canada (Bickford and others, 1990) into the United States (Sims and others, 1991, and references therein). These data indicate that the main igneous and metamorphic events in the Trans-Hudson orogen occurred between 1,910 and 1,830 Ma, approximately contemporaneously with igneous and metamorphic events within the Penokean orogen.

Except for the Black Hills uplift, which lies well within the orogen, and the Hartville uplift, which lies on its west margin, the Trans-Hudson orogen is not exposed in the United States and adjacent Canada. Consequently, the outline of the orogen is inferred largely from aeromagnetic and gravity data and sparse drill holes (Sims and others, 1991). The geophysical data comprise generally north trending anomalies that reflect a north-trending lithic and structural grain. These trends conform with those seen in outcrop in the Black Hills uplift (DeWitt and others, 1986; Redden and others, 1990) and in the Hartville uplift (Snyder, 1980).

Based largely on aeromagnetic data (Green and others, 1985), the Trans-Hudson orogen in the United States has been subdivided into four domains or belts (Sims and others, 1991). An eastern unit (unit XWb, pl. 1, A), the Superior-Churchill boundary zone, which is about 45 km wide, is correlated with the exposed Thompson belt in Canada (Hoffman, 1989). It is marked by two continuous and parallel magnetic features: (1) an abrupt truncation of the east-northeast-trending magnetic fabric of the Superior province to the east, and (2) a narrow, linear zone of low magnetization. In the exposed shield, this geophysical zone includes shelf and deeper water metasedimentary rocks, metavolcanic rocks, mafic and ultramafic intrusions, as well as probable reworked Archean basement. In the United States, pyroxene-rich mafic rocks underlie sharp positive magnetic anomalies (Sims and others, 1991) in the zone. In southern South Dakota, an apparent Early Proterozoic granitic batholith (unit Xg, pl. 1, A) truncates the Superior-Churchill boundary zone.

Immediately west of the Superior-Churchill boundary zone is a belt 70–125 km wide characterized by distinctive, high-amplitude, medium-wavelength magnetic anomalies and a positive gravity anomaly that has been called the central magnetic zone (unit XWvc, pl. 1, A; Sims and others, 1991). Green and others (1985) correlated this belt with arc-derived rocks of the Flin Flon–Snow Lake belt. In the United States, the unit contains Archean rocks as well as Early Proterozoic-derived rocks, which at least in part are metamorphosed to granulite grade. In the same way, Archean rocks are common in the buried portion of the orogen in Saskatchewan (Collerson and others, 1988).

The westernmost belt of the Trans-Hudson orogen in the United States, termed the western magnetic zone (unit XWvw, pl. 1, A), is characterized by variable low magnetic relief and long-wavelength anomalies, indicating probable diverse lithic assemblages. Green and others (1985) interpreted this unit to be composed dominantly of back-arc (or inter-arc) basin deposits, such as exposed in the Rottenstone–LaRonge magmatic belt in the Canadian Shield (Hoffman, 1989, p. 470).

A wedge-shaped segment of the orogen (unit XWbh, pl. 1, A), centered on the Black Hills uplift, has been named the Black Hills domain (Sims and others, 1991). In the Black Hills, both Early Proterozoic metasedimentary and metavolcanic rocks and Archean rocks crop out; accordingly, the Black Hills domain is inferred to have at least a partial Archean basement, which has been extensively reworked (Gosselin and others, 1988). The Early Proterozoic rocks record a transition from older rocks of miogeoclinal affinity to younger arc-related metasedimentary and metavolcanic rocks (Redden and others, 1990), which have been assigned to three age groups. Quartzite, taconite, metaconglomerate, and marble, which are older than 2.17 Ga, are unconformably(?) overlain by another sequence of continental margin rocks that are mainly 2.17–1.97 Ga. An overlying younger succession that includes arc-related rocks formed in the interval 1.97–1.88 Ga. The layered rocks are intruded by the Harney Peak Granite dated at 1,715±3 Ma by a discordant U-Pb monazite age (Redden and others, 1990). Sims and others (1991) suggested that the Black Hills and surrounding terrane correlate with the Cree Lake zone in northern Saskatchewan, as described by Lewry and others (1985)—an assemblage of high-grade miogeoclinal rocks that overlies Archean basement.

Sims and others (1991) delineated the east and west margins of the Trans-Hudson orogen on the basis of potential field data coupled with sparse drill holes to basement. The eastern boundary north of lat 44°30′ N. is moderately sharply defined by north-trending anomalies that truncate the conspicuous southwest-trending anomalies of the greenstone-granite terranes of the Superior province (Bond and Zietz, 1987). The west margin, as delineated, was interpreted as approximately coinciding with the Cedar Creek fault in eastern Montana (pl. 1, A) and the Hartville-Rawhide fault in eastern Wyoming and adjacent South Dakota (pl. 1, B). They separate a denser crust to the east from a less dense or thicker crust to the west. The location of the western boundary of the Trans-Hudson orogen north of the transverse Brockton-Froid fault has been uncertain because of nondefinitive potential field data and sparse drill control.

Recently acquired deep seismic reflection data by COCORP (Consortium for Continental Reflection Profiling; Nelson and others, 1993) have refined the boundaries of the

Trans-Hudson orogen along an east-west transect near lat 48°30′ N. and have provided data on the internal structure of the orogen. At about long 101° W., deep reflections dip moderately eastward, beneath rocks of the Superior-Churchill boundary zone, suggesting that rocks of the central magnetic zone (unit XWvc, pl. 1, A) are subducted beneath Archean rocks and their miogeoclinal cover of the Archean Superior province. Nelson and others (1993) suggested that eastward subduction could have taken place beneath an intraoceanic arc terrane that was later juxtaposed against the east margin of the orogen by transcurrent faulting, such as that bordering the west margin of the Thompson belt in northern Manitoba (Green and others, 1985).

The central part of the Trans-Hudson orogen is imaged as a crustal-scale antiform. The east-dipping reflectors at the east margin of the antiform coincide approximately with the boundary between the central and western magnetic regions (pl. 1, A). Possibly these reflectors indicate eastward subduction of rocks of the western magnetic region beneath those of the central magnetic region or westward thrusting of rocks of the central magnetic region over those of the western magnetic region. The west margin of the antiform marks the western, west-dipping boundary of the Trans-Hudson orogen at this latitude. The antiform generally coincides geographically with drill-hole samples in both the United States and Saskatchewan (fig. 1) that have Nd model ages ranging from about 3.4 to 2.4 Ga (Collerson and others, 1988). The Nd model ages together with U-Pb zircon ages indicate that the basement rocks beneath the Phanerozoic cover in Saskatchewan and the United States have a large component of reworked Archean rocks.

The western boundary of the Trans-Hudson orogen apparently is well defined seismically at lat 48°30′ N. by the COCORP transect. At about long 104°30′ W., a thick band of west-dipping reflectors (of western magnetic zone) truncates a thick band of subhorizontal reflectors to the west, presumably within the Wyoming craton. Thus, this band of west-dipping reflectors possibly marks the western limit of arc rocks. This pattern strongly suggests subduction of the Trans-Hudson rocks beneath the Wyoming craton. To the west of the band of west-dipping reflectors at about long 105° W., intracrustal reflections dip steeply east, suggesting that the east margin of the Wyoming province was imbricated in an east-over-west sense. Overall, the seismic profiling indicates that the Trans-Hudson orogen, at lat 48°30′ N., is essentially symmetrical; it is subducted eastward and westward, respectively, beneath Archean rocks of both the Superior and Wyoming cratons. This structural pattern requires that during the Trans-Hudson orogeny, compression was directed from the older cratonic crust of both cratons toward the Early Proterozoic rocks, perhaps essentially contemporaneously. The cause of this dual convergence is equivocal. This interpretation differs substantially from that reached in outcropping areas in Manitoba and Saskatchewan (Hoffman, 1989), which proposed that the Superior craton was a foreland area and the Wyoming (and Hearne) cratons the hinterland to the Trans-Hudson orogen.

The Hartville uplift, in eastern Wyoming (pl. 1, B), composes a west-verging fold-and-thrust belt along the west margin of the Trans-Hudson orogen, and provides insights into the nature of the exposed Wyoming province continental margin. That the uplift comprises a rifted, passive continental margin is indicated by the abundant, close-spaced mafic dikes along the length of the Hartville uplift (Snyder, 1980) and the Laramie Mountains to the west (Snyder, 1993) that trend mainly north-northeast, subparallel to the inferred edge of the continental margin as indicated by potential field data (Sims and others, 1991). In the Hartville uplift and Laramie Mountains, these dikes are mainly about 2.0 Ga—older than the granite of Flattop Butte (1.98 Ga; G.L. Snyder, oral commun., 1993) in the Hartville uplift and younger than a granodiorite body (2.05 Ga; Snyder and others, 1989, p. 12) in the northern Laramie Mountains. The metasedimentary and metavolcanic rocks exposed in the Hartville segment of the continental margin, named the Whalen Group (Smith, 1903), have been inferred by Snyder (1980) to be Archean in age. More likely, they comprise an Early Proterozoic continental-margin sequence deposited on the passive rifted margin during and shortly after the rifting. Carbonate rocks in the Whalen Group are definitely miogeoclinal deposits, and iron-formation in a biotite schist unit is of Lake Superior type. I now interpret the Hartville-Rawhide fault as a west-verging thrust within the continental margin fold-and-thrust belt that has a vertical displacement of about 5 km (Day and others, 1994); garnet-biotite assemblages exposed in rocks to the west of the fault are superposed with sillimanite-bearing rocks to the east. Judged from age data on the Barrovian metamorphism (amphibolite facies) in gneisses of the Laramie Mountains, these rocks were deformed at about 1.82 Ga (Patel and others, 1991); the deformation took place during collision of the Trans-Hudson orogen with the Wyoming Archean craton. 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 (1.81–1.82 Ga; Hoffman, 1989). That the metamorphism is related to the Cheyenne belt is highly unlikely, inasmuch as the oldest rocks in the Colorado province (Central Plains orogen) are 1.79 Ga (Premo, 1983; Premo and Van Schmus, 1989). Collision along the Cheyenne belt occurred between 1.78 Ga and 1.75 Ga. Thus, the rifting, possible sedimentation and volcanism, and subsequent metamorphism and deformation (1.82 Ga) in the Hartville uplift are attributed mainly to the opening and closing of the western part of the Trans-Hudson orogen. As noted following, deformation related to the younger Cheyenne belt (≈1.78–1.75 Ga) probably affected the southern part of the Hartville uplift, and was superposed on older ductile structures related to Trans-Hudson deformation.

Central Plains Orogen

The Central Plains orogen (pl. 1, A) is the eastern subsurface extension of the Early Proterozoic foldbelt exposed in the Laramide basement uplifts of Colorado (Colorado province; Reed and others, 1987) and southeastern Wyoming. It is an arcuate belt (convex to the north) of metamorphic and igneous rocks formed during the approximate time span 1.80–1.63 Ga (Sims and Peterman, 1986). Drilling and U-Pb zircon dating, particularly in Nebraska, indicate close resemblances in lithic units and geochronology to those in Colorado and Wyoming (Bickford and others, 1986; Sims, 1990; Sims and others, 1987), and the correlation of the basement and exposed segments is now rather well established. The northwestern boundary of the orogen, the Cheyenne belt (Houston and others, 1979), is exposed in southeastern Wyoming, in the Sierra Madre and Medicine Bow Mountains (Houston and Karlstrom, 1992), but its location is less certain east of these mountains. The Cheyenne belt is interpreted to be cut by the Laramie anorthosite-syenite complex (1,435 Ma) in the Laramie Mountains and to be exposed in the Richeau Hills, just east of the Laramie Mountains (Graff and others, 1982; Duebendorfer and Houston, 1987). From this point eastward, the location of the shear zone is inferred from magnetic and gravity maps (Sims and Peterman, 1986; Sims and others, 1991).

The Cheyenne belt of southeastern Wyoming is a mylonitic shear zone as much as 5 km wide that separates Archean gneiss and Early Proterozoic supracrustal (miogeoclinal) rocks of the Wyoming craton to the north from 1.8–1.63 Ga arc-related gneisses and calc-alkalic plutons to the south (Houston and others, 1989). It is interpreted as a north-verging suture along which were accreted the arc-related rocks of the Colorado province (Duebendorfer and Houston, 1987, and references therein), and on a broader scale the Central Plains orogen. It is inferred to dip about 55° SE. from seismic-reflection data obtained to the east of the exposed area (Allmendinger and others, 1982), which is more shallow than the dip at the surface. Collision along the Cheyenne belt culminated during the interval 1.78 Ga to 1.75 Ga.

In the Medicine Bow Mountains, four strands of the Cheyenne belt shear zone are exposed (Duebendorfer and Houston, 1987), which merge westward into a single shear zone (pl. 1, B). The northern mylonite zone of the belt, also called the Mullen Creek–Nash Fork shear zone (Houston and McCallum, 1961), separates continental margin Early Proterozoic metasedimentary rocks (unit Xsp, pl. 1, B; Libby Creek Group of the Snowy Pass Supergroup), to the north, from gneisses (unit Xm) of the Bear Lake block (Duebendorfer and Houston, 1987), to the south. The southernmost of the four shear zones, the Rambler, defines the north margin of the volcanic arc complex (unit Xvg, pl. 1, B) to the south (Karlstrom and Houston, 1984). Contrary to the earlier conclusions of Duebendorfer and Houston (1987), recently obtained Nd data (Ball and Farmer, 1991) indicate that rocks within the Cheyenne belt in the Medicine Bow Mountains (the structural blocks of Duebendorfer and Houston, 1987) are part of the Wyoming province, inasmuch as they have ε_{Nd} values and Archean model ages similar to those of the Early Proterozoic Libby Creek Group, north of the northern mylonite zone. The Nd data indicate that rocks of both the lower and upper parts of the Libby Creek Group were derived from Archean crust. The Nd data also require that the Rambler shear zone represents the suture between the Archean continental margin and its miogeoclinal cover and the Early Proterozoic arc rocks to the south. The Nd data further indicate that foredeep sedimentary rocks with 2.4–2.0 Ga model ages are absent north of the Cheyenne belt. Previously, Houston and others (1992) suggested on theoretical grounds that the Towner Greenstone and French Slate, at the top of the upper part of the Libby Creek Group, are possible foredeep deposits.

The extent of Cheyenne belt deformation on rocks of the Hartville uplift is uncertain, but deformation probably is limited to the southernmost part of the uplift. To the east of the Hartville-Rawhide fault, the 1.72 Ga granite of the Haystack Range (Snyder, 1980) forms a 3-km-wide dome in Whalen Group rocks in the Haystack Range, 15 km northeast of Guernsey. The granite and the slightly older (1.74 Ga) diorite of Twin Hills of Snyder (1980) can be accounted for by invoking melting immediately following collision along the Cheyenne belt to the south of the Hartville uplift (pl. 1, B). West of the Hartville-Rawhide fault, just north of Guernsey, kink folds and a crinkle lineation are superposed on the major structures in rocks of the Whalen Group; these late structures are attributed to Cheyenne belt deformation. A seemingly young U-Pb monazite age of 1.66 Ga on metamorphic minerals in the Hartville uplift has been attributed by Krugh and others (1933) to some event related to the Central Plains orogen.

PROBABLE COMPOUND NATURE OF THE SOUTH MARGIN OF THE WYOMING PROVINCE

The relatively long span of time represented by rocks on the south margin of the Wyoming province, the structural complexity of these rocks, and other known geologic relations strongly suggest that the evolution of this continental margin was complex.

Late Archean rocks in both the Medicine Bow Mountains and the Sierra Madre are overlain by as much as 10 km of quartz-rich Early Proterozoic metasedimentary rocks of miogeoclinal affinity (Karlstrom and others, 1983; Houston and others, 1992). From oldest to youngest, the Early Proterozoic comprises the Deep Lake Group, lower part, Libby Creek Group, and upper part, Libby Creek Group (fig. 2). Geologic mapping by Houston and Karlstrom (1992) and others in the Medicine Bow Mountains indicates that both the lower and upper parts of the Libby Creek Group are fault (thrust) bounded and that they have been thrust northward over the Deep Lake Group and underlying Archean rocks. Accordingly, both successions of the Libby Creek Group are presumably allochthonous and constitute a tectonic stratigraphy. Houston and Karlstrom (1992, pamphlet, p. 16) concluded that the Deep Lake Group is more intensely deformed than the Libby Creek Group and that deformation of the Deep Lake Group took place between about 2.5 and 2.1 Ga. With this interpretation, the Deep Lake Group was deformed, presumably by a collision, possibly along the Reservoir Lake fault (pl. 1, B), before ≈ 2.1 Ga. Following this collision, rifting of the continental margin resulted in deposition of the lower part of the Libby Creek Group, and later this margin evolved into an open marine basin in which rocks of the upper part of the Libby Creek Group, including the uppermost unit, the French Slate, were deposited (Karlstrom and others, 1983). The Libby Creek Group and its bounding thrust faults (Reservoir Lake and Lewis Lake faults) were later deformed by collision along the younger (≈ 1.78 Ga) Cheyenne belt. Thus, the continental margin records a time interval of at least 300 m.y. from 2.1 to 1.78 Ga, and probably more, during which at least two episodes of sedimentation and deformation occurred.

That the south margin of the Wyoming province is a compound margin is supported by data from the Hartville uplift. The miogeoclinal carbonate rocks and the ferruginous schist of the Whalen Group are possible continental-margin strata deposited on the rifted, passive margin during an early phase of development of the Trans-Hudson orogen; these rocks are shown on plate 1, B, as unit Xs. These rocks were subsequently deformed and metamorphosed during collision (≈1.82 Ga) of arc-related rocks of the orogen (not exposed) with the continental margin to the west. The possible suture, which lies east of the Hartville uplift (pl. 1, B), converges toward the Cheyenne belt to the south. I suggest that this structure possibly connects with either the Reservoir Lake fault or the Lewis Lake fault in the Medicine Bow Mountains (Houston and Karlstrom, 1992). Both of these faults are interpreted as being older than the Cheyenne belt.

REGIONAL CORRELATIONS OF EARLY PROTEROZOIC MARGIN SEQUENCES

Proposed stratigraphic correlations of Precambrian strata in the north-central United States can be examined with respect to the regional Precambrian tectonic framework presented herein.

Stratigraphic correlation of Early Proterozoic strata between the Lake Superior and Lake Huron segments of the

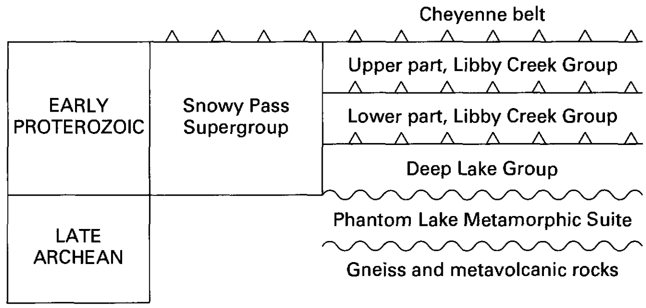

Figure 2. Stratigraphic succession of metasedimentary rocks of the Medicine Bow Mountains, southeastern Wyoming. Sawteeth, upper plate of thrust fault; wavy line, unconformity. (Modified from Houston and others, 1992.)

Penokean orogen has been debated for more than 100 years (Morey, in Sims and Carter, eds., in press, and references therein). Sedimentation was diachronous along the 1,400 km length of the Penokean continental margin, progressively evolving through time from east (Lake Huron area) to west (Lake Superior region). Sedimentation started at about 2.5 Ga in the Lake Huron area, but did not begin until about 2.2 Ga in Minnesota. Sedimentation had essentially ceased by 1.85 Ga in both areas, recording a depositional interval of about 650 m.y. Young (1983) has suggested that the Fern Creek and Enchantment Lake Formations in Michigan, the basal units of the Marquette Range Supergroup, can be correlated with the glaciogenic Gowganda Formation in Ontario, a lower platform sequence of the Cobalt Group of the Huron Supergroup. If so, only the lowermost (possibly glaciogenic) units of the Marquette Range Supergroup can be correlated with the Huron Supergroup. This possible correlation has been discussed recently by Morey (in Sims and Carter, eds., in press).

Young (1973), Houston and others (1992), and Roscoe and Card (1993) have suggested correlation of the thick siliciclastic rocks (Snowy Pass Supergroup) in the Medicine Bow Mountains with similar rocks in the Huron Supergroup. Houston and others (1992, fig. 21) and Roscoe and Card (1993) have suggested unit-by-unit correlations between the two areas. Although the proposed correlation is appealing because of strong lithologic similarities and a similar order of succession, the assemblages are homotaxial because they were formed on different cratonic margins (fig. 1) and are not necessarily contemporaneous. Houston and others (1992) also have suggested a correlation of strata in the Libby Creek Group (fig. 2) with the Marquette Range Supergroup in Michigan. Again, these assemblages are homotaxial because they were deposited on different continental margins. Houston (1992) has suggested that the French Slate and the underlying Towner Greenstone, the uppermost units in the upper part of the Libby Creek Group, are foredeep deposits, but as noted previously, Nd data (Ball and Farmer, 1991) do not support such an origin. The Nd studies indicate that these rocks were derived from the Wyoming Archean craton and not from erosion of advancing thrust sheets of the encroaching Early Proterozoic arc terrane of the Central Plains orogen.

Although contemporaneity of the continental-margin sequences of Early Proterozoic age in southeast Wyoming and the Lake Huron region is improbable, the lithologic similarities can be explained by their tectonic settings. As discussed by Morey (in Sims and Carter, eds., in press), the platform stratigraphic sequences can be equated generally with Holocene sequences along passive margins, as well as with older Phanerozoic sequences such as the Appalachians. The dominantly siliciclastic sequences of Early Proterozoic age along both the Wyoming and Superior cratonic margins can be explained by vast, long-enduring erosion of the quartz-rich Archean rocks in both cratonic source areas. The source areas provide ample material to yield the many-kilometers-thick quartzite, conglomerate, and related rocks now present on these continental margins. The apparent absence of foredeep deposits on both the Wyoming and Superior margins (Lake Huron area) possibly resulted from subsequent erosion rather than nondeposition.

REFERENCES CITED

Allmendinger, R.W., and five others, 1982, COCORP profiling across the Rocky Mountain Front in southern Wyoming, Part 2—Precambrian basement structure and its influence on Laramide deformation: Geological Society of America Bulletin, v. 93, p. 1253–1263.

Anderson, R.R., and Black, R.A., 1983, Early Proterozoic development of the southern Archean boundary of the Superior province in the Lake Superior region: Geological Society of America Abstracts with Programs, v. 15, no. 6, p. 515.

Ball, T.T., and Farmer, G.L., 1991, Identification of 2.0 to 2.4 Ga Nd model age crustal material in the Cheyenne belt, southeastern Wyoming—Implications for Proterozoic accretionary tectonics at the southern margin of the Wyoming craton: Geology, v. 19, p. 360–363.

Barovich, K.M., Patchett, P.J., Peterman, Z.E., and Sims, P.K., 1989, Nd isotopes and the origin of the 1.9–1.7 Ga Penokean continental crust of the Lake Superior region: Geological Society of America Bulletin, v. 101, p. 333–338.

Bennett, G., Dressler, B.O., and Robertson, J.A., 1992, The Huronian Supergroup and associated intrusive rocks, *in* Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, G.M., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, part 1, p. 549–591.

Bickford, M.E., Collerson, K.D., Lewry, J.F., Van Schmus, W.R., and Chiarenzelli, J.R., 1990, Proterozoic collisional tectonism in the Trans-Hudson orogen, Saskatchewan: Geology, v. 18, p. 14–18.

Bickford, M.E., Van Schmus, W.R., and Zietz, Isidore, 1986, Proterozoic history of the midcontinent region of North America: Geology, v. 14, p. 492–496.

Bond, K.R., and Zietz, Isidore, 1987, Composite magnetic anomaly map of the conterminous United States west of 96° longitude: U.S. Geological Survey Geophysical Investigations Map GP–977, scale 1:2,500,000.

Card, K.D., 1990, A review of the Superior Province of the Canadian Shield, a product of Archean accretion: Precambrian Research, v. 48, p. 99–156.

Card, K.D., and Ciesielski, André, 1986, DNAG No. 1 Subdivisions of the Superior Province of the Canadian Shield: Geoscience Canada, v. 13, p. 5–13.

Chamberlain, K.R., Patel, S.C., Frost, B.R., and Snyder, G.L., 1993, Thick-skinned deformation of the Archean Wyoming Province during Proterozoic arc-continent collision: Geology, v. 21, p. 995–998.

Collerson, K.D., Van Schmus, W.R., Lewry, J.F., and Bickford, M.E., 1988, Buried Precambrian basement in south-central Saskatchewan—Provisional results from Sm-Nd model ages and U-Pb zircon geochronology: Saskatchewan Geological Survey Miscellaneous Report 88-4, p. 142–150.

Condie, K.C., 1969, Petrology and geochemistry of Laramie Batholith and related metamorphic rocks of Precambrian age, eastern Wyoming: Geological Society of America Bulletin, v. 80, p. 57–82.

Corfu, F., and Andrews, H., 1986, A U-Pb age for mineralized Nipissing Diabase Gowganda, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 107–112.

Craddock, J.P., and van der Pluijm, Ben, 1989, Late Paleozoic deformation of the cratonic carbonate cover of eastern North America: Geology, v. 17, p. 416–419.

Day, W.C., Sims, P.K., Snyder, G.L., and Wilson, A.B., 1994, Hartville uplift, southeastern Wyoming—Revisited: Geological Society of America Abstracts with Programs, v. 26, no. 6, p. 10.

DeWitt, Ed, Redden, J.A., Wilson, A.B., and Buscher, David, 1986, Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming: U.S. Geological Survey Bulletin 1580, 135 p.

Drury, M.J., 1988, Tectonothermics of the North American Great Plains basement: Tectonophysics, v. 148, p. 299–307.

Duebendorfer, E.M., and Houston, R.S., 1987, Proterozoic accretionary tectonics at the southern margin of the Archean Wyoming craton: Geological Society of America Bulletin, v. 98, p. 554–568.

Fairbairn, H.W., Hurley, P.M., Card, K.D., and Knight, C.J., 1969, Correlation of radiometric ages of Nipissing Diabase and Huronian metasediments with Proterozoic events in Ontario: Canadian Journal of Earth Sciences, v. 6, p. 489–497.

Frost, C.D., 1993, Nd isotopic evidence for the antiquity of the Wyoming province: Geology, v. 21, p. 351–354.

Gable, D.J., 1987, Geologic maps of greenstone-granite areas, northern Laramie Mountains, Converse and Natrona Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–1724, scale 1:24,000.

Gosselin, D.C., Papike, J.J., Zartman, R.E., Peterman, Z.E., and Laul, J.C., 1988, Archean rocks of the Black Hills, South Dakota—Reworked basement from the southern extension of the Trans-Hudson orogen: Geological Society of America Bulletin, v. 100, p. 1244–1259.

Graff, R.J., Sears, J.W., Holden, G.S., and Hausel, W.D., 1982, Geology of the Elmers Rock greenstone belt, Laramie

Range, Wyoming: Geological Survey of Wyoming Report of Investigations 14, 23 p.

Green, A.G., Weber, W., and Hajnal, Z., 1985, Evolution of Proterozoic terranes beneath the Williston basin: Geology, v. 13, p. 624–628.

Gregg, W.J., 1993, Structural geology of parautochthonous and allochthonous terranes of the Penokean orogeny in Upper Michigan—Comparisons with northern Appalachian tectonics: U.S. Geological Survey Bulletin 1904–Q, 28 p.

Hauser, E.C., 1993, A Grenville foreland thrust belt hidden beneath the eastern U.S. midcontinent: Geology, v. 21, p. 61–64.

Hemming, Sidney, Hanson, G.N., McLennan, S.M., Southwick, D.L., and Morey, G.B., 1993, Nd isotopic constraints on the provenance of Early Proterozoic sediments and the locations of tectonic boundaries in central Minnesota: 39th Annual Institute on Lake Superior Geology, Eveleth, Minnesota, Proceedings, Part 1, p. 40–41.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer A.R., eds., The geology of North America—An overview: Boulder, Colo., Geological Society of America, The geology of North America, v. A, p. 447–512.

Houston, R.S., 1992, Proterozoic mineral deposits near plate margins of the Archean Wyoming Province, U.S.A., *in* Gaál, Gabor, and Schulz, K.J., eds., Precambrian metallogeny related to plate tectonics: Precambrian Research, v. 58, p. 85–97.

Houston, R.S., Duebendorfer, E.M., Karlstrom, K.E., and Premo, W.R., 1989, A review of the geology and structure of the Cheyenne Belt and Proterozoic rocks of southern Wyoming, *in* Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the southern Rocky Mountains: Geological Society of America Special Paper 235, p. 1–12.

Houston, R.S., and Karlstrom, K.E., 1992, Geologic map of Precambrian metasedimentary rocks of the Medicine Bow Mountains, Albany and Carbon Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2280, scale 1:50,000.

Houston, R.S., Karlstrom, K.E., Graff, P.J., and Flurkey, A.J., 1992, New stratigraphic subdivisions and redefinition of subdivisions of Late Archean and Early Proterozoic metasedimentary and metavolcanic rocks of the Sierra Madre and Medicine Bow Mountains, southern Wyoming: U.S. Geological Survey Professional Paper 1520, 50 p.

Houston, R.S., Karlstrom, K.E., Hills, F.A., and Smithson, S.B., 1979, The Cheyenne Belt—A major Precambrian crustal boundary in the western United States: Geological Society of America Abstracts with Programs, v. 11, p. 446.

Houston, R.S., and McCallum, M.E., 1961, Mullen Creek–Nash Fork shear zone, Medicine Bow Mountains, southeastern Wyoming [abs.]: Geological Society of America Special Paper 68, p. 91.

Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota: Canadian Journal of Earth Sciences, v. 25, p. 1060–1068.

Johnson, R.C., and Hills, F.A., 1976, Precambrian geochronology and geology of the Box Elder Canyon area, northern Laramie range, Wyoming: Geological Society of America Bulletin, v. 87, p. 809–817.

Jones, A.G., and Craven, J.A., 1990, The North American Central Plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow in Saskatchewan, Canada: Physics of the Earth and Planetary Interiors, v. 60, p. 169–194.

Jones, A.G., and Savage, P.J., 1986, North American Central Plains conductivity anomaly goes east: Geophysical Research Letters, v. 13, p. 685–688.

Karlstrom, K.E., Flurkey, A.J., and Houston, R.S., 1983, Stratigraphy and depositional setting of the Proterozoic Snowy Pass Supergroup, southeastern Wyoming—Record of an early Proterozoic Atlantic-type cratonic margin: Geological Society of America Bulletin, v. 94, p. 1257–1274.

Karlstrom, K.E., and Houston, R.S., 1984, The Cheyenne Belt—Analysis of a Proterozoic suture in southern Wyoming: Precambrian Research, v. 25, p. 415–446.

Klasner, J.S., and Sims, P.K., 1993, Thick-skinned, south-verging backthrusting in the Felch and Calumet troughs area of the Penokean orogen, northern Michigan: U.S. Geological Survey Bulletin 1904–L, 20 p.

Krogh, T.E., Davis, D.W., and Corfu, F., 1984, Precise U-Pb zircon and baddeleyite ages for the Sudbury area, *in* Pye, G.E., Naldrett, A.J., and Giblen, P.E., eds., The geology and ore deposits of the Sudbury structure: Ontario Geological Survey Special Volume 1, p. 449–489.

Krugh, K.A., Chamberlain, K.R., and Snyder, G.L., 1993, U-Pb evidence for ca. 1.66 Ga metamorphism and deformation in the Hartville uplift, southeastern Wyoming: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 64–65.

Lewry, J.F., Sibbald, T.I.I., and Schledewitz, D.C.P., 1985, Variation in the character of Archean rocks in the western Churchill Province and its significance, *in* Ayres, L.D., Thurston, P.C., Card, K.D., and Weber, W., eds., Evolution of Archean supracrustal sequences: Geological Association of Canada Special Paper 28, p. 239–261.

Morey, G.B., in press, Continental margin assemblage, *in* Sims, P.K., and Carter, L.M.H., eds., Archean and Proterozoic geology of the Lake Superior region, U.S.A., 1993: U.S. Geological Survey Professional Paper 1556.

Nelson, K.D., Baird, D.J., Walters, J.J., Hauck, M., Brown, L.D., Oliver, J.E., Ahern, J.L., Hajnal, Z., Jones, A.G., and Sloss, L.L., 1993, Trans-Hudson orogen and Williston basin in Montana and North Dakota—New COCORP deep profiling results: Geology, v. 21, p. 447–450.

O'Neill, J.M., and Lopez, D.A., 1985, Character and regional significance of Great Falls tectonic zone, east-central Idaho and west-central Montana: American Association of Petroleum Geologists Bulletin, v. 69, p. 437–447.

Patel, S.C., Frost, B.R., and Snyder, G.L., 1991, Extensive Early Proterozoic Barrovian metamorphism in the southeastern Wyoming Province, Laramie Range, Wyoming: Geological Society of America Abstracts with Programs, v. 23, p. 59.

Peterman, Z.E., and Futa, Kiyoto, 1988, Contrasts in Nd crustal residence ages between the Superior and Wyoming cratons: Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A137.

Premo, W.R., 1983, U-Pb zircon geochronology of some Precambrian rocks in the Sierra Madre Range, Wyoming: Lawrence, Kans., University of Kansas M.S. thesis, 106 p.

Premo, W.R., and Van Schmus, W.R., 1989, Zircon geochronology of Precambrian rocks in southeastern Wyoming and northern Colorado, *in* Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the southern Rocky Mountains: Geological Society of America Special Paper 235, p. 1–12.

Redden, J.A., Peterman, Z.E., Zartman, R.E., and DeWitt, Ed, 1990, U-Th-Pb geochronology and preliminary interpretation of Precambrian tectonic events in the Black Hills, South Dakota, *in* Lewry, J.F., and Stauffer, M.R., eds., The Early Proterozoic Trans-Hudson orogen of North America: Geological Association of Canada Special Paper 37, p. 229–252.

Reed, J.C., Jr., Bickford, M.E., Premo, W.R., Aleinikoff, J.N., and Pallister, J.S., 1987, Evolution of the Early Proterozoic Colorado province—Constraints from U-Pb geochronology: Geology, v. 15, p. 861–865.

Roscoe, S.M., and Card, K.D., 1993, The reappearance of the Huronian in Wyoming—Rifting and drifting of ancient continents: Canadian Journal of Earth Sciences, v. 30, p. 2475–2480.

Sims, P.K., compiler, 1990, Precambrian basement map of the midcontinent region, U.S.A.: U.S. Geological Survey Miscellaneous Investigations Series Map I–1853–A, scale 1:1,000,000.

Sims, P.K., 1991, Great Lakes tectonic zone in Marquette area, Michigan—Implications for Archean tectonics in north-central United States: U.S. Geological Survey Bulletin 1904–E, 17 p.

———1993, Structure map of Archean rocks, Palmer and Sands 7½-minute quadrangles, Michigan, showing Great Lakes tectonic zone: U.S. Geological Survey Miscellaneous Investigations Series Map I–2355, scale 1:24,000.

Sims, P.K., Card, K.D., and Lumbers, S.B., 1981, Evolution of Early Proterozoic basins of the Great Lakes region, *in* Campbell, F.H.A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81-10, p. 379–397.

Sims, P.K., Card, K.D., Morey, G.B., and Peterman, Z.E., 1980, The Great Lakes tectonic zone—A major crustal structure in central North America: Geological Society of America Bulletin, Part I, p. 690–698.

Sims, P.K., and Carter, L.M.H., eds., in press, Archean and Proterozoic geology of the Lake Superior region, U.S.A., 1993: U.S. Geological Survey Professional Paper 1556.

Sims, P.K., and Day, W.C., 1992, A regional structural model for gold mineralization in the southern part of the Archean Superior province, U.S.A.: U.S. Geological Survey Bulletin 1904–M, 19 p.

———1993, The Great Lakes tectonic zone—Revisited: U.S. Geological Survey Bulletin 1904–S, 11 p.

Sims, P.K., Kisvarsanyi, E.B., and Morey, G.B., 1987, Geology and metallogeny of Archean and Proterozoic basement terranes in the northern midcontinent, U.S.A.—An overview: U.S. Geological Survey Bulletin 1815, 51 p.

Sims, P.K., and Peterman, Z.E., 1981, Archean rocks in the southern part of the Canadian Shield—A review: Geological Society of Australia Special Publication 7, p. 85–98.

———1986, Early Proterozoic Central Plains orogen—A major buried structure in the north-central United States: Geology, v. 14, p. 488–491.

Sims, P.K., Peterman, Z.E., Hildenbrand, T.G., and Mahan, Shannon, 1991, Precambrian basement map of the Trans-Hudson orogen and adjacent terranes, northern Great Plains, U.S.A.: U.S. Geological Survey Miscellaneous Investigations Series Map I–2214, scale 1:1,000,000.

Sims, P.K., Van Schmus, W.R., Schulz, K.J., and Peterman, Z.E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 26, p. 2145–2158.

Smith, W.S.T., 1903, Hartville Folio: U.S. Geological Survey Folio No. 91.

Snyder, G.L., 1980, Map of Precambrian and adjacent Phanerozoic rocks of the Hartville uplift, Goshen, Niobrara, and Platte Counties, Wyoming: U.S. Geological Survey Open-File Report 80-779, scale 1:48,000.

———1993, Geologic map of the Esterbrook-Braae area, Albany, Converse, and Platte Counties, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2232, scale 1:24,000.

Snyder, G.L., Hausel, W.D., Klein, T.L., Houston, R.S., and Graff, P.J., 1989, Precambrian rocks and mineralization, Southern Wyoming province: 28th International Geological Congress, Field trip Guidebook T332, 48 p.

Snyder, G.L., and Peterman, Z.E., 1982, Precambrian geology and geochronology of the Hartville uplift, Wyoming: 1982 Archean geochemistry field conference, p. 64–94.

Southwick, D.L., in press, Archean Superior province, *in* Sims, P.K., and Carter, L.M.H., eds., Archean and Proterozoic geology of the Lake Superior region, U.S.A., 1993: U.S. Geological Survey Professional Paper 1556.

Southwick, D.L., and Morey, G.B., 1991, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota—An interpretation based on regional geophysics and the results of test-drilling: U.S. Geological Survey Bulletin 1904–C, 17 p.

Southwick, D.L., Morey, G.B., and McSwiggen, R.L., 1988, Geologic map (scale 1:250,000) of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p.

Thomas, M.D., Sharpton, K.L., and Grieve, R.A.F., 1987, Gravity patterns and Precambrian structure in the North American Central Plains: Geology, v. 15, p. 489–492.

Young, G.M., 1973, Tillites and aluminous quartzites as possible time markers for middle Precambrian (Aphebian) rocks of North America: Geological Association of Canada Special Paper 12, p. 97–127.

———1983, Tectono-sedimentary history of early Proterozoic rocks of the northern Great Lakes region, *in* Medaris, L.G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 15–32.

Zolnai, A.I., Price, R.A., and Helmstoedt, H., 1984, Regional cross section of the Southern Province adjacent to Lake Huron, Ontario—Implications for the tectonic significance of the Murray fault zone: Canadian Journal of Earth Sciences, v. 21, p. 447–456.

Manuscript approved for publication July 21, 1994
Published in the Central Region, Denver, Colorado
Photocomposition by Carol A. Quesenberry
Color design by Patricia L. Wilber
Graphic design by Patricia L. Wilber
Cartography by Springfield & Springfield

☆U.S. GOVERNMENT PRINTING OFFICE: 1995-673-066/86108