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Crustal structure and evolution of the Trans-Hudson orogen: Results from seismic reflection profiling

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Abstract. A 400-km-long deep seismic reflection transect across northeastern Montana and northern North Dakota reveals the crustal-scale structural fabric of the Early Proterozoic Trans-Hudson orogen beneath the Williston basin. Comparison with deep seismic reflection data across the Canadian portion of the same orogen ~700 km to the north reveals first-order similarities in crustal architecture but documents significant along-strike variation in orogenic evolution. Both transects display a broad crustal-scale antiform axial to the orogen. In the north, geologic data suggest that this antiform is cored by an Archean microcontinent. In the south, west dipping reflections on the western flank of the antiform extend from the upper crust to the uppermost mantle and truncate prominent subhorizontal lower crustal reflections of the Archean Wyoming craton. Within the Wyoming craton, the eastern limit of east dipping midcrustal reflections coincides with the subsurface age boundary between the craton and the Early Proterozoic Trans-Hudson orogen as interpreted from potential field and drill core data. On the basis of subsurface geochronologic data from the crystalline basement and by analogy with the Glennie domain within the exposed Trans-Hudson orogen in Canada, we suggest that the southern antiform is cored by an Archean crustal fragment that was caught up in the terminal collision of the Wyoming and Superior cratons during Hudsonian orogeny. The eastern side of the Trans-Hudson orogen is characterized on both seismic transects by predominantly east dipping crustal penetrating reflections. We interpret the easterly dip of these reflections as evidence that the Superior province was thrust westward over the internides of the orogen during terminal collision. Although juvenile Early Proterozoic terranes characterize the exposed segment of the Trans-Hudson orogen in Canada, limited drill core information within the Dakota segment of the orogen shows a predominance of granulitic Archean age crust. This difference in basement lithologies along strike within the orogen may indicate the following: either juvenile crust comparable to that exposed in the northern Trans-Hudson was never present in the south, or it was removed by progressive over thickening, erosion, and/or faulting. Postorogenic extensional collapse may be responsible for preservation of juvenile terranes in the north.

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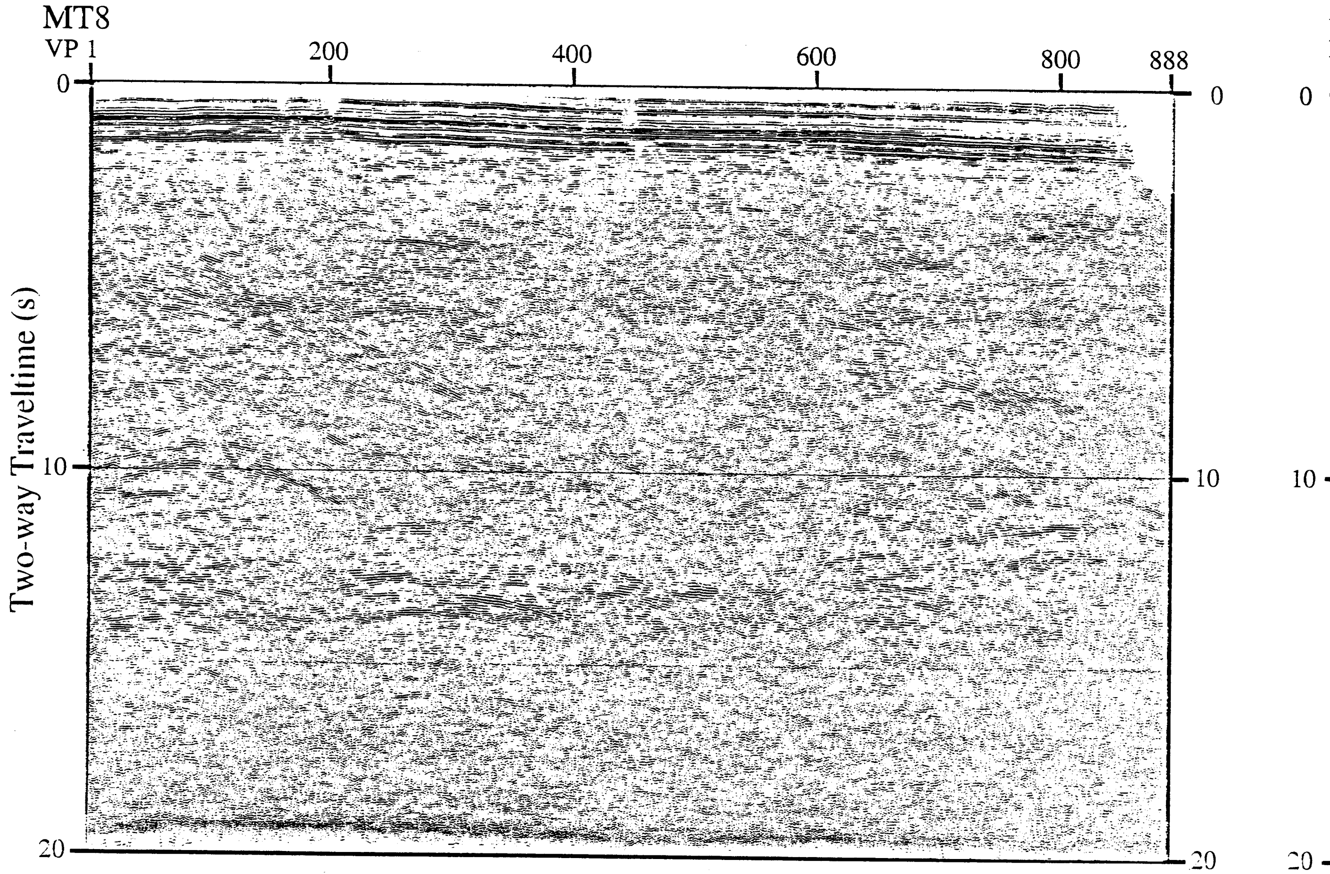
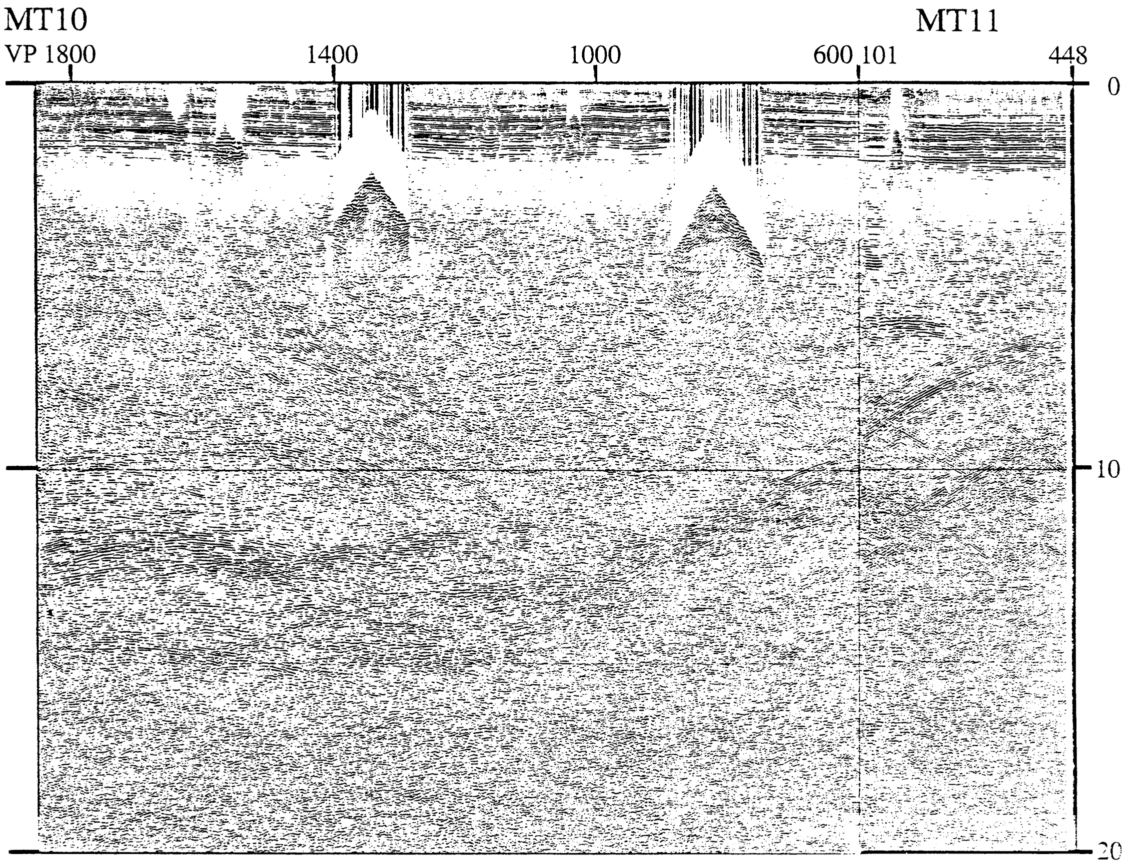
Introduction

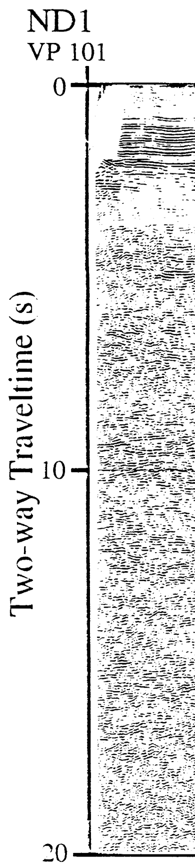
In the summer of 1990, the Consortium for Continental Reflection Profiling (COCORP) collected approximately 400 km of Vibroseis seismic reflection data across the Williston basin in Montana and North Dakota. Three new profiles (MT10, MT11, and ND1) extend COCORP's previous Northwest Cordillera transect eastward from the Archean Wyoming province across the Trans-Hudson orogen and into the Superior province (Figure 1). Major crustal features crossed by the new profiles include (1) the Phanerozoic intracratonic Williston basin; (2) the Proterozoic Trans-Hudson orogen; and (3) the North American Central Plains (NACP) conductivity anomaly. A summary report of this survey was given by *Nelson et al.* [1993]. Acquisition parameters are outlined in Table 1 and processing parameters are given below.

<u>COCORP Profile MT8</u>
Demultiplex
Vibroseis correlation
Antialias filter (48-Hz low pass)
Resample to 8 ms
Datum statics elevation 710 m
Trace amplitude balancing, window 1000 ms
FK Filter
CMP gather (cmp interval 50 m)
Deconvolution
Time varying band pass filter
Velocity analysis
Normal moveout
Mute
Stack (24-fold nominal coverage)
Coherency filter
Sum adjacent traces
Display (VA, no wiggle, 1:1 at 6 km/s)
Processed with Megaseis

<u>COCORP Profiles MT10, MT11 and ND1</u>
Demultiplex
Vibroseis correlation
Datum statics: elevation 640 m, velocity 2000 m/s
CMP gather (cmp interval 25 m)
Band pass filter (8-50 Hz)
Mute
Deconvolution
Band pass filter (8-50 Hz)
Velocity analysis
Normal moveout
Stack (50-fold nominal coverage)
Average amplitude normalize, window 6-20 s


MT8
VP 1
200
400
600
800
888
0
10
20
0
10
20
0
10
20
Two-way Traveltime (s)


MT10
VP 1800
1400
1000
600
101
MT11
448
0
10
20


ND1
VP 101
0
10
20
Two-way Traveltime (s)

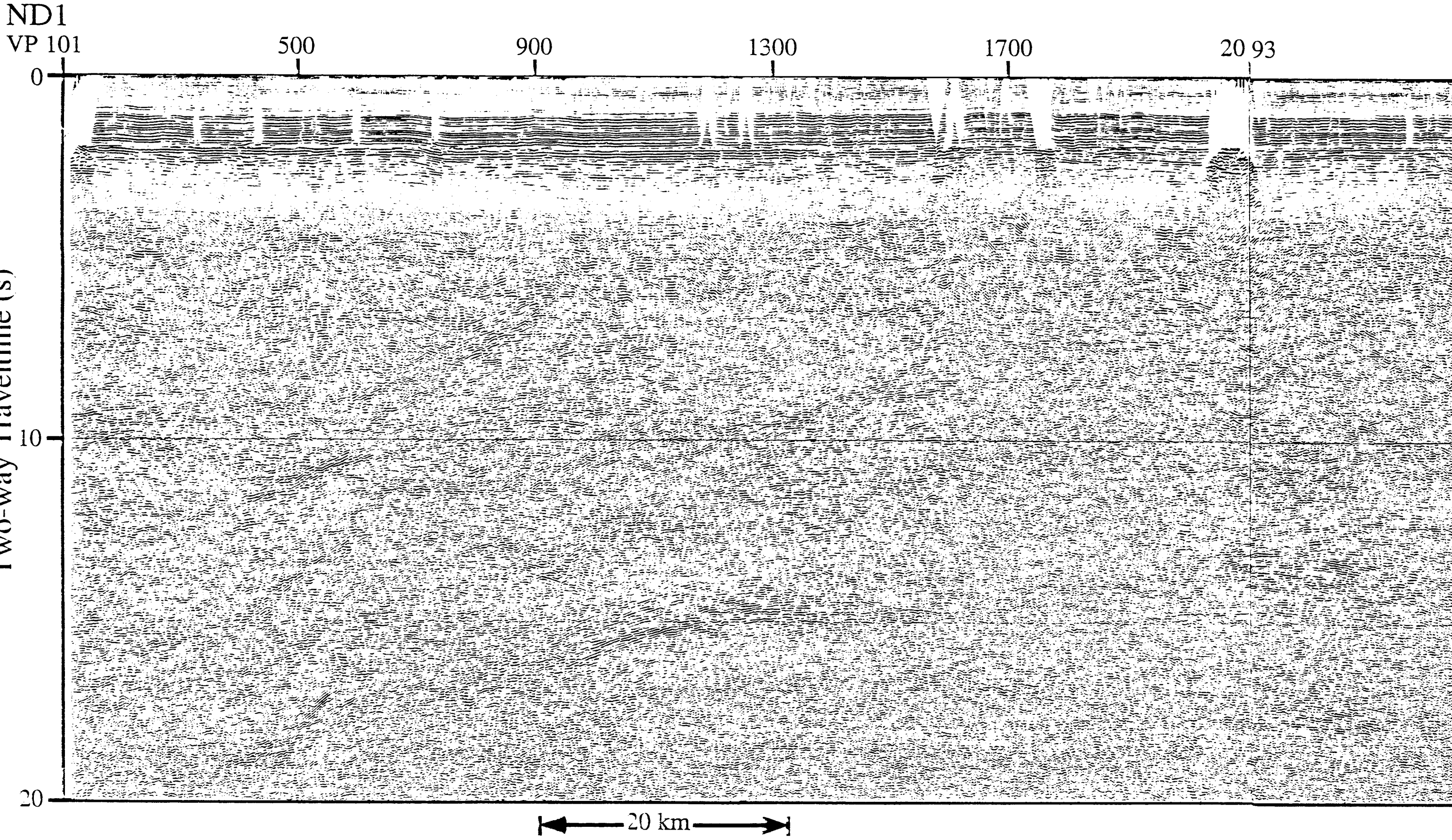
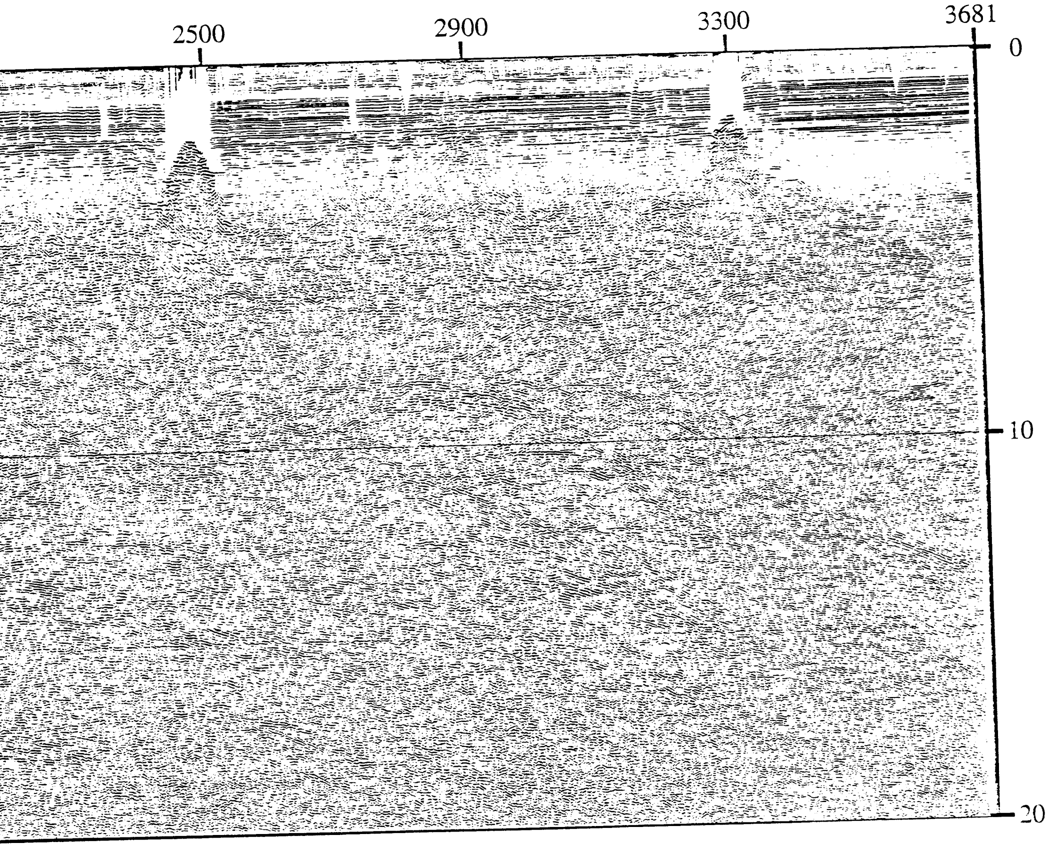
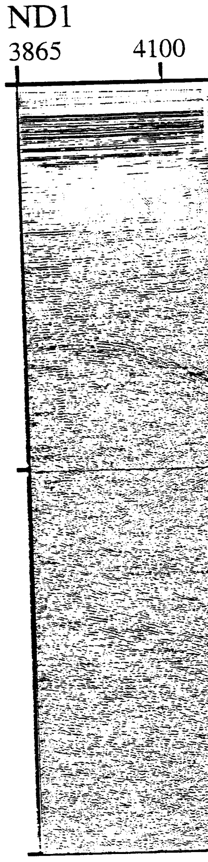
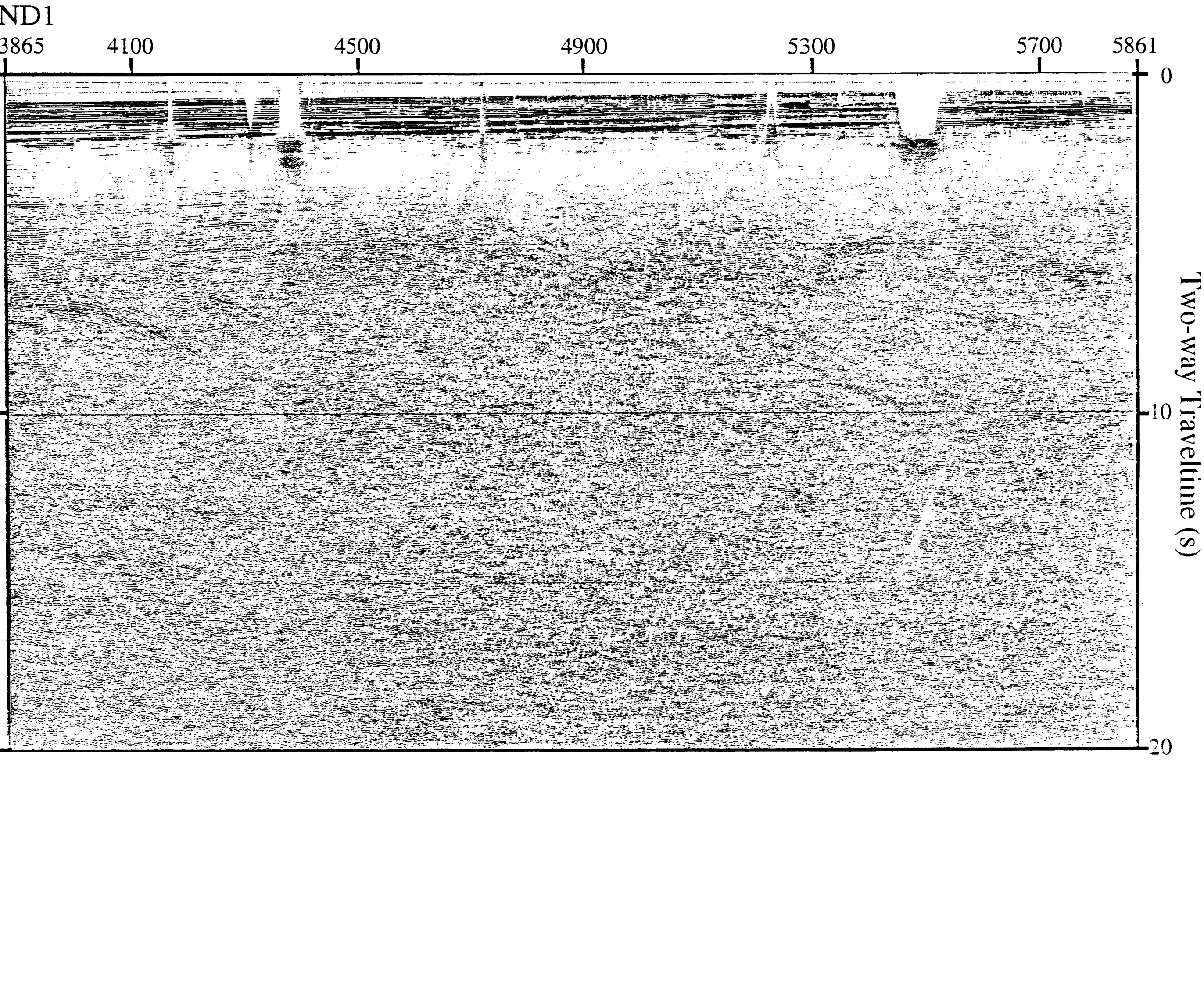


Plate 1. Unmigrated COCORP seismic reflection profiles across Williston basin and Trans-Hudson orogen (1:
at 6 km/s). See Table 1 and text for acquisition and processing parameters.





Hudson orogen (1:1



ND1
3865
4100
4500
4900
5300
5700
5861
0
10
20
Two-way Traveltime (s)

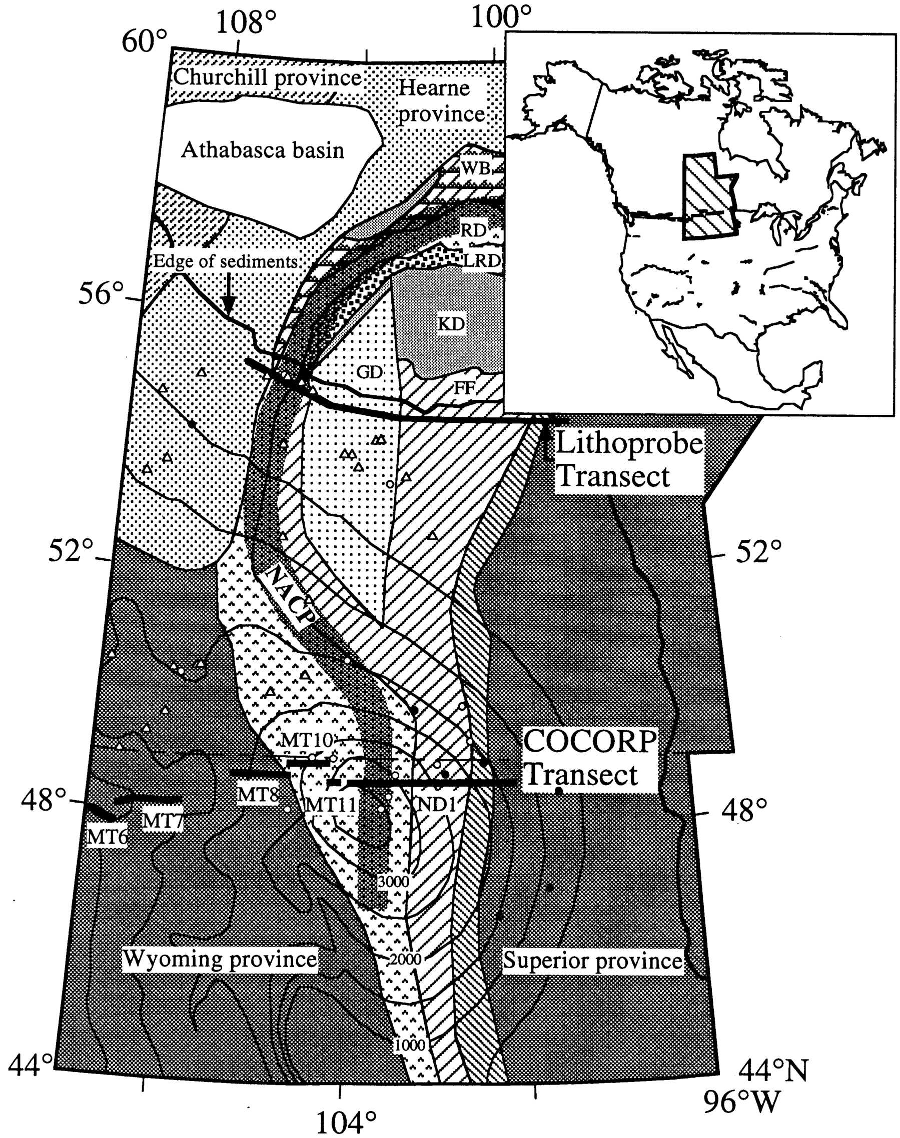


Figure 1. Regional map (simplified from *Green et al.* [1985b]) showing Consortium for Continental Reflection Profiling (COCORP) deep seismic reflection profiles crossing Williston basin and underlying Trans-Hudson orogen (THO). Trans-Hudson geology is from *Lucas et al.* [1993]; abbreviations are WB, Wathaman batholith; RD, Rottenstone domain; LRD, La Ronge domain; GD, Glennie domain; FFB, Flin Flon belt; KD, Kisseynew domain. Drill core data (solid and open circles, triangles) are from *Collerson et al.* [1988, 1990]; solid circles indicate Archean U-Pb ages; open circles indicate Proterozoic U-Pb ages; triangles indicate unknown U-Pb ages; all cores except one have Archean Sm-Nd ages (see Table 2). Contours (500-m interval) are to top of Precambrian basement. Approximate location of the North American Central Plains conductivity anomaly (NACP) is from *Jones and Craven* [1990]. In inset, thin black lines are COCORP seismic profiles.

Coherency filter
AGC, window 3 s
Sum adjacent traces
Display (VA, no wiggle, 1:1 at 6 km/s)
Processed with Sioseis, displayed with ProMAX

The seismic data described here were collected as part of a collaborative program to study the Williston basin and underlying Trans-Hudson orogen. During 1991, Lithoprobe (Canada's national geoscience project) collected over 1000 km of deep seismic reflection data immediately adjacent to the exposed Trans-Hudson orogen in Manitoba and Saskatchewan, approximately 700 km north of the southern transect (Figure 1). Initial results of this work were reported by *Lucas et al.* [1993, 1994] and *White et al.* [1994]. This paper presents the complete southern transect, discusses the rationale for our interpretation of these data, and describes the principal similarities and differences in crustal structure and evolution along-strike within the Trans-Hudson orogen.

Trans-Hudson Orogen: Geology

The Trans-Hudson orogen (THO) is the longest Early Proterozoic (1.77-1.89 Ga [*Bickford et al.*, 1990; *Machado*,

Table 1. Acquisition Parameters

Parameter	COCORP Profile MT8	COCORP Profiles MT10, MT11, ND1
Source	five Failing Y11 vibrators at 30 and 50 %	eight Mertz vibrators at 80 %
Source spacing	200 m	200 m
Mode	split spread	split spread
Sweep length	26 s	30 s
No. of sweeps/VP	8	8
Frequency Range	12-48 Hz	10-56 Hz
Filters Applied	60-Hz notch	10- to 56-Hz band pass
Recorders	MDS 10	SGR 4, SGR3
Station spacing	100 m	50 m
No. of channels	96	~400
Sampling interval	4 ms	4 ms
Stacking fold	24	~50
Correlated record length	16 s	20 s

COCORP is the Consortium for Continental Reflection Profiling

1990]) orogenic belt in North America and represents a major episode in the amalgamation of the North American continent [*Hoffman*, 1988]. The belt welds the Archean Wyoming and Hearne provinces, comprising the western part of the North American craton, to the Superior province, making up most of the central North American craton. The Trans-Hudson orogen is exposed in west-central Canada and extends southward beneath the Phanerozoic cover to South Dakota, where it is truncated by the younger (1.63-1.80 Ga) Central Plains orogen [*Sims and Peterman*, 1986]. In the north, the Trans-Hudson orogen swings eastward between the Hearne and Superior provinces and extends beneath the Phanerozoic Hudson Bay basin.

The terranes comprising the internides of the exposed Trans-Hudson orogen are composed of predominantly low metamorphic grade metasedimentary, metavolcanic and intrusive rocks that record the evolution and final closure of the Manikewan ocean in Early Proterozoic time (1890-1835 Ma [*Stauffer*, 1984; *Van Schmus et al.*, 1987]). U-Pb and Sm-Nd analyses of these rocks yield both crystallization and mantle separation ages of 1.8 to 1.9 Ga, corresponding to the Hudsonian orogeny [*Van Schmus et al.*, 1987; *Chauvel et al.*, 1987; *Bickford et al.*, 1990]. In contrast, basement drill cores from the Dakota segment of the orogen (wells MT1, MT2, ND8-ND10; Figure 2c, Table 2) sample rocks of granulite facies metamorphic grade yielding Archean mantle separation ages [*Burwash et al.*, 1962; *Peterman and Hedge*, 1964; *Peterman and Goldich*, 1982; *Collerson et al.*, 1988, 1990]. The dominant rock types sampled are leucogranite, mafic granulite, altered syenite, monzonite, biotite-garnet gneiss, and charnockitic tonalite gneiss [*Peterman and Hedge*, 1964; *Sims et al.*, 1990]. This metamorphic history appears to be distinct from the exposed rocks to the north. The lack of isotopic evidence for juvenile crust within the Dakota segment of the Trans-Hudson orogen implies that either the juvenile material has been removed by erosion or transcurrent faulting or such material was never incorporated in the orogen at this latitude.

COCORP Profiling Results (48° 30' N)

Wyoming Province - Trans-Hudson Orogen Transition

The Archean crust of the Wyoming province west of the Williston basin has remained essentially stable since the Middle Proterozoic [*Peterman*, 1981], except for gentle regional uplift (Sweetgrass arch) and subsidence (Williston basin) during Phanerozoic time and localized Cenozoic magmatism in the Bearpaw and Little Rocky mountains. The seismic reflection signature of this craton recorded on lines MT3 through MT8 [*Latham et al.*, 1988] shows gently dipping midcrustal reflections associated with the Sweetgrass arch and prominent west dipping reflections near the western edge of the Bearpaw mountains, possibly from steeply dipping intrusions in the area. Lines MT3-7 show no distinct zone of lower crustal or Moho reflections. In contrast, profile MT8, which extends into the Williston basin, is characterized by east dipping reflections in the upper crust and prominent, subhorizontal, lower crustal reflections between 13 and 15 s

Table 2. Basement Drill Cores Near COCORP Transect

Sample	Rock Type	Age Data		
		Sm-Nd	U-Pb (Zi)	Rb-Sr
MT1	mafic granulite, charnockite veins	2.4 WR	1.8	1.8 WRI
MT2	foliated leucogranite	2.3 WR		1.8 WR
MT3	amphibolite, granitic veins		1.9	1.9 KF
ND1	biotite granodiorite	2.8 WR		2.8 WR
ND5	biotite-garnet gneiss, tonalite gneiss			1.7 WRI, Bt
ND6	Bt-Ga-Hy gneiss, mafic granulite		3.0	
ND7	biotite-cordierite gneiss		2.9	2.0 WRI
ND8	biotite-garnet gneiss cuttings			0.5 Bt
ND9	altered syenite, monzonite	1.0 WR		0.7 KF
ND10	charnockitic tonalite gneiss	2.2 WR		1.8 WR, KF

Drill core data are from *Sims et al.* [1990]; See Figure 2c for locations. WR is the Rb-Sr or Sm-Nd whole rock model age (Rb-Sr based on calc-alkaline orogenic model of *De Paolo* [1981]). WRI is the whole rock isochron age. KF is the K-feldspar age. Bt is the biotite age.

two-way travel time (see Figures 2 and 4 of *Latham et al.* [1988] and Figure 2 and Plate 1 of this paper). The spatial correlation of these lower crustal reflections with the western edge of the Williston basin led to the earlier suggestion that the seismic layering marked the presence of an anomalous mass in the lower crust; a mass that was later transformed to eclogite, inducing subsidence of the Williston basin [*Latham et al.*, 1988]. The seismic profiles presented here, however, show that the lower crustal reflections imaged on profile MT8 do not continue beneath the center and eastern portions of the basin. We consider these reflections to be a precollisional (pre-Hudsonian) feature of the eastern Wyoming province.

The eastern edge of the Wyoming province, interpreted from potential field data and basement drill cores [*Green et al.*, 1985a, b; *Sims et al*, 1990], lies at the eastern end of profile MT8, approximately at the up dip projection of a zone of east dipping upper crustal reflections imaged on line MT10 (Figures 1 and 2c). The reflective lower crust imaged on profile MT8 continues eastward onto profile MT10. In the middle of MT10, both the lower crustal reflections and the overlying east dipping upper crustal reflections are truncated by a strong band of west dipping reflections [*Nelson et al.*, 1993]. On the unmigrated data (Plate 1), these reflections are visible from 6 s two-way travel time (beneath VP 450 on line MT11) to 26 s two-way travel time (beneath the western end of line MT10). Coincident seismic data recorded using explosive sources confirm that the west dipping reflectivity penetrates the entire crust and extends into the upper mantle [*Baird et al.*, 1995]. We interpret the western edge of this west dipping assemblage to represent a crustal-scale boundary, specifically, a west dipping suture zone between the continental margin rocks of the Wyoming craton to the west and thrust-imbricated rocks comprising the internides of the Trans-Hudson orogen to the east. East dipping reflections in the upper crust of the Wyoming province (profiles MT8 and MT10) may be an Archean feature predating Hudsonian orogeny or may represent back arc thrusting associated with Hudsonian-age subduction beneath the eastern edge of the Wyoming province. The conventional interpretation of the evolution of the western margin of the exposed Trans-Hudson orogen in Canada, involving northwest directed subduction beneath the Rae-Hearne craton [*Lewry*, 1981], is consistent with the latter interpretation. In Canada, continental-arc magmatism is manifest by the Wathaman batholith, a 900-km-long, Early Proterozoic composite granodioritic batholith lying along the western margin of the orogen [*Lewry*, 1981; *Lewry et al.*, 1981; *Fumerton et al.*, 1984; *Stauffer*, 1984]. The lower crustal layering visible on profiles MT8 and MT10 might mark intrusions associated with pre-Hudsonian extension at the margin of the Wyoming craton; similar prominent subhorizontal lower crustal reflectivity has been shown to be common in Phanerozoic extensional provinces [e.g., *Nelson*, 1991].

Trans-Hudson Internides

Using regional geophysical data sets (e.g., aeromagnetic, gravity, seismic reflection, and refraction), *Green et al.* [1985a, b] extrapolated terranes mapped within the exposed Trans-Hudson orogen in Canada southward beneath the Phanerozoic cover as far as the Dakotas (Figure 1). Further division of lithotectonic terranes within the southern THO was based on both geophysical data (aeromagnetic and gravity) and limited available drill cores [*Klasner and King*, 1986, 1990; *Sims et al.*, 1990]. Projections by *Green et al.* [1985a, b] suggest that the crust beneath the Williston basin corresponds with the exposed Rottenstone domain. This zone extends from the western margin of the orogen (VP 800 on line MT8) to the Tabbernor fault and fold zone (VP 2400 on line ND1). Unfortunately, sparse spatial sampling of the basement in this region, combined with relatively little isotopic data, makes separation of the crust into distinct terranes problematic.

The internal belts of the buried Trans-Hudson orogen are traversed by profiles MT10, MT11, and ND1. On these profiles the upper 2 to 3 s of the crust below the Phanerozoic cover appear relatively transparent (Figure 2c and Plate 1). This is an unfortunate byproduct of processing applied to the data to suppress high-amplitude multiples produced by the overlying sedimentary section. Beneath this artificial transparent zone, the crust is characterized by west dipping reflectivity in the western part of the orogen, an antiformal culmination axial to the orogen, and east dipping reflectivity in the eastern part of the orogen. The antiformal culmination underlying the Williston basin is centered beneath VP 1600 (103° W) on profile ND1 (Figures 2c and 2d and Plate 1). A similar crustal-scale culmination, axial to the orogen, is observed beneath the Glennie domain on the seismic transect to the north and is interpreted to be cored by Archean crust, which is exposed in three basement windows [*Lewry*, 1981; *Lewry et al.*, 1990; *Lucas et al.*, 1993] (see Figures 2a and 2b). The similarity in reflection geometry and the presence of Archean rocks in basement drill cores beneath the Williston basin and exposed in windows in the Glennie domain in Canada lead us, by analogy, to interpret the antiform on profile ND1 as an Archean continental fragment, here named

Figure 2. Comparison of Lithoprobe seismic transect across the northern THO and COCORP's seismic transect across the southern THO beneath the Williston basin. Both data sets reveal west dipping structures in the western part of the orogen and east dipping structures in the eastern part of the orogen. Moho is reflective in the north but not in the south, indicating a fundamental change in evolution along strike. See text for more detailed discussion. (a) Lithoprobe data are migrated at 6 km/s. (b) The corresponding interpretation is from *Lucas et al.* [1993] (Reprinted with permission from *Nature*, vol. 363, pp. 339-342. Copyright 1993 Macmillan Magazine Limited. Abbreviations are as in Figure 1; ALSZ, Athapapuskow Lake shear zone; GCT, Guncoat thrust; HLB, Hanson lake block; HSZ, Hartley shear zone; NFSZ, Needle Falls shear zone; NGC, Namew gneiss complex; PGB, Pikwitonei granulite belt; SC, Superior craton; SF, Stanley fault; SWF, Sturgeon Weir fault; TB, Thompson belt; TFF, Tabbernor fault zone; WD, Wollaston domain. (c) Migrated line drawing of COCORP southern Trans-Hudson orogen transect is shown. Drill cores are from *Sims et al.* [1990]. (d) Corresponding interpretation is shown.

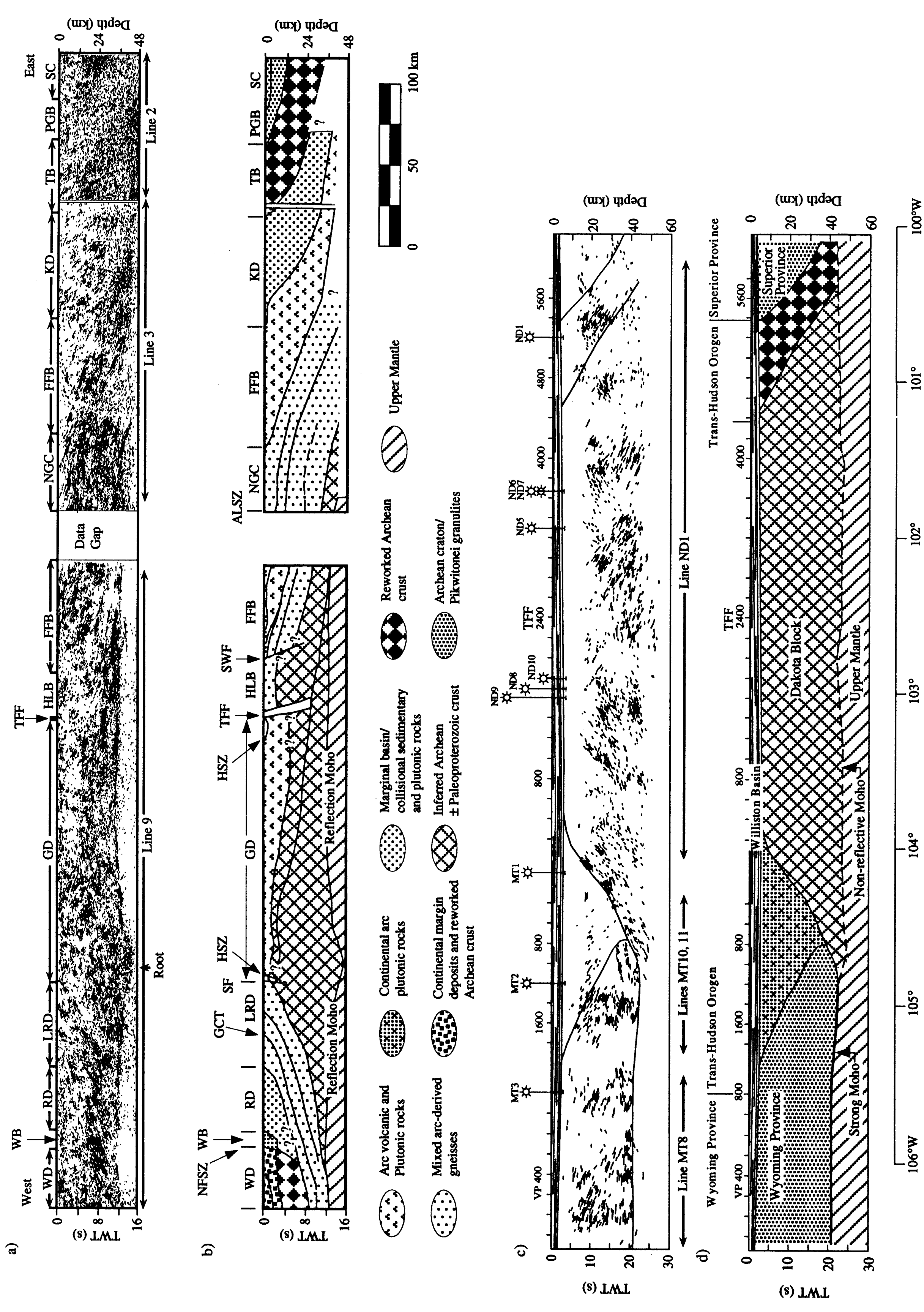

a)
West
East
WD
WB
RD
LRD
GD
TFF
HLB
FFB
Data Gap
NGC
KD
TB
PGB
SC
Line 9
Line 3
Line 2
Root
TWT (s)
Depth (km)
b)
NFSZ
GCT
SF
HSZ
SWF
ALSZ
Reflection Moho
Arc volcanic and Plutonic rocks
Mixed arc-derived gneisses
Continental arc plutonic rocks
Continental margin deposits and reworked Archean crust
Marginal basin/ collisional sedimentary and plutonic rocks
Inferred Archean ± Paleoproterozoic crust
Reworked Archean crust
Archean craton/ Pikwitonei granulites
Upper Mantle
100 km
c)
Line MT8
Lines MT10, 11
Line ND1
d)
Wyoming Province
Trans-Hudson Orogen
Superior Province
Williston Basin
Dakota Block
Strong Moho
Non-reflective Moho
106°W
105°
104°
103°
102°
101°
100°W

Figure 2.

the Dakota block (Figure 2). The north-south extent of the Dakota block is presently unknown, although we speculate that its northern limit may coincide with the westward bend in the NACP at 50°N (Figure 1). It differs from the exposed Glennie domain in that the overlying juvenile Proterozoic crust has apparently been removed.

Eastern Trans-Hudson Orogen

Reflections on profile ND1 between ~VP 3000 and 4400 are variable in strength and orientation but dominantly east dipping (Figure 2c and Plate 1). *Green et al.*'s [1985a, b] geophysical correlations suggested that this part of the buried Trans-Hudson orogen is continuous with the Early Proterozoic Flin Flon - Snow Lake belt exposed in the northern part of the orogen. However, drill core from near the eastern part of profile ND1 (ND-5,-6,-7) sampled biotite - garnet gneiss, mafic granulite, and biotite - cordierite gneiss (Figure 2c; Table 2). These rocks have Proterozoic (Hudsonian) crystallization ages but Archean mantle separation ages. Their high grade of metamorphism indicates that like the basement in the western part of the orogen, they equilibrated at deep crustal levels and were derived from Archean material before being transported to the upper crust. As in the case of the southern extrapolation of the Rottenstone domain, we consider the difference in rock type and geochronologic data evidence against simple southward extrapolation of the Flin Flon domain.

Trans-Hudson Orogen - Superior Province Transition

Perhaps one of the most surprising results of the southern Trans-Hudson orogen seismic transect is that the eastern end of profile ND1 is characterized by east dipping midcrustal reflections (Figure 2c and Plate 1). In fact, both the COCORP and Lithoprobe profiles record east dipping reflections near the eastern margin of the orogen (Figure 2) [*Nelson et al.*, 1993; *Lucas et al.*, 1993; *White et al.*, 1994]. This is opposite to what was predicted by existing interpretations of the evolution of the eastern margin of the orogen [e.g., *Lewry et al.*, 1990; *Klasner and King*, 1990]. The southward projection of the Thompson belt, based on magnetic and gravity anomaly maps and basement-penetrating wells [*Green et al.*, 1985ab; *Klasner and King*, 1986; *Sims et al.*, 1990], places it approximately between VP 4400 and 5400 on line ND1. One distinct package of east dipping reflections projects updip to VP 4400 (Figure 2c). The exposed Thompson belt in Canada (also referred to as the Superior boundary zone) is composed primarily of amphibolite facies felsic gneisses, which are interpreted as retrograded equivalents of the Pikwitonei granulites found immediately to the southeast in the Archean Superior province [*Weber and Scoates*, 1978]. Its complex tectonic history has been interpreted variably as involving northwest subduction of the Superior province beneath the Trans-Hudson orogen [*Lewry et al.*, 1981; *Thomas and Gibb*, 1985; *Bleeker*, 1990], followed by sinistral faulting [*Lewry et al.*, 1981; *Bleeker*, 1990], reverse faulting, and dextral faulting [*Fueten and Robin*, 1989; *Bleeker*, 1990]. Finally, *Fueten and Robin* [1989] concluded that the dominant sense of shear was dip slip, with Superior craton rocks being transported up relative to Trans-Hudson rocks.

We interpret the east dipping reflections within the eastern Trans-Hudson orogen, as well as those marking the Trans-Hudson orogen - Superior province transition (beneath VP 5300 on profile ND1, Figure 2c and Plate 1), to be evidence against the continuation of the Superior province westward beneath the Trans-Hudson, as has been previously proposed [e.g., *Lewry*, 1981; *Klasner and King*, 1990]. Rather, we favor an interpretation in which the east dipping reflections mark (1) east dipping thrust faults that carried Superior province rocks over the eastern margin of the orogen and (2) east dipping thrusts within the orogen that transported high metamorphic grade, lower crustal rocks to upper crustal levels during final collision (Figure 3).

Comparison of Northern and Southern Transects / Discussion

Seismic reflection transects across the northern and southern Trans-Hudson orogen both reveal a crustal-scale antiform flanked by crustal penetrating, west dipping reflections extending to the western margin of the orogen and east dipping reflections extending to the eastern margin of the orogen. We interpret this similarity in reflection geometry as evidence for a common tectonic style along strike within the orogen. However, certain aspects of the orogen (e.g., width, Moho signature, metamorphic grade of basement rocks) differ from north to south: The exposed segment of the orogen in northern Manitoba and Saskatchewan is approximately 650 km wide (including reworked margins), whereas the segment beneath the Williston basin is considerably narrower (420 km). More importantly, the northern transect exhibits a well-defined reflection Moho across much of the orogen, unlike the southern profiles (Figure 2). Finally, limited drill core information indicates that the internides of the Trans-Hudson orogen beneath the Dakotas are comprised largely of reworked Archean, high-grade metamorphic rocks, as compared to a preponderance of juvenile Early Proterozoic, lower-grade rocks to the north.

A model for the evolution of the Trans-Hudson orogen must honor the reflection data and the basic differences in metamorphic grade and mantle separation ages of rocks along strike in the orogen (see Figure 3). We suggest that convergence during collision thrust lower crustal rocks to higher structural levels over much of the Dakota segment of the orogen. These thrusts are represented by west dipping reflections in the western part of the orogen and by east dipping reflections in the eastern part of the orogen. We propose that subduction of oceanic crust westward beneath the Wyoming province is represented in the seismic reflection data by strong west dipping reflectors that truncate both upper crustal east dipping reflectivity and lower crustal layering imaged in the Wyoming province (see Figures 2c and Plate 1 beneath VP 800 on line MT10). The triangular zone of non reflective crust between approximately VP1800 on line MT10 and VP200 on line ND1 (Figures 2c and 2d and Plate 1) could represent a batholith analogous to the Wathaman batholith in northern Saskatchewan. Drill cores near this part of the transect (MT-1,-2, Figure 2c; Table 2) sampled foliated leucogranite and mafic granulite, both with Archean Sm-Nd model ages and Hudsonian crystallization ages. Prominent lower crustal reflections characterizing the eastern edge of the

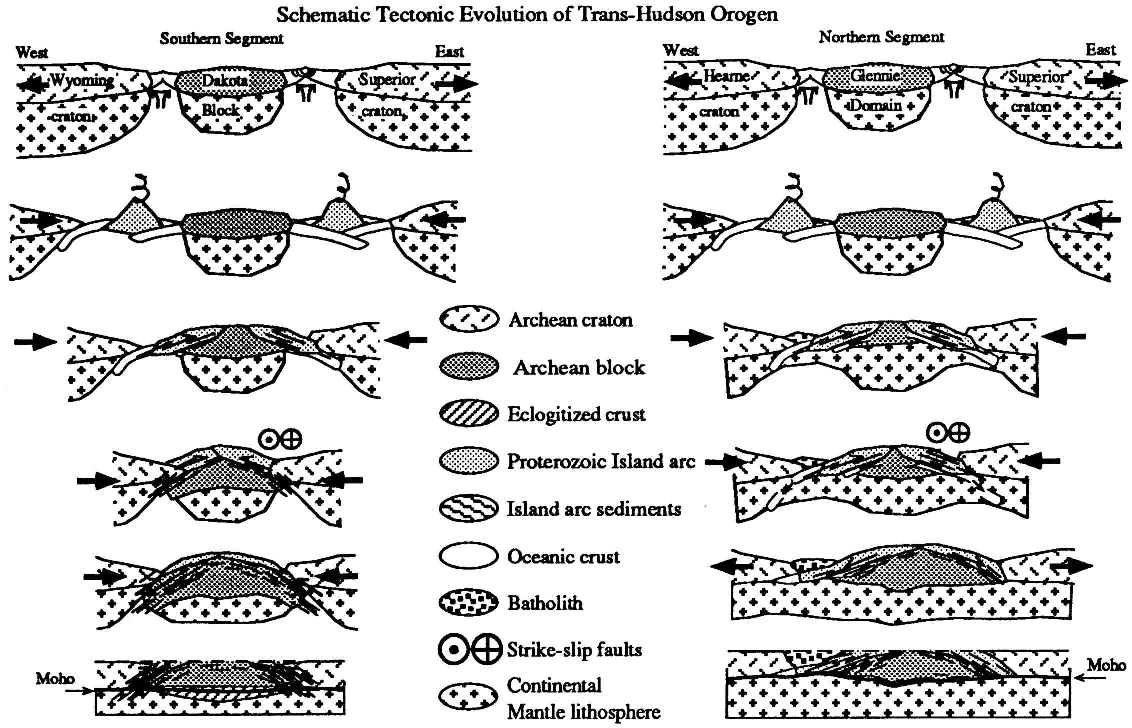


Figure 3. Tectonic model for the evolution of the northern and southern segments of the Trans-Hudson orogen (THO). Juvenile Proterozoic crust is shown to exist in the south (by analogy with exposed terranes in the north) for comparison only; that is, its presence in the southern THO is unconfirmed. In the south, compression reduced the width of the orogen, entrapping the Archean Dakota block. Further compression, accommodated by thrusts flanking both sides of the Dakota block, thickened the crust and transported lower crustal rocks to higher structural levels through progressive uplift and erosion. Strike-slip faulting combined with crustal thickening and erosion to remove any Early Proterozoic upper crust. In the north, postorogenic extensional collapse may be responsible for the preservation of juvenile Proterozoic terranes and the development of a strong reflection Moho. In the south, the overthickened crustal root eventually transformed to eclogite, inducing subsidence of the Williston basin.

Wyoming province may be associated with cumulate or restitic layering formed beneath this batholith. However, if the proposed continental margin batholith were comparable in width to the Wathaman batholith, then the underlying seismic layering would extend far to the west of the batholith's western edge. For this reason, we interpret the layering as either a preexisting (localized) Archean fabric or (more likely) an width to the Wathaman batholith, then the underlying seismic layering would extend far to the west of the batholith's western edge. For this reason, we interpret the layering as either a preexisting (localized) Archean fabric or (more likely) an extensional feature associated with the initial opening of the Manikewan ocean. East dipping upper crustal reflections within the eastern Wyoming craton are interpreted to mark west vergent, collision-related thrusts within continental margin rocks.

East dipping reflections at the eastern margin of the southern Trans-Hudson orogen (profile ND1) support the interpretation that, at least during the final stage of Hudsonian collision, the Superior province crust was thrust westward over the internides. *Lucas et al.* [1993] interpret analogous east dipping reflectivity at the eastern margin of the orogen in the north as a postcollisional feature that masks any evidence of prior west directed subduction. We see no requirement for the Superior province to ever have been subducted toward the west. The boundary could have been characterized by east directed underthrusting throughout its convergent history. The lack of a continental margin arc on the Superior margin could be explained in two ways: Either little oceanic crust separated the Dakota block from the Superior margin prior to the initiation of subduction, or, alternatively, juxtaposition of the Dakota block against the Superior margin was accomplished principally by transcurrent faulting [e.g., *Burke and Sengor*, 1986]. It is noteworthy that crustal penetrating zones of dipping reflections mark both margins of the Trans-Hudson orogen, yet their origins are herein proposed to be distinct. In the west, these reflections are interpreted to mark subduction before collision as well as suturing during collision.

We wish to emphasize that the reflection sections of the Trans-Hudson orogen beneath the Dakotas differ in two striking ways from the seismic reflection profiles across all collapsed Phanerozoic collisional orogens of which we are aware.

1. There is no prominent low-angle reflector on the Trans-Hudson profile that extends from a "foreland" into the interior, which can be associated with underthrusting of the interior orogen by a passive continental margin. A prominent reflection of this type is characteristic of Phanerozoic

collisional orogens like the Appalachians and Variscides [*Ando et al.*, 1984; *Meissner and the DEKORP Research Group*, 1991].

2. The Moho beneath the internides of the Dakota segment of the Trans-Hudson orogen is characterized by the gradual downward cessation of dipping reflections, rather than a distinct subhorizontal reflection or band of reflections [*Baird et al.*, 1995]. In contrast, the Moho beneath the internides of collapsed Phanerozoic orogens, as well as the northern segment of the Trans Hudson orogen [*Lucas et al.*, 1993], is characteristically sharply defined and marked by a subhorizontal band of reflections, this character being generally argued to be associated with postorogenic crustal extension [*Nelson*, 1991]. The clear along-strike variation in the reflective character of the Moho within the Trans-Hudson orogen indicates that age is not the relevant control on the presence or absence Moho reflectivity (Figure 2).

The available data reveal a spatial correlation between the buried antiform imaged on the southern transect, the portion of the Trans-Hudson orogen that is narrowest (most intensely shortened?), and the location of the Williston basin. Elsewhere, we have argued that subsidence of the Williston basin may have resulted from eclogitization of a remnant crustal root that remained beneath the Dakota segment of the orogen after Hudsonian terminal collision and orogenic collapse. We suggest that eclogitization of this root was subsequently triggered by a continent-wide thermal/metasomatic event associated with the breakup of the Late Precambrian supercontinent Rodinia [*Nelson et al.*, 1993; *Baird et al.*, 1995]. This event initiated subsidence of the Williston basin in the manner proposed by *Fowler and Nisbet* [1985] and resulted in the formation of a new "metamorphic" Moho beneath the Dakota segment of the orogen characterized by the observed downward disappearance of crustal reflections.

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