Trans-Hudson orogen and Williston basin in Montana and North Dakota: New COCORP deep-profiling results

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ABSTRACT

COCORP (Consortium for Continental Reflection Profiling) deep reflection profiling across the Williston basin and underlying Trans-Hudson orogen shows the following: (1) There is no evidence for a precursor rift basin beneath the axis of the Williston basin. With the exception of small-scale structures (e.g., Nesson and Cedar Creek anticlines), the basement surface beneath the Williston basin is smooth and has a dish-shaped geometry. (2) Crustal penetrating reflections within the eastern Trans-Hudson orogen dip eastward, in apparent contradiction to the "conventional view" that the Superior province underthrusts the eastern side of the orogen. (3) Basement reflections beneath the center of the orogen define a broad crustal-scale antiform, the axis of which coincides approximately with the depocenter of the overlying Williston basin. Midcrustal reflections defining the crest and western flank of this antiform also coincide generally with the location and shape of the source of the North American Central Plains conductivity anomaly. (4) Crustal penetrating reflections beneath the western side of the orogen dip westward, supporting the current view that subduction polarity was to the west beneath the Wyoming province. (5) The eastern edge of the Wyoming province is marked by east-dipping upper-crustal reflections and subhorizontal lower-crustal reflections that are truncated by the west-dipping reflectivity of the Trans-Hudson orogen.

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INTRODUCTION

During the summer of 1990, COCORP acquired 400 km of Vibroseis deep seismic reflection data across the Williston basin and underlying Trans-Hudson orogen (Fig. 1). The work is part of a collaborative effort between COCORP and the Canadian Lithoprobe project to study these major crustal features. The COCORP survey consists of three profiles, MT-10, MT-11, and ND-01, which together with COCORP's previously acquired line MT-08, constitute an east-west transect of the Williston basin and underlying Trans-Hudson orogen at approximately lat 48°30′N. Principal results of this work are summarized in Figure 2, which is based on initial common midpoint stacks incorporating elevation statics, band-pass filter, velocity analysis, mute, deconvolution, and coherency filter. Also shown in Figure 2

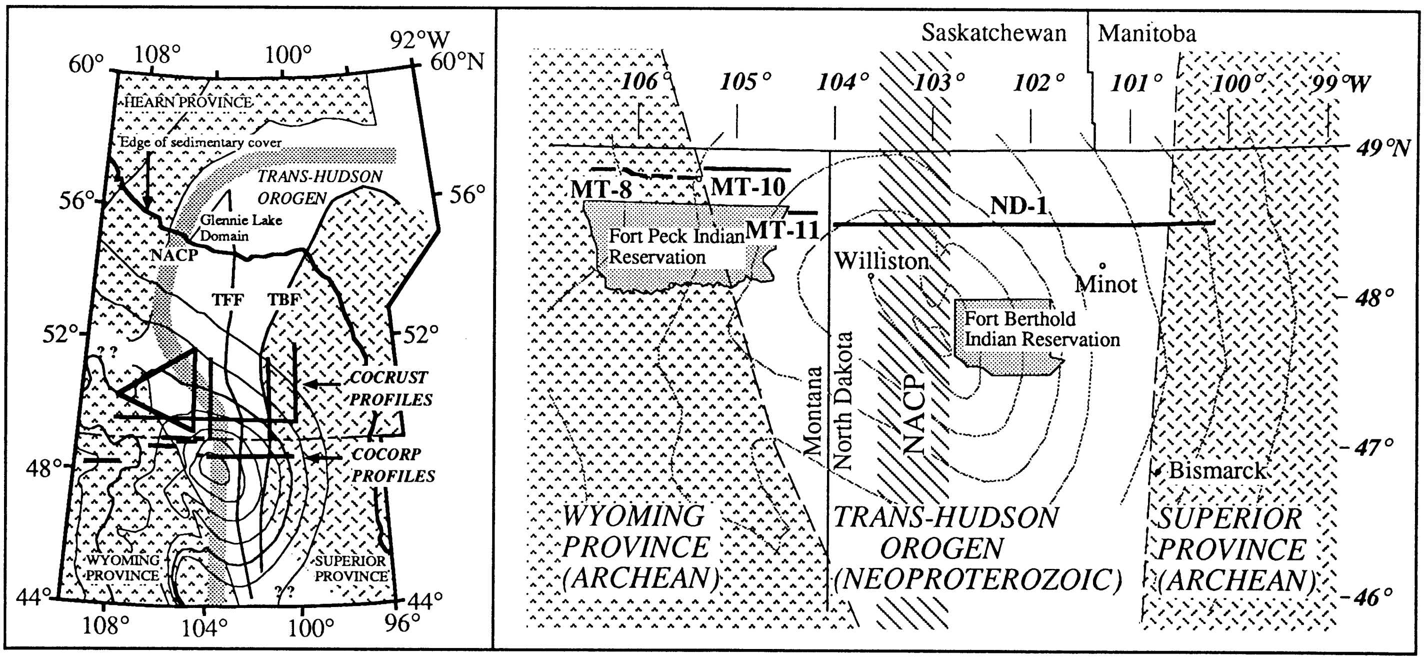

Figure 1. Regional (left) and detail (right) maps showing locations of new COCORP seismic reflection profiles crossing Williston basin. Regional map simplified from Green et al. (1985). Boundaries of Trans-Hudson orogen and contours on top of Precambrian shown in detail from Sims et al. (1990). North American Central Plains conductivity anomaly (NACP) data from Jones and Savage (1986). TFF = Tabbernor fault-fold zone; TBF = Thompson boundary fault.

is a recent interpretation of nearby seismic refraction data collected by the Canadian COCRUST group during the late 1970s and early 1980s (Morel-à-l'Huissier et al., 1987) and the location of the source body of the North American Central Plains conductivity anomaly, as modeled by Jones and Craven (1990) on the basis of magnetotelluric data acquired a short distance north of the U.S.-Canadian border. The latter is the most areally extensive conductivity anomaly identified in North America (Alabi et al., 1975; Fig. 1).

RESULTS

The Phanerozoic sedimentary fill of the Williston basin is clearly imaged in the shallow part of the COCORP profiles. Analysis of interval velocities and comparison with nearby basement-penetrating wells indicate that there is no substantial late Precambrian–Early Cambrian (i.e., before deposition of the Deadwood Formation) rift basin beneath the Williston basin at the latitude of the COCORP survey. At the scale of the entire crust, the basement surface has a smooth, dish-shaped geometry.

The eastern part of the Wyoming province, imaged on MT-08 and the western two thirds of MT-10, exhibits a very prominent band of reflectivity, up to ~3.5 s thick, at the base of the crust (Fig. 3). Similar lower-crustal reflectivity is not observed elsewhere on the survey. Intracrustal reflections above this prominent band on MT-08 and MT-10 dip steeply east, suggesting that the eastern margin of the Wyoming province was imbricated in an east-over-west sense during the Trans-Hudson orogeny. The eastern limit of this east-dipping intracrustal reflectivity projects updip to the western edge of the Trans-Hudson orogen defined by Sims et al. (1990) on the basis of scattered well penetrations to basement. Beneath VP (vibrator point) 900 on MT-10, both the prominent band of lower-crustal reflectivity and overlying east-dipping reflections appear to be cut off by west-dipping reflections that extend through the entire crust (Figs. 2, 3).

Within the central part of the Trans-Hudson orogen there is an overall change in the dip direction of mid- to lower-crustal reflections. Reflections beneath the western part of the orogen dip predominantly westward, whereas those beneath the eastern part dip predominantly eastward. Together the two sets appear to define a crustal-scale antiform centered at approximately long 103°E (about VP 1700 on ND-01; Fig. 2), the approximate longitude of the depocenter of the overlying Williston basin. The reflections defining the center and western flank of this antiform coincide generally with the modeled location and shape of the source body for the North American Central Plains conductivity anomaly, although the individual reflections have a steeper dip after migration than the interpreted source. Jones and Craven's (1990) modeling showed that the source of the anomaly could be either a continuous, gently west-dipping conductive body or, alternatively, several disconnected bodies having the same overall geometry. An interpretation consistent with the seismic data is that the source body is a conductive lithologic unit that has been imbricated (dismembered) along a number of east-vergent thrust faults, such that the enveloping surface of the imbricated unit dips less steeply than the individual thrusts.

Moderately steeply *east*-dipping reflectors dominate the middle to lower crust of the eastern Trans-Hudson orogen. The reflections are visible on ND-01 between approximately VP 2500 to 4300 in the depth range 7 to 17 s two-way traveltime (Fig. 2). Their migrated dip is in the range 40°–50°. The eastern termination of the dipping reflectors coincides closely with the position of the Thompson boundary fault, inferred to project southward from its outcrop in Canada on the basis of aeromagnetic data by Green et al. (1985). Where exposed, the Thompson boundary fault is a major steeply dipping mylonite zone separating juvenile arc and oceanic terranes of the Trans-Hudson orogen on the west from a marginal belt of Superior province rocks on the east that were deformed during the Trans-Hudson orogeny ("Thompson belt"; Green et al., 1985). Several diffractions are visible on the COCORP section in the general vicinity of the Thompson boundary fault, consistent with the idea that this is a major transcurrent fault system at the latitude of the COCORP survey (e.g., apex at 6.7 s beneath VP 3930, Fig. 2). This is also the location of a prominent north-trending conductivity anomaly ("TOBY" anomaly of Jones and Craven, 1990). A region of east-dipping reflections is also visible within the middle crust of the western Superior province (between VP 5200 and 5600, 6 to 11 s) (Fig. 2), although in general the Superior province appears less reflective than the Trans-Hudson orogen to the west.

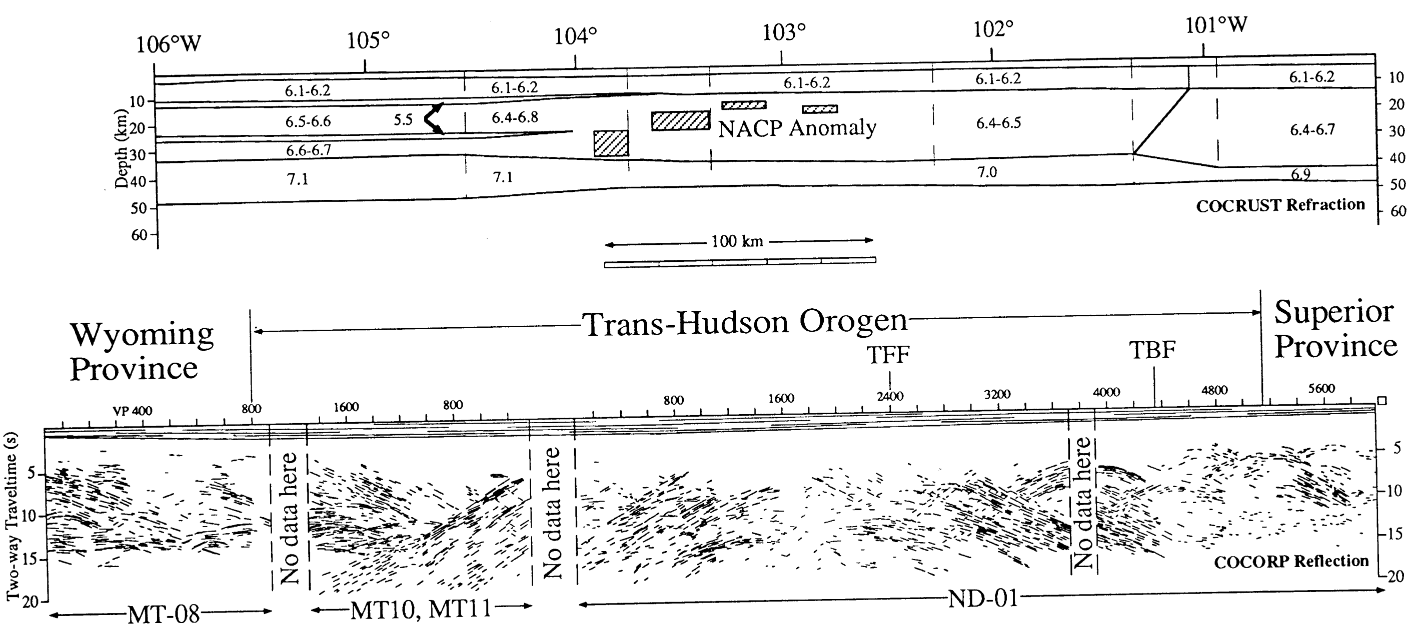

Figure 2. Top: Interpretation of COCRUST seismic refraction–wide-angle reflection data (Morel-à-l'Huissier et al., 1987) plotted at 1:1 scale. Average layer velocities in kilometres per second. Bottom: Line drawing (unmigrated) of COCORP seismic reflection data. Bottom panel is 1:1 at crustal velocity of 6 km/s. Abbreviations as in Figure 1.

DISCUSSION AND CONCLUSIONS

Evolution of the Trans-Hudson Orogen

Only recently has sufficient geological information become available with which to attempt plate-tectonics interpretations of the evolution of the Trans-Hudson orogen. Nevertheless, it is conventionally held that, prior to suturing, the Superior province was bordered on the west by a passive margin and that during collision this margin underthrust the juvenile terranes, now composing the interior of the belt, toward the west. This concept was developed largely on the basis of surface geologic relations within and adjacent to the exposed part of the orogen (Lewry, 1981; Lewry et al., 1990) and has been extended to the entire belt, in part on the basis of a very short seismic reflection profile within the inferred Thompson belt in southern Saskatchewan that showed west-dipping reflections within the middle crust (Green et al., 1980, 1985; Klasner and King, 1990). The new COCORP data suggest that this interpretation is not appropriate at the latitude crossed by the survey. In particular, the crustal-penetrating east-dipping reflectors beneath the eastern Trans-Hudson orogen seem to imply the opposite vergence. One possibility is that east-dipping reflections record eastward subduction that took place beneath an intraoceanic arc terrane that was subsequently juxtaposed against the margin of the province by transcurrent faulting.

The deep west-dipping reflections beneath the western part of the Trans-Hudson orogen are consistent with the current view that an active continental-margin arc developed along the edge of the Wyoming province during ocean closure (e.g., Lewry et al., 1981; Green et al., 1985). A simplistic interpretation is that this continental margin arc and the oceanic arc composing the eastern part of the orogen oppose each other, with an exotic terrane caught in between, the latter represented by the antiformal culmination imaged on ND-01 (Fig. 4). An ~40 mgal gravity high associated with this culmination (Jones and Craven, 1990) implies the existence of relatively dense continental(?) material at depth. We speculate that this exotic terrane might be a southerly extension of the antiformal Glennie Lake domain, exposed in the interior of the Trans-Hudson orogen in Canada. Recent neodymium model ages on post-tectonic granites within the Glennie Lake domain suggest that it is cored at depth by very old continental material (T_{DM} = 3.2 to 3.5 Ga) (Bickford et al., 1992) and thus might represent an Archean microcontinental fragment caught up in the orogen. East-dipping reflections present within the Wyoming province might represent back-arc thrusting within and cratonward of the continental-margin arc that bordered the orogen.

Moho and the Williston Basin

A principal result of the new COCORP survey is the observation that pronounced, subhorizontal, lower-crustal reflectivity is restricted to the eastern margin of the Wyoming province. Similarly prominent lower-crustal lamination is commonly observed in Phanerozoic extensional provinces (e.g., Basin and Range province; McCarthy and Thompson, 1988). When this feature was

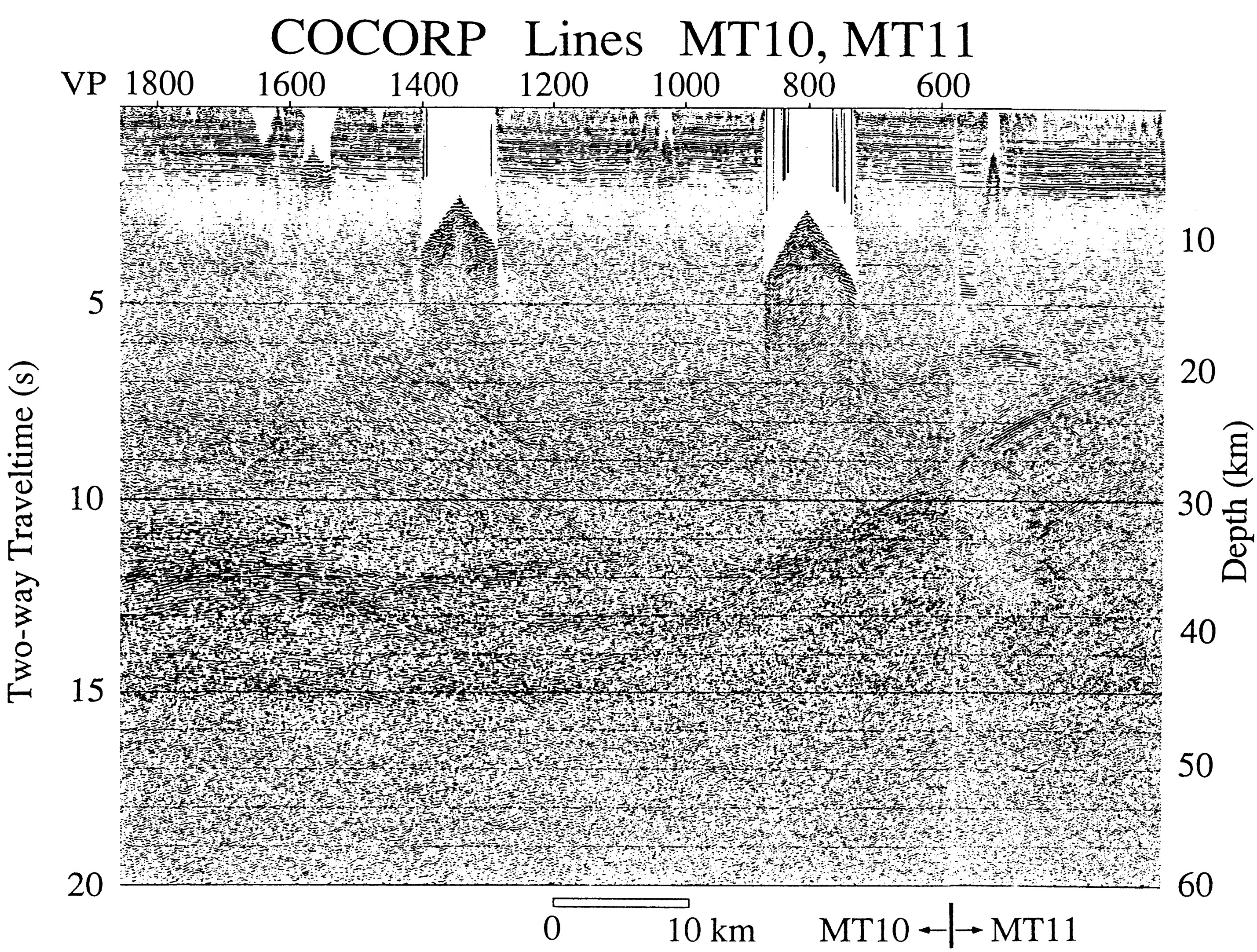

Figure 3. COCORP lines MT10 and MT11 showing termination of lower-crustal layering (Archean) by west-dipping reflectors (Proterozoic).

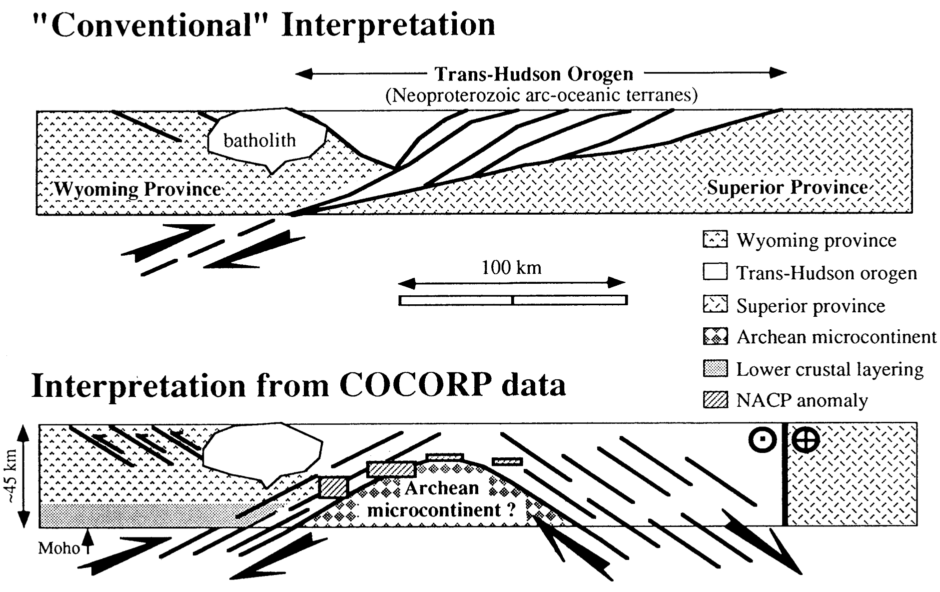

Figure 4. Schematic diagrams contrasting "conventional" (top) view of Trans-Hudson orogen crustal structure (generalized from Klasner and King, 1990) with that suggested in this paper on the basis of new COCORP data (bottom). Figure is 1:1 at crustal velocity of 6 km/s.

first observed beneath the edge of the Williston basin on line MT-08, it was speculated that it might be a manifestation of lower-crustal stretching and/or associated magmatic underplating of the crust related to the formation of the Williston basin (Latham et al., 1988). The fact that the lamination is not areally disposed beneath the basin, but rather is restricted to the margin of the Wyoming province, renders this hypothesis invalid. The location of the lamination, along with the observation that it appears to be cut off by structure within the orogen, implies that the rock fabric producing this distinctive reflectivity is of Trans-Hudson age or older. One possibility is that it marks a layered restite and/or cumulate assemblage formed at the base of a continental-margin arc.

The lack of an obvious rift basin or a sharply defined Moho beneath the Williston basin militates against the idea that crustal stretching played a significant role in the formation of the basin. Possible mechanisms for the initiation of basin subsidence that do appear to be compatible with the COCORP data include decay of a thermal anomaly within the lithosphere (imposed without substantial crustal stretching) (Turcotte and Ahern, 1977; Ahern and Mrkvicka, 1984) and a metamorphic phase change in the lower crust (Fowler and Nisbet, 1985). These two processes may have operated in concert. With regard to the latter, the diffuse appearance of the Moho beneath the basin may be characteristic of a Moho produced by eclogitization of the lower crust.

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REFERENCES CITED

Ahern, J.L., and Mrkvicka, S.R., 1984, A mechanical and thermal model for the evolution of the Williston basin: Tectonics, v. 3, p. 79–102.

Alabi, A.O., Camfield, P.A., and Gough, D.I., 1975, The North American Central Plains anomaly: Royal Astronomical Society Geophysical Journal, v. 43, p. 815–834.

Bickford, M.E., Collerson, K.D., and Lewry, J.F., 1992, Subduction of Superior craton during Trans-Hudson collisional orogenesis: Isotopic evidence [abs.]: Eos (Transactions, American Geophysical Union), v. 73, p. 322.

Fowler, C.M.R., and Nisbet, E.G., 1985, The subsidence of the Williston basin: Canadian Journal of Earth Sciences, v. 22, p. 408–415.

Green, A.G., Stephenson, O.G., Mann, G.D., Kanasewich, E.R., Cumming, G.L., Hajnal, Z., Mair, J.A., and West, G.F., 1980, Cooperative seismic surveys across the Superior-Churchill boundary zone in southern Canada: Canadian Journal of Earth Sciences, v. 17, p. 617–637.

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

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 data 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.

Klasner, J.S., and King, E.R., 1990, A model of tectonic evolution of the Trans-Hudson orogen in North and 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. 271–286.

Latham, T.S., Best, J., Chaimov, T., Oliver, J., Brown, L., and Kaufman, S., 1988, COCORP profiles from the Montana plains: The Archean cratonic crust and a lower crustal anomaly beneath the Williston basin: Geology, v. 16, p. 1073–1076.

Lewry, J.F., 1981, Lower Proterozoic arc-microcontinent collisional tectonics in the western Churchill Province: Nature, v. 294, p. 69–72.

Lewry, J.F., Stauffer, M.R., and Fumerton, S.L., 1981, A Cordilleran-type batholithic belt in the Churchill Province in northern Saskatchewan: Precambrian Research, v. 14, p. 277–313.

Lewry, J.F., Thomas, D.J., Macdonald, R., and Chiarenzelli, J., 1990, Structural relations in accreted terranes of the Trans-Hudson orogen, Saskatchewan: Telescoping in a collisional regime?, *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. 1–14.

McCarthy, J., and Thompson, G., 1988, Seismic imaging of extended crust with emphasis on the western United States: Geological Society of America Bulletin, v. 100, p. 1361–1374.

Morel-à-l'Huissier, P., Green, A., and Pike, C., 1987, Crustal refraction surveys across the Trans-Hudson orogen/Williston basin of south central Canada: Journal of Geophysical Research, v. 97, p. 6403–6420.

Sims, P.K., Peterman, Z.E., Hildenbrand, T.G., and Mahan, S., 1990, Precambrian basement map of the Trans-Hudson orogen and adjacent terranes, northern Great Plains, U.S.A.: U.S. Geological Survey Miscellaneous Investigations Map I-2214, scale 1:1,000,000.

Turcotte, D.L., and Ahern, J.L., 1977, On the thermal and subsidence history of sedimentary basins: Journal of Geophysical Research, v. 82, p. 3762–3766.

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