Upper-mantle reflectivity beneath the Williston basin, phase-change Moho, and the origin of intracratonic basins

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ABSTRACT

COCORP (Consortium for Continental Reflection Profiling) deep-reflection profiles crossing the northern Williston basin show (1) dipping reflections within the crust of the underlying Trans-Hudson orogen that extend downward into the upper mantle and (2) no clearly defined reflection Moho. In contrast, Lithoprobe (Canada's national geoscience project) profiles crossing the Trans-Hudson orogen north of the basin show dipping reflections within the crust that terminate at a sharply defined subhorizontal reflection Moho—a reflection character typical of the interior of collapsed Phanerozoic orogens. We suggest that a crustal root produced during Hudsonian collision was incompletely removed by "normal" postorogenic extension in the region now underlain by the Williston basin. This remnant crustal keel much later underwent eclogite-facies metamorphism, which overprinted a new nonreflective Moho across the root and induced the subsidence of the Williston basin.

INTRODUCTION

Intracratonic basins are large elliptical depressions within the interiors of the continents that episodically accumulated sediments over hundreds of millions of years (Sloss, 1987). Two of the most popular mechanisms proposed to explain the origin of these basins are subsidence resulting from conductive cooling of the lithosphere (e.g., Turcotte and Ahern, 1977; Sleep et al., 1980) and subsidence resulting from a metamorphic phase change in the lower crust (e.g., Haxby et al., 1976; Fowler and Nisbet, 1985; Hamdani et al., 1994). Although the conductive cooling mechanism proved successful in explaining the subsidence of continental margins, its application to intracratonic basins has been problematic. Regional uplift immediately prior to the start of subsidence is not generally recognized in association with these basins, nor are there precursor rift basins of appropriate age beneath them (e.g., Nelson et al., 1993), both of which would be expected in association with a lithospheric thinning (heating) event (Quinlan, 1987). Fowler and Nisbet (1985) also argued that the subsidence of these basins does not follow the characteristic $t^{1/2}$ form of thermal subsidence. For these reasons, the phase-change mechanism remains a popular alternative hypothesis. In this paper, we present evidence from COCORP and Lithoprobe seismic reflection data that lends support for the phase-change mechanism and suggests that its operation is contingent on preexisting crustal structure.

COCORP AND LITHOPROBE DEEP-REFLECTION PROFILES

Recently, COCORP and Lithoprobe profiled parallel deep seismic reflection traverses across the ca. 1.8 Ga Trans-Hudson orogen (Fig. 1). The orogen is overlain by the Phanerozoic Williston basin in the region crossed by COCORP, whereas no overlying basin exists in the region traversed by Lithoprobe. The goals of this cooperative effort were to image the large-scale structure of the orogen and determine if there were any observable differences in lithospheric structure between the two areas that might be associated with the development of the Williston basin. The profiles show a striking similarity in the crustal-scale structure of the orogen in the two areas, despite their being separated by 700 km along strike. Both transects show dominantly west-dipping reflections extending through the crust in the western part of the orogen, a crustal-scale antiformal culmination defining the center of the orogen, and east-dipping reflections extending through the crust in the eastern part of the orogen. Tectonic interpretations of these reflections in terms of structures formed during the evolution of an Early Proterozoic ocean basin and subsequent continent-continent collision are given in Lucas et al. (1993, 1994), Nelson et al. (1993), Lewry et al. (1994), White et al. (1994).

Although the large-scale crustal structure in the two areas appears similar, the reflection character of the crust-mantle transition is distinctly different. On the Lithoprobe transect, dipping reflections within the crust terminate at, and/or flatten into, a relatively sharply defined subhorizontal reflection Moho, the only exception being beneath the axis of the crustal antiform where a small crustal root exists, at the base of which the Moho is indistinct. Deep-reflection profiling in orogenic belts worldwide has demonstrated that sharply defined subhorizontal reflection Mohos that define a lower bound to dipping reflectivity within the crust are characteristic of the interior of collapsed (or collapsing) Phanerozoic orogens (see, e.g., Nelson, 1991). Apparently, postcollisional ductile flow in the lower crust, perhaps aided by extensional or magmatic processes, acts to remove crustal roots and imposes a more or less flat, sharply defined Moho beneath old orogens.

In contrast to the Moho on the Lithoprobe transect, no clearly defined reflection Moho is visible within the Trans-Hudson orogen on the COCORP transect. Rather, dipping reflectivity within the orogen dies away downward at traveltimes appropriate for the upper mantle. This feature is particularly evident beneath the western part of the orogen where west-dipping reflections, probably marking a structural fabric formed during Paleoproterozoic west-dipping subduction or collision beneath the Wyoming province, are traceable down to 20 s two-way traveltime (TWT) (Figs. 2, 3[1]). As discussed subsequently, this depth is substantially below the depth of the Moho as defined locally by seismic refraction experiments. This observation suggests that in the vicinity of the COCORP survey, the Moho within the interior of the Trans-Hudson orogen is a gradational boundary that was superimposed across structural fabrics produced during the Hudsonian orogeny.

COCORP EXPLOSIVE-SOURCE PROFILING

To test the possibility that the lack of distinct Moho reflections on the COCORP Vibroseis profiles was due to inadequate signal penetration, and to explore for deeper reflections, COCORP subsequently collected several low-fold explosive-source profiles

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[1] Loose insert: Figure 3 is on a separate sheet accompanying this issue.

(MT12, ND2, and ND3 in Fig. 1; Steer et al., unpublished). The explosive-source profiling results confirm and extend the COCORP Vibroseis results. No throughgoing subhorizontal reflection or abrupt downward cessation of dipping reflections, which might reasonably be associated with the Moho, is observed on the explosive-source profiles. Conversely, the dipping reflections imaged on the Vibroseis profiles can be seen to extend deeper on the explosive-source profiles, confirming that the lack of a reflection Moho is not due to a lack of signal penetration (Figs. 2, 3). Line MT12, which images the west-dipping reflections beneath the western side of the Trans-Hudson orogen, shows that these reflections extend downward to at least 25 s TWT. Line ND2, a north-south cross line, further demonstrates that these west-dipping reflections extend southward along the regional strike of the orogen, toward the center of the Williston basin. Line ND3, at the eastern margin of the orogen, also shows dipping reflections disappearing downward, though at a shallower level than in the west. Two-dimensional migration and depth conversion using velocities derived from nearby refraction data indicate that the dipping fabric beneath the western side of the orogen extends downward to at least 60 km depth.

COMPARISON WITH NEARBY REFRACTION DATA

Coincident deep seismic reflection and refraction data acquired in a variety of areas around the world demonstrate that, with rare

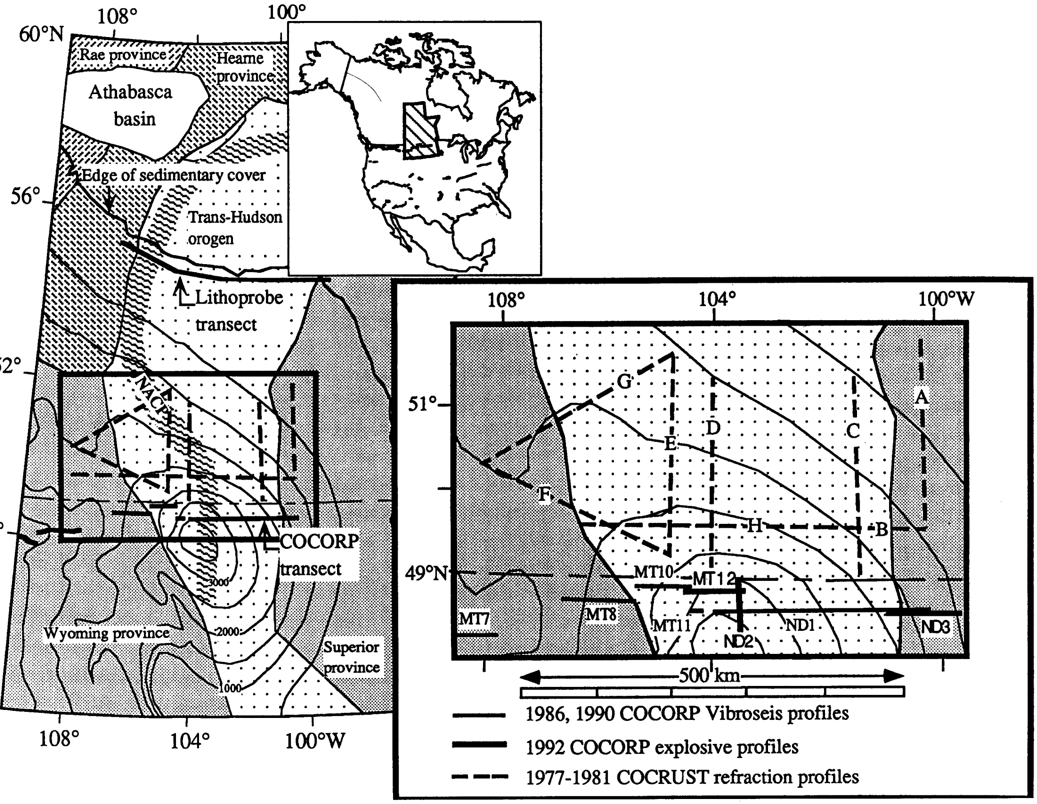

Figure 1. Locations of COCORP and Lithoprobe deep seismic reflection profiles and COCRUST seismic refraction profiles across Trans-Hudson orogen and Williston basin. Contours (500 m interval) are to top of Precambrian basement. NACP is North American Central Plains conductivity anomaly.

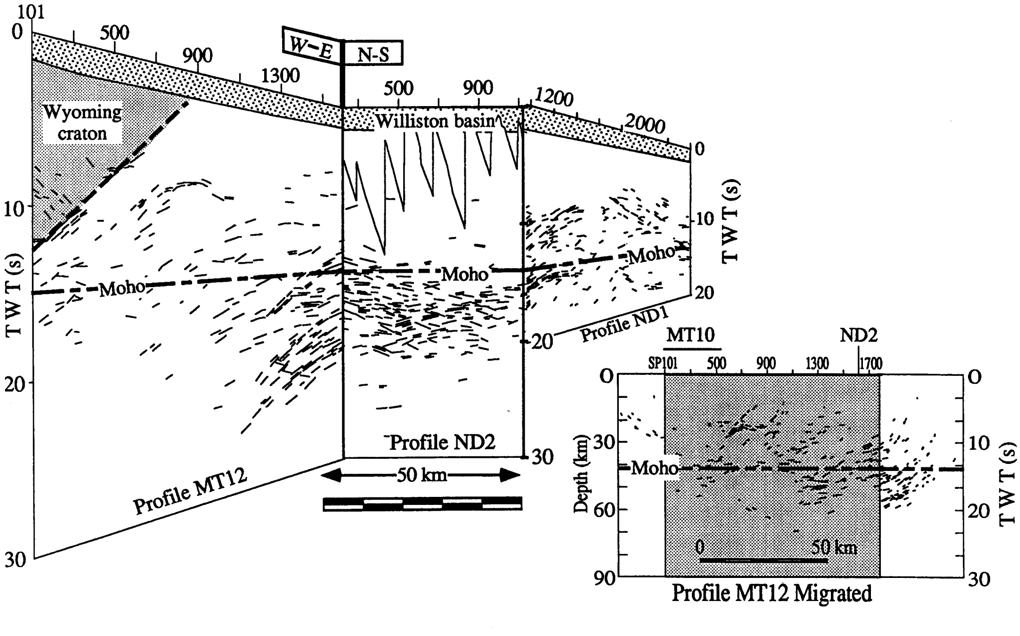

Figure 2. Fence diagram of profiles MT12, ND2, and ND1 (unmigrated). Inset shows migrated position of west-dipping reflections on profile MT12. Ties with ND2 indicate that these reflections are subhorizontal in the north-south direction. Southward extrapolation of Moho from nearby COCRUST refraction data (dashed line) places Moho above strong, subhorizontal reflections present on COCORP profile ND2.

exception, the reflection Moho coincides with the classically defined Moho (Mooney and Meissner, 1992). Although coincident refraction data are not available for the COCORP Williston basin–Trans-Hudson orogen traverse, a substantial wide-angle reflection-refraction data set was acquired a short distance to the north by COCRUST (Consortium for Crustal Reconnaissance Using Seismic Techniques) in the late 1970s (Fig. 1). These data have been interpreted by several different groups, with generally convergent results (e.g., Hajnal et al., 1984; Morel-à-l'Huissier et al., 1987).

COCRUST line H crosses the buried Trans-Hudson orogen 80 km north of the COCORP transect. According to Morel-à-l'Huissier et al. (1987), the Moho beneath the interior of the orogen on line H is at about 42 km depth. This location is along regional strike of the deepest reflections observed on the COCORP data and along strike of the area where the COCORP data show no reflection Moho. COCRUST line D indicates that the Moho shallows gently southward toward the COCORP transect, consistent with isostatic considerations, which imply that as the low-density sedimentary fill of the Williston basin thickens southward, the crust should concomitantly thin.

Because the interpretation of the depth to Moho along the COCORP transect depends critically on the COCRUST data, we reexamined the data for COCRUST line H. Our forward ray-trace modeling of the seismograms given in Morel-à-l'Huissier et al. (1987) generally confirms their Moho placement and demonstrates that a change in their interpreted depth to Moho by more than a few kilometres yields an unacceptable fit to observed Moho reflected and refracted arrivals. Regional isostasy and the southward shallowing of the Moho observed on COCRUST line D imply that the Moho shallows slightly southward toward the center of the Williston basin and toward the COCORP survey. Hence, the dipping reflectivity imaged on the COCORP profiles below about 12–13 s TWT (40–45 km depth) apparently lies within the upper mantle (Figs. 2, 3). On the basis of these observations, we conclude that the Moho beneath the interior of the Trans-Hudson orogen, in the vicinity of the COCORP survey, is a gradational velocity transition that is not reflective at the frequencies employed in deep-reflection profiling, and that this gradational Moho was superimposed on deformation fabrics produced during the Hudsonian orogeny.

PHASE-CHANGE MOHO AND THE ORIGIN OF THE WILLISTON BASIN

In the phase-change model of intracratonic basin formation, recrystallization of a broadly mafic lower crust to eclogite increases the density of the rock column, causing the overlying crust to subside (Hamdani et al., 1994). Transformation of a rock to eclogite involves the growth of high-density, high-velocity minerals, principally garnet and omphacitic pyroxenes, at the expense of lower-density, lower-velocity minerals, principally plagioclase. Given a sufficient degree of recrystallization, eclogites exhibit compressional-wave velocities in excess of 8 km/s (Manghnani et al., 1974). From a velocity standpoint, such rocks would be considered mantle. Upward migration of an eclogite metamorphic front through the lower crust would be expected to produce a gradational Moho (macroscopic-scale, gradational, downward increase in percentage of garnet relative to plagioclase) that is not reflective at the wavelengths used in seismic reflection experiments. Dipping reflections produced by preexisting, dipping, mesoscopic-scale layering (e.g., compositional layering, ductile shear zones) would reasonably be expected to extend downward through this superposed transition—ultimately dying away downward due to increasing reflector distance, perhaps aided by preferential growth of garnet in felsic layers, which might tend to decrease impedance contrasts between mafic and felsic layers. This is the deep reflection character observed on the COCORP profile.

The observation that this character is not observed on the Lithoprobe profile leads to the suggestion that, after Hudsonian collision, processes associated with postorogenic collapse effectively removed the collisional crustal root from that region, whereas these processes did not effectively remove the collisional root in the Williston area. The remnant crustal root in the Williston area subsequently transformed to eclogite, producing a new, shallower, gradational Moho and the subsidence that produced the Williston basin (Fig. 4). This hypothesis is qualitatively consistent with the southward narrowing of the Trans-Hudson orogen and parallel increase of metamorphic grade of rocks subcropping within the orogen (Green et al., 1985a, 1985b), both of which suggest that collisional shortening was greater in the south (deeper crustal root formed) and/or that postcollisional extension was less in the south (less complete removal of the root).

TIMING PROBLEM

Problematic to any model that connects the Williston basin to the Trans-Hudson orogen is the observation that Hudsonian orogeny was over by ~1.7 Ga (Machado, 1990) whereas subsidence of the basin, as evidenced in the sedimentary record, did not commence until the Cambrian (~520 Ma., Leighton and Kolata, 1990). A substantial time lag between the last precursor tectonic event and the onset of subsidence is a feature of a number of intracratonic basins. For example, the Michigan basin lies atop the ca. 1.1 Ga Keweenawan rift but, like the Williston basin, did not begin to subside until the Cambrian. As several workers have noted, a substantial number of the world's intracratonic basins began to form in Cambrian–Middle Ordovician time, despite their having formed over lithosphere with widely differing presubsidence tectonic histories (e.g., Williston, Michigan, Illinois, Baltic, Moscow, and Paraná basins—Sloss, 1987; Klein and Hsui, 1987; Sloss, 1991; papers in Leighton et al., 1990). This implies a global triggering event.

Following Klein and Hsui (1987), we suggest that this triggering

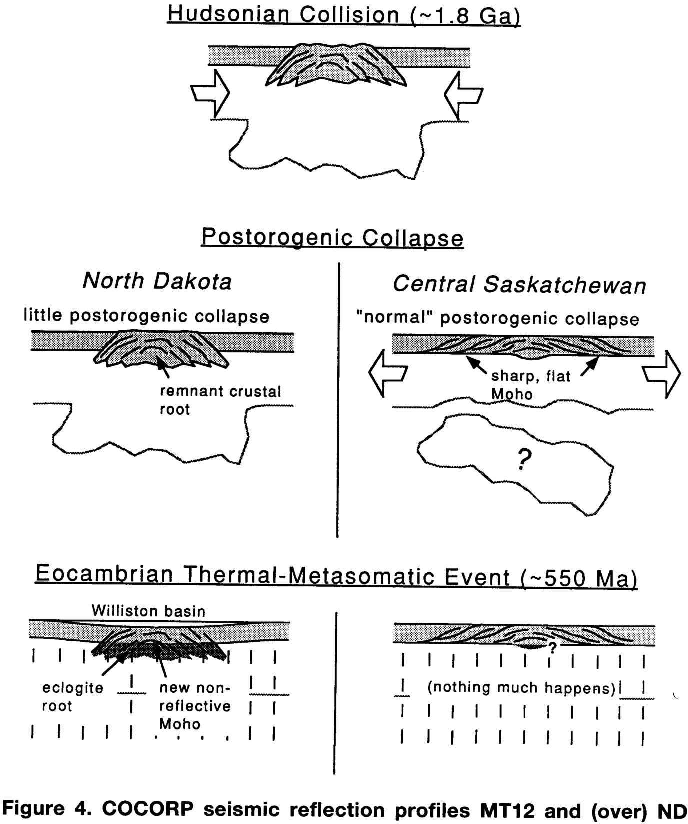

Figure 4. COCORP seismic reflection profiles MT12 and (over) ND2 (unmigrated, 1:1 at 6 km/s).

event was a supercontinent-wide thermal or metasomatic event associated with the breakup of the Neoproterozoic supercontinent Rodinia. Numerical modeling of mantle convection suggests that when a supercontinent amalgamates, it produces a thermal blanketing effect, which in turn forces reorientation of mantle convection, such that upwelling begins beneath the supercontinent—in essence sealing its own destruction (Gurnis, 1988). Such an event could trigger eclogitization of metastable lower-crustal keels either through transient heating and subsequent cooling of the lower crust (e.g., as modeled by Hamdani et al., 1994) or by injection of mantle-derived metasomatic fluids into the lower crust (e.g., see Fountain et al., 1994, for a field example of fluid-triggered eclogitization)—in either case resulting in the eclogitization of previously less dense lower crust. The lower-crustal keels might have a variety of origins. Some, as in the case of the Williston and Hudson Bay basins, might have been remnant collisional crustal roots. Others, as in the case of the Michigan basin, might have been gabbroic pillows (magmatic underplate) added to the lower crust in an earlier rifting episode. In each case the crustal keels would have remained unaltered prior to the breakup of the supercontinent because of the unfavorable kinetics of the gabbro-eclogite phase transformation in dry rocks at the relatively low temperature of normal cratonic lower crust (Ringwood, 1972). Transient heating-cooling and/or injection of metasomatic fluid would have allowed eclogitization to go to completion. This hybrid phase-change hypothesis is attractive because it provides an explanation for the spatial association of intracratonic basins with major precursor structures such as orogenic belts and rifts, while at the same time explaining the apparent synchrony of inception of these basins, independent of the age of their underlying structures. On a broader level the hypothesis suggests a view of the base of the cratonic crust wherein epeirogeny is caused by the activation of remnant crustal keels.

CONCLUSIONS

COCORP profiling across the northern Williston basin shows dipping reflections extending downward into the upper mantle beneath the interior of the Trans-Hudson orogen. These reflections likely manifest structural fabric formed during the Hudsonian (Early Proterozoic) orogeny. This structural fabric is overprinted by a gradational (nonreflective) Moho that resulted from the upward migration of an eclogite phase transition across a remnant crustal root left over from Trans-Hudson collision. Comparison of the COCORP data with Lithoprobe data crossing the Trans-Hudson orogen north of the Williston basin and consideration of the history of other intracratonic basins lead to a view of the base of the crust wherein preexisting remnant crustal keels, originally formed by a variety of processes, can be triggered into undergoing a metamorphic phase transition by a continent-wide thermal or metasomatic event. Mantle upwelling beneath a supercontinent might produce such a trigger.

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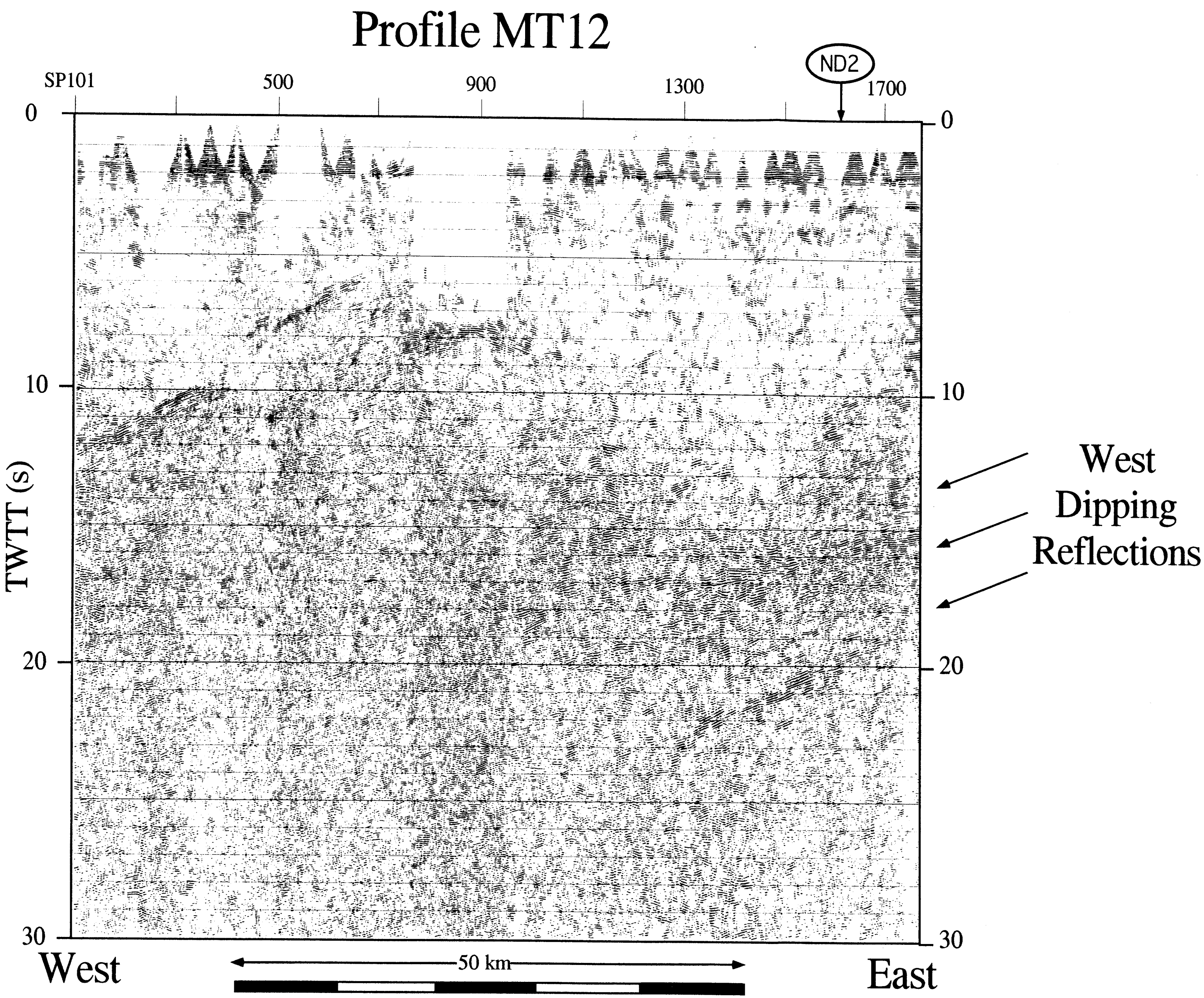
Figure 3. Contrasting postcollisional evolution of Trans-Hudson orogen in North Dakota and central Saskatchewan (see text). Continued on other side of sheet.



Insert 1, Fig 3A

Upper-mantle reflectivity beneath the Williston basin,
phase-change Moho, and the origin of intracratonic basins

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Figure 3A

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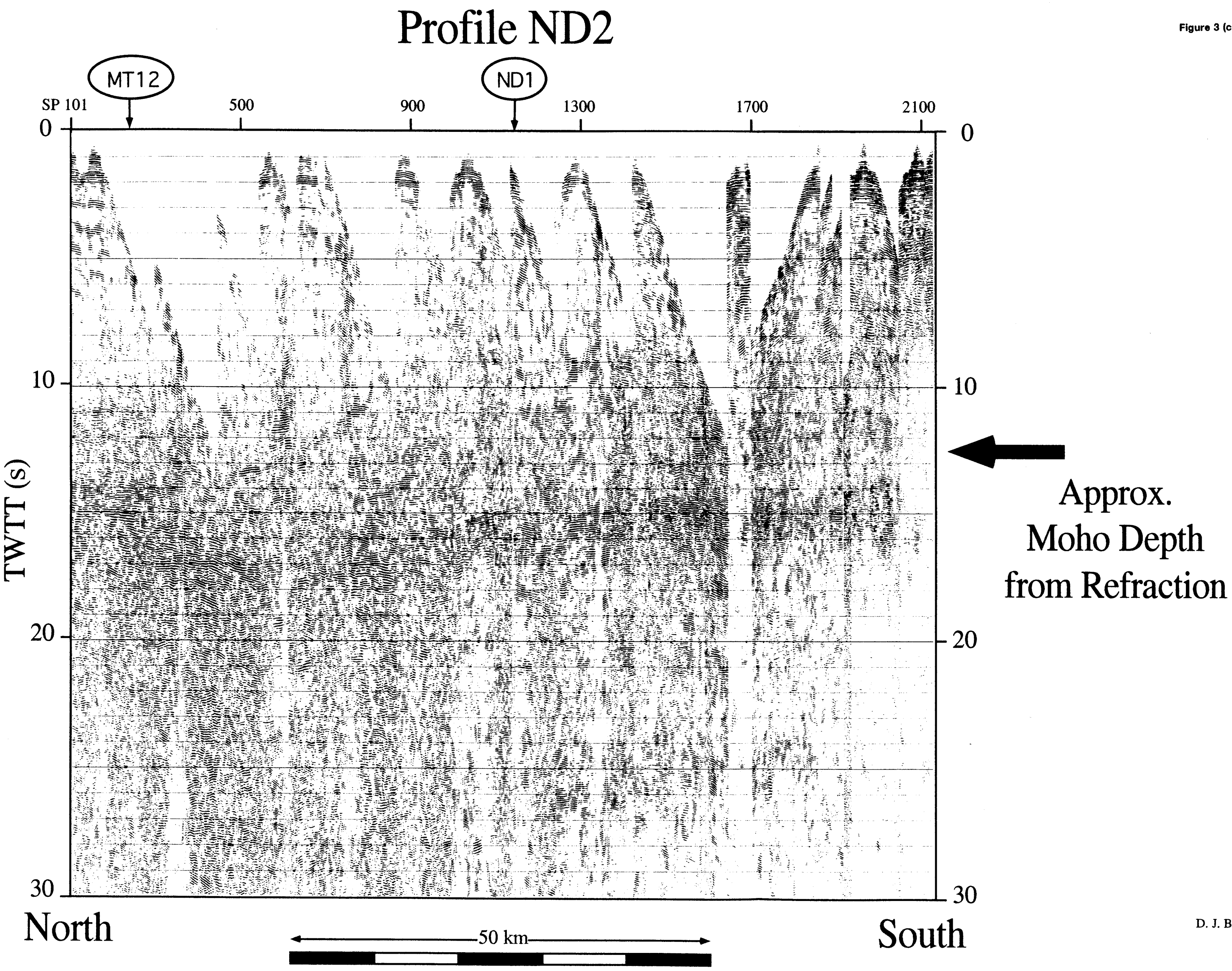

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Figure 3B

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