The Potential of Deep Seismic Profiling for Hydrocarbon Exploration
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THE CRUST BENEATH THE INTRACRATONIC WILLISTON BASIN FROM GEOPHYSICAL DATA

P. MOREL-A-L'HUISSIER, A.G. GREEN, A.G. JONES[1]
T. LATHAM[2], J.A. MAJOROWICZ[3], M.J. DRURY[1] and M.D. THOMAS[1]

ABSTRACT

It is generally acknowledged that the nature of the crust beneath sedimentary basins, particularly intracratonic ones, has a significant impact on their structural evolution, sedimentary histories and hydrocarbon enrichment. Deep seismic profiling, in conjunction with other available information, will certainly play a major role in imaging deep structures relevant to hydrocarbon exploration. Although the Williston Basin has been the subject of study for many years, its origin and the character of the underlying Precambrian basement have been the subject of considerable controversy. In recent years, a number of studies have led to new views on the nature of the crust in this region. The structural character of the Precambrian basement is revealed in recent images of gravity and magnetic data. The interpretation of several seismic refraction profiles collected by the Canadian COCRUST group suggested the presence of a lower crustal high velocity (>7.0 km/s) layer overlying a relatively flat Moho with a minor 3 to 4 km thinning of the crust towards the centre of the basin in Canada. Recent COCORP seismic reflection data collected in Northern Montana, just south of the refraction lines and closer to the depocentre, suggest that the high velocity layer may be coincident with a zone of strong reflectivity at the base of the crust. Whether this anomalous lower crustal layer is associated with the Phanerozoic origin of the Williston Basin or with the evolution of the underlying Early Proterozoic Trans-Hudson orogen, or both, has yet to be determined. A major crustal electrical conductivity anomaly (the North American Central Plain anomaly - NACP) spatially associated with the Trans-Hudson orogen has been found to coincide with a N-S trending high heat flow anomaly. These basement structures and anomalies have influenced or controlled the development of important oil-bearing structures within the Williston Basin.

INTRODUCTION

Sedimentary basins, especially those of Phanerozoic age, have been prime targets in the world's quest for energy. The Williston Basin became a prime area for deep hydrocarbon exploration at the time of World War II when the demand for oil rose (Sloss, 1987). Along with the Hudson Bay, Michigan and Illinois basins, it is one of North America's major intracratonic basins. It is located on the western margin of the North-American craton and its sub-circular shape is characteristic of numerous intracratonic basins. It extends across southeastern Alberta, southern Saskatchewan and southwestern Manitoba in Canada and across western and central North Dakota, northwestern South Dakota and northeastern Montana in the U.S. (Fig. 1).

The Williston Basin is a major producer of oil, gas, lignite and potash. The major bordering, and to, some extent, controlling structures are: the Sioux arch to the south, the Transcontinental arch to the southeast, the Severn arch to the northeast, the Sweetgrass arch to the north-northwest and the Western Alberta arch to the west (Fig. 1).

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(1) Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario K1A OY3, Canada.
(2) ARCO Oil & Gas Co., 2300 W. Plano Parkway, Plano, Texas 75075, USA.
(3) Institute of Earth and Planetary Physics, University of Alberta, Edmonton, Alberta T6G 2J1, Canada.

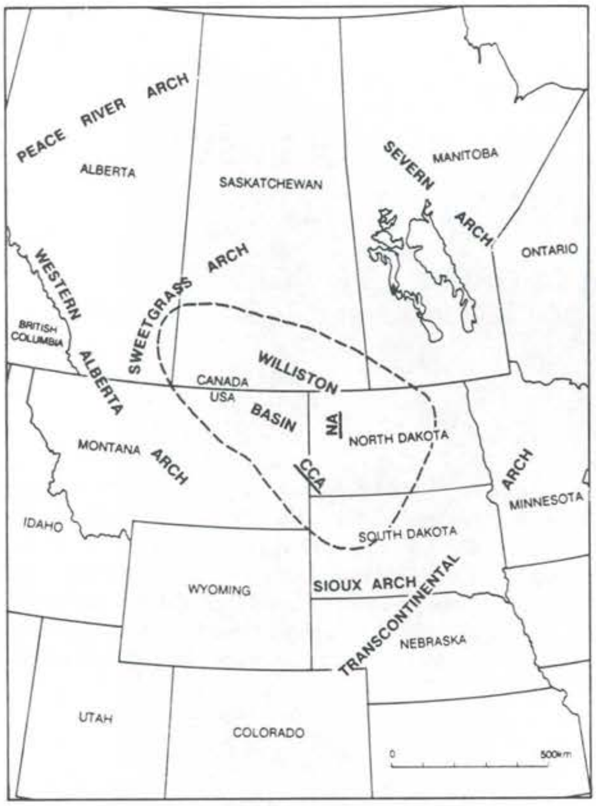

FIG. 1. General location map of the Williston Basin with major surrounding tectonic structures. CCA - Cedar Creek anticline, NA - Nesson anticline.

PHANEROZOIC GEOLOGY

Of the North American intracratonic basins (see Bally, 1989, for a review), the Williston Basin is the only one in which all Phanerozoic periods are represented (Sloss, 1963; Porter et al., 1982; Peterson and MacCary, 1987; Gerhard and Anderson, 1988). Originally an integral part of the Western Canada Basin during deposition of the Cambrian Sauk Formation, the Williston Basin became a separate entity in the Ordovician during the deposition of the Tippecanoe Sequence. The basin has a maximum thickness of sedimentary rocks of 4875 m near its centre in North Dakota and its sedimentary history is reflected in a suite of transgressive and regressive formations indicative of a shallow marine environment. Porter et al. (1982) suggested that the various flanking arches played a relatively important role in basin evolution. The basin contains several internal structures which are of importance to oil exploration (Gerhard and Anderson, 1988), some of which are indicated on the generalized cross-section shown in Fig. 2.

Major oil reserves in the U.S. part of the Williston Basin are entrapped in large basement arches - Nesson and Cedar Creek anticlines; with the major accumulations in Carboniferous and Ordovician rocks. These features are related to major basement structures, possibly reactivated during the evolution of the basin. In Canada (Manitoba and southeastern Saskatchewan), the majority of the reserves are associated with traps resulting from unconformities between Carboniferous rocks and impervious Jurassic or Triassic red beds. Other types of traps are found throughout the basin but are a secondary contribution to oil reserves.

POTENTIAL FIELDS

Outcropping basement rocks in the Canadian Shield north of the basin and potential field maps aided Dutch (1983), Green et al. (1985a, b), Klasner and King (1986) and Thomas et al. (1987) in their extrapolation of the basement geology beneath the Williston Basin. It includes rocks from the Wyoming, Churchill and Superior Archean cratons and the terranes of the Proterozoic Trans-Hudson orogen (Lewry, 1981; Hoffman, 1988). Green et al. (1985a, b), for example, relied heavily on the characteristics and patterns of aeromagnetic anomalies in proposing the basement geology shown in Fig. 3 and superimposed on the aeromagnetic and gravity maps of Figs. 4 and 5, respectively. In northern Canada, the Flin Flon-Snow Lake and La Ronge-Lynn Lake belts, regarded as remnants of Proterozoic island arcs (Green et al., 1985a, b), are particularly well characterized by strong linear positive aeromagnetic anomalies. The Glennie Lake domain, containing late Archean and early Proterozoic elements, is characterized by a chaotic pattern of both positive and negative anomalies and is defined on the basis of its position between the aforementioned arcs. The Kisseynew and Reindeer-South Indian Lake belts, considered to contain elements of small "oceanic" terranes (Green et al, 1985a, b), are typified by a rather quiet magnetic field. Boundaries between the early Proterozoic Trans-Hudson orogen, which includes the vestiges of the various island arc and oceanic terranes, and the flanking Wyoming and Superior Archean cratons are also defined by aeromagnetic data.

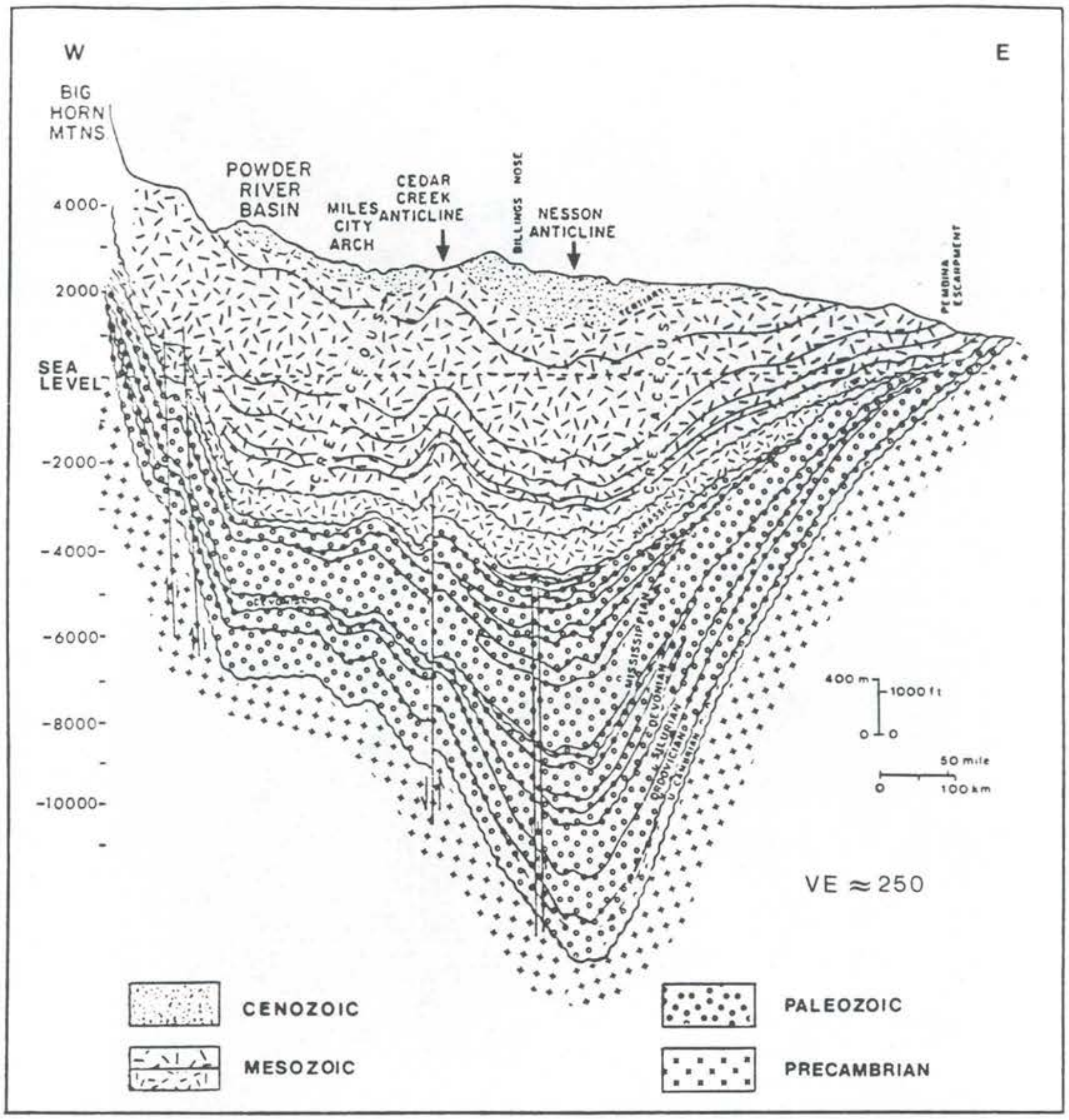

FIG. 2. Generalized west-east structural-stratigraphic cross section of the Williston Basin (modified from Peterson and MacCary, 1987).

Thomas et al. (1987) used the horizontal gradient of Bouguer gravity anomalies to derive first-order structural trends, and used the patterns of these trends to refine the western and eastern limits of the Trans-Hudson orogen. The boundaries so defined are illustrated in Fig. 6 where they are compared with boundaries drawn by Dutch (1983) and Green et al. (1985a, b). A difference between the trend of the North American Central Plain conductivity anomaly (NACP) and trends of linear gradient features suggests that the NACP is the expression of a series of discontinuous, perhaps "en échelon", conductors (Jones and Craven, 1990) that have not been resolved by the coarse spacing of the magnetometer stations (roughly 50 to 300 km) of Alabi et al. (1975).

Potential field maps have been useful for relating structures of the Williston Basin to basement features. For example, the Cedar Creek anticline which has been intermittently active throughout the entire evolution of the basin (Clement, 1987), appears to be closely related to a basement feature, as indicated by both gravity and magnetic maps. The Nesson anticline, one of the major structures as far as oil concentration is concerned (see below), from potential field maps alone does not seem

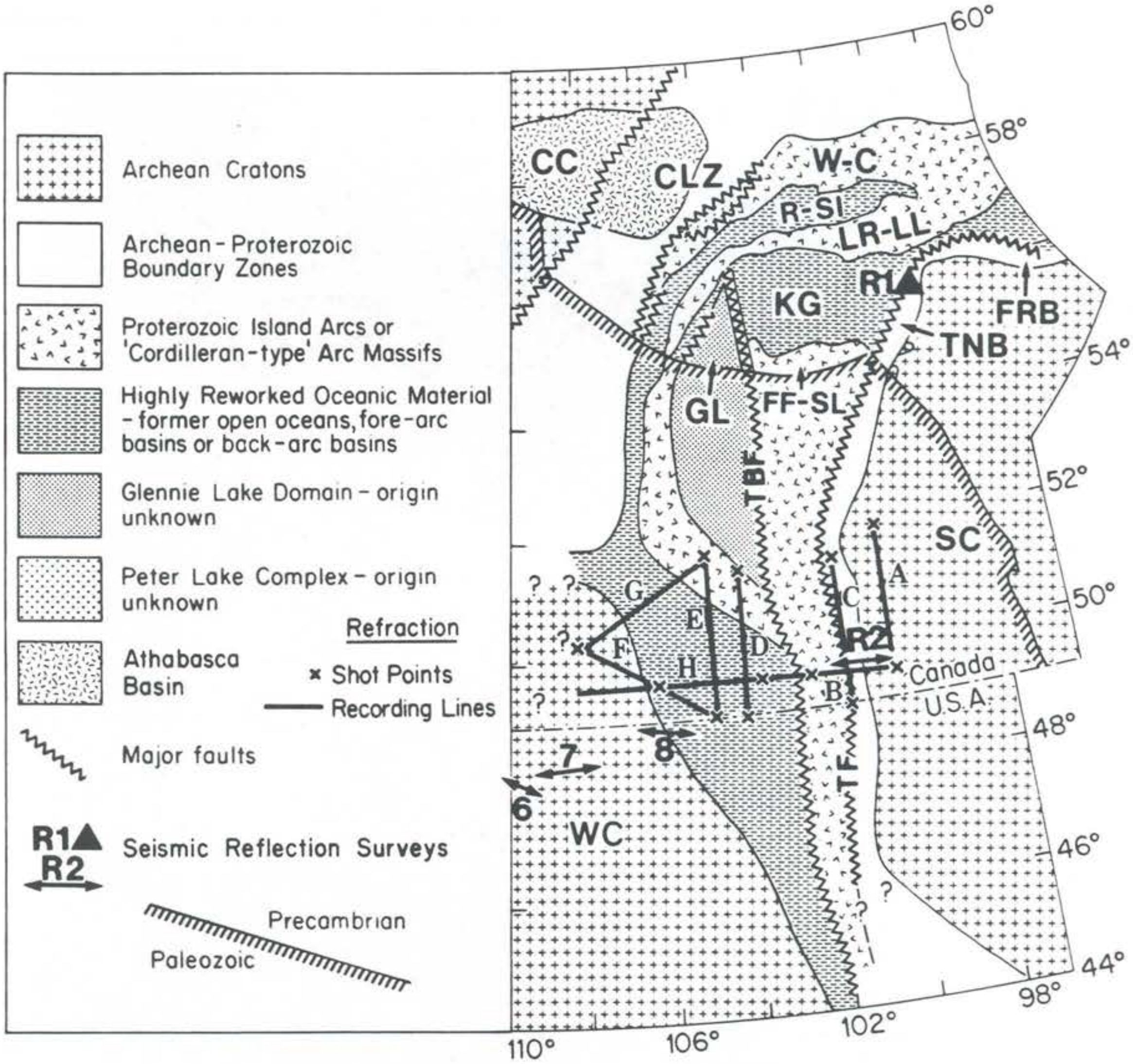

FIG. 3. Precambrian basement map of the Williston Basin and adjacent exposed shield regions after Green et al. (1985a, b). CC -Churchill craton; CLZ - Cree Lake zone; FF-SL - Flin Flon-Snow Lake belt; FRB - Fox River belt; GL - Glennie Lake domain; LR-LL - La Ronge-Lynn Lake belt; KG - Kisseynew belt; R-SI - Reindeer-South Indian Lakes belt; SC - Superior craton; TBF - Tabbernor fault/fold zone; TF - Thompson fault; TNB - Thompson Nickel belt; W-C - Wathaman-Chipewyan batholith; WC - Wyoming craton. Locations of seismic reflection and refraction surveys are indicated.

to be associated with a basement feature. However, Gerhard et al. (1987) have shown unequivocally that the Nesson anticline is closely associated with a basement feature that has been active since the initiation of the basin; according to the potential field maps of Green et al. (1985a, b) the Nesson anticline overlies the southern extension of the Tabbernor fold/fault zone recognized in northern Canada (Lewry, 1981).

SEISMIC REFRACTION

During three field seasons (1977, 1979 and

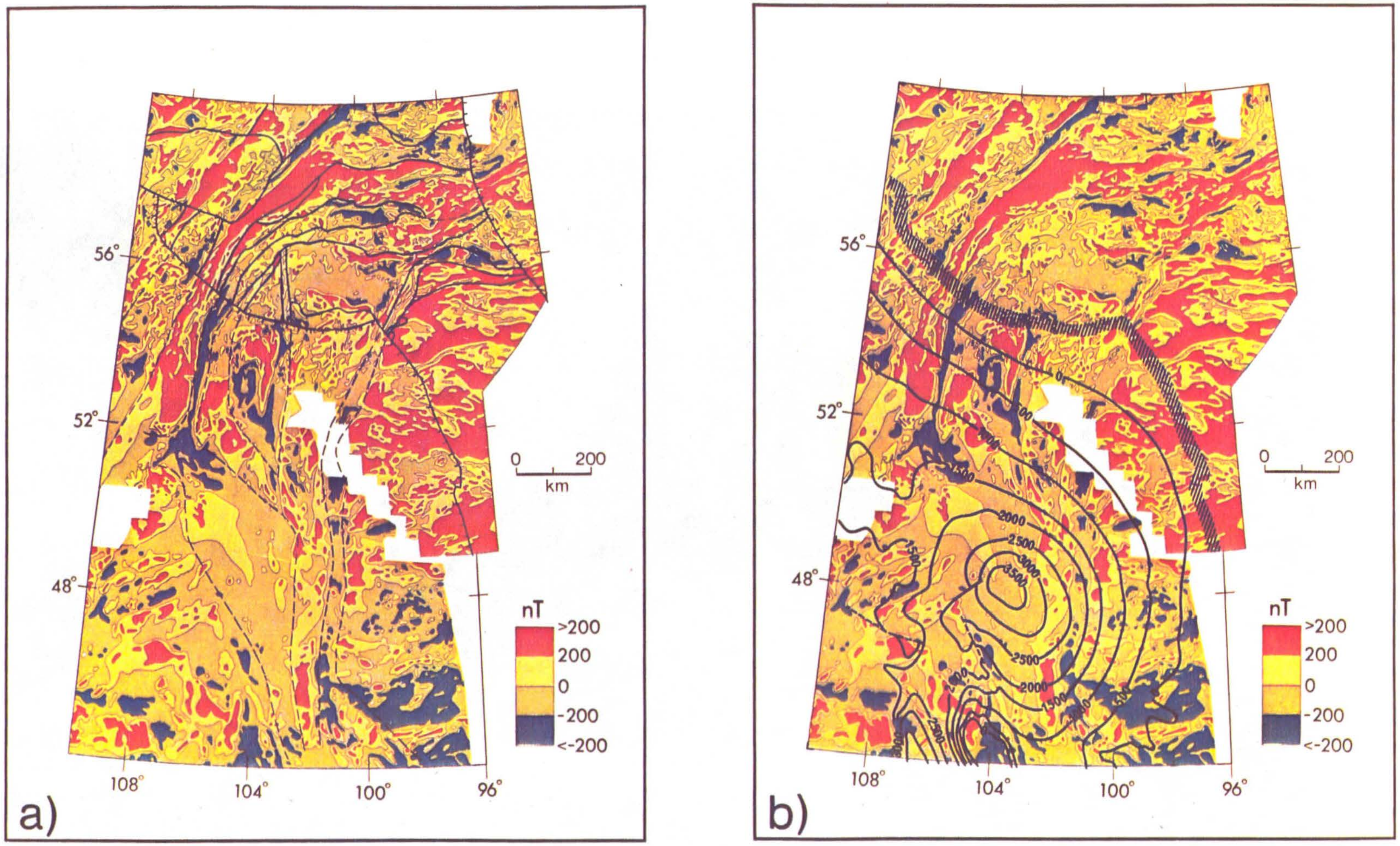

FIG. 4. Aeromagnetic map of the Williston Basin and adjacent areas (from Green et al., 1985a); a) with exposed and extrapolated tectonic boundaries; b) with depth to basement isolines (from Christopher et al., 1973). Datum is sea level and contour interval is 500 m.

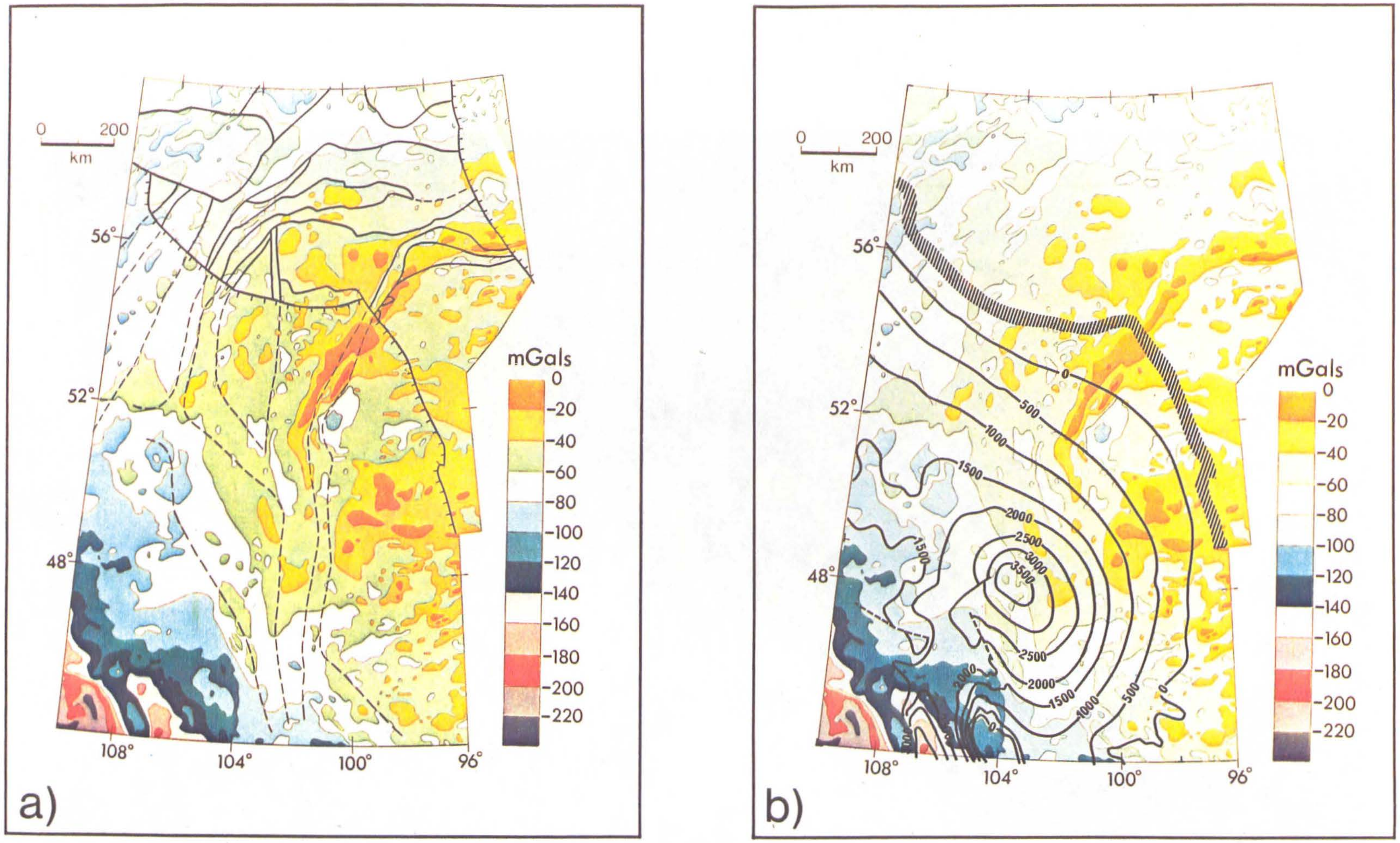

FIG. 5. Bouguer gravity anomaly map of the Williston Basin and adjacent areas (from Green et al., 1985a); a) with exposed and extrapolated tectonic boundaries; b) with depth to basement isolines (from Christopher et al., 1973). Datum is sea level and contour interval is 500 m.

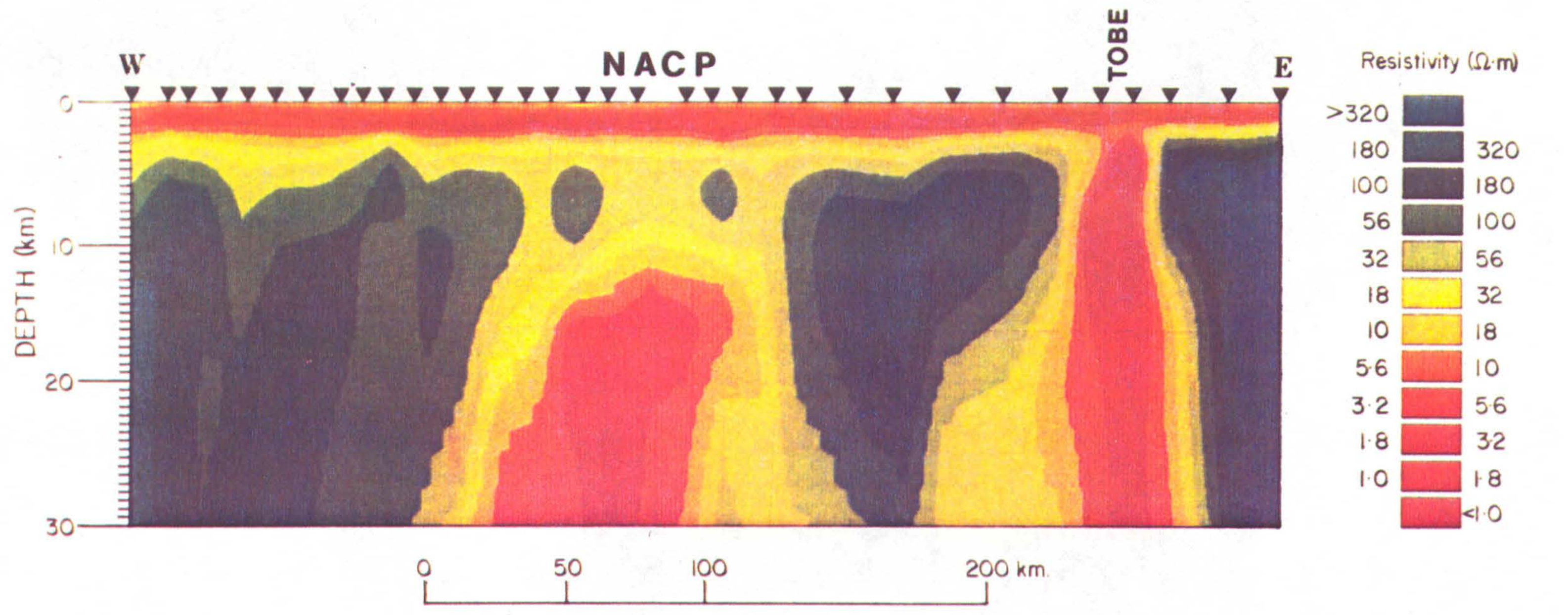

FIG. 10. Pseudo 2D section compilation of the 1D OCCAM (Constable et al., 1987) inversions of the E-polarization apparent resistivities and their phases observed at the 35 locations (inverted solid triangles) along MT profile S. The two anomalies are the NACP and the TOBE structures (see Jones and Craven (1990) for details).

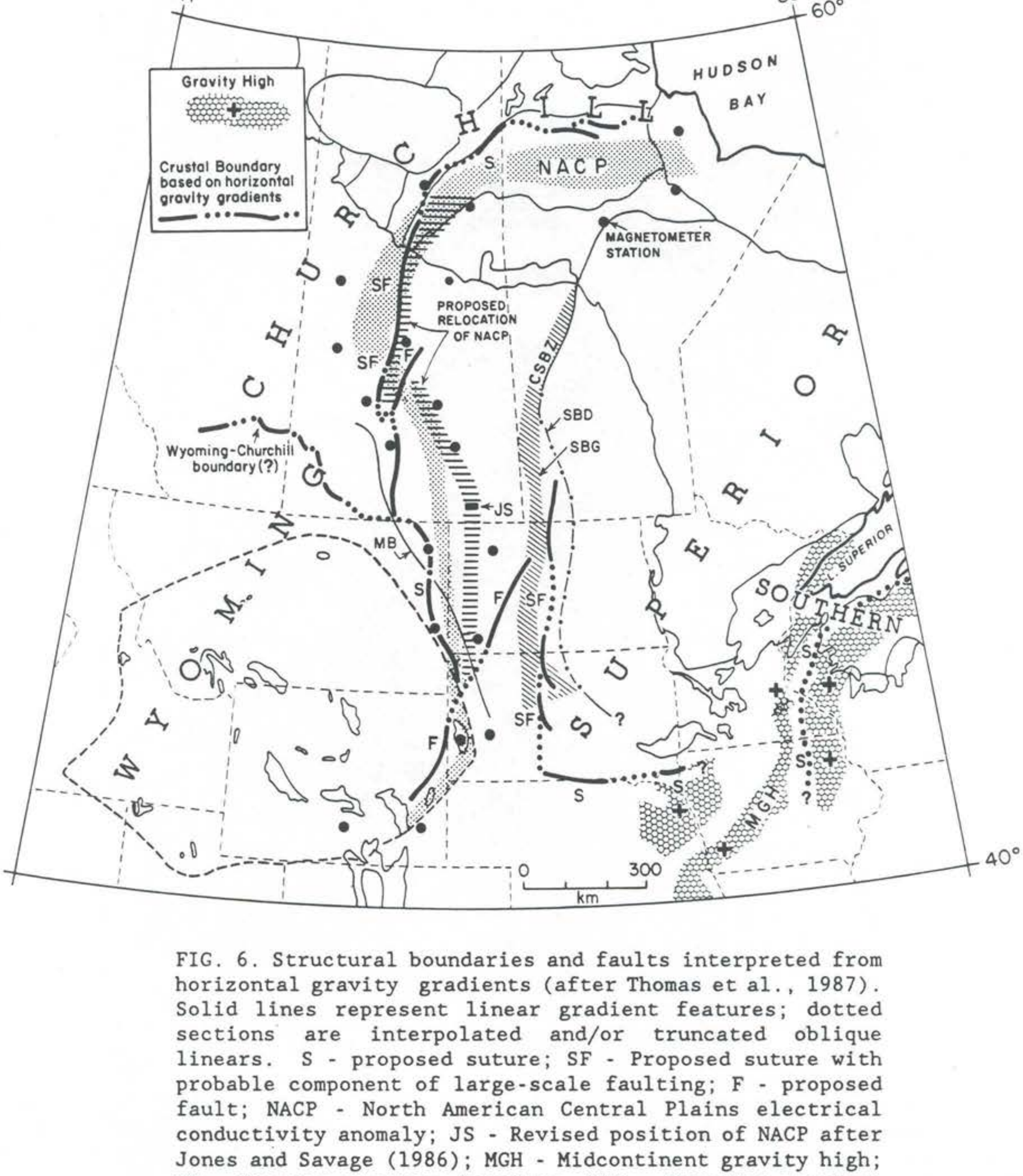

FIG. 6. Structural boundaries and faults interpreted from horizontal gravity gradients (after Thomas et al., 1987). Solid lines represent linear gradient features; dotted sections are interpolated and/or truncated oblique linears. S - proposed suture; SF - Proposed suture with probable component of large-scale faulting; F - proposed fault; NACP - North American Central Plains electrical conductivity anomaly; JS - Revised position of NACP after Jones and Savage (1986); MGH - Midcontinent gravity high; MB - Wyoming province boundary, SBG - Superior province boundary, and CSBZ - Churchill-Superior boundary zone (all after Green et al., 1985a, b); SBD - Superior boundary after Dutch (1983).

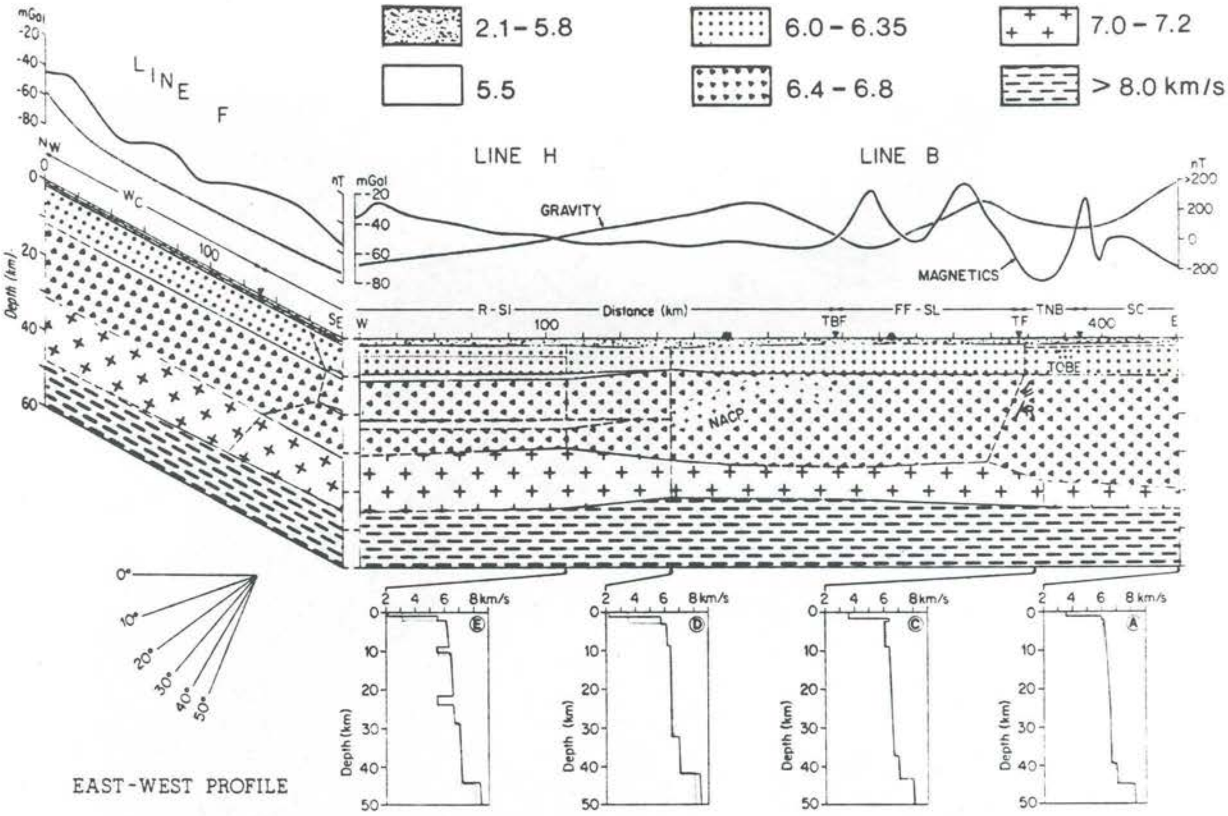

FIG. 7. Composite E-W crustal Williston Basin model (modified from Morel-à-l'Huissier et al., 1987). Comparison of the velocity-depth functions determined from the N-S profiles (A, C, D, E in Fig. 3) with those determined from the composite E-W profile are shown beneath the model; N-S velocity-depth functions are indicated by solid lines and E-W functions by dotted lines. Inverted solid triangles at the surface indicate the location of the lithotectonic boundaries taken from Fig. 3; labels for the lithotectonic units and faults as in Fig. 3. Shot points are indicated by asterisks. Position and shape of the NACP and TOBE (ThOmpson BElt) electrically conductive structures are indicated. Crustal layering is based on seismic velocities.

1981), the Canadian COCRUST group recorded eight reversed seismic refraction profiles across the Williston Basin in south-central Canada (Green et al., 1980; DeLandro and Moon, 1982; Hajnal et al., 1984; Kanasewich and Chiu, 1985; Kanasewich et al., 1987; Morel-à-l'Huissier et al., 1987). These profiles (locations shown in Fig. 3) sample from west to east the Archean Wyoming craton, the early Proterozoic Trans-Hudson orogen and the Archean Superior craton. Morel-à-l'Huissier et al. (1987) modelled these data using two-dimensional ray-tracing techniques to match both the times and amplitudes of primary and coherent secondary arrivals. Fig. 7, a composite E-W crustal model located just north of the Canada-U.S. border, gives a summary of their interpretation and permits direct comparison with the COCORP seismic reflection data recorded just south of the border (Fig. 8; see below). On average, velocities increase from about 6.1 km/s beneath the Paleozoic sediments to 6.2-6.4 km/s at depths of 8-13 km. Near this level, there is a general change in gradient with velocities increasing smoothly to 6.5-6.8 km/s at depths varying from 28 to 40 km where velocities increase abruptly to values greater than 7.0 km/s. Upper mantle velocities of 8.0-8.4 km/s are encountered at "Moho discontinuities" in the depth range 41-48 km. There appears to be a slight 3-4 km thinning of the crust beneath the deepest part of the Williston Basin in Canada. The Trans-Hudson orogen is characterized by upper and mid-crustal low-velocity zones (5.5 km/s in the model, although velocities and thicknesses are not well constrained), which were required to match secondary energy visible on profiles E and F.

SEISMIC REFLECTION

In 1986, COCORP recorded six multichannel seismic reflection profiles in northern Montana, three of which (6, 7 and 8) are located on Fig. 3 (Latham et al., 1988). Two of these profiles (7 and 8) are of direct interest to understanding the evolution of the Williston Basin. Profile 7 (Fig. 8a) was recorded near the western margin of the Williston Basin whereas profile 8 (Fig. 8b) was recorded within the basin just south of the Canada-U.S. border, parallel to the western part of the reversed east-west seismic refraction line H (see Fig. 3).

On line 7 (Fig. 8a), the Phanerozoic sediments of the Williston Basin are underlain by a relatively transparent basement layer which seems to increase in thickness eastward (bottom of the layer at 2.5-3 s in the west and at 4.5-5 s in the east). When compared with the superimposed velocity-depth profile obtained for the Wyoming craton (lines G and H) of the refraction study (Morel-à-l'Huissier et al., 1987), it is clear that this transparent basement layer coincides with the 6.1 to 6.4 km/s smoothly increasing refraction layer. Below, and for the remainder of the section, the crust seems to be more reflective with reflections dipping in various directions. In this mid- to lower crustal layer, velocity increases from 6.6 km/s at the top to 7.2 km/s at the bottom. At about 14.5 s, where the refraction data places the "Moho discontinuity", there appears to be a tenuous broken zone of sub-horizontal weak reflectors which may be indicative of the reflection "Moho".

Profile 8 probably samples crust that belongs to the Wyoming craton along its western half and crust that belongs to the Trans-Hudson orogen along the eastern half. The western half bears some resemblance to Line 7: relatively transparent upper crust underlain by more reflective mid and lower crust. The lower crustal reflectors are more prominent and spread over 2 s (between 12.5 and 14.5 s). In the middle of the section, where the line crosses the boundary between the Wyoming craton and the Trans-Hudson orogen, there is a marked change in the character of the reflections. On the Trans-Hudson orogen side, the crust appears to be more homogeneous throughout its entire thickness. The low velocity (5.5 km/s) layers inferred from the seismic refraction data seems to correspond with zones of more pronounced reflectivity. However, it must be emphasized that the reflection and the refraction profiles are more than 50 km apart, so this coincidence may be purely fortuitous. To test this relationship, more coincident reflection and refraction profiling is required in this region. The velocity-depth profile of the western part of refraction line H superimposed on the eastern part of seismic reflection profile 8 (Fig. 8b) indicates that there may be a relationship between the high velocity (>7.0 km/s) lower crustal refraction layer and the lower crustal reflective layer that appears to increase in thickness towards the centre of the basin (about 3.5 seconds in the easternmost part of profile 8). It is not clear whether this high velocity lower crustal layer, which might be the result of underplating (Furlong and Fountain, 1986; Fountain, 1989), is related to the Trans-Hudson orogen or to the formation of the Williston Basin. Although not conclusive, the presence of high amplitude reflections at the bottom of the crust throughout the entire length of profile 8 seems to favour a relationship with the Williston Basin.

MAGNETOTELLURICS

The area of the Williston Basin includes a section of the well known North America Central Plain conductivity anomaly (NACP), first discovered in the late 1960's by geomagnetic depth sounding (GDS; Reitzel et al., 1970). Further GDS studies (Alabi et al., 1975; Handa and Camfield, 1984; Gupta et al., 1985) have suggested that the NACP was a linear feature extending for over 2000 km from the central U.S. to Hudson Bay in northern Canada (see Fig. 6). A recent magnetotelluric (MT) survey (profile S in Fig. 9) conducted just north of the Canada-US border has

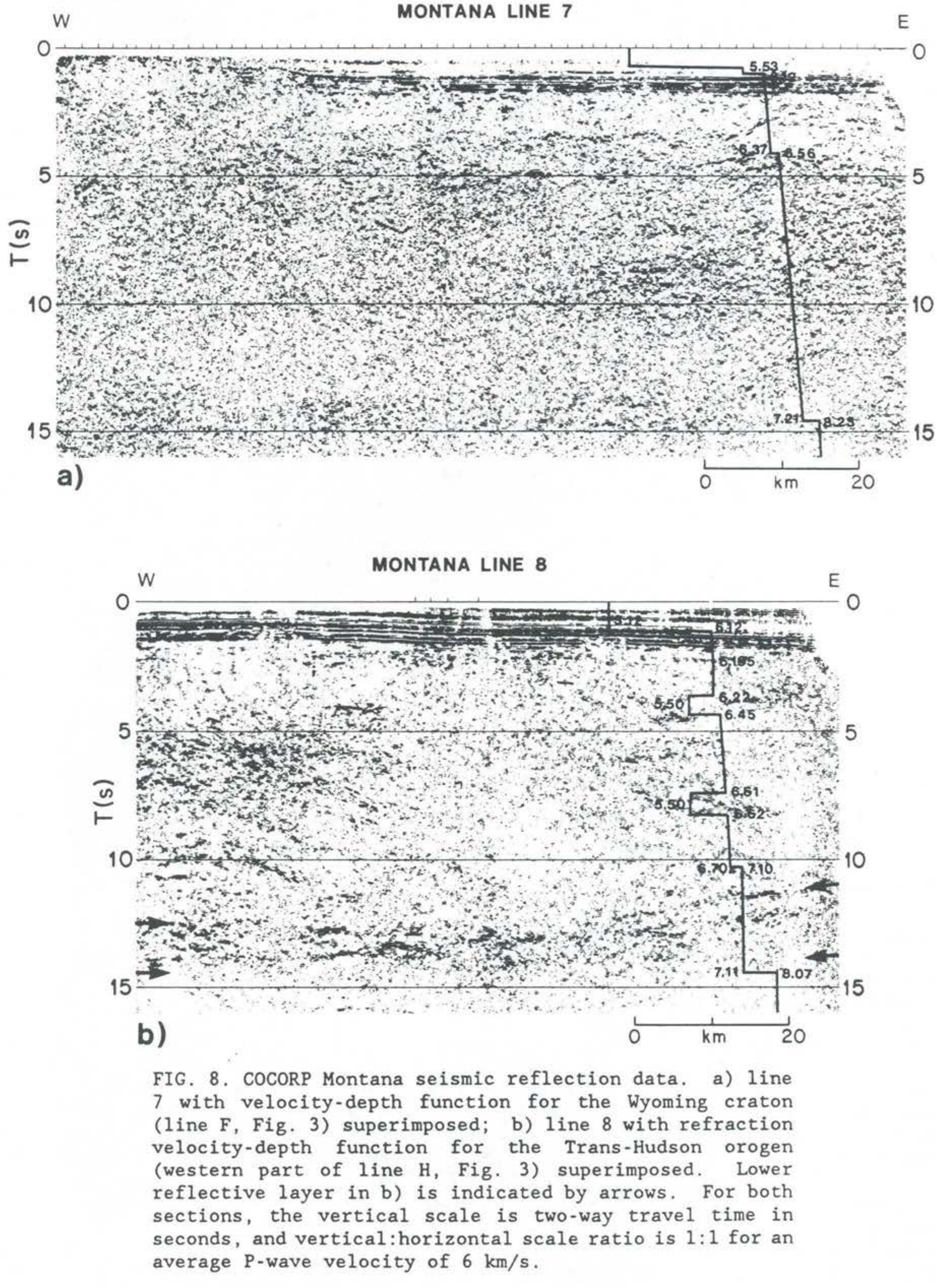

FIG. 8. COCORP Montana seismic reflection data. a) line 7 with velocity-depth function for the Wyoming craton (line F, Fig. 3) superimposed; b) line 8 with refraction velocity-depth function for the Trans-Hudson orogen (western part of line H, Fig. 3) superimposed. Lower reflective layer in b) is indicated by arrows. For both sections, the vertical scale is two-way travel time in seconds, and vertical:horizontal scale ratio is 1:1 for an average P-wave velocity of 6 km/s.

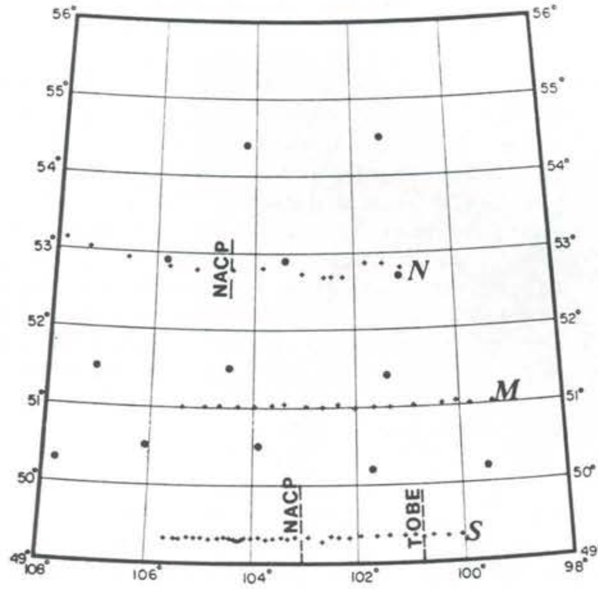

FIG. 9. Location map of the MT surveys S, N and M with some of the GDS stations (large dots) of Alabi et al. (1975). The MT locations of the NACP and TOBE electrical conductivity anomalies are indicated.

indicated that in this region, the NACP should be about 75 km to the east of the location determined by the GDS surveys (Jones and Savage, 1986; Jones, 1988). Furthermore, Jones and Craven (1990) have presented results from two other MT profiles (M and N in Fig. 9) recorded in 1987 and that show that the NACP's position varies laterally with an important break at latitude 51° N demonstrating that the NACP is not a continuous linear feature as previously inferred from the GDS studies. Thomas et al. (1987) had arrived at a similar conclusion based on discordances observed between gravity trends and the trend of the NACP. A second major electrical conductivity (ThOmpson BElt anomaly, or TOBE) has been detected by two magnetotelluric surveys in the vicinity of the Superior cratonic margin (Rankin and Kao, 1978; Jones and Savage, 1986). Both the NACP and the TOBE anomalies are basement features which are well imaged by the Occam 1D inversions shown in Fig. 10* (Jones and Craven, 1990). In contrast to the TOBE anomaly which is a narrow vertical feature (minimum of 4 km vertical extent beneath the sediments), the NACP has been found to be "thin" with a relatively large lateral extent in the order of about 80 km. It is arcuate in section and its top approaches within about 10 km of the surface (Figs. 10 and 11; Jones, 1988; Jones and Craven, 1990). The model given in Fig. 11 indicates that the electrical structure is also discontinuous at depth and may be indicative of an "en échelon" geometry.

Jones and Craven (1990) have discussed both the possible origins and interpretations for these electrical anomalies, with more emphasis on the NACP. The latter had been associated with conductive minerals (Camfield et al., 1970; Gough and Camfield 1972), with the presence of saline water circulating in a zone of fractured rocks (Handa and Camfield, 1984), or with partial serpentinization of oceanic mafic and ultramafic rocks from an ancient oceanic domain (Gupta et al., 1985; Green et al., 1985a, b). It has also been interpreted as a geosuture resulting from the collision of two Archean plates in early Proterozoic times (Camfield and Gough, 1977). Jones and Craven (1990) conclude that the high conductivity

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* See colour figure p. 147.

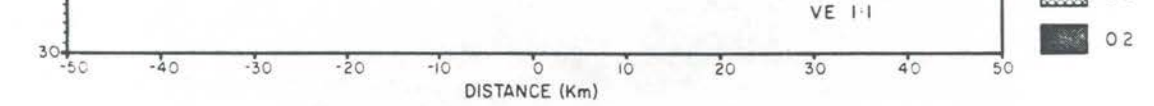

FIG. 11. Two-dimensional MT model for the E- and B-polarizations responses over the NACP structure. Inverted solid triangles indicate MT sites.

(>1 S/m) associated with the NACP cannot be explained by the presence of fluids because such an explanation would require implausibly high porosities in the order of 12-20%. Some highly conductive mineral, such as graphite, is a potential candidate, but the evidence is not conclusive.

GEOTHERMICS

Geothermal studies of sedimentary basins commonly indicate a large-scale redistribution of heat from the crystalline crust and upper mantle through gravity-forced water circulation within the sediments. Such redistribution makes it difficult to assess the basement contribution to the geothermics of the basin. Majorowicz et al. (1986) showed that regional heat flow variations with depth in Mesozoic-Cenozoic sediments were closely related to the hydrodynamics governed by topography and geology. They also discovered a high temperature anomaly in Paleozoic sediments beneath southeastern Saskatchewan that could not be completely explained by the blanketing effect of thick shaly units present in the area and they concluded that there may be a significant contribution from a high temperature zone located in the basement. S_2 pyrolysis peak studies by Price et al. (1986) indicate that this north-south trending high heat flow anomaly (80-100 mWm^{-2}; Majorowicz et al., 1986) may extend through the centre of the Williston Basin in North Dakota (Fig. 12) and is coincident with the new position of the NACP electrical conductivity anomaly as mapped by Jones and Savage (1986) on the basis of magnetotelluric studies.

Figure 13 shows the distribution of major oil fields in the Williston Basin and areas of high heat flow (Majorowicz et al., 1988). If a correlation between the high heat flow and the major oil fields seems apparent from Fig. 13, there is also an excellent

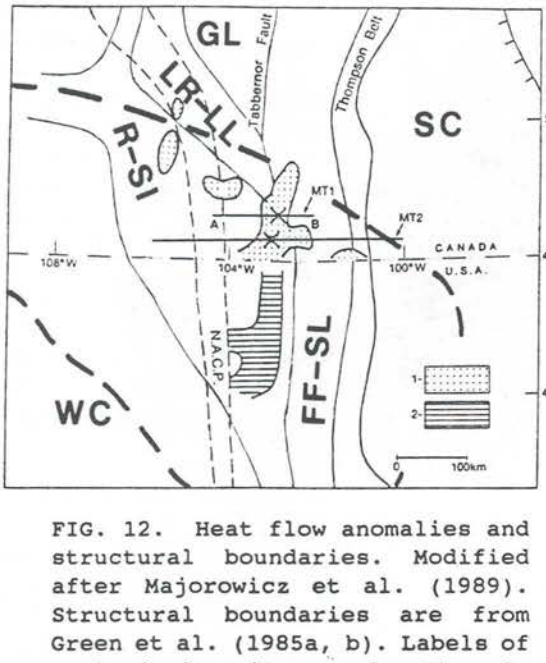

FIG. 12. Heat flow anomalies and structural boundaries. Modified after Majorowicz et al. (1989). Structural boundaries are from Green et al. (1985a, b). Labels of geological units as in Fig. 3. Location of the NACP is from Alabi et al. (1975). MT1 is Rankin and Pascal (1990) MT profile and MT2 is Jones and Savage (1986) MT profile. Crosses indicate maxima MT anomaly. 1: anomaly from Majorowicz et al. (1986); 2: anomaly from Price et al. (1986). Heavy dash line is outline of the Williston Basin.

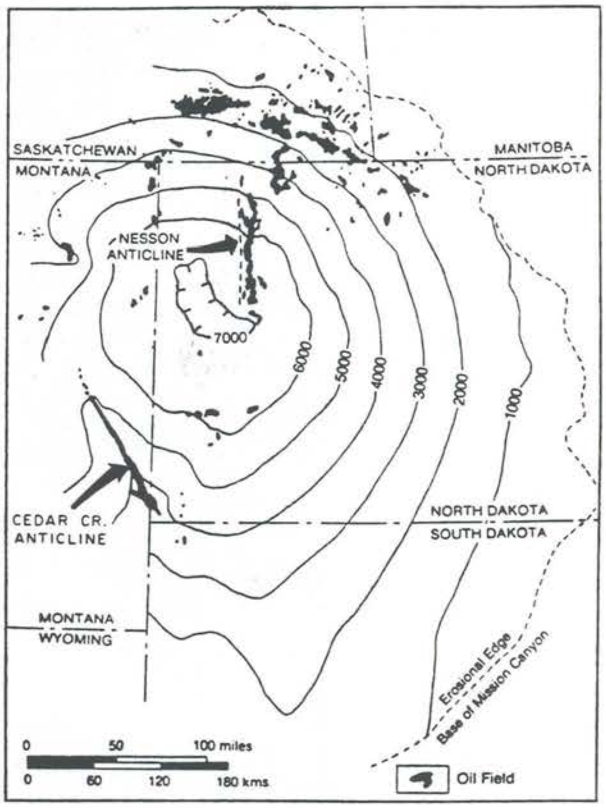

FIG. 13. Heat flow anomalies (shaded) and the major oil occurrences in the Williston Basin. Contours in feet are top of the Mississipian Mission Canyon Limestone. After Majorowicz et al. (1988).

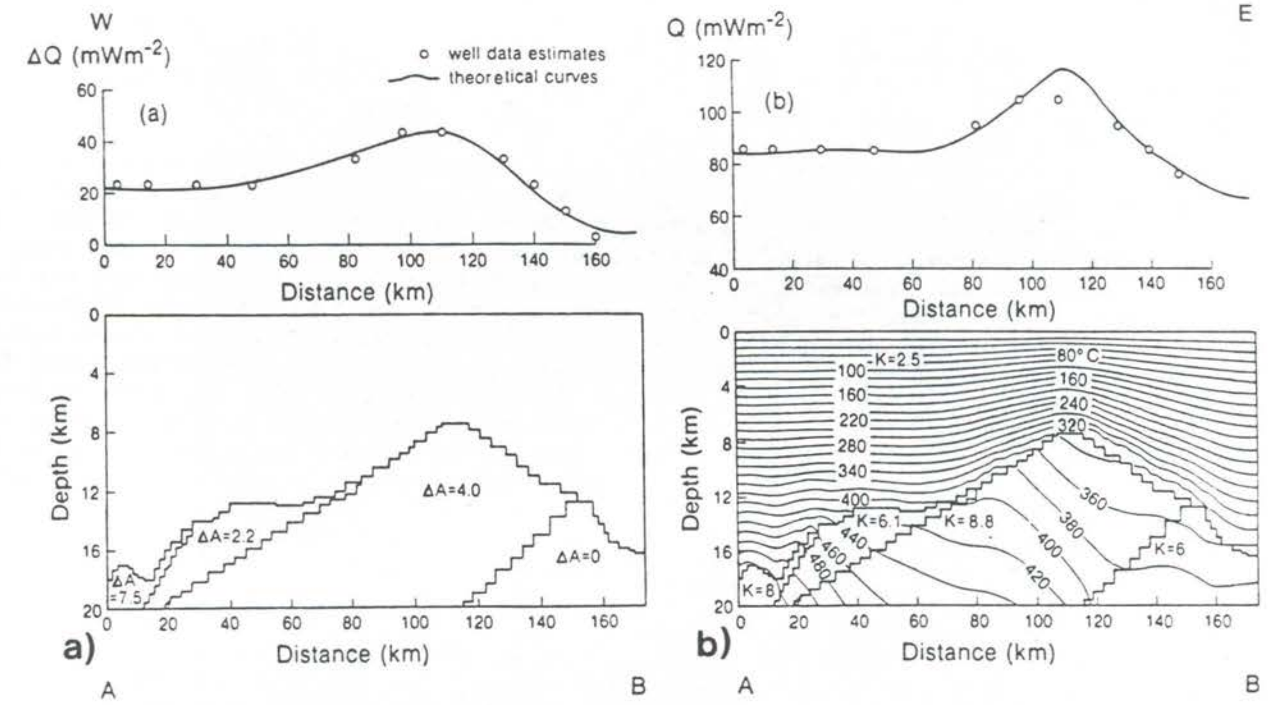

FIG. 14. Two-dimensional model of the crustal structure beneath the Williston Basin and the numerically calculated geothermal effect along profile A-B in figure 12. a) anomalous heat generation normalized to an assumed regional heat flow of 60 mWm^{-2}. ΔA is the difference between the heat generation in each block and that in the surrounding crust above it (in μWm^{-3}). The average uncertainty for heat flow estimates is 25%. b) thermal conductivity structure. Conductivities K are in $Wm^{-1}K^{-1}$. Isotherms are in °C. For both models (a and b), the upper boundary was maintained at 0°C and an initial temperature distribution of 25°C km^{-1} was used. A time duration of 15 million years in $30x10^3$ years increments was allowed for the thermal field to develop.

correlation between the major oil fields and the major structural trends of the basin defined by Gehrard and Anderson (1988), whether these structures are internal or basement related. The apparent correlation between the proposed location of the NACP (Jones and Savage, 1986), the high heat flow anomaly (Price et al., 1986; Majorowicz et al., 1988) and the important oil-producing Nesson anticline may be indicative of a genetic relationship between them. Because of the apparent association between high heat flow and oilfields shown in Fig. 13, there is reason to believe that the Cedar Creek anticline might also be associated with an area of high heat flow with significant contribution from the basement rocks. Majorowicz et al. (1989) used the two-dimensional finite difference method of Jones and Ertman (1985) to investigate the possible character of the thermal regime associated with the NACP. For their numerical model (Fig. 14), they used the geometry provided by the MT interpretation (Jones and Craven, 1990) and matched the high heat flow values using (i) anomalous heat generation (Fig. 14a) or (ii) anomalous thermal conductivity values (Fig. 14b). Majorowicz et al. (1989) favoured interpretation involved enhanced radioactive heat generation in the upper crust related to mineralization. Hydrothermal circulation in deep penetrating fault zones could generate such a concentration of radioactive minerals, or, since the Superior-Churchill boundary zone involved collision of continental fragments, anomalous concentration could have resulted from tectonic juxtaposition.

Drury (1988) recognized, through an interpretation of geothermal data, the presence of two geothermal provinces: an eastern province comprising the Superior craton and the Trans-Hudson orogen with relatively low heat flow values (23 to 59 mW/m^2) and a western province formed by the Wyoming and Churchill cratons with higher heat flow values (50 to 90 mW/m^2). The fact that the high heat flow basement anomaly reported by Majorowicz et al. (1986) is within the low heat flow province defined by Drury (1988) may indicate that the former is associated with a major basement structure along which there has been redistribution of lower crustal heat producing elements into the upper crust.

DISCUSSION AND CONCLUSIONS: ORIGIN AND EVOLUTION OF THE BASIN

The origin and evolution of intracratonic basins have been the focus of much controversy (Klein and Hsui, 1987; Quinlan, 1987; Bally, 1989). In a review of existing models of subsidence mechanisms for intracratonic basins, Quinlan (1987) concluded that while some features of the North American intracratonic basins are compatible with one or more models, no single model can explain all features. Quinlan (1987) also highlighted the paucity of information on crustal structure beneath the basins as one problem that needed to be addressed.

The Williston Basin became a separate entity very early (Ordivician) in the evolution of Western Canada Basin (Porter et al., 1982) with its depocentre located in North Dakota and its origin has been the subject of many studies and speculations. Models for the Williston Basin have included:

(a) cooling of a local lithospheric thermal anomaly leading to contraction of the lithosphere (Turcotte and Ahern, 1977; Sleep et al., 1980; Ahern and Mrkvicka, 1984; Ahern and Ditmars, 1985; Crowley et al., 1985);
(b) intrusion of a sill-like body of gabbro (could be the >7.0 km/s lower crustal layer observed in seismic refraction) from the mantle into the cool lower continental crust followed by a phase change into eclogite (Fowler and Nisbett, 1985);
(c) localized left-lateral shearing along the Colorado-Wyoming and Fromberg zones (Gerhard et al., 1982);
(d) uplift and erosion of the cratonic arches surrounding the basin and differential subsidence during transgressive and regressive cycles (Porter et al., 1982), and;
(e) most recently an extraterrestrial impact (Sears and Alt, 1990).

The geophysical data across the Williston Basin suggest that the basement of the basin encompasses crustal units of various ages, including the Archean rocks of the Superior, Churchill and Wyoming cratons and the early Proterozoic terranes of the Trans-Hudson orogen. The recognition of these units is based primarily on the potential field data, with limited support from drill holes reaching basement. The seismic refraction data shows some differences in the seismic signature of the major crustal blocks and recognized the presence of a high velocity (>7.0 km/s) layer at the base of the crust. The seismic reflection data suggest that this high velocity layer is strongly reflective. The age and character of this anomalous lower crustal layer is critical to any evolutionary model of the region. It is not yet clear if this high velocity/high reflectivity layer is to be associated with the Trans-Hudson orogen or with the formation of the Williston Basin. If this high velocity/high reflectivity layer is an early Proterozoic feature, then the Williston Basin sediments would have been deposited on a relatively thick crustal section (≈ 43 km). In contrast, if this lower crustal layer is associated with late Precambrian/early Phanerozoic underplating and related to the formation of the Williston Basin, then the original crust would have been anomalously thin, (reduced by one quarter to one third of its original value), perhaps indicating that the basin formed in an extensional environment. However, simple extension of the crust does not explain the nearly circular outline of the basin, and any underplating would need to have involved intrusion of relatively low temperature material, as there is no evidence for magmatism or other anomalous geothermal effects of the appropriate age. Pinet (1989), in a review of deep seismic data recorded across sedimentary basins, has argued that sub-horizontal reflections in the lower crust postdate the formation of intracratonic basins or that these basins were formed with some specific post-orogenic mechanisms not taken into account by the current extensional models. If the lower crustal sub-horizontal reflections postdate the formation of the Williston Basin, then they may be the result of some lower crustal-upper mantle transformations associated with the origin of the basin or they may have no relationship with the origin of the basin.

Magnetotelluric surveys have revealed the presence of an anomalously electrical conductive zone, the NACP, at mid-crustal depth (top at about 10 km). Analysis of the geothermal data from the Williston Basin has shown that, at least in the central part of the basin, the NACP is spatially associated with a high heat flow anomaly that probably requires some contribution from a basement geothermal source. If the origin of this high heat flow anomaly is located at crustal depths comparable to depths quoted for the NACP conductivity anomaly, then its preferred explanation is enhanced radioactive heat generation related to mineralization, probably through a fractured zone. This idea is supported by the suggestion made by Drury (1985), on the basis of geothermal studies of exposed terrains of the Trans-Hudson orogen, that widespread hydrothermal circulation takes place in the crust. It is however unknown whether such a fractured zone played any active role in the formation and/or evolution of the Williston Basin. Although the Tabbernor fold-fault zone has probably existed since the early Proterozoic Trans-Hudson orogen, it is noteworthy that related geophysical (magnetic, gravity, electromagnetic and heat flow) anomalies pass very close to the depocentre of the Williston Basin. Moreover, there is strong evidence that the Nesson anticline, one of the major oil-producing structures within the Williston Basin, overlies the southern extension of the Tabbernor fold-fault zone. Rejuvenation of this and other major crustal fault zones prior and/or during the formation of the sedimentary basin may, therefore, have contributed to its development.

Despite the fact that the Williston Basin is probably one of the best studied intracratonic basins, its origin and evolution remain enigmatic. It is not even possible to determine unequivocally the principal stress regime (extension, transtension, transpression or compression) under which the basin formed and evolved. It is clear however that the basement played a major role in both the evolution of the basin and the concentration of its important hydrocarbons. Deep seismic reflection, along with the integration of other geoscientific information, will image and define the characteristics of the major structures which may, in turn, provide the necessary framework to trigger renewed exploration.

ACKNOWLEDGMENTS

The authors would like to thank the COCORP group from Cornell University for providing plots of the Montana seismic reflection profiles 7 and 8, and P.J. Savage of PanCanadian for making MT data available to them. Dr. Bernd Milkereit of the Geological Survey of Canada is greatly thanked for the discussions he had with the lead author. Many thanks to Dr. Kirk Osadetz for providing the information on the nature of the oil traps. Comments by Dr. R.J. Korsch and an anonymous reviewer greatly helped to improve the manuscript. Geological Survey of Canada contribution 33289.

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