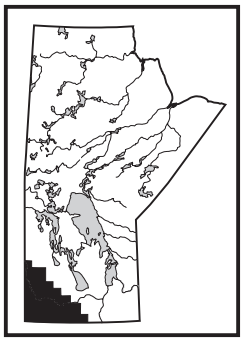
GS-17 Devonian Three Forks Formation, Manitoba (NTS 62F, parts of 62G, K): preliminary hydrocarbon and stratigraphic investigations

by M.P.B. Nicolas



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Summary

The Sinclair Field (Twp. 7–8, Rge. 28–29, W 1st Mer.) is the newest oilfield discovery in Manitoba and has greatly expanded in size and production since its discovery in 2004. The locality had been previously explored in the 1960s, but the pay was missed by early exploration efforts. Proven and probable reserves are estimated at 6.8 million m^3.

The Devonian Three Forks Formation is a cyclical transgressive-regressive sequence of shaly, silty dolarenite, interbedded with shale and brecciated in many places. The deposition of the Three Forks Formation was influenced by several weathering events due to transgressive and regressive cycles and basin tectonics. It is subdivided into four units, from bottom to top:

- Unit 1 is highly oxidized and is the lowermost and most widespread of the units; this unit is productive as a secondary reservoir in small isolated pools.
- Unit 2 is a sequence of interbedded siltstone and shale, massive shale and brecciated siltstone. The unit is productive as a secondary reservoir at the Sinclair and Daly fields (Twp. 9–10, Rge. 27–29, W 1st Mer.).
- Unit 3 is a thin, red-brown, highly oxidized silty shale.
- Unit 4, the uppermost unit represented in Manitoba, is an interbedded siltstone and silty shale with thick subunits of highly distorted and brecciated siltstone beds.

Unit 4 is the primary and most productive reservoir in the Sinclair Field. Units 2, 3 and 4 are productive at the unconformity surface as a subcrop-type play. In contrast, the production from Unit 1 is due to a stratigraphic-type play. The thinning of the Three Forks Formation and the truncation of the best reservoir units toward the east suggest the eastern expansion of the Sinclair Field may be limited. Mapping of these units toward the south along Rge. 29, W 1st Mer. indicates that Unit 4 is preserved up to the Manitoba–North Dakota international border, thereby extending the reservoir potential to the south.

The sub-Paleozoic extension of the Precambrian Superior Boundary Zone (SBZ) runs north-south in the study area. The Birdtail-Waskada Axis (BWA) runs roughly through the middle of the southern extent of the SBZ. Isopach, structural and geophysical evidence suggest the presence of faults running parallel to the SBZ eastern and western margins; these faults were active at the end of the Devonian. Movements along these faults caused the preservation of the primary reservoir (Unit 4) of the Three Forks Formation east and west of the SBZ margins, while the secondary reservoir unit (Unit 2) was exposed as a plateau on the BWA. The preservation of Unit 4 in some wells east of the BWA margin and along the SBZ margin opens up the possibility that, under the right trapping conditions, there may be another Sinclair-type play yet to be discovered east of Rge. 24, W 1st Mer.

Introduction

The study area consists of the entire depositional area of the Three Forks Formation in southwestern Manitoba (Figure GS-17-1).

The Sinclair Field is Manitoba's newest oilfield discovery. Since its discovery in 2004, it has been greatly expanded in size and production. The Sinclair Field has produced approximately 1.96 million m^3 of oil (cumulative to April 2007) and in 2006, represented 44% of Manitoba's total oil production. Proven and probable reserves are estimated at 6.8 million m^3 (J. Fox, pers. comm., 2007).

The productive interval of the Sinclair Field is dominantly the Devonian Three Forks Formation of the Qu'Appelle Group, with minor production from the overlying Middle Member of the Mississippian Bakken Formation (Figure GS-17-2). Minor production also comes from uphole, in the Lodgepole Formation.

The Three Forks Formation was influenced by transgressive and regressive cycles, periods of exposure, gravity flows (Karasinski, 2006) and basin tectonics.

Fifteen cores from the Sinclair Field and two cores from outside the field were logged as a first phase of this study (Nicolas, 2006). Geophysical logs for all wells that penetrated the Three Forks Formation (1355 wells in total) were viewed, and formational, member and unit tops were picked whenever possible in the Bakken, Three Forks and Birdbear formations. The final phase of this study will include logging Three Forks Formation cores from a more representative sampling of wells in the study area.

Geological setting

Southwestern Manitoba is situated along the northeastern flank of the Williston Basin. Strata from the Paleozoic, Mesozoic and Cenozoic form a basinward-thickening, southwesterly sloping wedge. The basin

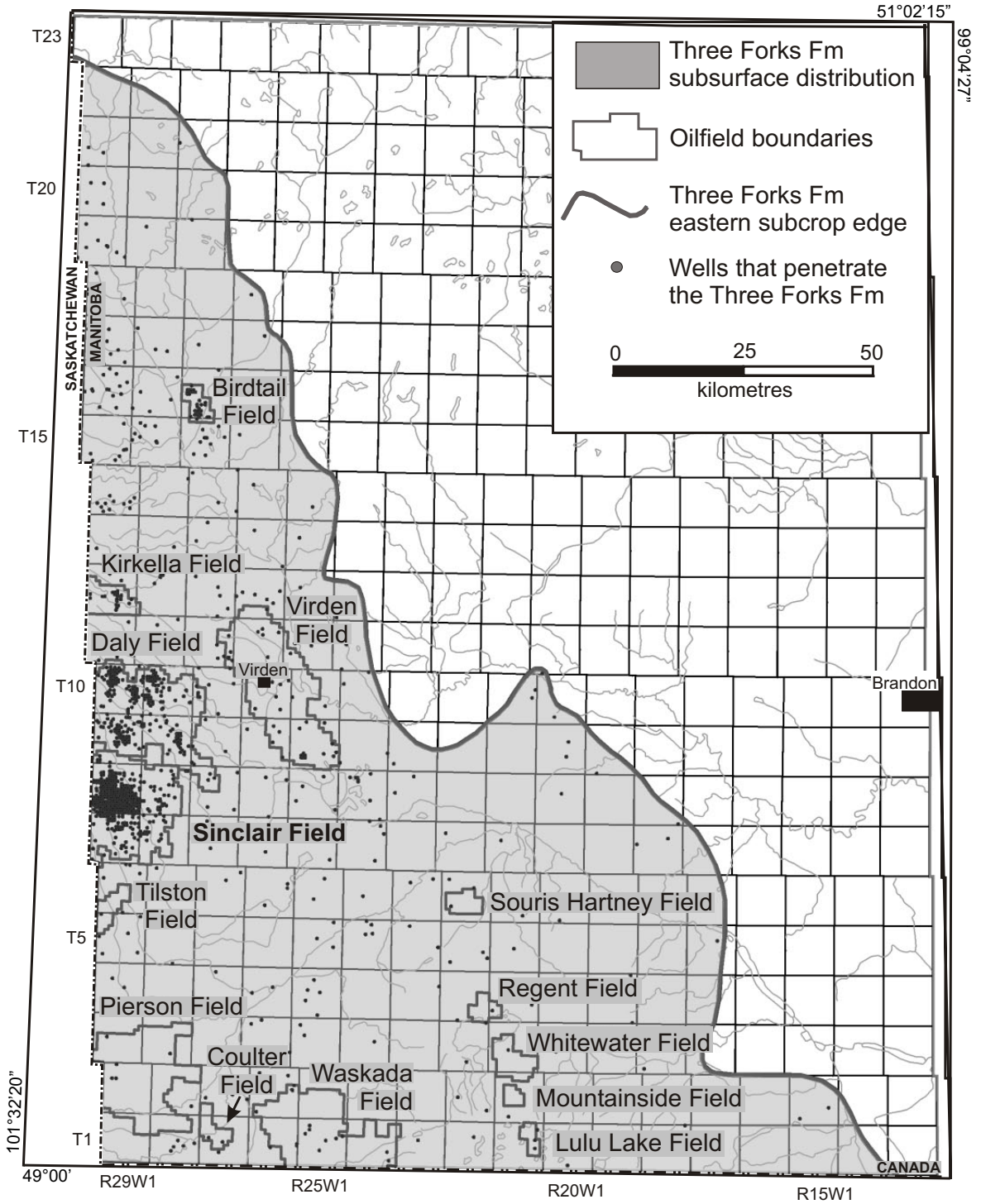

Figure GS-17-1: *Map showing the study area and the Three Forks Formation subsurface distribution in southwestern Manitoba.*

reaches a total thickness of 2.3 km at its thickest point in the extreme southwestern corner of Manitoba, near the Saskatchewan interprovincial border and the North Dakota, United States international border.

Beneath the Phanerozoic cover in southwestern Manitoba is the southern extension of the Precambrian Superior Boundary Zone (SBZ), a major cratonic suture zone that runs north-south through the study area. The northern extent of the SBZ is host to world-class mineral deposits, but evidence of fluid movement and active faulting along this zone is not limited to the Precambrian: it extends into the Phanerozoic sedimentary cover. The Birdtail-Waskada Axis (BWA; McCabe, 1967; Dietrich et al., 1998; Dietrich et al., 1999) is a Devonian-

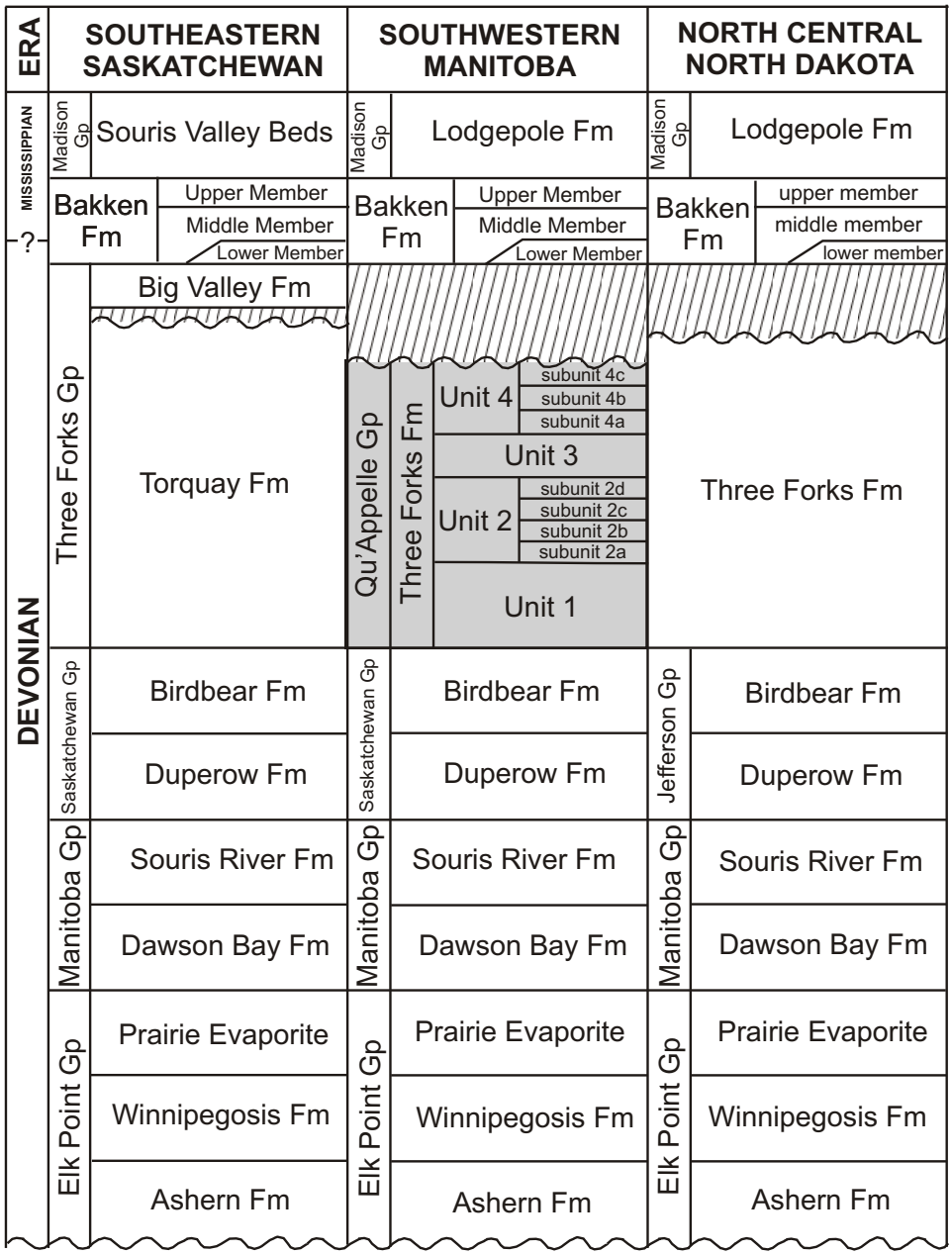

Figure GS-17-2: *Stratigraphic correlations of the Mississippian and Devonian units in southwest Manitoba to neighbouring jurisdictions. Abbreviations: Fm, Formation; Gp, Group.*

Mississippian structure that runs roughly through the middle of the southern extent of the SBZ (Figure GS-17-3) and is the result of increased fluid movement through a basement-driven active fault and fracture system, causing the rapid dissolution of the Prairie Evaporite and subsequent collapse of the overlying strata.

The Paleozoic unconformity represents the largest time lapse in the history of the Phanerozoic, and is mostly due to tectonic uplift (McCabe, 1959). A progressive erosional truncation of the Paleozoic formations, from youngest in the west to oldest in the east, toward the basin margin, reflects the dynamic tectonic forces affecting the Williston Basin during this time. A widespread and significant erosional unconformity marking the end of the Devonian represents a period of uplift, which continued until the early Mississippian. The deposition, reworking and erosion of the Three Forks Formation were most affected by this event, in combination with salt dissolution effects from the dissolution of the underlying Prairie Evaporite.

Stratigraphy

The Three Forks Formation is a silty, shaly dolarenite stratigraphically positioned between the overlying

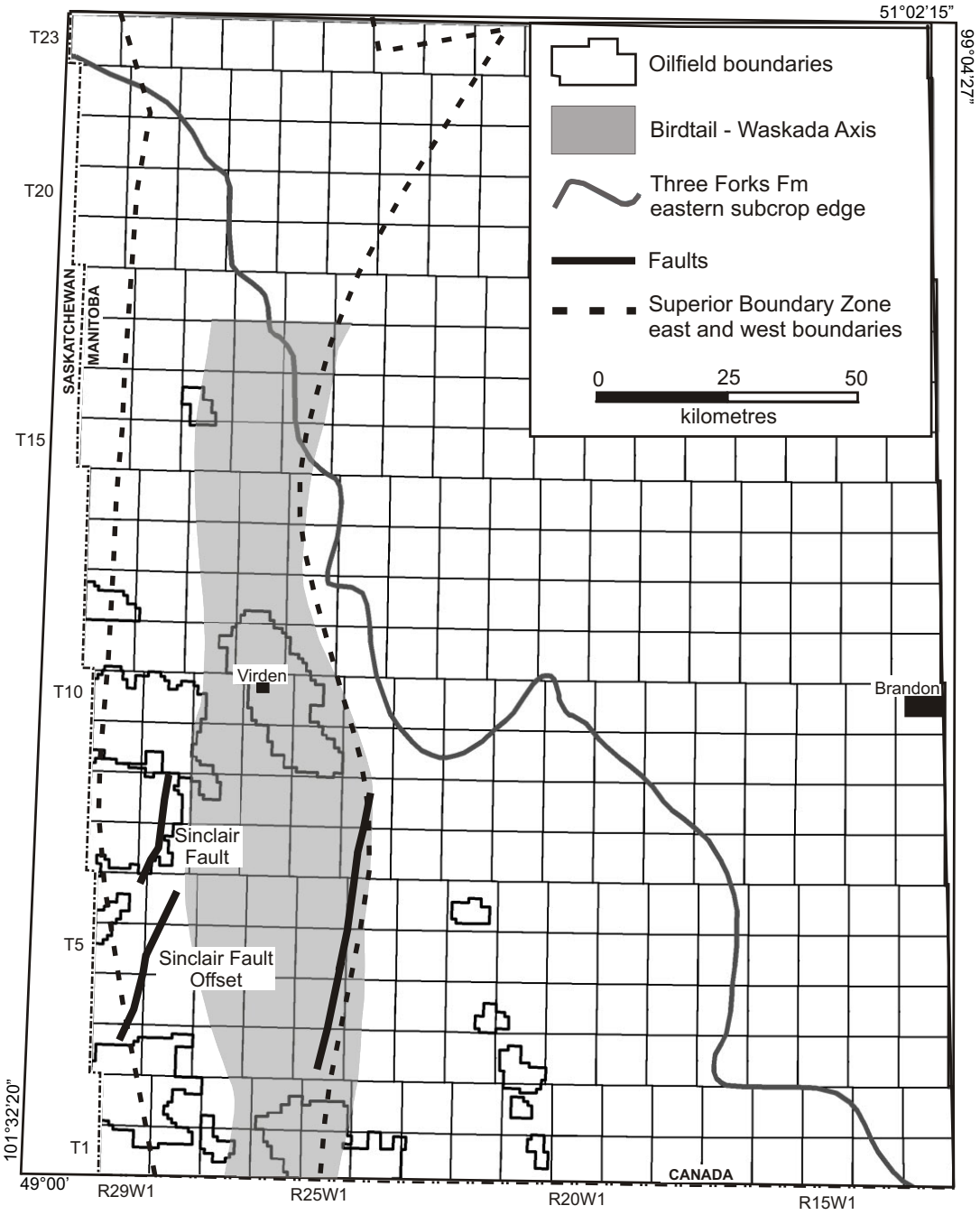

Figure GS-17-3: *Simplified tectonic map of the study area showing the Superior Boundary Zone (SBZ), the Birdtail-Waskada Axis (BWA) and fault lines.*

siltstone, sandstone and shale layers of the Mississippian Bakken Formation, and underlying carbonate and evaporite layers of the Devonian Birdbear Formation, Saskatchewan Group (Figure GS-17-2). The Three Forks Formation is subdivided into four units (described below); similar to those recognized in southeastern Saskatchewan by Christopher (1961). In this study, Units 2 and 4 are further subdivided into subunits (Figure GS-17-4). Figure GS-17-4 shows a reference log for the Three Forks Formation.

Unit 1

Unit 1 is the lowermost unit of the Three Forks Formation (Figure GS-17-2) and is present uniformly up to the subcrop edge (Figure GS-17-5a). This unit is the least understood of all four units due to its limited core availability. It has a fairly constant isopach, averaging 16 m. It is highly oxidized with occasional grey-green reduction haloes. The original fabric may have been a brecciated argillaceous dolomite with grey-green silty shale matrix. Unit 1 is productive within two small

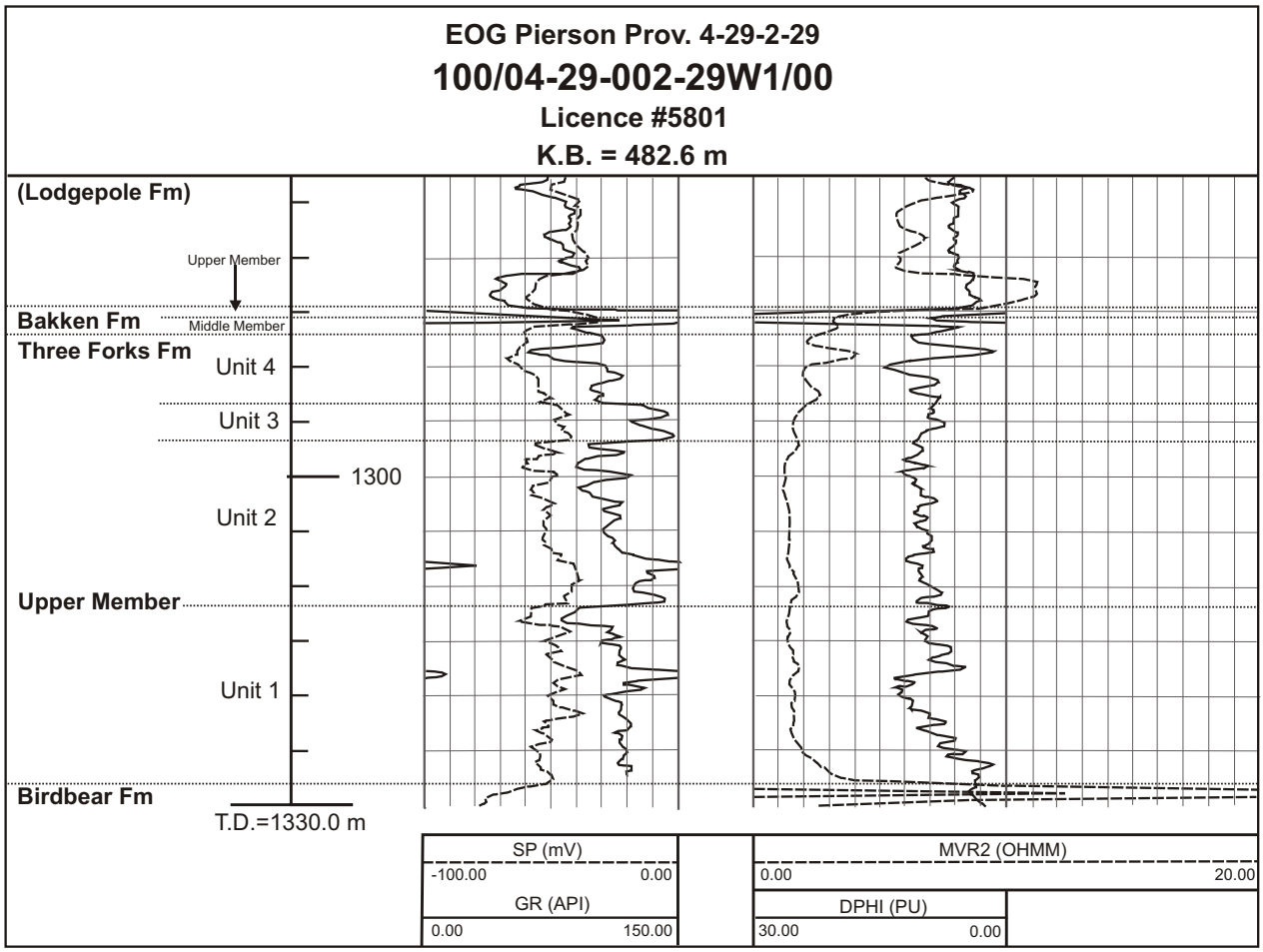

Figure GS-17-4: *Three Forks Formation reference log of the 04-29-002-29W1 well.*

isolated pools in the Sinclair Field. Its future reservoir potential is unknown, but looks promising.

Unit 2

Unit 2, shown in Figure GS-17-2, is a sequence of interbedded siltstone and shale, massive shale and brecciated siltstone that have been partially oxidized. Unit 2 is subdivided into four subunits; from bottom to top they are named subunits 2a, 2b, 2c and 2d. The isopach for this unit averages 15 m, reaching a maximum thickness of 19 m in the Sinclair area to less than 1 m as the distribution limit in the east is approached (Figure GS-17-5b). The distribution limit for Unit 2 roughly follows the eastern boundary of the BWA and the SBZ. With porosity decreasing with depth, its best reservoir locations are where the upper half of the unit is exposed at the unconformity surface. It is productive as a secondary reservoir in the Sinclair Field, where production from this unit is 1) only economical when commingled with a better producing zone uphole, or 2) the oil production is economically borderline compared to other wells in the field. In the Daly and Kirkella fields (Twp. 9–12, Rge. 27–29, W 1st Mer.), Unit 2 is a primary reservoir when its production is commingled with that of the Middle Member of the Bakken Formation.

Unit 3

Unit 3 (Figure GS-17-2) is a red-brown, highly oxidized, tight silty dolomitic shale with rare grey-green reduction haloes. Its distribution follows Unit 4 closely, and is present in isolated wells east of its main subcrop edge (Figure GS-17-5c). It is easy to see on logs with its consistent log signature (Figure GS-17-4) and uniform isopach, averaging 3.5 m. While this unit is tight, it can be productive when perforated in conjunction with Unit 2 (when Unit 3 occurs at the Devonian unconformity surface).

Unit 4

Unit 4, depicted in Figure GS-17-2, is the uppermost unit represented in the Three Forks Formation in Manitoba, and is an interbedded siltstone, with argillaceous dolomite and silty dolomitic shale of highly distorted and brecciated dolomitic siltstone beds. Unit 4 is subdivided into three subunits; from bottom to top they are named subunits 4a, 4b and 4c. Its isopach ranges from 1 to 14 m, but more commonly averages 6 m. This unit has a limited

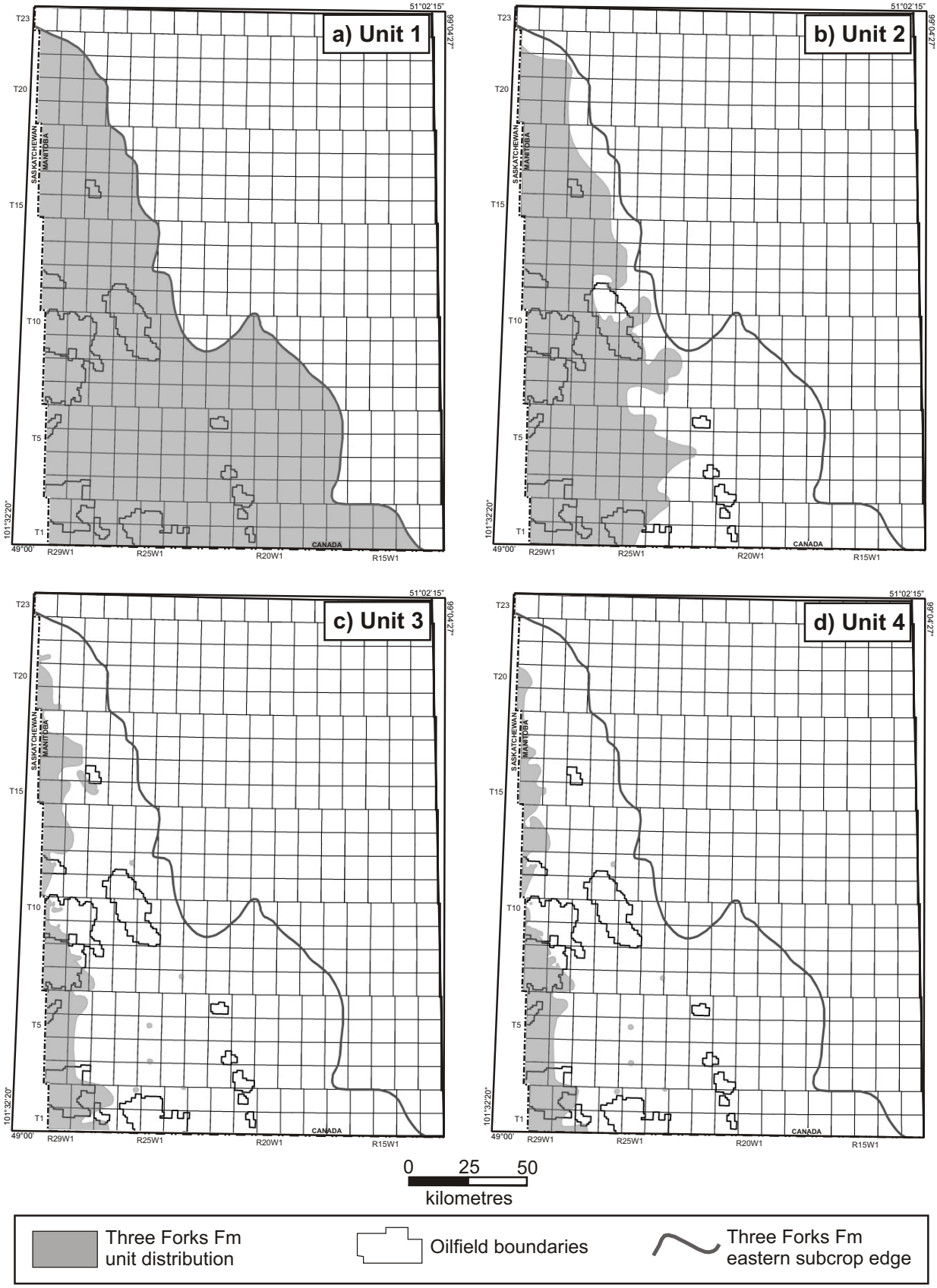

Figure GS-17-5: *Distribution map and subcrop edge for each unit in the Three Forks Formation, Manitoba:* ***a)*** *Unit 1 distribution;* ***b)*** *Unit 2 distribution;* ***c)*** *Unit 3 distribution and* ***d)*** *Unit 4 distribution. Abbreviation: Fm, Formation.*

distribution in Manitoba, being restricted to Rge. 28–29, W 1st Mer., and westward into Saskatchewan; like Unit 3, it is preserved in isolated wells east of its main subcrop edge (Figure GS-17-5d). Unit 4 production is commingled with the Middle Member of the Bakken Formation, and together they comprise the primary and most productive reservoir in the Sinclair Field. In addition, the combined interval forms a small isolated pool in Twp. 4, Rge. 29, W 1st Mer. (abbreviated 4-29-W1). It should also be noted that production also originates from subunits 4b and 4c, whichever is present at the unconformity surface. Minor production from Unit 4 is present in the southern sections of the Daly Field and one well in the Kirkella Field (Figure GS-17-1, -5d). At the Sinclair Field, the average core permeability is 4.3 mD, and average core porosity is 16.5%.

Deposition and diagenesis

The Three Forks Formation is a cyclical transgressive-regressive sequence of argillaceous dolomite, brecciated, interbedded and interlaminated with silty dolomitic shale and claystone. This formation was influenced by transgressive and regressive cycles, periods of exposure, gravity flows (Karasinski, 2006) and basin tectonics. According to Karasinski (2006), the Three Forks Formation was deposited along a temperate, carbonate tidal flat that grades basinward toward an unrimmed carbonate platform. Karasinski's report is based on an area six townships in size, centred on the Sinclair Field. The final phase of the Three Forks Formation study will attempt to verify Karasinski's model on a larger scale; and if necessary, a more appropriate depositional model will be developed.

Karasinski (2006) noted that several stages of diagenesis have occurred with dolomitization of the entire sequence occurring at early and middle stages of diagenesis. He also reported that porosity development and occlusion developed as early- and late-stage diagenetic alterations.

Isopach and structure

The regional isopach of the Three Forks Formation generally thickens east to west, with its greatest thickness observed from 8-29-W1 south to the international border with the United States (Figure GS-17-6). The trend of the isopach contours parallels the SBZ and BWA margins. The formation thins eastward with a rapid successive truncation of the units of the Three Forks Formation toward the east. The units are truncated at the pre-Mississippian erosional surface. Units 3 and 4 are sharply truncated along a north-south trend between Rge. 28 and 29, W 1st Mer. East of this truncation, the isopach gradually thins eastward toward the subcrop edge, east of Rge. 25, W 1st Mer. Anomalously thick sections occur in a few wells far to the east, in Rge. 24 and 25, W 1st Mer., where Units 3 and 4 are preserved. Anomalous thicknesses of the Three Forks Formation are also noted in wells located at the Virden Field to the northeast (Figure GS-17-6).

The structure of the Three Forks Formation shows a general southeast trend, with synclinal flexures in the structure contours visible at the Sinclair, Daly and Virden fields (Figure GS-17-7). Pronounced structural highs occur in the Daly Field, mimicking those seen in the Mississippian (Klassen, 1996). A prominent synclinal flexure of the contours is seen in the western half of 8-28-W1.

Tectonics

The sub-Paleozoic extension of the Precambrian SBZ runs north-south in this area. The BWA runs roughly through the middle of the southern extension of the SBZ (Figure GS-17-3). Isopach and structural evidence suggest the presence of faults running parallel to the SBZ eastern and western margins (Nicolas, 2006); these faults were active at the end of the Devonian. The western faults are referred to as the Sinclair Fault and Sinclair Fault Offset (Nicolas, 2006), the latter being an en échelon extension of the former (Figure GS-17-3). Block faulting along this zone caused the preservation of the primary reservoir (Unit 4) of the Three Forks Formation east and west of the SBZ margins, while the secondary reservoir unit (Unit 2) was exposed as a plateau on the BWA. The preservation of Unit 4 in some wells east of the SBZ margin opens up the possibility that, under the right trapping conditions, there may be another Sinclair-type play yet to be discovered east of Rge. 24, W 1st Mer.

To support this faulting theory, Dietrich et al. (1998, 1999) identified several faults using seismic data along a transect from southeastern Saskatchewan to southwestern Manitoba, one of which coincides precisely with the subcrop edge of Unit 4, which is truncated in Rge. 28, W 1st Mer. This same transect identified a fault running roughly north-south around Rge. 25, W 1st Mer., which may explain the preservation of Unit 4 near the eastern limit of the SBZ. The margin of a well-defined magnetic and gravity anomaly (Viljoen et al., 1999) also coincides with the location of the eastern fault shown in Figure GS-17-3.

Conclusions

Up to this point, exploration of the Three Forks Formation has been combined with the Bakken Formation exploration in Manitoba. The two formations are often considered a continuous, commingled reservoir with no hydrological barrier between them, and are therefore pooled together. The Three Forks Formation is currently productive in the Sinclair, Daly and Kirkella fields and 4-29-W1. It is a new exploration target, and has to be explored in detail in other areas of the province.

The uppermost of the Three Forks Formation units, Unit 4, is the primary and most productive reservoir at the Sinclair Field and in the small pool in 4-29-W1 (Figure GS-17-1). Production is also derived from Unit

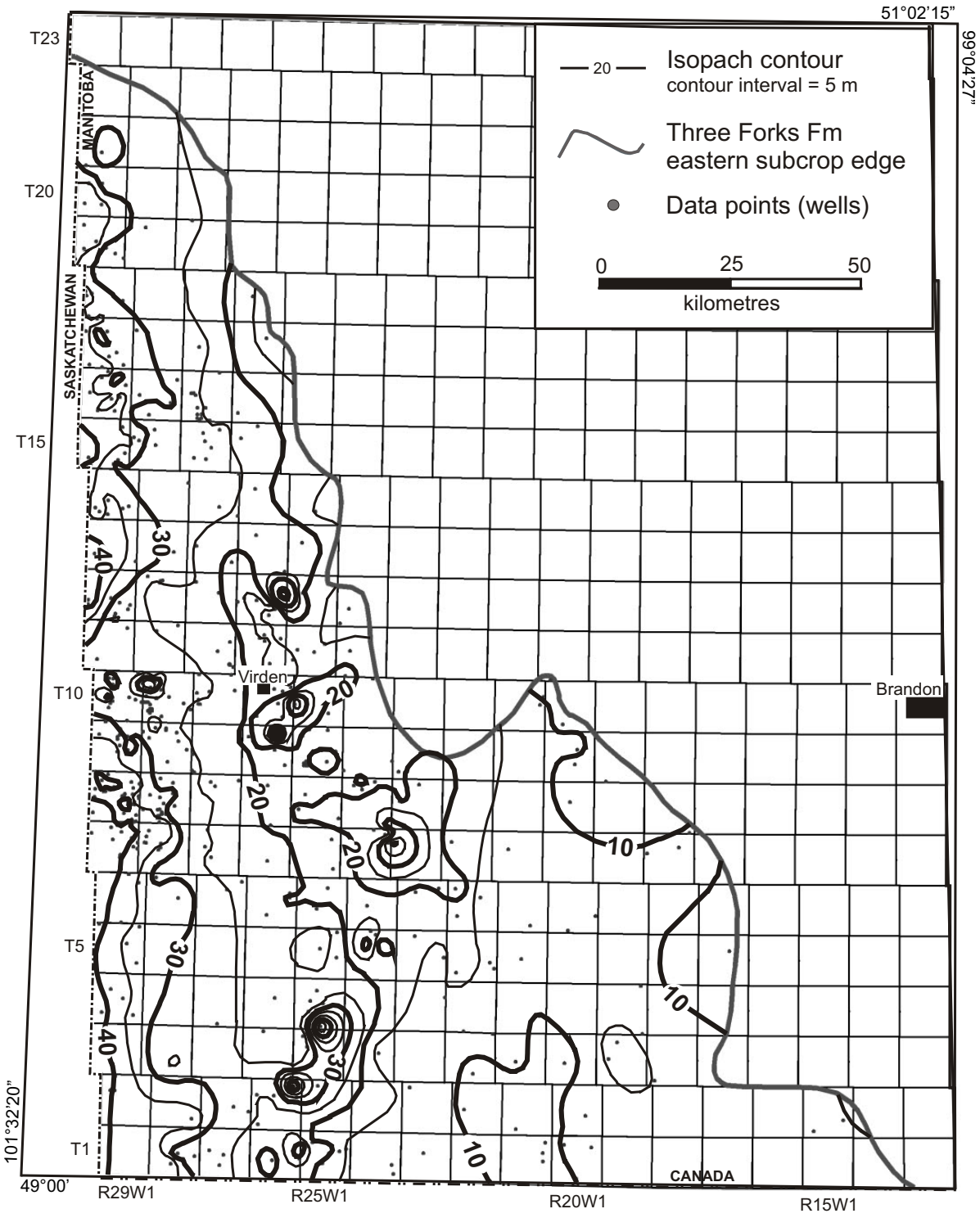

Figure GS-17-6: *Isopach of the Devonian Three Forks Formation; contour interval is 5 m.*

2, a secondary reservoir in the Sinclair, Daly and Kirkella fields. The thinning of the Three Forks Formation and the truncation of Unit 4 eastward suggests that the eastern expansion of the Sinclair Field may be limited. In contrast, the thick isopach trend running north-south along Rge. 29, W 1st Mer., where Unit 4 is still present, suggests a southern expansion of the Sinclair Field and northern expansion of the Daly and Kirkella fields may also be successful. It should be noted that much of 4-29-W1 remains unexplored.

Isopach and structural evidence suggests block faulting may have occurred in the western sections of

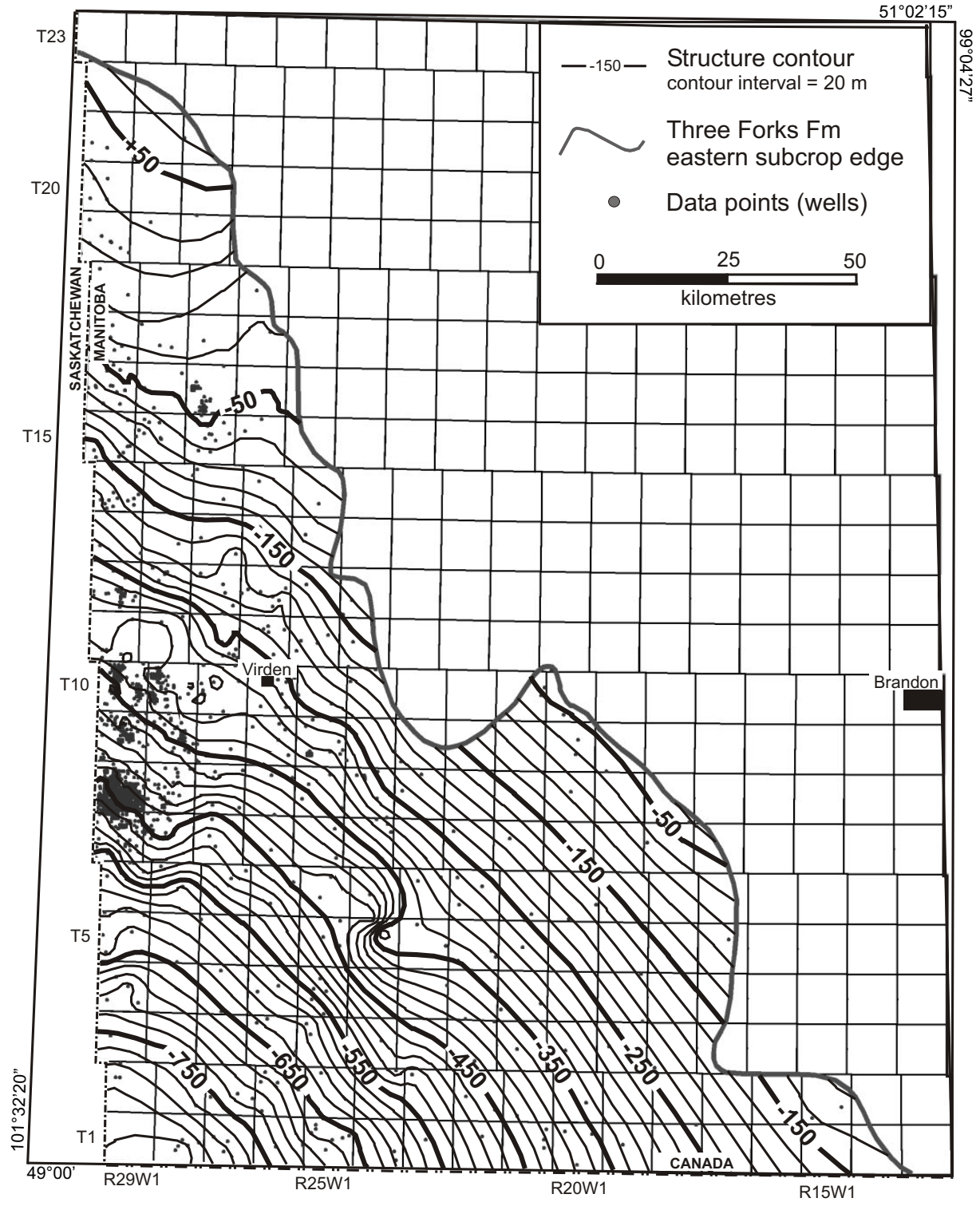

Figure GS-17-7: *Structure contours of the Devonian Three Forks Formation; contour interval is 20 m.*

Rge. 28, W 1st Mer., south of Twp. 9. This faulting would have resulted in uplift and the subsequent erosional truncation of Units 3 and 4 along eastern limits of Rge. 28, W 1st Mer. The fault trend may serve as a geological boundary in determining the eastern boundary of the Sinclair Field. The identification of a fault on the eastern edge of the BWA along Rge. 24 and 25, W 1st Mer. (Figure GS-17-3), coinciding with wells having preserved sections of Units 3 and 4, may provide a similar reservoir in the west.

Economic considerations

The Devonian Three Forks Formation of the Qu'Appelle Group in southwestern Manitoba has tremendous hydrocarbon exploration potential. Future development of known oil pools exists potentially along the north-south trend of Unit 4. Unit 2 has its best development potential in areas where subunit 2b is present and where subunit 2c has been minimally affected by oxidation.

New exploration efforts should be targeted north and east of the Sinclair Field within Unit 2, and possibly Unit 1. The fact that Unit 1 is productive in a small pool in the Sinclair Field suggests that more potential exists in this unit in all areas where the Three Forks Formation is present. Log signatures of Unit 1 look promising west of the Unit 2 subcrop edge, but core of this unit is not available to correlate with the log signatures. Possible target zones may occur along the north-south trend parallel to the eastern limit of the SBZ, from Rge. 24 to 25, W 1st Mer., where local occurrences of Unit 4 have been preserved, based on log correlations. It is possible that another Sinclair Field is yet to be discovered along this eastern trend. Figure GS-17-8 summarizes the most promising Three Forks Formation exploration target areas.

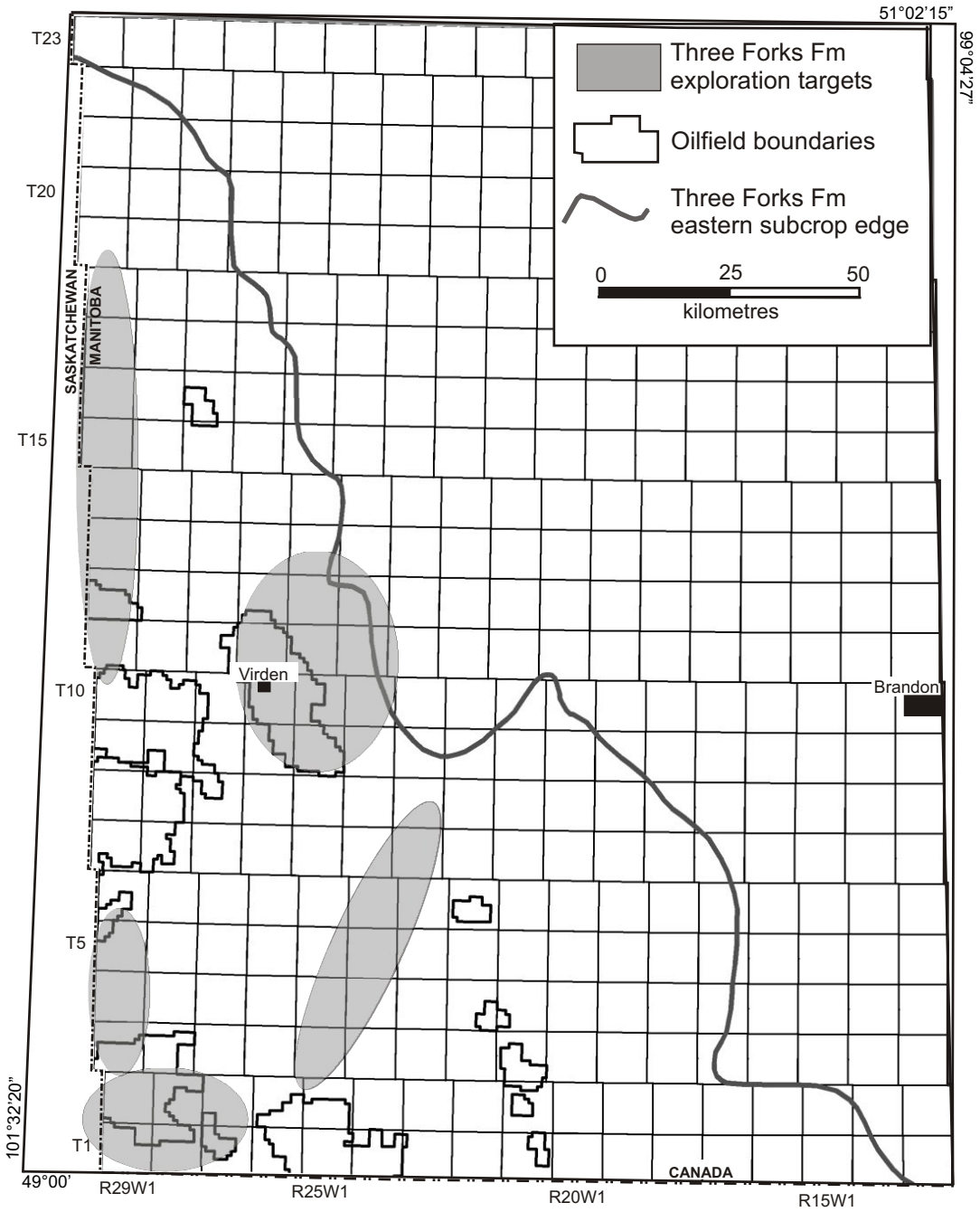

Figure GS-17-8: *Devonian Three Forks Formation recommended exploration target areas.*

Acknowledgments

The author would like to thank J. Fox (Mineral Resources Division, Manitoba Science, Technology, Energy and Mines) for his Sinclair Field reserves estimates.

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