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Stratigraphy and regional geology of the Late Devonian–Early Mississippian Three Forks Group, southwestern Manitoba (NTS 62F, parts of 62G, K)

By
M.P.B. Nicolas

Manitoba

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Cover illustration: Core from the oil reservoir in the Daly Sinclair Field, showing unit 4 of the Torquay Formation at a depth of 995–997 m in L.S. 2, Sec. 8, Twp. 8, Rge. 29 W 1st Mer.

Abstract

The Sinclair Field in Townships 7–8, Ranges 28–29, W 1st Mer., now amalgamated with the Daly Field and renamed the Daly Sinclair Field, is the largest oil field discovery in Manitoba in decades and has greatly expanded in size since its discovery in 2004. Exploration and development in the Bakken and Torquay formations have gone beyond the oil-field boundaries, and more than 45% of Manitoba's reported oil production for 2011 comes from these formations. Total cumulative oil production from these formations exceeds 5.4 x 10^6 m^3 (34 x 10^6 bbl).

The Three Forks Group comprises the Torquay, Big Valley and Bakken formations. The Torquay represents a cyclical sequence of dolomitic claystone and mudstone with interbedded siltstone, and intraformational siltstone breccias. The Big Valley consists of an interbedded dolomitic mudstone and siltstone overlying a thick bioturbated sandstone. The Bakken Formation is a siliciclastic sandstone unit between two massive, black, organic shale beds. The Torquay is subdivided into units 1 to 4, of which units 4 and 2 have proven to have the best petroleum reservoirs in the formation. The Middle Member of the Bakken Formation is subdivided into a lower unit, comprising lithofacies 1 and 2, and an upper unit, comprising lithofacies 3 and 4. The former is the better oil-producing subunit of the formation.

The Three Forks Group is the uppermost of the Palliser sequence, wherein the Torquay Formation evaporitic deposits represent a mini-regression, followed by an early transgressive marine shale of the Big Valley Formation, followed by the final maximum flooding event that is marked by the deposition of the Bakken Formation. In Manitoba, the Torquay represents a giant evaporitic mudflat on an epeiric shelf in an arid climate. The Big Valley sediments are dominantly nearshore, and the Bakken comprises transitional-offshore to offshore sediments. The oscillatory regressions and transgressions recorded in these rocks are attributed to eustatic sea-level changes due to glaciation in the southern hemisphere and to tectonic movement within the basin.

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Introduction

This study incorporates all of the Torquay Formation in southwestern Manitoba, which forms a triangle-shaped area between Twp. 1 and 23, Rge. 13 and 29, W 1st Mer. (Figure 1). The Torquay Formation is the lowermost of a clastic sequence that makes up the Three Forks Group. The succeeding Big Valley and Bakken formations complete the succession. However, preservation of the Big Valley Formation in Manitoba is sporadic; where it is absent, the Bakken directly overlies the Torquay Formation (Figure 2). This stratigraphic relationship is important because it indicates that the reservoirs of the Bakken and Torquay are hydraulically connected. Thus, a discussion on the Torquay Formation in Manitoba from a hydrocarbon exploration perspective must include the Bakken Formation. Stratigraphy and regional geology of these formations are discussed in the context of oil production and potential, and are the primary focus of this study.

Prior to the discovery of the Sinclair oil field (Twp. 7 and 8, Rge. 28 and 29, W 1st Mer.) in 2003, which has now been amalgamated with the Daly Field and renamed the Daly Sinclair Field, little was known about the Torquay Formation in Manitoba. Very few wells intercepted it, and companies that did usually categorized it as a tight, oxidized, shaly clastic unit with no oil potential. In addition, oil shows within this unit were so high in gravity that, without regular detailed observation and tests of the chip samples, its productive potential was bypassed. Now more than 2100 vertical wells and more than 350 horizontal wells penetrate the Torquay, and more than 400 cores are available through the formation. Oil production from the Bakken Formation has been consistent, with slow development since the first discovery in 1985. Recent horizontal development within the Bakken and commingled Bakken-Torquay pools has increased production to record levels throughout the Williston Basin. The discovery of the Sinclair Field in 2003 prompted a surge of exploration and development in these formations never before seen in Manitoba.

By the end of 2011, the total cumulative commingled Bakken-Torquay oil production was 5.00 x 10^6 m^3, and total Bakken-only oil production was 0.40 x 10^6 m^3. However, since the Bakken and Torquay systems are interrelated, it is suspected that some of the Bakken production is actually commingled Bakken-Torquay oil, especially in the Daly Sinclair Field but also from pools in the Kirkella, Birdtail and Manson fields, and small pools outside field boundaries.

A total of 82 cores located throughout the project area were logged for this study (Figure 1), and core analyses from 223 wells in the Daly Sinclair Field were compiled.

Previous work and nomenclature

Early work on the Bakken and Torquay formations included papers by Berry (1943), Holland (1952) and Nordquist (1953) in Montana; Fuller (1956), MacDonald (1956), Kents (1959) and Christopher (1961) in Saskatchewan; and McCabe (1959) in southwestern Manitoba. A re-examination of the Bakken Formation was prompted by technological advancements in drilling and completion techniques, and particularly the introduction of horizontal-well technology in the late 1980s. Martiniuk (1988) and LeFever et al. (1991b) provided a detailed look at the formation and its recent developments. Recent studies in Saskatchewan include those by Kreis et al. (2005, 2006), Angulo et al. (2008), Angulo and Buatois (2009), Kohlruss and Nickel (2009) and Angulo and Buatois (2010).

Bakken Formation

The Bakken Formation–equivalent strata were first described from outcrops in Montana. Berry (1943) applied the name Sappington Sandstone to Mississippian-age sandy beds in south-central Montana. Holland (1952) expanded the Sappington Sandstone to include a thin black shale at the base of the sandstone, but excluded the overlying thin black shale, interpreting it as being basal to the Lodgepole Formation. Nordquist (1953) combined Holland's (1952) Sappington Sandstone and the basal black shale of the Lodgepole Formation into the Bakken Formation. The names Kinderhook (derived from the Mississippi Valley region), Englewood (derived from the Black Hills region in South Dakota) and Exshaw (derived from western Alberta) were also used to refer to these same units (Fuller, 1956). Confusion due to the multitude of names being used led to the formal definition of the Bakken Formation by the Williston Basin Correlation Committee in 1953 and published by Nordquist (1953). Nordquist's (1953) formal definition of the Bakken Formation states that it consists of two thin, black, highly radioactive shale beds separated by calcareous and dolomitic sandstone and siltstone beds. This is the definition used at present for these strata in the Williston Basin of southern Saskatchewan, southwestern Manitoba, North Dakota, Montana and eastern Alberta. The Bakken Formation correlates with the Exshaw Formation of western Alberta.

The type section for the Bakken Formation is between depths of 2930.6 and 2962.7 m in the Amerada H.O. Bakken No. 1 well in C SWNW Section 12, Township 157N, Range 95W, Williams County, North Dakota, (Glass, 1997). This location is close to the depositional centre of the Williston Basin, where the formation is at its thickest (Fuller, 1956). With a continuous core of the entire Bakken Formation available, and in contrast to the previous type section, Kume (1963) designated a standard subsurface reference section at the C. Dvoack No. 1 well in SENE Section 6, Township 141N, Range 94W, Dunn County, North Dakota.

Three Forks Formation versus Torquay Formation

The correlation and stratigraphic nomenclature of the Devonian Three Forks Formation have undergone a long and complex evolution (Figure 3). Christopher (1961) provided an excellent detailed chronology of the definition and correlation of the Three Forks Formation in Montana and North Dakota, and the Three Forks Group in Saskatchewan, which is briefly summarized here. Peale (1893) first described and named the type section, near the town of Three Forks in south-central Montana, the 'Three Forks shale'. Haynes (1916) recommended the name be formally adopted as the Three Forks Formation. Work done in Montana by Perry (1928), Sloss and Laird (1947), Wilson (1955) and Sandberg and Hammond (1958) further described, subdivided and categorized the Three Forks Formation. In 1953, the Williston Basin Nomenclature Committee defined the Three Forks Formation in Saskatchewan. Kents (1959) correlated the

Montana Three Forks Formation into west-central Saskatchewan, and subdivided it into the Stettler and Big Valley members (oldest to youngest). Christopher (1961) modified Kents' (1959) Stettler and Big Valley members by renaming the former as 'Torquay', raised both to formation status and grouped them with the Bakken Formation to form the Three Forks Group. Christopher's (1961) report is a detailed look at the Three Forks Group, with particular focus on the Torquay Formation, and provides thorough, comprehensive and first-hand arguments to support stratigraphic correlations and his proposed nomenclature. His decision to create the Three Forks Group was based on 1) the three formations, Bakken, Big Valley and Torquay, together forming a dominantly clastic sequence between two carbonate groups; and 2) these three formations together being correlative with the Three Forks Formation type section of Peale (1893). Christopher's (1961) stratigraphic nomenclature is currently used in Saskatchewan.

In Manitoba, Allan and Kerr (1950) proposed the name Lyleton Shale for the red shale below the Bakken Formation that marks the top of the Devonian in the 'Gordon White No. 1' well in L.S. 5, Sec. 14, Twp. 1, Rge. 28 W 1st Mer. (abbreviated hereafter as 5-14-1-28W1). Baillie (1953, 1955) named the Qu'Appelle Group for "the upper strata of the Devonian System in the Williston Basin area…that includes all silty, argillaceous and anhydritic strata that overlie the Nisku Formation" (Birdbear Formation), which includes the Lyleton Formation. McCabe (1956) defined the Lyleton in greater detail, mostly by geophysical wireline logs and drill cuttings. Sandberg and Hammond (1958) rejected Allan and Kerr's (1950) naming of the red shale at the top of the Devonian as the Lyleton Shale on the basis that 1) there were inaccuracies in the definition of the lower contact; 2) the type section is too proximal to the basin margin and therefore likely attenuated; and 3) there was uncertainty in the interpretation of its true stratigraphic position. Nonetheless, they substituted the Three Forks Formation name for the Lyleton Shale on the assumption that the Lyleton Shale is, in fact, a local facies of the Three Forks Formation. After McCabe (1956), very little work was done on the Lyleton Shale in Manitoba, other than brief mentions of the formation in McCabe (1967, 1971). Interest in the Three Forks Formation had been minimal until the discovery of the Sinclair Field (renamed Daly Sinclair Field in 2010) in southwestern Manitoba in 2003. Extensive drilling and coring of the Three Forks Formation followed and, as a consequence, more understanding. The studies by Nicolas (2006, 2007, 2008a) and Karasinski (2006) on the Three Forks Formation in Manitoba, based on the new data, provided detailed stratigraphic, lithological and diagenetic information. Karasinski (2006) covered the Bakken and Three Forks formations in the Sinclair Field area, with emphasis on detailed lithology and diagenetic history. Nicolas (2006, 2007, 2008a) examined the Three Forks Formation throughout southwestern Manitoba.

Manitoba nomenclature

Manitoba stratigraphers used the term 'Lyleton Formation' until 1991, when LeFever et al. (1991a, b) substituted the 'Three Forks Formation' name in reference to Manitoba stratigraphy. The cross-border correlations of the Lyleton Formation in Manitoba with the Three Forks Formation in North Dakota in these two reports suggest that the Lyleton Formation is a facies equivalent to the Three Forks Formation, as defined by Sandberg and Hammond (1958). However, other than a brief mention in LeFever et al. (1991a) that the name 'Lyleton' is "former Manitoba stratigraphic terminology", no official statement of name change from 'Lyleton Formation' to 'Three Forks Formation' has been found by the author that would be in accord with the North American Code of Stratigraphic Nomenclature (1983, 2005). The lack of official statement for the adoption of the Three Forks Formation name in Manitoba causes confusion, as is apparent in Halbertsma (1994), Glass (1997) and Angulo et al. (2008), where the term 'Lyleton Formation' was still being used years later. In Karasinski (2006), Nicolas (2006, 2007, 2008a) and Nicolas and Barchyn (2008), the name 'Three Forks Formation' was used on the assumption that the name change had been clearly defined, and it was only during the research for this report that it became apparent that no declaration for nomenclatural change had been made.

There is also confusion in the exploration industry, where some of the technical well files in Manitoba show both Lyleton Formation and Torquay Formation names applied to core and drill cuttings from the same well. Industry geoscientists put the boundary between these two formations at the location where the lithology changes from dominantly light brown and grey-green to dominantly red-brown. This is inaccurate in that the former is a result of reducing conditions and the latter a result of oxidizing conditions, making the boundary chemical rather than lithostratigraphic. This phenomenon can be explained by the fact that the Lyleton Formation at its type locality, the Robert Moore No. 1 well in 5-20-1-27W1 between the depths 1244 and 1268 m, is red dolomitic siltstone and shale, in contrast to the Torquay Formation type section, in 8-32-3-11W2 between 2015.3 and 2067.2 m, that consists of grey and green to red and brown dolomite, shale and minor anhydrite, where the colouration depends on the degree of oxidation of the strata (Christopher, 1961). This oxidation boundary, which moves vertically through this Torquay/Lyleton sequence from well to well, is not distinguishable on logs and transcends correlatable units, and is therefore not a stratigraphic marker. Christopher (1961) discussed this chemical relationship in detail and displayed in cross-section its lack of correlativity on geophysical logs. This boundary can only be distinguished with core or drill cuttings.

Christopher (1961) proposed the currently accepted nomenclature for the Three Forks Group, which encompasses, from oldest to youngest, the Torquay, Big Valley and Bakken formations. The thorough reasoning given for the name change in Saskatchewan could be applied to Manitoba's stratigraphy through the same logic of correlations and intraformational lithological changes. It therefore seems logical to extend Saskatchewan's current nomenclature to Manitoba. The 'Three Forks Formation' of Manitoba is directly correlatable with the Torquay Formation, as discussed in Nicolas and Barchyn (2008) and shown in Manitoba-Saskatchewan cross-border mapping during the Williston Basin Targeted Geoscience Initiative (TGI) Project (TGI Williston Basin Working Group, 2008a, b). Therefore, the author proposes the formal adoption of the term 'Torquay Formation' to replace the previous official name 'Lyleton Formation' and the unofficial name 'Three

Forks Formation'. The author also proposes the abandonment of the term 'Qu'Appelle Group' in favour of the Three Forks Group of Christopher (1961), and thereby inclusion of the Bakken Formation, for the sake of consistency with Saskatchewan stratigraphic nomenclature.

Geological setting

The study area is in the eastern portion of the Western Canada Sedimentary Basin (WCSB), and includes strata at the northeastern edge of the Williston Basin and the southeastern portion of the Elk Point Basin (Figure 1). The Cambrian and Ordovician clastic and carbonate sequence of Manitoba is part of a large cratonic deposit that extends from the Hudson Platform in the east and northeast to New Mexico in the south (Norford et al., 1994). Paleozoic, Mesozoic and Cenozoic strata form a basinward-thickening, southwesterly sloping wedge that is 2.3 km thick in the extreme southwestern corner of Manitoba (Twp. 1, Rge. 29W1). Figure 2 shows the generalized stratigraphic column of the Phanerozoic for southwestern Manitoba.

The Paleozoic and Mesozoic strata are separated by a major unconformity that represents the largest hiatus in the Phanerozoic stratigraphic column and is mostly due to tectonic uplift (McCabe, 1959). Continental tectonic elements were agents of basinal changes. Of particular importance is the southward extension of the Precambrian Superior Boundary Zone (SBZ) beneath the Phanerozoic strata in southwestern Manitoba. The SBZ imposed local structural effects, including control of depositional trends and preferential salt-dissolution zones, through episodic basement reactivation.

Erosional truncation of the southwesterly dipping Paleozoic formations, from youngest in the west to oldest in the east, toward the erosional edge of the sedimentary basin reflects the dynamic tectonic forces affecting the WCSB. Discordance between the current structural trend of the Ordovician strata and their regional depositional (isopach) trend is a result of higher rates of subsidence in the Manitoba portion of the basin (Bezys and Conley, 1998; Bezys and Bamburak, 2004). The earlier Ordovician strata represent basinal deposition, with the latest Ordovician to Silurian strata recording a change to stable shelf deposits as a function of the stabilization of the tectonic framework (Bezys and Conley, 1998; Bezys and Bamburak, 2004). The Devonian strata record another significant change in tectonic framework of the WCSB. The Early Devonian was a time of erosion, with uplift along the Severn Arch (Figure 4), resulting in the complete loss of Ordovician and Silurian strata that had been continuous between the WCSB and the Hudson Basin (Norford et al., 1994), and marked a change from deposition centred in the Williston Basin (in northwestern North Dakota) to that centred in the Elk Point Basin (in south-central Saskatchewan; Baillie, 1951, 1953; Bezys and Bamburak, 2004) The Middle to Late Devonian is characterized by deposition of carbonate-evaporite cycles that are affected by transgressive and regressive pulses (Moore, 1988) and represent deposition from basinal to shelf environments. This is due to tectonic fluctuations that are mostly recorded as localized uplift, and subsidence and differentiation of basins (Bezys and Bamburak, 2004). A widespread and significant erosional unconformity marking the end of the Devonian represents yet another tectonic shift, which continued until the Early Mississippian. Eustatic fluctuations at the end of the Devonian are due to widespread glaciation in the southern hemisphere (Moore, 1988). The Devonian–Mississippian boundary represents a change in basin dynamics and accompanying sea-level changes, and marks a return to deposition centred in the Williston Basin.

Superior Boundary Zone

The Superior Boundary zone (SBZ) is a 40–50 km wide suture between Archean and Proterozoic crustal blocks (Dietrich and Magnusson, 1998). This zone has been defined "by gravity, magnetic and electromagnetic anomalies associated with crystalline basement features" by Dietrich and Magnusson (1998), as well as Rankin and Kao (1978), Green et al. (1979), Jones and Savage (1986) and Lyatsky et al. (1998). The geophysical expression of the SBZ and its relationship to other Precambrian crustal blocks within the southeastern Saskatchewan and southwestern Manitoba area are discussed in Li and Morosov (2007) and Nicolas and Barchyn (2008).

In the study area, the SBZ has had widespread effects on the Phanerozoic section, through periods of basement reactivation and differential subsidence. Episodes of SBZ reactivation are manifested mostly as deep extensive faults and fracture networks that resulted in structural anomalies and stratigraphic-facies variations during sedimentary deposition; and diagenetic and porosity variations after burial, and salt dissolution anomalies due to fluid movement at collapse sites (Dietrich and Bezys, 1998; Dietrich and Magnusson, 1998; Bamburak and Klyne, 2004; Fedikow et al., 2004; Bamburak, 2007). In the subsurface, Dietrich et al. (1999) reported that basement-related structures are relatively small in amplitude but have an important role in petroleum plays throughout the Paleozoic sequence (Nicolas and Barchyn, 2008).

Effects of the SBZ are most pronounced in the Birdtail-Waskada Zone (BWZ; Figure 4). This zone is 20–35 km wide and north trending in southwestern Manitoba, and its axis extends from beneath the Waskada Field to north of the Birdtail Field. Originally defined as the Birdtail-Waskada Axis by McCabe (1967, 1971), it covers an area that is broader than initially thought and was renamed the Birdtail-Waskada Zone by Dietrich and Magnusson (1998). The redefinition is supported by Nicolas and Barchyn (2008). McCabe (1967, 1971) described this zone as having "numerous sharply defined structure and isopach anomalies, mostly related to post–Middle Devonian salt collapse." According to Dietrich and Magnusson (1998), it is "characterized by numerous structural and stratigraphic irregularities in Paleozoic strata, most of which are associated with Middle Devonian Prairie Formation salt." Although the zone is strongly influenced by salt dissolution in the Devonian Prairie Evaporite, its origin is deeper and its effects are greater than those caused by salt dissolution and collapse during the post–Middle Devonian. The preferential dissolution of salt in this area is directly related to the basement tectonic framework. Dietrich and Magnusson (1998) reported, from seismic records, several large, basement fault systems within the BWZ; they also identified a basement hinge that runs the length of the BWZ and represents a belt of flexures (Figure 4). Fault and fracture systems on either side of this hinge facilitate movement of crustal blocks in response to increased and decreased overburden loading through geological time. Additionally, basinal fluids migrating through them resulted in localized dolomitization, sulphide precipitation and porosity variations (Nicolas and Barchyn 2008).

Stratigraphy

Underlying beds

Thick Ordovician, Silurian and Devonian carbonate, evaporite and minor clastic sequences underlie the Three Forks Group. The Devonian beds comprise (oldest to youngest) the Ashern, Winnipegosis, Prairie Evaporite, Dawson Bay, Souris River, Duperow and Birdbear formations. The Prairie Evaporite is a 0–130 m thick salt and anhydrite formation some 540 m below the Torquay Formation; through various stages of dissolution, it has impacted the deposition and preservation of the Three Forks Group clastic sequence.

The Birdbear Formation underlies the Torquay Formation conformably in some areas of Manitoba and disconformably in other areas. The formation is subdivided into a lower carbonate member of fossiliferous, porous limestone and dolostone, and an upper evaporite-carbonate member of dolostone with interbedded anhydrite (Martiniuk et al., 1995). The Birdbear subcrop lies east of the Torquay Formation edge and is similarly aligned. The subcrops of Birdbear, Torquay, Bakken and Lodgepole formations form a southeast-trending ridge in the subsurface, referred to herein as the Birdbear-Lodgepole escarpment (Figure 5).

Overlying beds

Mississippian Lodgepole Formation

The Lodgepole Formation conformably overlies the Bakken Formation. It consists of a marine shelf to slope sequence of argillaceous, oolitic, crinoidal and cherty limestone. The slope-deposited Basal Limestone facies and the shelf-equivalent Scallion Member directly overlie the Bakken shale, and comprise limy mudstone to wackestone with thin interbedded shale (Klassen, 1996). The shale is locally very dark and resembles the Upper Bakken Member shale. In some areas, the Routledge Shale facies of the Lodgepole is locally preserved between the Bakken Formation and the Scallion Member. The Routledge Shale is organic, black and highly radioactive, and is difficult to distinguish from the Upper Bakken shale in core without the assistance of a geophysical log. The distinguishing factor is the higher gamma-ray signature of the Upper Bakken.

Amaranth Formation, Lower (Red Beds) Member

Along the eastern Torquay subcrop beyond the Bakken erosional edge, the Torquay Formation is disconformably overlain by the Triassic Amaranth Formation, Lower (Red Beds) Member, which consists dominantly of red argillaceous dolomitic siltstone and very fine grained sandstone.

The Lower (Red Beds) Member represents a flooding stage after the erosional event at the end of the Paleozoic. The isopach map of this member shows infilling of the Paleozoic erosional surface and gives a good indication of post-Mississippian paleotopographic relief (Figure 6). Thinned Red Beds are associated with the Lodgepole producing fields, such as Daly Sinclair, Virden and the 'Lodgepole trend', which includes the Whitewater, Regent and Souris Hartney fields. Dramatic thickening of this member is evident immediately east of the Birdbear-Lodgepole escarpment.

Torquay Formation

Stratigraphic correlation

Detailed Torquay Formation stratigraphy was introduced by Christopher (1961) with the designation of six units regionally mapped throughout south-central and southeastern Saskatchewan. Correlations and extrapolations from these original units have been done by Kreis et al. (2006), Nicolas (2006, 2007) and LeFever and Nordeng (2009), each with slight differences (Figure 7).

Lithology

The Torquay Formation in Manitoba comprises a cyclical sequence of dolomitic claystone and mudstone, interbedded siltstone, and intraformational siltstone breccia that has been subjected to erosion, weathering and oxidation. The unoxidized siltstone is light brown to tan and the claystone and mudstone are grey-green, but the oxidized form is earthy red-brown. There are four units correlative to those recognized in southeastern Saskatchewan by Christopher (1961), the distributions of which are shown in Figure 8. The upper two units of Saskatchewan are lost to eastward truncation, and only the four lower units are preserved in Manitoba (Figure 9). Each of units 1, 2 and 4 represents a single coarsening-upward cycle, visible on logs (Figure 10); when viewed as a package, the cyclical nature of their deposition is apparent. These units are further divided into subunits, based on sedimentary characteristics and geophysical-log signatures, and are described below from oldest to youngest. Figure 11 is a schematic summary of the Torquay stratigraphy.

All porosity ranges given in the formational lithological descriptions are based on visual estimates from core.

Unit 1

Unit 1 may rest conformably or disconformably in places on the Birdbear Formation, and is correlative to unit 1 and the lower half of unit 2 of the Torquay Formation in southeastern Saskatchewan. Unit 1 is the most weathered and its red-brown earthy discolouration often masks the original sedimentary fabric and lithology. Sections that are still in reduced form are generally grey-green (claystone to mudstone) and light brown (siltstone), and provide unoxidized 'windows' (reduction haloes, herein referred to as redox haloes) into the original rock fabric. These windows of unoxidized rock make up only 10–15% of the unit. Unit 1 is subdivided into three subunits based on available core data; the subunits are also distinguishable on geophysical logs and are described below in stratigraphic order.

Log correlation throughout southeastern Manitoba shows the thickness of unit 1 to be fairly uniform, averaging 17 m. Log signatures vary regionally, but the upper section is generally the more porous and siltstone rich part of the unit, similar to subunits 2c and 4c (described below). In the east, where unit 1 survived the pre-Mississippian erosional event (Twp. 10, Rge. 24W1), the Mississippian section is also completely eroded, so that the Triassic Lower Amaranth (Red Beds) Member directly overlies the basal Torquay unit. Overall, the gamma-ray log signature of unit 1 shows a general increase with depth. The resistivity is highest at the top of the unit (subunit 1c) and then decreases steadily, except for a slight increase at the top of subunit 1b, as it approaches the Birdbear Formation and terminates with a blocky signature (subunit 1c).

Subunit 1a

Subunit 1a consists of a thin, basal, buff to brown dolostone with overlying interbedded red-brown to light brown dolomitic siltstone and red-brown to grey-green dolomitic claystone and mudstone. Anhydrite nodules increase in size and concentration with increasing depth, ranging from 1 cm to more than 10 cm in diameter, and can be white, pink or blue-grey. Disseminated pyrite is common throughout the unoxidized claystone and mudstone beds, but is altered to rusty iron oxide in the oxidized portions. Porosity within the unoxidized portions is variable but generally good, averaging 10–15%, and, in the siltstone and dolostone, is characterized as microporous, intergranular/intercrystalline, vuggy and fractured. Fractures are common, making the core rubbly in places and occurring as long, open, vertical fractures and as hairline fractures along bedding. The oxidized portions of the subunit average 85%. The proportion of siltstone to claystone and mudstone is variable, but siltstone is generally predominant. Oil shows were not identified in core for this subunit.

A basal dolostone appears to be present only locally and is commonly separated from the Birdbear Formation by a thin grey-green shale bed (Figure 12a). This dolostone was identified in core in 5-11-11-26W1. Where present, the dolostone bed conformably overlies the Birdbear Formation; where it is absent, the Torquay Formation is in disconformable contact with the Birdbear Formation. The dolostone represents the Birdbear-Torquay transition zone and is massive, oxidized in places, vuggy and fractured. In Saskatchewan, the basal dolostone is widespread (Christopher, 1961).

Where the dolostone is absent or very thin, there is a bed of highly oxidized, dolomitic mudstone with occasional anhydrite nodules and angular siltstone and dolostone fragments. The degree of oxidation affecting this bed varies but is commonly extreme. This makes the primary rock fabric and textures difficult to identify because they are masked by an earthy red-brown to orange-brown dusty coating rich in iron-oxide minerals such as hematite and goethite.

Interbedded within the mudstone are thin siltstone beds and claystone laminae. The siltstone is wavy bedded and commonly exhibits soft-sediment deformation, including load structures and in situ brecciation. Repetitive brecciated siltstone, rhythmites (alternating siltstone and claystone) and massive to faintly bedded claystone to mudstone can be seen through the oxidation veil; similar sequences are well developed in subunit 2b (described below).

Subunit 1b

Subunit 1b consists of interbedded dolomitic siltstone and claystone to mudstone between overlying and underlying, massive, waxy claystone to mudstone (Figure 13). Most of the subunit is extensively oxidized (red-brown to earthy, rusty, orange-brown), and rock fabrics and textures are difficult to see. Unoxidized haloes provide windows into the original rock fabric and are commonly grey-green for claystone and mudstone, and light brown for siltstone. The interbeds are between 50 and 95% siltstone; a good example of redox haloes is shown in Figure 13. Siltstone beds are wavy bedded, brecciated, and soft-sediment deformed. Alternating brecciated beds, wavy beds and mudstone laminae are common. Mudstone flasers are common within the siltstone, and thicker beds display relict siltstone fragments in subparallel alignment, giving them the appearance of faint bedding in places. Disseminated pyrite or iron oxides are common within the mudstone and claystone; white, pink and grey-blue anhydrite occurs as occasional blebs, nodules and fracture fills. Occasionally, core in this subunit is rubbly and crackles when wet, and commonly has open vertical fractures and hairline horizontal fractures. Subunit 1b was productive in 9-30-7-28W1 and 1-14-8-29W1 in the Daly Sinclair Field, and represents the stratigraphically lowest oil pools in Manitoba to date. Spotty, pale yellow ultraviolet fluorescence was identified in unoxidized siltstone in this unit in 5-11-11-26W1, suggesting a potential for production from this unit in other locations.

Subunit 1c

Subunit 1c is dominantly wavy bedded, red-brown to light brown, dolomitic sandy siltstone, and mudstone in beds, laminae, lenses, flasers and matrix (Figure 14). The mudstone interbeds are blocky in places or faintly bedded with relict siltstone fragments, and commonly have disseminated pyrite or rusty iron-oxide minerals. Fractures are common, often seen as rubble, long open vertical joints and open horizontal fractures parallel to bedding. Porosity is highest in the siltstone, averaging between 10 and 15%, and rarely between 15 and 20%, and occurs as micropores, intergranular spaces and small vugs. Porosity of the claystone and mudstone is low, between 5 and 10%, and is mostly microgranular and intergranular. Pink anhydrite blebs and nodules are rare. This subunit is extensively oxidized and, like the subunits below it, has redox haloes providing windows into the original fabric and texture of the rock. Oil staining and pale yellow ultraviolet fluorescence have been recorded from the unoxidized siltstone beds in 6-7-4-21W1 and 5-11-11-26W1, but there has been no production.

Unit 2

Unit 2 generally consists of interbedded siltstone and claystone, and massive mudstone; it is locally brecciated and bioturbated. Log correlation throughout southeastern Manitoba shows the thickness of unit 2 to be fairly uniform, averaging 14 m. It correlates with unit 2 of Christopher (1961) in southeastern

Saskatchewan and, in this report, is divided into four subunits based on available core data and correlation with geophysical logs. These subunits are described below, from oldest to youngest.

Subunit 2a

Subunit 2a is a blocky, faintly mottled, red-brown to grey-green dolomitic claystone and mudstone with minor thin, light brown, dolomitic siltstone laminae and rhythmites (Figure 15). It is generally oxidized to red-brown but includes redox haloes of light brown in the siltstone to grey-green in the claystone and mudstone; Figure 15 shows an exceptionally good section with minimal oxidation effects. Soft-sediment deformation is displayed in the siltstone beds. Porosity is generally low, increasing to 10–15% in zones with higher siltstone content; it occurs mostly as micropores, intergranular spaces and open vertical fractures.

Subunit 2b

Subunit 2b comprises irregular alternating cycles of 1) brecciated dolomitic shaly siltstone, 2) laminated dolomitic siltstone and claystone (rhythmites), and 3) massive mudstone (Figure 16). Oxidized patches occur within the more reduced zones, and reduction haloes remain within the more oxidized zones. Siltstone clasts and laminae within the reduced zones are commonly light brown to tan, and claystone and mudstone are grey-green. The oxidized zones are a uniform red-brown. Disseminated pyrite is common in the reduced zones, occurring mostly along bedding planes and as blebs. Anhydrite is rare and occurs as very small blebs. Contact with unit 2c is sharp. On logs, this unit appears as dirty siltstone with alternating gamma-ray and porosity signatures, responding to the variations in lithology and porosity over short depth ranges.

Unit 2b breccia consists of light brown to tan, dolomitic siltstone clasts in a grey-green dolomitic claystone to mudstone matrix. Original bedding is highly distorted, bioturbated and brecciated, but it still partially preserves a faint fabric based on the bedding orientation of the clasts. Porosity is low in the claystone and mudstone but 10–15% in the siltstone, dominantly as micropores and intergranular spaces. Oil staining and yellow ultraviolet fluorescence were noted in some cores of the siltstone beds, such as in 16-8-8-28W1 and 3-1-11-29W1.

The rhythmites of subunit 2b exhibit alternating thin beds of tan dolomitic siltstone and grey-green claystone. Sedimentary structures include flasers, ripple marks, lenticular bedding, trough crossbedding, bioturbation, load structures and soft-sediment deformation. Bedding fractures are common: some that occurred early are filled with silt and others are late stage. Porosity is best developed in the siltstone as micropores, intergranular spaces and small vugs, and ranges from 10 to 15%. No oil staining or ultraviolet fluorescence was observed.

The massive mudstone beds in subunit 2b consist of grey-green to rusty-brown mudstone with disseminated pyrite or ferric minerals. The beds are often the most oxidized of the subunits, and commonly feature reduced haloes. Occasional faint relict pseudomorphs of small subangular to subrounded red-brown siltstone clasts are visible, either scattered throughout the mudstone or as accumulations in thin beds, with clast alignment suggestive of faint bedding. These beds are low in porosity, and no oil staining or ultraviolet fluorescence was observed.

Subunit 2c

Subunit 2c features light brown to tan, dolomitic sandy siltstone (~75%) with grey-green claystone to mudstone as laminae, interbeds and matrix (~25%; Figure 17a). The siltstone is massive in places and commonly laminated to wavy bedded; sedimentary structures include ripple marks, trough crossbedding, load structures, escape structures and soft-sediment deformation features. Escape structures are characteristic and occur over a 0.5 m interval (Figure 17b). Their internal structure suggests *Skolithos* ichnofacies. Pyrite is disseminated along bedding planes and as blebs. Anhydrite occurs as rare millimetre-size blebs. Millimetre-scale infilled vertical and bedding-aligned fractures are common, and open vertical and bedding-aligned fractures occur occasionally. Porosity is about 15% and is mostly microporous and intergranular. Oil staining and ultraviolet fluorescence were observed in several cores, such as 9-16-8-29W1 and 8-25-7-29W1. The contact with subunit 2d is sharp and erosional. Subunit 2c is occasionally partially oxidized, as shown by rusty-brown mudstone and pyrite altered to iron oxides. On logs, this unit features a low gamma-ray count and a corresponding decrease in resistivity, neutron porosity and density porosity, in contrast to the overlying high gamma-ray response typical of unit 3. Where combined with the Middle Member of the Bakken Formation, this unit is productive.

Subunit 2d

Subunit 2d is a thin, dense, massive, grey-green dolomitic claystone to mudstone (Figure 18). The upper contact with unit 3 is gradational. In core, it is characteristically grey-green in contrast to the rusty-brown mudstone of unit 3. The unit is indistinguishable from unit 3 where it is oxidized. No oil staining or ultraviolet fluorescence was observed.

Unit 3

Unit 3 consists of a dense, rusty-brown dolomitic mudstone (~90%), grading to claystone in places and with faint relict pseudomorphs of rotted, angular, fine-grained, dolomitic siltstone fragments (~10%), which occurs in a thin bed in the centre of unit 3 (Figure 19). It correlates with the lower part of unit 3 of the Torquay Formation (Christopher, 1961) in southeastern Saskatchewan. The mudstone ranges from mostly massive to faintly mottled and bedded in places. Scattered small haloes of grey-green mudstone and minute anhydrite are present. Porosity is low and no oil staining or ultraviolet fluorescence was detected. The upper contact is sharp.

Where unit 3 forms the top of the Torquay Formation at the unconformity, beneath the Bakken Formation, its colour is grey-green and intergranular porosity is increased by the absence of the iron-oxide minerals that can occlude porosity. This unit is oil productive where perforations combine reservoirs in the overlying unit 4 or the underlying unit 2. Porosity and permeability decrease with increasing depth and distance from the unconformity.

On logs, this unit is distinguished by an abrupt increase in gamma-ray count in contrast to the overlying and underlying siltstone-rich zones, and by a counterclockwise rotated 'W'-shaped profile. The gamma-ray signature, where it decreases slightly in the middle of the unit, does so in response to an increase in relict siltstone fragments. Log correlation throughout southeastern Manitoba shows the thickness of unit 3 to be fairly uniform, averaging 3.5 m

Unit 4

Unit 4 is composed of interbedded siltstone and mudstone with thick subunits of highly distorted and brecciated siltstone beds. It correlates with unit 4 of the Torquay Formation in southeastern Saskatchewan and is subdivided into four subunits. In Manitoba, it forms the uppermost unit of the Torquay Formation and is the primary reservoir of the Daly Sinclair Field. Unit 4 is present in the southern half of the Daly Sinclair Field but is truncated to the east. The subunits, which are correlatable in cores and on geophysical logs, are described below. Since unit 4 is always present at the unconformity surface, its isopach is strongly affected by erosion. In the Daly Sinclair Field, this unit averages 7.5 m in thickness, but it can reach thicknesses of up to 23 m in other parts of Manitoba when the Lower Bakken Member and/or Big Valley Formation are preserved.

Subunit 4a

Subunit 4a is a thin, massive, dense, grey-green dolomitic claystone to mudstone (Figure 20) similar to subunit 2d. No oil staining or ultraviolet fluorescence was observed. Although difficult to distinguish on logs, it is recognized by a small increased gamma-ray deflection.

Subunit 4b

Subunit 4b is characterized by light brown to tan, dolomitic siltstone fragments in a grey-green claystone to mudstone matrix (Figure 21). Original bedding, although highly distorted and brecciated, is preserved as a faint fabric delineated by orientation of the clasts. The clasts are angular, range in size from less than 0.5 cm to more than 7 cm and commonly exhibit internal sedimentary structures but no evidence of transport. The overall subunit is poorly sorted. The upper and lower thirds have a higher concentration of siltstone clasts than the middle, which is more shaly and lenticularly bedded. Pyrite is disseminated throughout. Anhydrite occurs as rare minute blebs. Porosity is low in the shale and 10–15% in the siltstone, occurring as intergranular spaces and millimetre-scale vugs. Oil staining, a petroliferous odour and bright yellow ultraviolet fluorescence are common throughout but more concentrated in zones with a higher content of siltstone fragments. Subunit 4b is part of the primary reservoir in the southern half of the Daly Sinclair Field and is expressed on logs as alternating shale and silt with variable porosities and resistivities.

Subunit 4c

Subunit 4c is a light brown to tan, dolomitic sandy siltstone (~75%) with grey-green mudstone as laminae, interbeds and matrix (~25%; Figure 22). It is massive in places and commonly laminated to wavy bedded; sedimentary structures include gently inclined laminations, ripple marks, trough crossbedding, load structures, and soft-sediment deformation. Disseminated pyrite occurs on bedding surfaces and as blebs, and anhydrite forms rare minute blebs. Infilled and open vertical fractures are rare. Porosity is about 15% and is represented by minute pores, intergranular space and small vugs. Oil staining, a petroliferous odour and ultraviolet fluorescence were noted in all cores of this subunit. This unit is lithologically similar to subunit 2c but is thicker and not affected by oxidation. Its sharp erosional contact with the Bakken Formation is commonly capped with a thin erosional lag. Subunit 4c is part of the primary reservoir in the Sinclair Field and shows up on geophysical logs as a relatively clean, porous siltstone.

Units 5 and 6

Christopher's (1961) units 5 and 6 have not been positively identified in Manitoba. However, evidence from a core in 3-30-11-29W1 indicates they may be locally preserved. For the purpose of this study, these bodies are included in unit 4, as part of subunit 4c in 3-30-11-29W1.

Big Valley Formation

The Big Valley Formation is only now recognized in Manitoba. As described and mapped in Saskatchewan (Christopher, 1961), its eastern erosional limit lies just west of the Manitoba-Saskatchewan boundary. However, its presence in a core in 12-24-11-29W1 is the first physical evidence that the formation extended east into Manitoba but was subsequently extensively eroded (Nickel and Lake, 2010).

Although core recovery was poor in the 12-24-11-29W1 core, there are two units (Figure 23). The upper is an interbedded claystone to mudstone and siltstone, variegated red-brown, purple, light brown and grey-green. It resembles typical Torquay lithology and has sharp, erosional upper and lower contacts associated with an erosional lag of poorly sorted shale conglomerate. The lower unit is a light brown, massive, mottled, highly bioturbated, very fine grained sandstone. The sandstone is dominantly quartz with rare black grains; the sand grains are moderately well sorted, subangular to subrounded, and frosted and embedded in a fine dolomitic matrix with high porosity (>15%) and permeability attributable to micro and intergranular pores. The rock has a strong petroliferous odour, is entirely oil stained, displays yellow ultraviolet fluorescence and is oil productive.

On a geophysical log, the upper unit is too thin for identification because its signature is lost in the high gamma-ray response of the overlying Lower Member of the Bakken Formation (Figure 24). On the other hand, the lower unit, with its 10 m thickness, dominates the log response by its blocky, clean, low gamma-ray signature. Although the contact with the Torquay Formation is not seen in this core, the log indicates it to be sharp by the abrupt increase in gamma-ray reading at the top of a typical Torquay expression. A similar gamma log signature is seen in a well farther south in 16-35-2-24W1, where a 26 m thick sandstone is indicated (Figure 24). LeFever et al.

(1991b) and Nicolas (2008a) suggested that this body is correlative with the Sanish sandstone of North Dakota. Nordeng et al. (2010) and LeFever and Nordeng (2010) suggested that it may be a basal Bakken unit referred to as the 'Bakken silt', due to its conformable nature with the Lower Bakken Member shale. Recent work by LeFever et al. (2012) and LeFever and Nordeng (2012) has named this 'Bakken silt' the Pronghorn Member of the Bakken Formation and discontinued the use of the term 'Sanish sandstone'. LeFever et al. (2012) correlated the Pronghorn Member with the Big Valley Formation in Saskatchewan (Nickel and Lake, 2010).

Both occurrences of the Big Valley Formation in Manitoba are related to localized salt-collapse structures (Figure 25), where collapse occurred during and immediately after deposition of the Big Valley. All three members of the Bakken Formation are present at these locations. Given that the Big Valley in 11-29W1 is a good reservoir, it would make a good target elsewhere; however, its presence is random and difficult to predict. Areas of known localized salt-collapse structures are the most prospective. In the event that the Lower Bakken Member is not preserved, the Big Valley can be mistaken on geophysical logs for either unit 4 of the Torquay or a blocky sand of the Middle Bakken Member, and can only be confirmed in core.

Bakken Formation

The Bakken Formation comprises Upper and Lower members of black to brownish-black organic shale, and a Middle Member of siltstone and sandstone. The Bakken conformably underlies the Mississippian Lodgepole Formation and is continuously distributed throughout the entire Torquay Formation area, with the exception of a narrow strip near the Torquay subcrop edge.

Lower Member

The Lower Member is a black, noncalcareous, siliceous, radioactive, massive, blocky to fissile organic shale with occasional disseminated pyrite that once blanketed the Torquay Formation throughout the basin (Figure 26). However, extensive erosion at the end of the Devonian, prior to deposition of the Middle Member, has left only outliers in Manitoba. Thus, the member is regionally absent in Manitoba and eastern Saskatchewan but for a few small anomalous sites where it is preserved locally in salt-collapse sinkholes attributed to the dissolution of salt beds in the Devonian Prairie Evaporite. The Lower Member has been identified in a few wells in Manitoba, most of which are located in and adjacent to the Waskada Field in Twp. 1 and 2 and Rge. 25 and 26W1. It has also been identified farther north, in Twp. 11 Rge. 29W1 (Figure 25). Thickness of the Lower Member attenuates to less than 1 m, making it difficult to recognize on logs; a core is required to confirm its presence. The Lower Member has sharp, erosional upper and lower contacts.

Middle Member

The Middle Member extends throughout southwestern Manitoba, right up to the Bakken Formation subcrop edge (Figure 27), and disconformably overlies the Torquay Formation where the Lower Member is absent and likewise the Lower Member where the latter is present. It consists of light to dark grey, bioturbated, laminated, wavy-bedded, noncalcareous, quartz-rich siltstone and porous sandstone, and is variegated purple and green at a few localities (Figure 27). Purple colouration decreases with depth and disappears in lithofacies units 1 and 2. It indicates the passage of post–Middle Bakken oxidizing fluids.

The thickness of the Middle Member is variable throughout Manitoba (Figure 27) and, where thin, can be difficult to pick on logs without a core for reference. In fact, the Middle Member is less than 1 m thick at many localities and may even be completely absent in places. The core report from the well in 14-24-1-25W1 indicates the absence of the Middle Member there, and no Bakken picks can be made in four wells within the Hartney Structure. Another example is in 5-8-4-29W1, where a questionable Middle Member designation is given to an erosional lag less than 10 cm thick. In contrast, the Middle Member is anomalously thick in rare cores from the Daly Sinclair Field.

LeFever et al. (1991b) identified and described seven lithofacies of the Middle Member in North Dakota, Manitoba and Saskatchewan. In Manitoba, which is situated on the northeastern rim of the Williston Basin, only two are present. These are each subdivided into two sublithofacies and are herein grouped as lithofacies unit 1–2 and lithofacies unit 3–4 (as described below). The lithostratigraphic subdivisions and facies assemblages of the Bakken Formation by various authors are depicted in Figure 28.

Lithofacies unit 1–2

Lithofacies unit 1–2 is the same as Manitoba lithofacies units 1 and 2 of LeFever et al. (1991b), unit B2 of Kreis and Costa (2006) and ichnofacies 3B, 6, 7 and 8 of Angulo and Buatois (2010). For the purposes of this study, these units are combined in the core descriptions although displayed separately in Figure 29. Lithofacies unit 1–2 consists of a medium to dark grey to medium brown, very fine to fine-grained sandstone that is noncalcareous, quartz rich and finely laminated to wavy bedded, with occasional disseminated pyrite. Medium- to coarse-grained sandstone lenses increase in abundance with depth, especially in the lower part of the unit. Occasional high-angle planar crossbedding is present. Porosity averages 15% and is microporous and intergranular, with rare small vugs. This unit incorporates the best reservoir of the Middle Member and is commonly patchy to continuously oil stained. North of Township 16, the sandstone lenses become coarser grained and more prominent, and increase in porosity and permeability. The basal contact is sharp. LeFever et al. (1991b) distinguished lithofacies unit 1 from unit 2 on the basis that unit 1 is wavy bedded with coarser grained sandstone lenses and unit 2 is more interbedded, parallel laminated to wavy bedded or slightly undulatory.

Lithofacies unit 3–4

Lithofacies unit 3–4 is the combined Manitoba lithofacies units 3 and 4 of LeFever et al. (1991b), and ichnofacies 3B of Angulo and Buatois (2010; Figure 28). The two units are displayed in Figure 30. Lithofacies unit 3–4 consists of massive to interbedded, noncalcareous, quartz-rich, mottled and highly bioturbated, occasionally massive, argillaceous, dark grey siltstone to very fine grained sandstone. The trace fossil *Nereites missouriensis* is common and seen as thin black wispy lenses throughout; brachiopods occur occasionally as rare thin coquina beds but more commonly scattered throughout (Figure 30c). The rare thin coquina beds may be correlative to ichnofacies 10 of Angulo and Buatois (2010). Occasional, thin, very fine grained sandstone laminae and beds are present, the latter being commonly crossbedded and ripple marked. Porosity in this unit averages 10% and it is lower in permeability than unit 1–2. Accordingly, patchy light oil staining is common. The contact with unit 1–2 is gradational, but that with the Upper Member is sharp, erosional and occasionally lined with very fine grained pyrite crystals. LeFever et al. (1991b) distinguished lithofacies unit 3 from unit 4 based on unit 3 being dominantly interbedded and unit 4 being more massive and highly bioturbated.

Upper Member

The Upper Member, like the Lower Member, consists of black to brownish-black, noncalcareous, siliceous, highly radioactive, moderately hard, massive, blocky to fissile organic shale with occasional disseminated pyrite and conodont fragments (Figure 31a). It is present throughout the study area. Extensive oxidation of the shale to a dark purple (Figure 31b) occurs in the same wells that exhibit purple colours in the Middle Member, and is most common in Rge. 28W1 north of Twp. 9, and in Twp. 11 and 12, Rge. 26W1, especially in the eastern half of the Daly Sinclair Field. Alteration of the shale to a grey-green is less common but occurs randomly north of Twp. 16 (Figure 31c).

The Upper Member is an excellent geophysical log marker and is easily picked due to its high gamma-ray readings in comparison to the sandstone below and the carbonate above. In localities of thicker sections, some geophysical logs show an unusually high gamma-ray count with correlative low density and high resistivity excursions. Geochemical analysis of the petrophysically 'hot' shale suggests that, compared to more 'normal' shale, it is richer in organic matter, with total organic carbon values of up to 24.1 wt. % (Nicolas and Barchyn, 2008), reflecting high uranium levels. Despite the high organic content, the Upper Member is thermally immature and is not a source rock in this part of the basin. The deeper parts of the basin are where thermal maturity is attained.

Isopach, structure and tectonics

The structure-contour and isopach maps for the Middle and Upper members of the Bakken Formation and the Torquay Formation are shown in Figures 27 and 32–36. The structure maps all display a general southwesterly dip toward the basin centre in North Dakota.

The structure contours of the Upper and Middle members of the Bakken Formation generally mimic each other (Figures 32 and 34), except at a few locations where the Middle Member fills in paleotopographic lows on the Devonian erosional surface. The most dramatic structural differences occur where there has been post-Bakken subsidence. These anomalies are reflected on the isopach maps by thickening (Figures 27 and 33). The isopach of the Upper Member does not show much variability, ranging from less than 0.5 to 16 m in thickness, and averaging 2–3 m in thickness. Anomalous thickening occurs in areas attributed to salt collapse (Figure 33). The unit thins toward its subcrop edge to the northeast.

In contrast, the Middle Member shows significant variability in isopach values (Figure 27). It thins dramatically in the Daly Sinclair Field, ranging from 9 m to less than 10 cm. In core, the Middle Member is often less than 1 m thick and its presence at some sites is questionable. Thus, in 5-8-4-29W1, the Middle Member is represented by an erosional lag less than 10 cm thick. Without core, it is difficult to identify the Middle Member on logs where it is less than 1 m thick. Its absence in a core in 14-24-1-25W1 indicates similar ambiguities in other locations. These attenuations are likely due to erosion. The greatest isopach values are local, where salt dissolution of the Devonian Prairie Evaporite below caused sub-Bakken penecontemporaneous collapse (e.g., 9-34-7-29W1 and 16-8-8-28W1). Elsewhere, thickening of the Middle Bakken may represent infill of depressions on the Torquay erosional surface. These depressions consist of repetitive, fining-upward, planar-laminated to wavy-bedded, medium grey to light brown sandstone that grades to a coarse, porous sandstone in places, similar to but with differences from lithofacies unit 1–2 of LeFever et al. (1991b), and similar to ichnofacies 6, 7 and 8 of Angulo et al. (2008) and Angulo and Buatois (2009, 2010).

Identification of the attenuated Middle Member on wells logs is difficult with respect to the underlying Torquay Formation, particularly in the Daly Sinclair area (Figure 9). The 'photoelectric effect' (PE) curve is useful in this regard due to the contrast between the high silica content of the Middle Member and the high dolomite content of the Torquay Formation (Figure 10). As a general rule in the Daly Sinclair area, a thickness of 0.5 m is assumed where the Middle Member is too attenuated to distinguish. Although this method is not ideal, extensive core and log correlations done by the author suggest that the Middle Member is present everywhere in this area as a thin veneer on the Torquay surface. This assumption is reflected in the Middle Member isopach map (Figure 27).

In contrast to the Bakken Formation, the Torquay generally thickens westward to its maximum along Rge. 29W1 and irregularly southward from Twp. 20 to the Canada–United States border (Figure 36). Maximum thickness is 63 m in 16-35-2-24W1. The formation thins eastward by truncation, as seen by the steepened isopach gradient and the unit subcrop edges at the pre-Mississippian erosional surface. Units 3 and 4 end between Rge. 28W1 and 29W1. To the east, unit 2 emerges at the unconformity where the isopachs range between 18 and 22 m to form a flat roughly between Rge. 25 and 27W1, before gradually thinning to the subcrop edge. Outliers of units 3 and 4 are preserved in wells to the east in Rge. 24W1 and 25W1 (e.g., 7-25-7-24W1 and 9-21-5-25W1). Anomalous thicknesses of the Torquay Formation also occur in the Virden Field and are attributed to the multiple-stage salt dissolution in the underlying Devonian Prairie Formation (Martiniuk, 1988) associated with the BWZ.

Features apparent on the structure-contour maps of the Torquay and Bakken formations are synclinal flexures along the east edge of the Daly Sinclair Field and southward into Twp. 4.

A pronounced structural high occurs in the southern half of the Daly Sinclair Field, with a moderately steep slope on the southern and eastern ends of the field (Figure 37). This structural knob, referred to herein as the 'Sinclair high', is present at the levels of the Birdbear, Torquay, Bakken and Mississippian formations. Structural data below the Birdbear are lacking. It is suspected that this feature continues at a minimum to the base of the Dawson Bay Formation, because the latter overlies the Prairie Evaporite nearby, where the salt edge of this formation is still extant. At a maximum, it could extend through the Paleozoic sequences as a Precambrian basement fault or tectonic flexure on the southern extension of the SBZ. The subcrop edges of Torquay units 3 and 4 are coincident with the synclinal flexure east of the Daly Sinclair Field. In addition, the area located between the steep truncation of units 3 and 4 and the isopach flat of unit 2 coincides with the BWZ. (Figure 4).

Localized structural anomalies in the vicinity of Twp. 5, Rge. 24W1 are related to the Hartney Structure (Sawatzky, 1975; Anderson, 1980). This feature is late Jurassic to early Cretaceous in age and has affected all formations below the Swan River Formation.

A structural low on the structure-contour maps of the Bakken and Torquay formations is present on the north edge of the Daly Sinclair Field, around the township line between Rge. 28 and 29W1 in Twp. 11. This feature is present at the Birdbear horizon but is lost at the top of the Lodgepole Formation. In this area, an erosional remnant of the Big Valley Formation is preserved.

The isopach map of the Triassic Amaranth Formation, Lower (Red Beds) Member depicts inversely topographic relief on the Paleozoic unconformity surface (Figure 6). The clastic Lower (Red Beds) Member blankets the Paleozoic erosional surface and represents a fill of structural and paleotopographic lows, similar to the Middle Bakken member on the Devonian unconformity surface. Thus, the Amaranth infill, by levelling of the underlying terrain, masks most structural features dominant during the Paleozoic, as shown by the structure-contour map of the Amaranth Formation (Figure 38). The member is thinnest over the Paleozoic structural highs, and the sites of thickening coincide with increased sand deposition. The Waskada and Pierson fields produce oil from the latter (Figure 1).

The Devonian strata have had many structural effects imposed on them, most of which are the result of dissolution of the Prairie Evaporite and the tectonic effects of the SBZ. At the end of the Devonian, there was a major tectonic shift from the Elk Point Basin to the Mississippian Williston Basin as the dominant centre of deposition (McCabe, 1967). This tectonic shift would have had its effects exaggerated at the SBZ due to the compositional and structural differences between the Precambrian Churchill Province and the Superior Province. The Superior crustal block was the more active during these times, resulting in subsidence and uplift. Uplift of this crustal block was more pronounced during times of erosion (McCabe, 1967), such as that at the end of the Devonian. Such uplift would, in turn, affect the hydrodynamics of the basin, inviting more fresh water into the deeper parts to dissolve the salts of the Prairie Evaporite. Early Bakken time, which straddles the Devonian–Mississippian boundary, is well known for having many salt-collapse events throughout southwestern Manitoba. The effects this tectonic change would have had on pre-Birdbear strata is difficult to ascertain, since there is currently insufficient deep well control.

Dietrich et al. (1998) identified several faults along a seismic transect from southeastern Saskatchewan to southwestern Manitoba, one of which coincides with the preservation and subcrop edge of unit 4 of the Torquay Formation in Rge. 28W1, and referred to in Nicolas (2007) as the Sinclair Fault and its offset fault. The offset fault is a southern en échelon extension of the Sinclair Fault. The transect also intercepted a fault trending roughly north in Rge. 25W1, which coincides with the trend and location of the wells identified in logs in which unit 4 is preserved. Dietrich et al. (1998) extrapolated this eastern fault to the Precambrian basement. In contrast, they interpreted the deepest penetration of the Sinclair Fault and its offset fault to be just above the remnant salt of the Prairie Evaporite and not the Precambrian basement. However, the coincidence of location and trend of these faults with the eastern margin of the BWZ suggests that reactivation of basement faults should not be dismissed.

Structural evaluations of some of the isolated Torquay unit 4 preservations support a salt-collapse model, wherein compensatory strata were deposited in space created as salt dissolution occurred. This can be explained by the salt-budget model, whereby the amount of salt dissolved during the deposition of overlying strata will result in that amount of sediment filling in the collapse (Halabura and Potter, 2000). Upon burial, the compensatory sediment then appears as a thickening of the strata. For example, in 7-25-7-24W1, there are approximately 20 m of extra strata within the Three Forks Group and Lodgepole Formation, which make up 66% of the approximately 30 m of missing Prairie Evaporite (Figure 39). At this location, the Three Forks Group is seen as a structural high. Other such sites of local thickening support the block-faulting model, where up to 20 m of structural displacement is seen between closely spaced wells. The occurrence of both block faulting and salt dissolution/collapse along the same fault zone would be expected, since the fractures would act as fluid conduits for preferential dissolution of the Devonian salts. This is shown in Figure 40, in which extra Torquay section is preserved in 9-21-8-25W1 but not in 12-22-5-25W1, both wells being low compared to the regional structural trend.

An overview of the structural, isopach and erosional trends on the Torquay Formation suggests that tectonic overprints played an important role in shaping this formation to its current configuration. A compilation of seismically identified faults, along with suggested extrapolations of those faults, and lineaments mapped by compiling structural and erosional trends is shown in Figure 41. This map shows four dominant groups of lineaments. Many of these lineaments are also present in overlying and underlying formations, suggesting that tectonism may be the cause of some of them and that they likely represent fracture sets. For example, a northeast-oriented lineament drawn diagonally through Twp. 1–3, Rge. 23–25W1 is adjacent to four key wells. The first, in 14-24-1-25W1, shows high-angle bedding juxtaposed with low-angle (25°) bedding in Torquay unit 2, and an anhydrite-annealed vertical fracture that reveals vertical movement by the preservation of black shale between fractures. The second well, in 16-35-2-24W1, is one of the locations where the Big Valley Formation is preserved; in addition, it penetrates the thickest Torquay body in the study area, thereby suggesting either salt collapse or block faulting. The third and fourth wells are paired in 8-31-2-23W1, where all of the Paleozoic formations are offset with respect to each other to indicate basement fault movement between these wells. Likewise, the alignment of the outliers of Torquay unit 4 in the east indicates fault control. The northwest- and northeast-trending lineaments may represent a southwesterly extrapolation of bedrock fracture patterns mapped in the Paleozoic bedrock surface by McRitchie (1997). These dominant fracture sets are indicative of the current stress regime in this part of the Williston Basin (Kendall, 2008).

The set of lineaments trending north and east may be orthogonal fracture sets that are reflecting stresses on the SBZ, which trends north in this area (Figure 4). McRitchie (1997) interpreted this trend in the Interlake region to be the dominant fracture pattern over the SBZ.

Depositional environment

Previous work

The depositional environment of the Torquay Formation has received little attention in the past. The first significant attempt was by Christopher (1961), who attributed the oxidation and brecciation of the units to regional intraformational weathering processes and the development of soil horizons. He provided little insight into the depositional environment of the units, but focused mostly on the sedimentation process as transitional to marine in an arid climate, either far away from an active land source for sediments or a land of very low relief. Christopher's (1961) discussion on the sedimentation process of the Torquay mostly fits with the description of the depositional model described herein, but there are some notable exceptions, particularly regarding the origin of brecciation.

Karasinski (2006) developed a depositional model based on his work in the area of the Daly Sinclair Field. His interpretation was that the Torquay was deposited along a prograding, temperate, carbonate tidal flat that graded basinward toward an unrimmed carbonate platform, with sporadic, subaqueous debris-flow conglomerates. Parts of Karasinski's (2006) model fit with the model described herein, but again there are some significant differences. The present author does not concur with the debris-flow theory, but attributes the brecciation ('conglomerates') to an in situ process resulting from a barrier-island–rimmed platform.

Torquay Formation deposition

Eustatic changes

The Devonian is subdivided into five rock sequences bounded by discontinuities, each sequence representing a transgression followed by a period of regression (Moore, 1988). The Torquay Formation occurs near the end of the last sequence (the Palliser sequence), with the Lower Bakken marking the end of the sequence (Moore, 1988). Within the Palliser sequence, the Torquay represents a mini-regression before the final maximum flooding event that is marked by deposition of the Bakken Formation (Figure 42; Johnson et al., 1985; Moore, 1988). During this mini–regressive event, there were three transgressive pulses (Johnson et al., 1985), recorded in subunits 1c, 2c and 4c of the Torquay. In contrast, during this mini-regression, there were two pulses with further regression and exposure, represented by subunit 2a and unit 3, with the latter being the most widespread and prolonged of these events. Up to 11 regressive breaks are recorded in the Johnson et al. (1985) sea-level curve for the Famennian. Sea-level fluctuations during the Famennian are thought to have been the result of glaciation in the southern hemisphere (Johnson et al., 1985), but the more significant regressive and transgressive events may also be attributed to tectonic events within the basin, such as movement along the SBZ (McCabe, 1967) and uplift along the Severn and Transcontinental arches.

Sedimentary model

The deposition of the Three Forks Group marks a shift in the depositional environment from the dominantly carbonate chemical sedimentation of the Birdbear Formation and underlying Devonian strata to siliceous and carbonate clastic sedimentation of the Three Forks Group. Deposition of the latter occurred on a very gentle, westerly sloping coastal shelf of an epicontinental sea, forming a long clastic wedge that thins from west to east (Christopher, 1961).

There is no modern analogue for the depositional setting preserved in the Torquay Formation. The depositional environment is best described as a giant evaporitic mudflat platform (Figure 43). The challenge lies in the large scale needed for deposition of the areally extensive evaporitic deposits. The closest modern model is a sabkha (Kendall, 1992), but on a giant basin-wide scale. The eastern edge of the basin (southwestern Manitoba and eastern Saskatchewan) best fits the model of an evaporitic mudflat on an epeiric shelf described in Warren (2006). Due to proximity to the basin edge, the depositional setting may have, at times, graded to continental evaporites. The arid climate at the end of the Devonian, combined with tectonism and sea-level fluctuations, provided the right conditions for deposition of the evaporitic, oscillatory sedimentary cycles.

At the base of the sequence, the regressive Birdbear shallowing-upward sequence, topped by anhydritic carbonate beds, and the basal Torquay dolostone beds, intermixed with carbonate clastic sedimentary rocks, record the transition from a marine-carbonate platform shelf to marine-evaporite platform. This is evidenced by the massive dolostone beds with anhydrite nodules preserved at base of the Torquay unit 1. Up-section, the dominant rock type shifts to carbonate clastic rocks, mostly dolomitic siltstone, mudstone and claystone.

The thin sequences of interbedded siltstone and claystone that dominate unit 1 and subunit 2b represent periodic flooding and desiccation cycles. Oxidized mudstone units, such as subunit 2a and unit 3, represent times of low sediment supply and exposure, resulting in extensive oxidation of the sediment and destruction of most of the primary sedimentary fabric and structures by haloturbation[1] and weathering. After a brief sediment influx that formed the siltstone of subunit 2c, unit 3 represents a long period of exposure throughout the basin due to its areally extensive distribution (Christopher, 1961), with periodic flooding/storm events to contribute some sediment, in an otherwise sediment-deprived environment. Oxidation of this unit was further affected by groundwater, resulting in the occasional occurrence of grey-green redox haloes. These haloes are most commonly found along fractures and around siltstone clasts, which acted as preferential conduits for reducing fluids. Christopher (1961) attributed this unit to weathering and the development of early soil profiles.

Following the deposition and weathering of unit 3, the platform was subjected to periodic flooding that created large salt pans or salinas, leading to the deposition of subunit 4b. Subunit 4b is the thickest continuous section of haloturbated sediment in the Torquay Formation of Manitoba and southeastern Saskatchewan. This deposition was interrupted by storm events that provided argillaceous and silty sediment from upwelling seas and periods of eolian sediment deposition. Evaporitic minerals were not preserved due to dissolution by storm-driven floods and groundwater movement after burial (Kendall, 1992). Haloturbation caused the intraformational brecciation of the siltstone beds into fragments floating within a claystone to mudstone matrix, which are characteristic of subunit 4b. Similar bedding structure and brecciation have been attributed to evaporitic environments, such as those discussed in Kendall (1992) and Warren (2006).

In late Torquay time, evaporitic conditions lessened in the east, resulting in the deposition and preservation (i.e., with minimal haloturbation effects) of the subunit 4c siltstone-dominated beds. This subunit, like subunit 2c, represents a shallow, gently sloping shoal with intermittent storm events, as indicated by the commonly recurring gently sloping laminations, cross-stratification and ripple marks, and occasional argillaceous laminae and rip-up clasts.

Although not preserved in Manitoba, Christopher's (1961) units 5 and 6 represent another short cycle of regression, with the deposition of evaporitic beds (unit 5) followed by a transgression over the platform (unit 6).

Post-Torquay erosion

Selective preservation of Torquay units, and the Big Valley and Bakken formations in salt-collapse structures, indicates that there were significant erosional events after the deposition of the Torquay and Big Valley formations, and of each of the Bakken members, with the most extensive after deposition of the Lower Member.

Post-Torquay regression resulted in subaerial exposure of the platform and erosion of the Torquay beds. At this time, active movement along the SBZ in southwestern Manitoba (McCabe, 1967) caused uplift relative to the rest of the basin. Although most of the movement is recorded as being part of the BWZ, the entire length and width of the SBZ would have been active. Part of the eastern boundary of the SBZ is characterized by basement faults that penetrate the Paleozoic sequence (Dietrich et al., 1999) as strike-slip en échelon faults. These permitted the entry of fresh water into the sedimentary basin and thus effectively accelerated dissolution in the Prairie Evaporite. Subsidence in salt-collapse structures along this fault zone preserved from erosion a thicker section of Torquay east of the main body. Thus, the presence of units 3 and 4 in this fault zone indicates an erosional limit to the Torquay Formation. Further support for SBZ uplift and erosion is the similar alignment (north-south) of the unit edges versus the northwest-southeast depositional orientation of the basin in southwestern Manitoba. The erosional edge of unit 2 roughly corresponds to the eastern edge of the SBZ, even as the mass of the unit spread with little variation in thickness over most of the width of the SBZ.

Local bodies of units 3 and 4 on a northwest trend from the Virden Field to the Birdtail Field indicate the presence of another fault/fracture system perpendicular to the SBZ. Likewise, similar dissolution of the Prairie salt beds along this system could be invoked to account for their preservation.

The absence of Christopher's (1961) units 5 and 6 anywhere in Manitoba, even in the salt-collapse structures where the Lower Bakken Member is preserved, suggests that the units were offlapping toward the west by this time and were likely not deposited in Manitoba. This may have been due to uplift along the SBZ or a retrograding shoreline, forcing any new deposition westward. During the deposition of units 5 and 6, erosion was likely occurring in the east.

Big Valley Formation deposition

After the deposition and partial erosion of the Torquay, a significant transgressive event led to the deposition of the Big Valley Formation. In south-central Saskatchewan, the Big Valley is characterized as a green silty shale (Christopher, 1961). Recent work by Nickel and Lake (2010) suggests that the Big Valley is not only a silty shale but, in the eastern parts of Saskatchewan, it fines upward from a highly bioturbated siltstone sitting disconformably on the Torquay into the more characteristic green silty shale that is in contact with the Lower Bakken Member black shale, indicating continued deposition. However, farther eastward toward and into Manitoba, this contact is erosional (Nickel, pers. comm., 2011).

The presence of an erosional upper contact with the Lower Bakken and an intraformational erosional conglomeratic bed between the shaly siltstone and bioturbated siltstone bed indicate that this sedimentary package was deposited along the rim of the basin, where sediments are more susceptible to sea-level fluctuations and subaerial exposure. This unit between the Torquay and Bakken is interpreted to be the eastern, coarser grained facies of the Big Valley Formation in Saskatchewan, likely representing a shoreline-beach environment.

The deposition of the Big Valley Formation sandstone and siltstone followed the erosion of the Torquay, with the coastline advancing farther east and south as sea level rose. The Big Valley sedimentary rocks, by their extensive bioturbation, represent nearshore deposits, probably below wave base. This formation

[1] brecciation caused by repetitive growth and dissolution of evaporitic minerals

undergoes a facies change from Manitoba westward into Saskatchewan, from silty shale to shale, indicative of deeper water deposition.

Bakken Formation deposition

Deposition of the Bakken Formation indicates a significant sea-level rise. Generally, the Lower and Upper black shales were deposited in an offshore deep-marine environment, and the Middle Member is indicative of a temporary regression, allowing the deposition of shelf, nearshore to shoreline, and some channel sediments.

Deposition of the Lower Bakken Member was immediately followed by regression that exposed and extensively eroded the Lower Bakken and Big Valley shales, resulting in their preservation in Manitoba only as outliers in salt-collapse sinks. This erosive event formed a low-rising paleotopography that, under advancement of the sea from the west, became a shelf for Middle Bakken sandstone onlap. Thus, the uppermost sequence, unit C of Kohlruss and Nickel (2009), is broadly distributed across Manitoba where the lower units filled in paleotopographic lows.

Extensive salt-collapse depressions created greater accommodation for thicker Middle Bakken sand, such as in the northeastern quarter of the Daly Sinclair Field (centred around Twp. 9–10, Rge. 28W1), whereas paleotopographic highs permitted deposition of only a thin veneer of sand, such as in the south-central part of the Daly Sinclair Field (Twp. 8, Rge. 29W1). In Twp. 4, Rge. 29W1, the sandstone is less than 10 cm thick and is seen in core more as an erosional lag than the usual sandstone beds. Generally, the Middle Bakken Member thickens and coarsens northward; north of Twp. 16, it thickens to 8 m in places, with dominant coarser grained sandstone lenses, laminae and beds. These bodies are on the eastern extension of the Rocanville-Torquay trend (Christopher, 1961; Kohlruss and Nickel, 2009). Christopher (1961) characterized the Rocanville-Torquay trend as a band of northeasterly aligned furrows in which the Torquay beds are downwarped. The coarser sand bodies may represent channel deposits.

Renewed transgression led to deposition of the Upper Bakken Member black shale in deep-water normal-marine conditions ((Nicolas, 2008b), to end the clastic depositional cycles of the Three Forks Group. Shallowing seas accompanied a return to carbonate slope-shelf conditions of the Mississippian Madison Group.

Burial and diagenesis

Upon shallow burial, groundwater movement through the Torquay sequence resulted in partial to complete oxidation of the sequence. Units 1–3 were subjected to redox conditions from groundwater for extended periods of exposure, and so were oxidized to red-brown. Beds rich in shale and pyrite, such as unit 3, were particularly susceptible due to the lack of included neutralizing carbonate. Unit 4 (and 5 and 6 in Saskatchewan) were less affected by oxidation, with a small amount in subunits 4a and 4b in a few localities. Evaporitic deposits would have been dissolved away, particularly in units that were subaerially exposed for long periods, as would be expected toward the rim of the basin. Westward into the basin, more macroscopic anhydrite and microscopic halite (Karasinski, 2006) were preserved.

Christopher (1961) indicated that exposure of the upper Torquay sedimentary rocks at the unconformity to the reducing conditions of the Bakken basin may have played a role in the upper units being reduced to the ferrous light brown and grey-green rather than oxidized to the ferric rusty- to red-brown. In this case, there is a reduction halo beneath the Bakken that deepens as the Bakken thickens. This observation has some validity in that the usually red-brown unit 3 is grey-green where it is in contact with the Bakken Formation because unit 4 is very thin or completely eroded. Redox haloes preserved in the core are evidence of this effect. An increase in porosity and permeability recorded in the core analyses of the affected units at the unconformity surface within the Daly Sinclair Field lends support to the phenomenon as a significant diagenetic effect, attributed to reducing fluids percolating down from the Bakken sedimentary rocks.

The Upper Bakken Member shale occasionally displays a maroon to deep purple, instead of its usual black. This same discolouration is also common but not always present in the underlying Middle Bakken Member, and grades upward over a short distance into the overlying Lodgepole Formation. The locations of cores with these colours are concentrated in a north-trending region that extends from approximately Twp. 9, Rge. 27–28W1 to Twp. 17, Rge. 27–28W1, including a well in Twp. 11, Rge. 26W1. The cause of this oxidation is uncertain; however, in Saskatchewan, Lower Amaranth–age waters seeping through Lodgepole joints oxidized the Bakken locally (Christopher, 1961). This same mechanism may have occurred in Manitoba. An in-depth analysis of the diagenetic changes that occurred in the affected units compared to unaffected units nearby would be useful to better understand the conditions that make this trend unique.

Karasinski's (2006) examination of the diagenetic history of the Torquay Formation and Middle Bakken Member in the Daly Sinclair Field area concluded that it was complex and included dolomitization; phosphate, pyrite, halite, hematite, silicate and anhydrite precipitation; and dissolution and fracture-porosity development (Karasinski, 2006). Figure 44 shows his paragenetic sequence for the Torquay Formation and Middle Bakken Member.

Hydrocarbon-play development and exploration

The Bakken Formation has been productive in the northern part of the Daly Sinclair Field since 1986. In 2003, oil was discovered in the Torquay Formation in the southern part of the field (Figure 45). Production from the Bakken and Torquay formations is commingled in the Daly Sinclair, Kirkella, Birdtail and Manson fields, and in other smaller outlying pools (Figure 46). Exploration outside these fields has been focused north of the Birdtail Field in Twp. 16–17, Rge. 27–28W1 and south and east of the Tilston Field. Within the fields, commingled Bakken-Torquay oil reserves were first exploited through vertical wells and then by extensive horizontal-well development.

From the southern end of the Daly Sinclair Field, exploration has moved to the north-trending isopach thick of the Torquay unit 4. Torquay unit 2 has also been targeted and developed east of the unit 4 subcrop edge, where subunit 2b underlies moderately thick Middle Bakken sandstone and where subunit 2c has been minimally affected by redox reactions. North of Twp. 16, the Middle Bakken thickens and changes to a coarse-grained sandstone, with excellent reservoir potential. It displays porosity of up to 20% in lenses and beds, and is commonly oil stained. The area represents the northeastern continuation of the Rocanville-Torquay trend (Figure 4; Christopher, 1961) and the Rocanville oil-field trend of Kohlruss and Nickel (2009) in eastern Saskatchewan.

Exploration efforts could be directed northward and eastward of the Daly Sinclair Field within Torquay unit 2 and possibly unit 1, where good potential exists in the Virden Field. Log signatures of unit 1 look promising west of the unit 2 subcrop edge, but little core from this unit is available for correlation with the log signatures. Possible targets may be along the north trend parallel to the eastern limit of the BWZ, in Rge. 241 and 25W1, where unit 4 is preserved locally. Oil staining has been reported in the core from 12-22-5-25W1. Structural traps related to the compensatory thickening of the Three Forks Group and Lodgepole Formation in the areas with localized preservation of unit 4 are also potential targets. A potential subcrop play may be present in unit 1 along the Birdbear-Lodgepole escarpment (Figure 5).

Daly Sinclair Field reservoir and production history

The Sinclair Field was officially designated on January 1, 2005. The discovery well is located in 3-6-7-29W1. In 2010, the Daly and Sinclair fields were amalgamated as the Daly Sinclair Field, which covers more than eight townships. As of December 31, 2011, the Daly Sinclair Field had a cumulative Bakken and Torquay production of 5.4 x 10^6 m^3 (34 x 10^6 bbl), representing 45% of Manitoba's total production for 2011.

The 01 62B Bakken-Torquay B pool is the largest of the Bakken-Torquay pools in the Daly Sinclair Field and supplies more than 80% of cumulative Bakken and Bakken–Three Forks oil in the province (Figure 46). Development of the 01 62B pool is still ongoing, mostly with horizontal wells, and its growth was enhanced by the amalgamation of smaller pools on its periphery. Enhanced-oil-recovery operations have led to the development of several oil units, including one pilot CO_2-injection operation. The CO_2-injection enhanced-oil-recovery project is being conducted in Sinclair Unit No. 1 in Twp. 8, Rge. 29W1.

Fox (pers. comm., 2012) conducted a review of waterflood applications in Twp. 7 and 8, Rge. 28 and 29W1, in the southern portion of the Daly Sinclair Field. The average original oil-in-place (OOIP) for the nine waterflood units approved in this portion of the field is 742 821 m^3/section. Estimated primary recovery ranges from 8.0 to 18.8% OOIP, and predicted secondary recovery under waterflooding from 15.6 to 27.0% OOIP. Table 1 summarizes the typical reservoir rock and fluid properties for the nine units.

In the 01 62B pool, 229 wells were cored through the Bakken-Torquay interval, and all cores were analyzed. The core analyses of 223 wells were filtered, sorted and averaged according to their respective Torquay unit and Bakken member. The compiled porosity and permeability results are presented in Figures 47 and 48. Observations can be made on the predictability of porosity and permeability, and their relation to lithology. For the Middle Bakken Member, the slope is slightly lower than for Torquay units 2 and 4, and the data points are scattered; these trends agree with the tight siltstone lithology of lithofacies 3–4 in this part of the field, where it is very thin and often lacks the coarse to medium sandstone beds and lenses of lithofacies 1–2. For unit 4, the data points are clustered tighter than for the other units, likely due to the lithological consistency of the siltstone in subunit 4c; the variability in the siltstone:shale ratio in the breccia of subunit 4b causes the data points to scatter, resulting in variable and less predictable porosity and permeability values. Torquay unit 3 has the lowest intercept due to the extensive oxidation that has resulted in occluded pores and reduced permeability. Torquay unit 2 data points are widely scattered, mostly due to the sporadic oxidation affects imposed on this unit, although subunit 2c, when unoxidized, provides porosity and permeability results similar to those in unit 4. There was insufficient core-analysis data available for unit 1 to draw any observations.

Table 1: Typical Bakken-Torquay reservoir rock and fluid properties for the nine waterflood units.

Parameter	Value
Formation pressure	9500 kPa
Formation temperature	30–35°C
Gas:oil ratio (GOR)	6–10 m^3/m^3
Oil gravity	40–41 API
Initial water saturation	40–45%
Average permeability	0.97–8.12 mD
Average porosity	11.5–17.6%

Examination of Figure 48 shows that the best porosity and permeability in unit 4 occur where subunit 4c is at the unconformity. Where the lower part of subunit 4b is subjacent to the unconformity, porosity and permeability decrease. Unit 3 porosity and permeability are good only in proximity to the unconformity. Also, unit 2 porosity and permeability are highest where subunit 2c is completely preserved beneath unit 3 at the unconformity. The latter unit provided a protective cover for the thin, but porous and permeable, subunit 2c during the post-Torquay erosive events. In the absence of unit 3, subunit 2b, which is less porous and permeable than subunit 2c, is subjacent to the unconformity. The reservoir quality of subunit 2b decreases rapidly with depth below the Bakken contact. Where the Torquay is eroded down to subunit 2b, the Middle Bakken Member sandstone becomes the dominant reservoir, as is the case in the Birdtail Field.

The fact that the porosity and permeability of the Torquay units are highest at the unconformity indicates that sub-Bakken diagenetic effects play an important role in Torquay reservoir development. Core-analysis data are unavailable for subunit 2a and available only for one core in unit 1, making it difficult to ascertain whether or not these units would also be productive at the unconformity farther to the east. In contrast, oil production has been obtained from unit 1 in the Daly Sinclair Field at two locations, but no further development of these pools has been attempted. The siltstone beds at the top of unit 1 are thin and often partly to completely oxidized, making them a less attractive target.

It is significant that unit 4 and parts of unit 2 were not oxidized in the Daly Sinclair Field, but underwent only the effects of compaction and chemical reduction. Reduction caused the growth of pyrite cubes and compaction created horizontal stress fractures. Both increase effective porosity. Whereas much of the siltstone has 10–15% porosity, the porosity of the shale enclosing the siltstone-breccia clasts is also good. Oil fluorescence is commonly seen within the shale matrix but is most pronounced near large siltstone-breccia clasts, giving a 'bird's-eye' texture to the fluorescence, typical of pressure-solution effects, which lower compaction pressures on the corners of the breccia to create fracturing and increase pore space in the shale.

In the Daly Sinclair Field, unit 4 and portions of unit 2 are the dominant reservoir units. Production of the wells decreases where unit 4 is truncated at the pre-Mississippian unconformity and unit 2 becomes the dominant reservoir. Unit 2 is more sporadically affected by oxidation-reduction reactions, as indicated by the haloes common in this unit that effectively decrease porosity and permeability, and therefore oil production. The unpredictability of the redox effects makes development of the reservoir difficult. Unit 4 generally does not have redox haloes and has proven to be predictable and consistent in its reservoir characteristics. The Middle Bakken thins over the best unit 4 reservoir areas. The best production from unit 2 is where the Middle Bakken is thicker.

Examination of the cumulative water:oil ratio from production of the Bakken-Torquay pools in the Daly Sinclair Field reveals more controls on the oil pools. Figure 49 shows a contour map of the water:oil ratios from the first 12 months of production for all Bakken and Torquay pools. A sharp water-oil contact can be seen in the southwestern corner of the field, bounded by the –485 m contour between Twp. 8, Rge. 29W1 and Twp. 7, Rge. 28W1. The lowest water:oil ratios occur in Twp. 8, Rge. 29 and Twp. 7, Rge. 28, and coincide with the peaks of the Sinclair High where the edge of the water line reflects the edges of unit 4 and 3. The moderate water:oil ratios east of these edges coincide with production from subunit 2c, in the absence of which the water:oil ratio increases dramatically. In the northern half of the field, where the Middle Bakken Member thickens, there is an increase in water:oil ratio.

With the exception of the Sinclair High, the sites with cumulative water:oil ratios of less than one for Bakken and Torquay production are smaller and generally follow southeast and northeast trends. These trends coincide with the orientation of two dominant orthogonal fracture sets that have been recorded in the Paleozoic bedrock to the east by McRitchie (1997), and with the two sets of lineaments shown in Figure 41. These sets of fractures are used to control horizontal-well development in the Daly Sinclair Field.

Conclusions and economic considerations

The Three Forks Group in southwestern Manitoba has demonstrated remarkable hydrocarbon development capacity, with excellent potential for new discoveries. Extensions of known Torquay oil pools should follow the northerly trend of the isopach thick of unit 4. The best development potential for unit 2 occurs in areas where subunit 2b is present and subunit 2c has been minimally affected by oxidation. New exploration efforts could be directed northward, eastward and southward of the Daly Sinclair field within unit 2, and possibly unit 1. The fact that unit 1 is productive in a small pool in Daly Sinclair suggests that more potential exists in this unit where the Three Forks Group 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 validate the log signatures. Exploration of the Three Forks Group beneath the Virden Field has been limited and, given the structural character of the Lodgepole oil pools in that field, it is easy to extrapolate such structural effects to underlying formations. This case can also be made for the Waskada Field. Other possible targets may be present along the northerly trend parallel to the eastern limit of the SBZ, in Rge. 24 and 25W1 where local sections of unit 4 have been preserved. Based on fracture orientations and the local stress regime, the best production will lie along southeast and northeast trends.

Bakken potential exists north of the Birdtail Field, particularly north of Twp. 16, where coarse sandstone beds are commonly oil stained. The northeastern extension of the Rocanville-Torquay trend into Manitoba has excellent potential for migrating hydrocarbons to have been funnelled and trapped, particularly in combination with the structural effects of the BWZ and SBZ.

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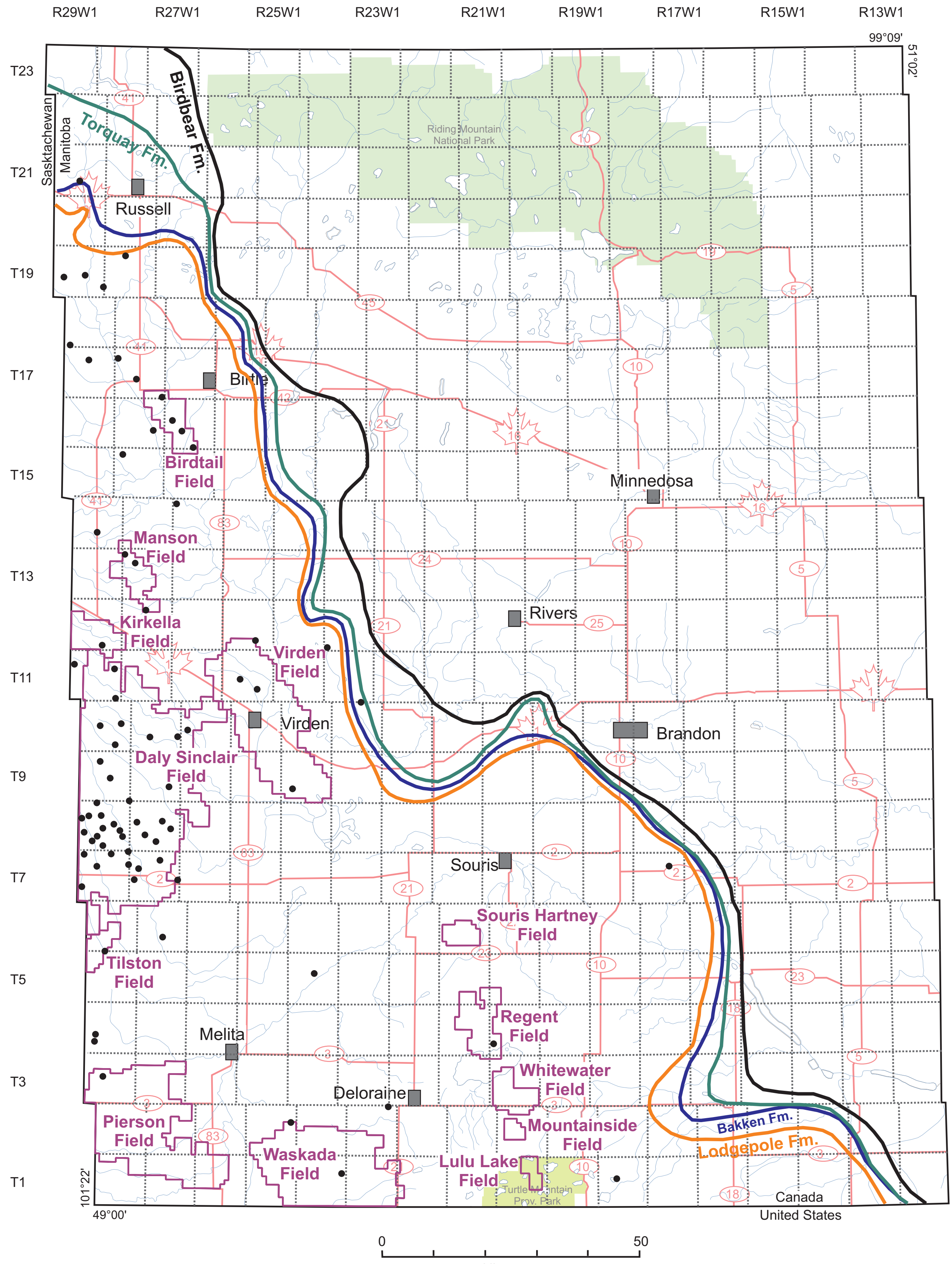


__Figure 1:__ Location of the study area in southwestern Manitoba, showing oil fields and the Lodgepole (orange line), Bakken (blue line), Torquay (green line) and Birdbear (black line) subcrop edges; black dots represent locations of 80 cores logged for this study. Oil-field boundaries are from Fulton-Regula (2012). Abbreviation: Fm., Formation.

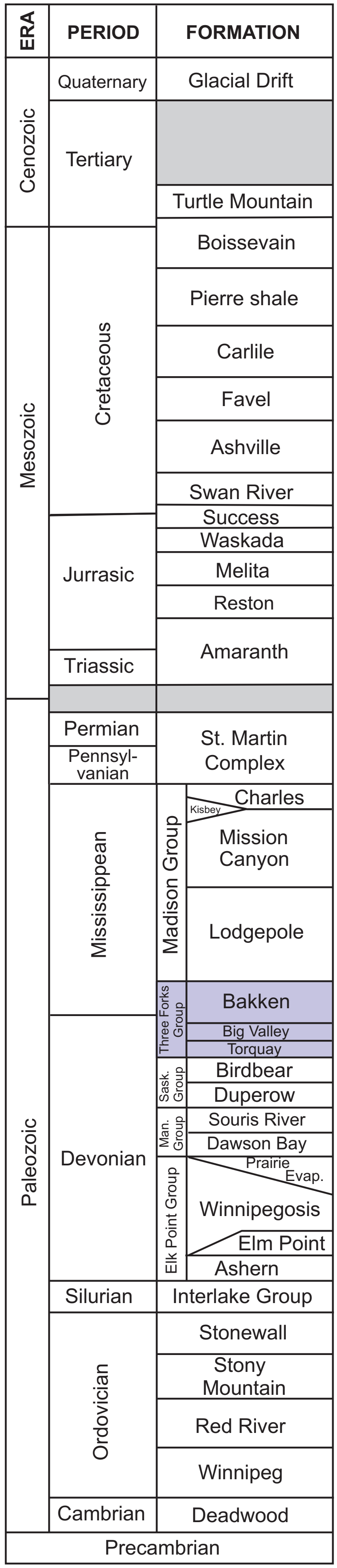


Figure 2: *Stratigraphic chart of the Phanerozoic rocks in southwestern Manitoba. Abbreviations: Man., Manitoba; Sask., Saskatchewan.*

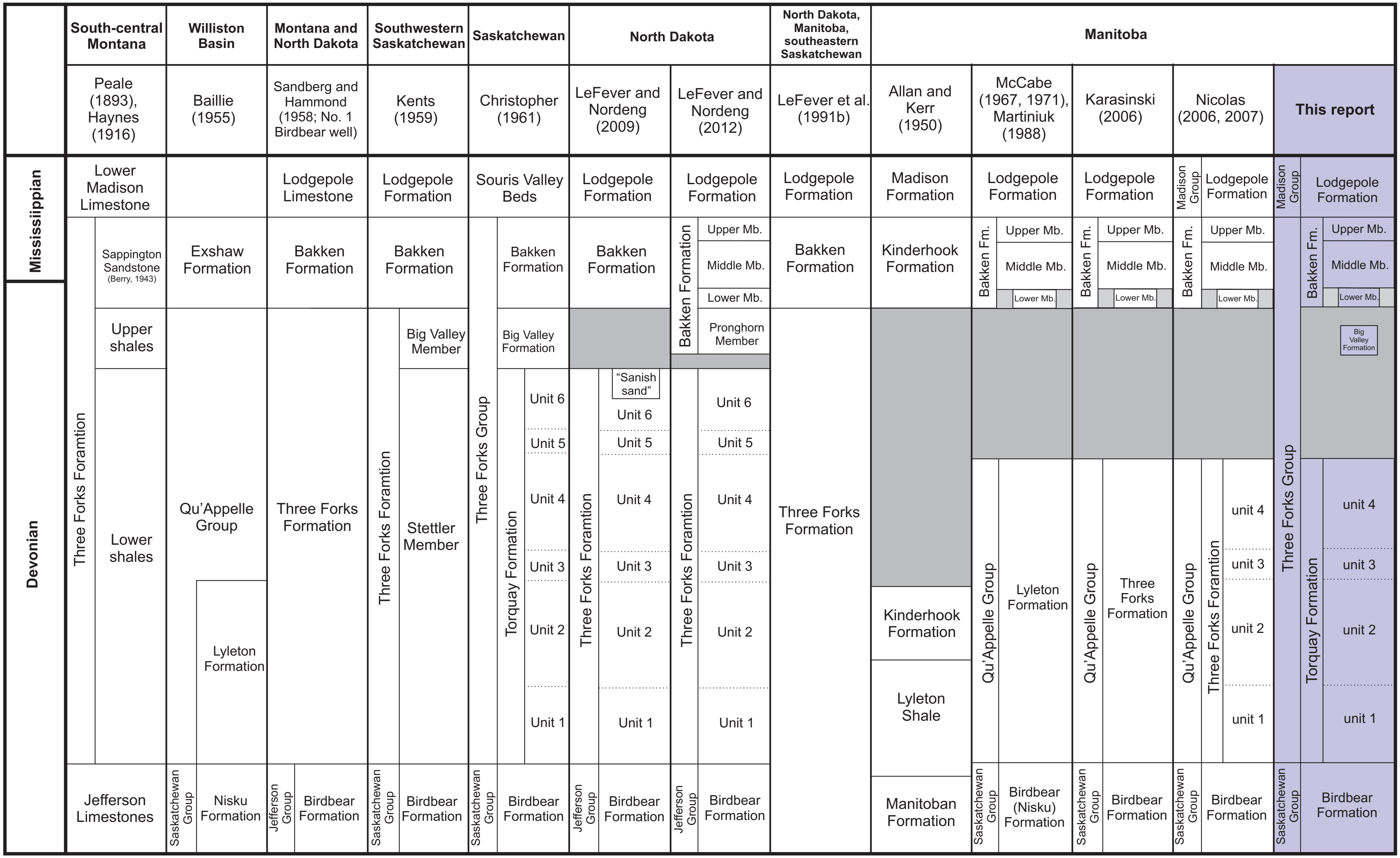


Figure 3: *Historical stratigraphic correlation chart of the Upper Devonian and Lower Mississippian units throughout the Williston Basin and used in this report. Abbreviations: Fm., Formation; Mb., Member.*

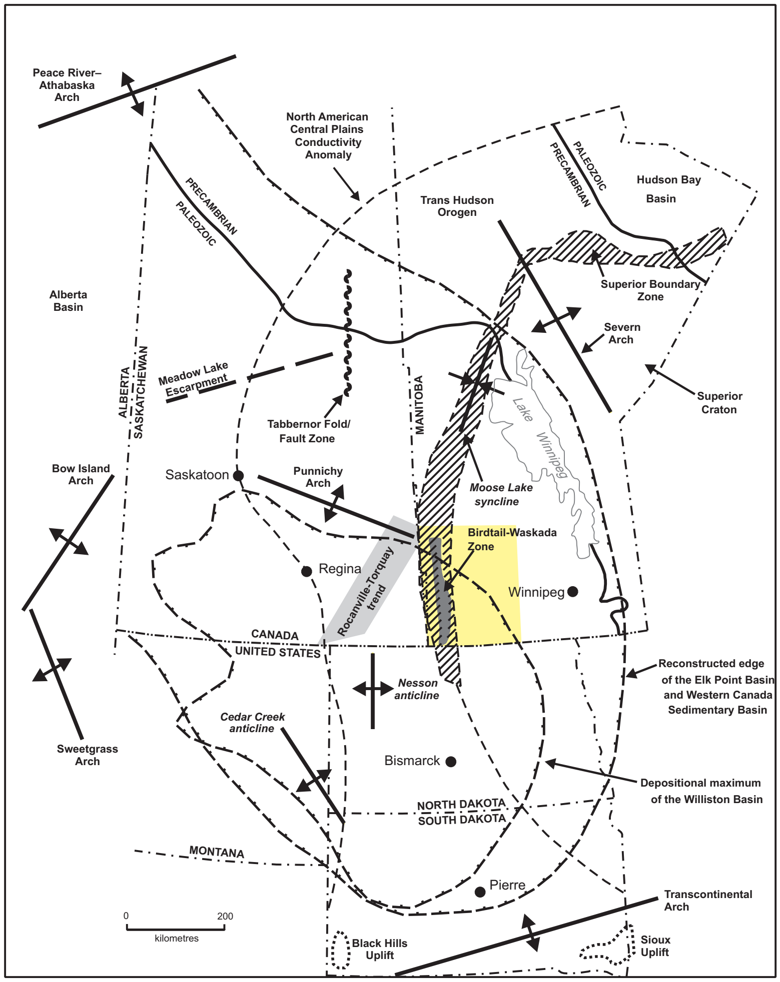


Figure 4: *Tectonic map (modified after Gerhard et al. [1990] and Nicolas and Barchyn [2008]), showing locations of the Superior Boundary Zone (SBZ), Birdtail-Waskada Zone (BWZ), Severn Arch, Transcontinental Arch, Rocanville-Torquay trend (after Christopher, 1961) and other major features; yellow box shows study area.*

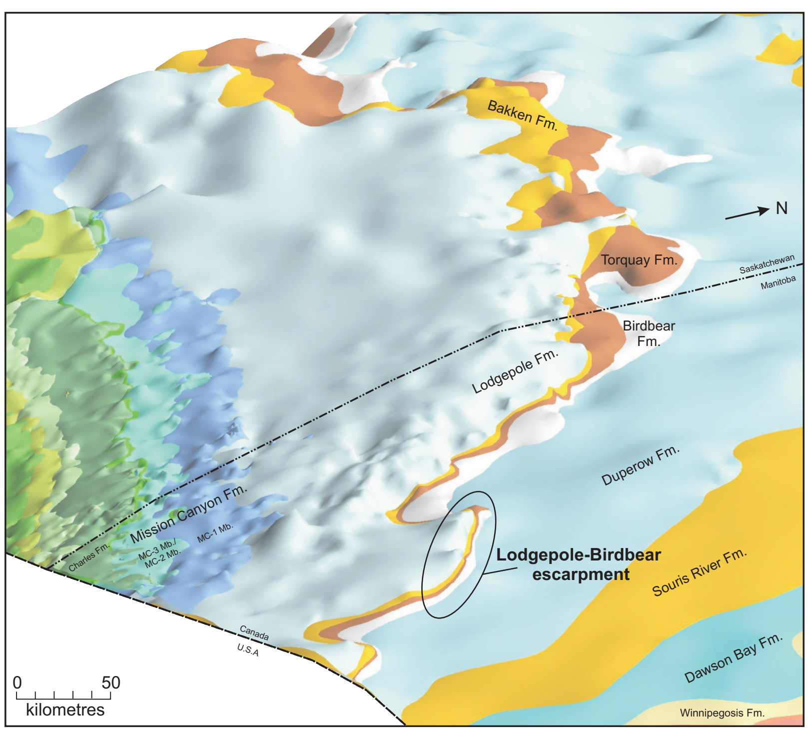


Figure 5: *Three-dimensional model of the Paleozoic formations in southwestern Manitoba and southeastern Saskatchewan, showing the relief of the Lodgepole-Birdbear escarpment. View is toward the west. Abbreviation: Fm., Formation.*

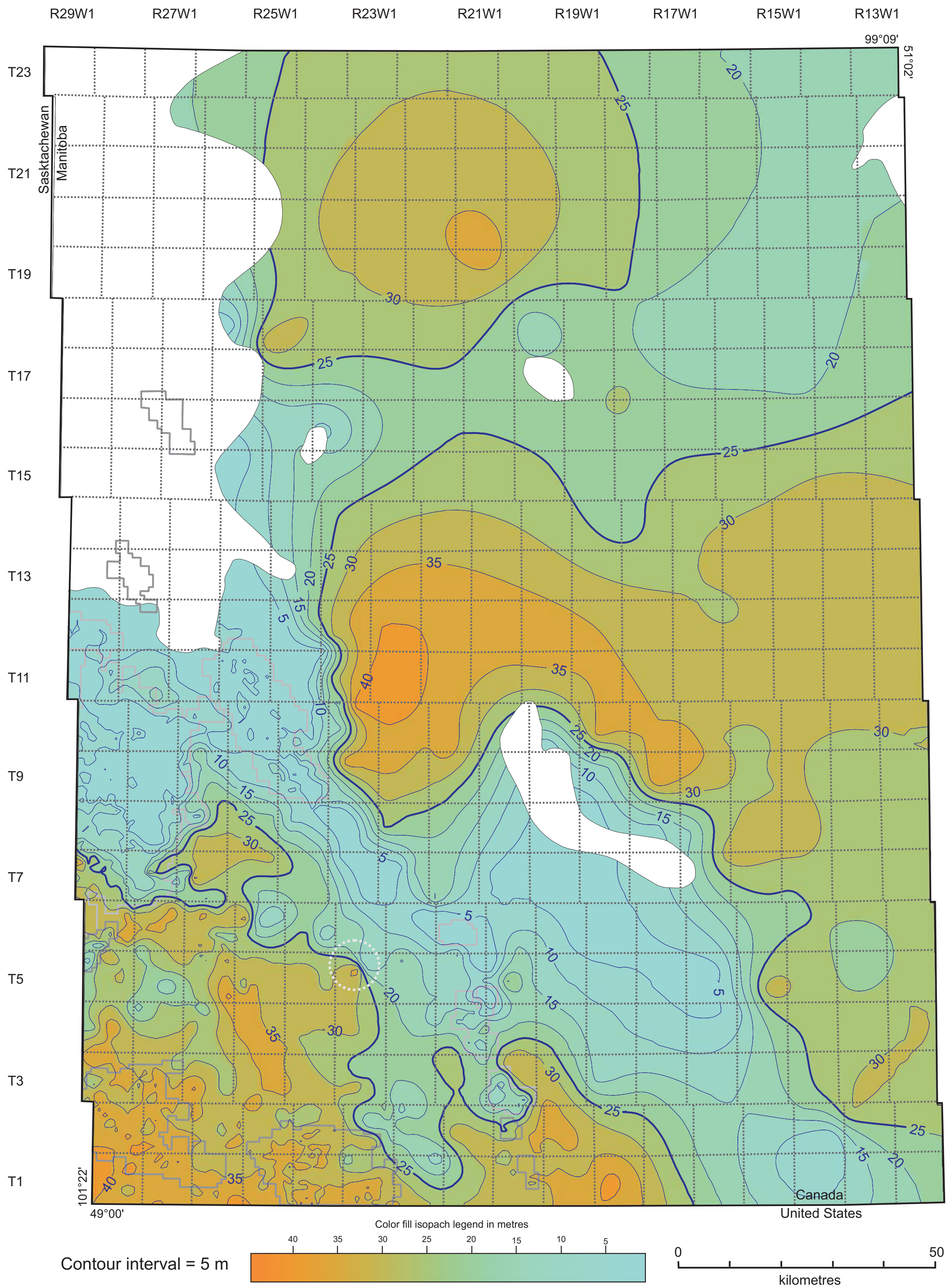


***Figure 6:** Isopach map of the Lower (Red Beds) Member, Amaranth Formation in southwestern Manitoba; contour interval is 5 m. Computer generated using the kriging method at a grid-point spacing of 1000 m. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

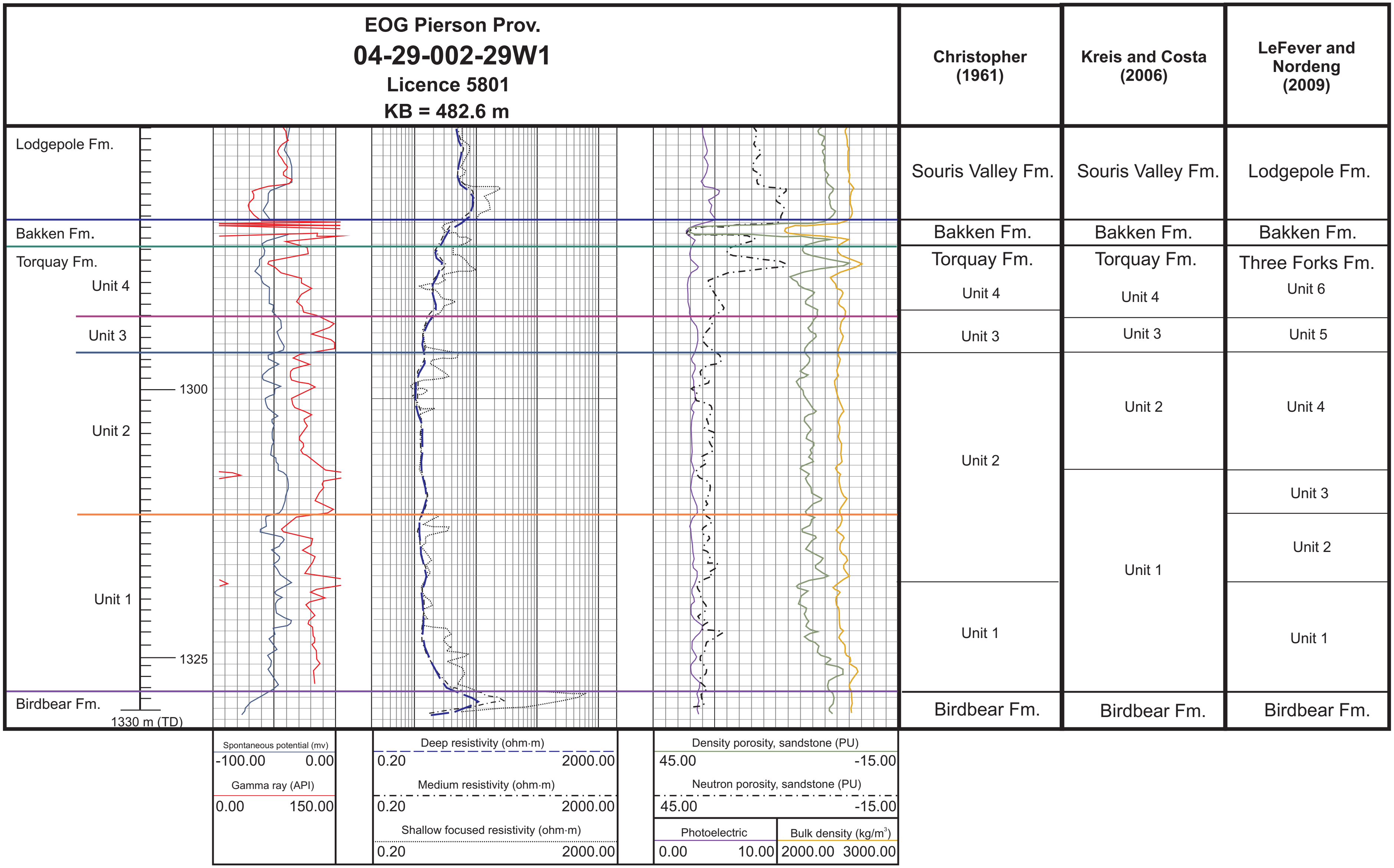


Figure 7: *Geophysical log of the Torquay Formation in 4-29-2-29W1, showing stratigraphic correlations of Torquay unit subdivisions of the other authors. Abbreviation: PU, porosity units.*

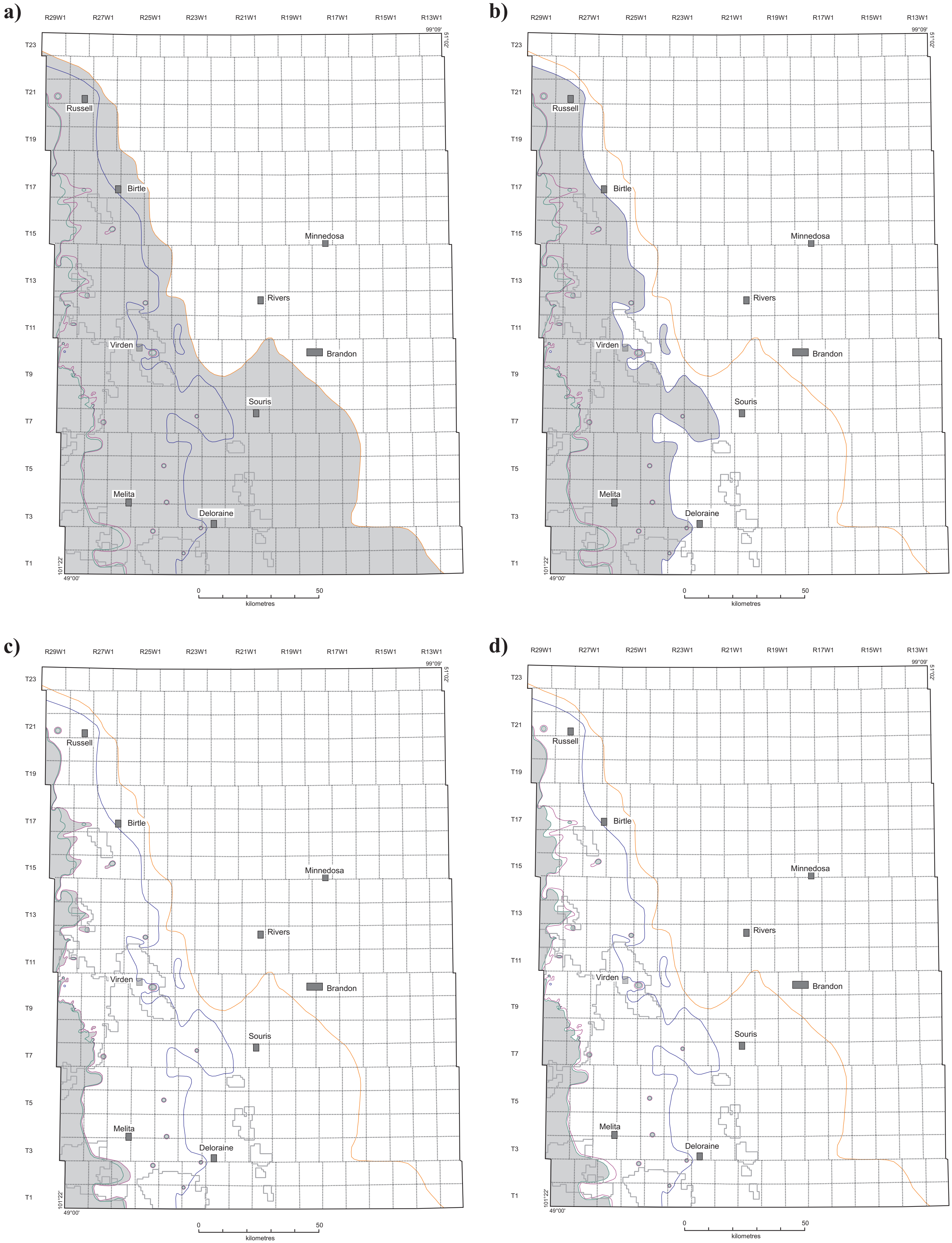


__Figure 8:__ Distribution and subcrop edge for each unit in the Torquay Formation, southwestern Manitoba: __a)__ unit 1, __b)__ unit 2, __c)__ unit 3, and __d)__ unit 4. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names.

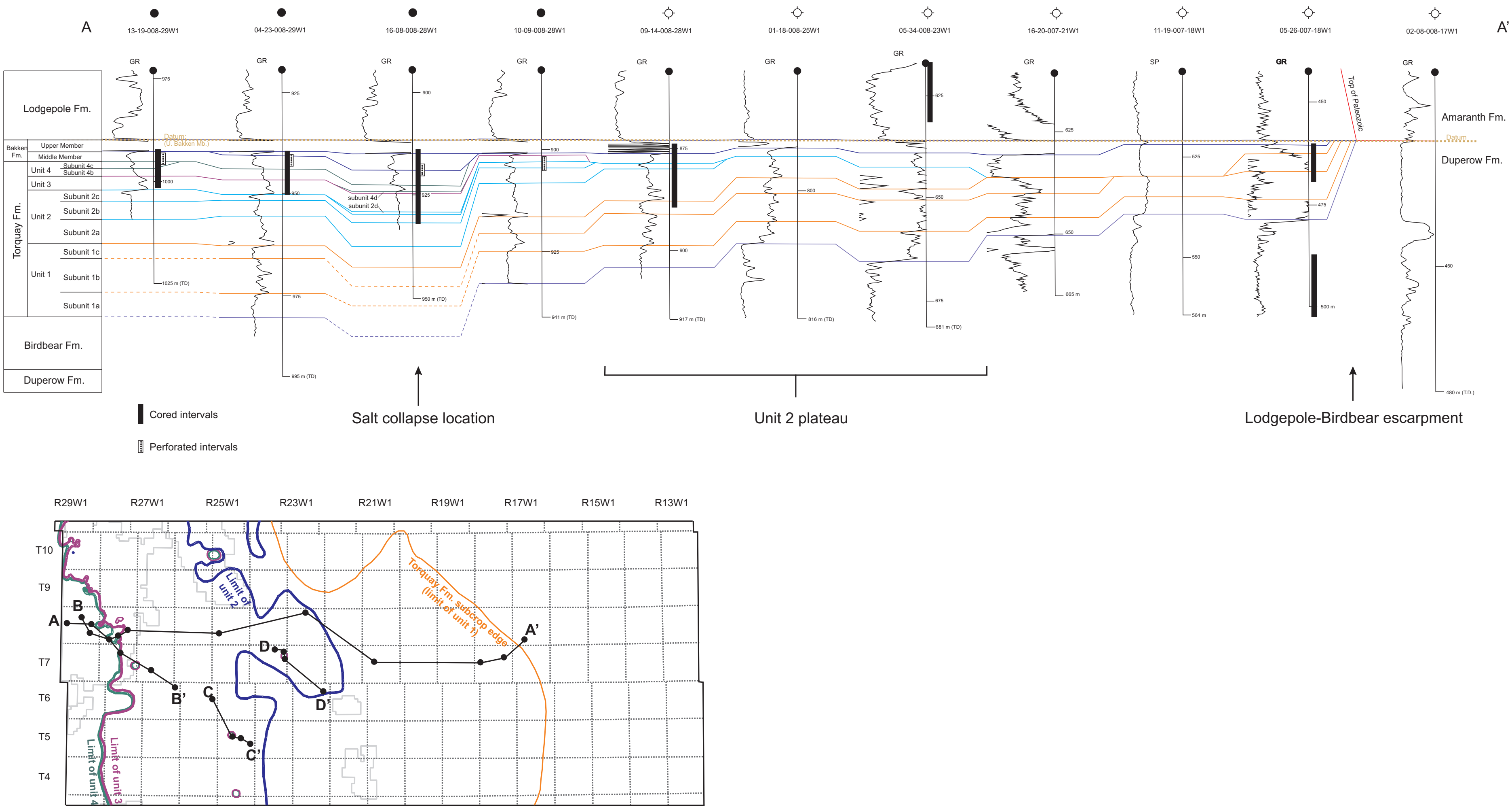


Figure 9: *West to east stratigraphic cross-section AA', showing the progressive truncation of the Torquay units toward the east. Abbreviation: Fm., Formation; GR, gamma ray.*

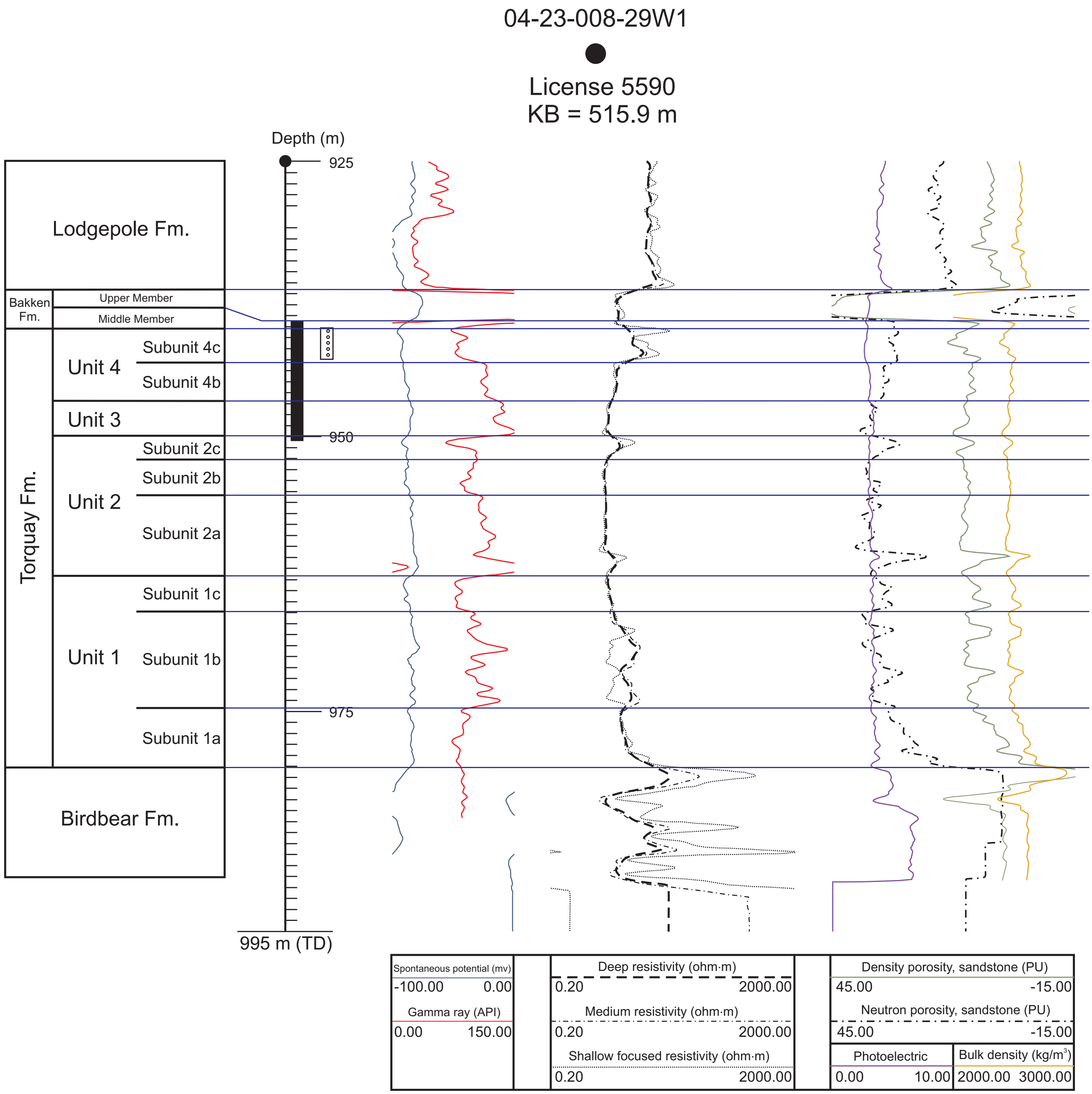


Figure 10: *Geophysical log of the Torquay Formation for a well in 4-23-8-29W1. Abbreviation: Fm., Formation. Abbreviation: PU, porosity units.*

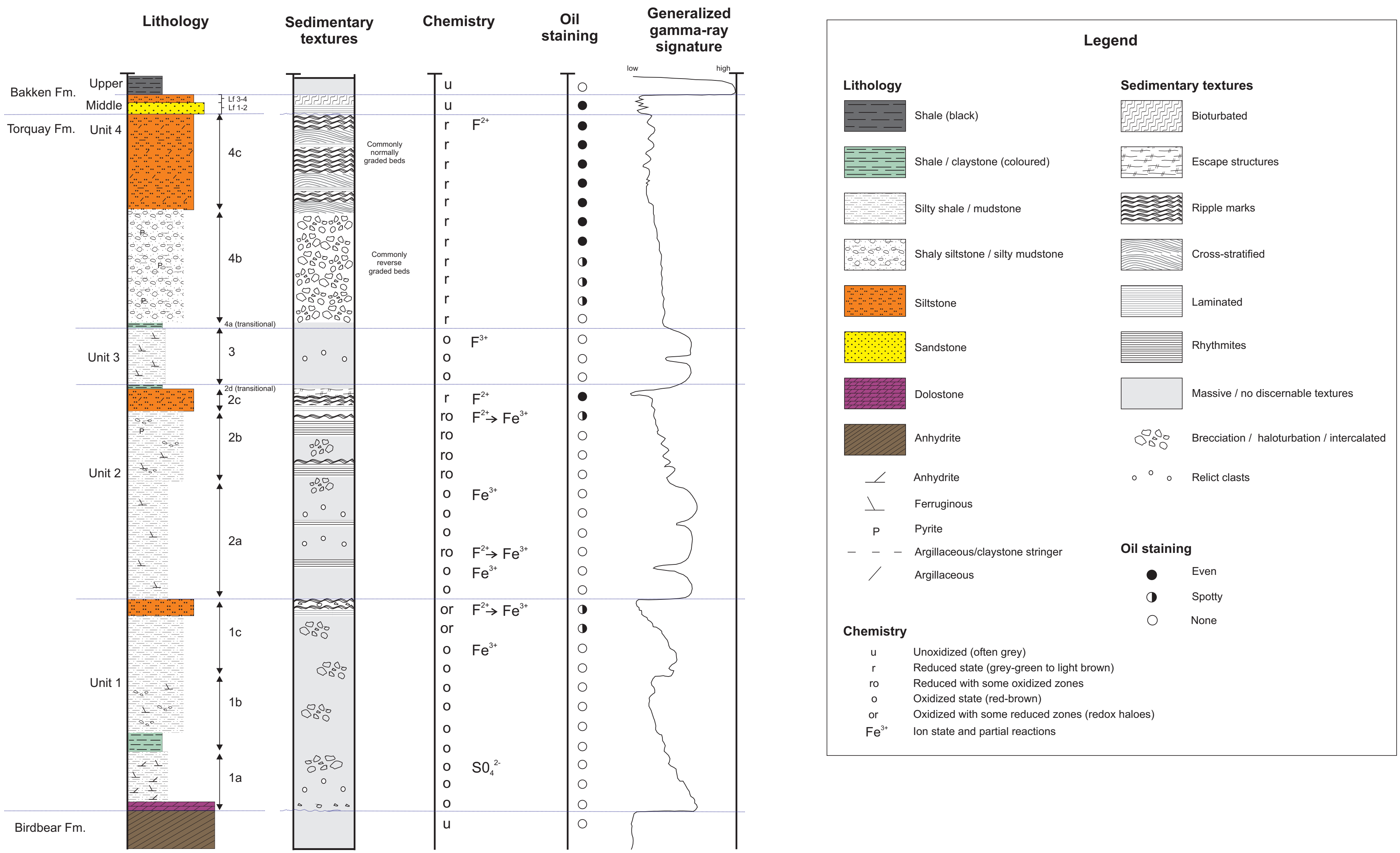
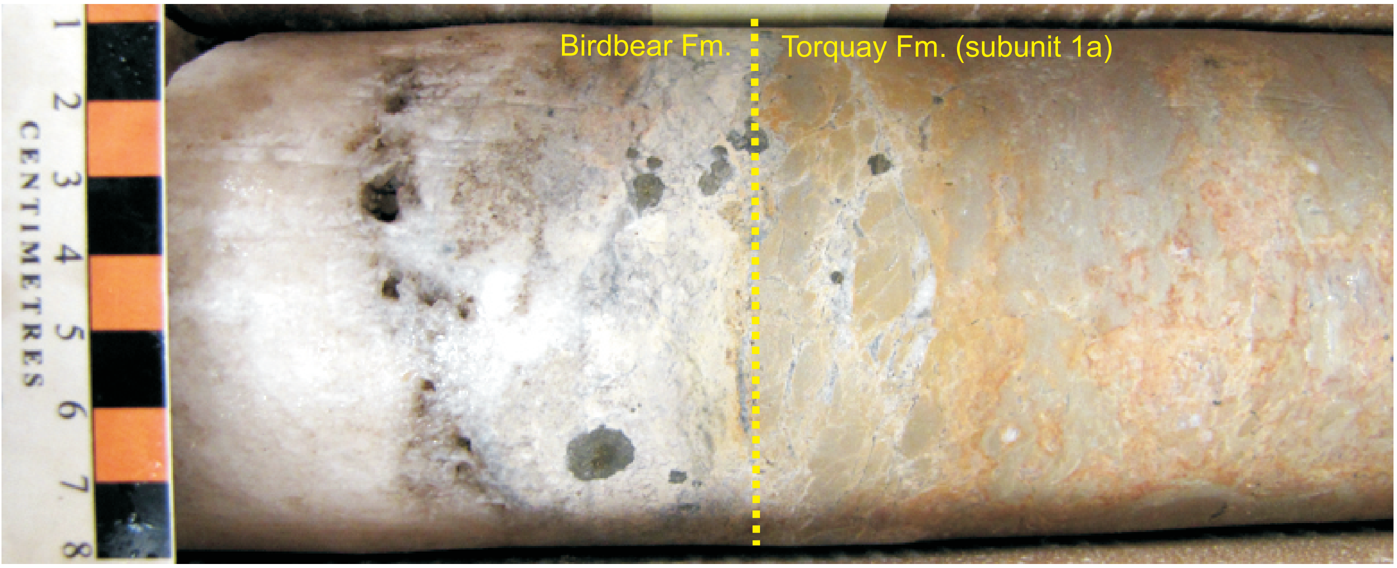


Figure 11: *Schematic stratigraphic column of the Torquay Formation, showing generalized composite lithology, sedimentary structures, oxidized and reduced zones, oil shows and gamma-ray log signature. Abbreviation: Fm., Formation.*

a)



b)

Figure 12: *Core photographs of subunit 1a from 9-9-21-29W1, showing **a)** Birdbear-Torquay contact, and **b)** brecciated silty dolostone within silty shale matrix.*

Figure 13: *Core photograph of subunit 1b at depths of 962 m **(top left)** to 969 m **(bottom right)** in 8-14-8-29W1; note the red-brown (oxidized) and light grey-green (reduced) redox haloes; nodules and veins are anhydrite (AN).*

a) Top

b) Bottom

Figure 14: *Core photographs of* ***a)*** *subunit 1c at a depth of 918.7 m to 921.69 m in 12-22-5-25W1, and* ***b)*** *close-up of a sandy siltstone near the top of the core in the previous photo.*

Figure 15: *Core photograph of subunit 2a at depths of 951 m* ***(top left)*** *to 957 m* ***(bottom right)*** *in 8-14-8-29W1, showing sections affected by oxidation and reduction.*

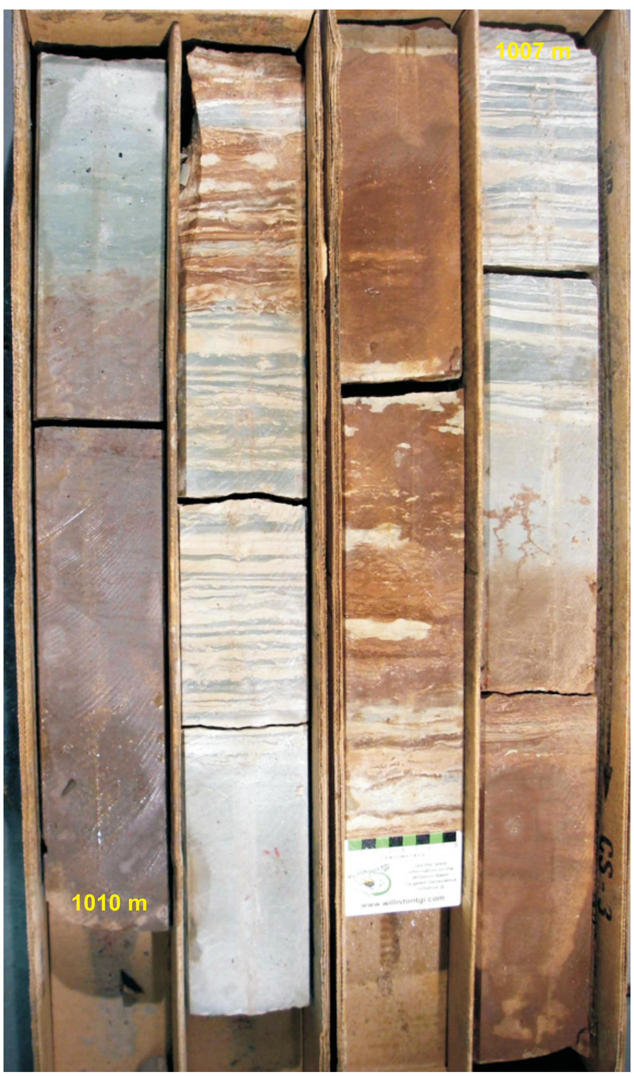


Figure 16: *Core photograph of subunit 2b at a depth of approximately 1007–1010 m in 2-8-8-29W1.*

a)

b)

Figure 17: *Core photographs of* ***a)*** *subunit 2c at a depth of 1003 m in 2-8-8-29W1, and* ***b)*** *escape structures (es) in subunit 2c at a depth of 1016.6 m in 4-28-7-29W1.*

Figure 18: *Core photograph of subunit 2d at a depth of 1003.5 m in 2-8-8-29W1.*

Figure 19: *Core photograph of unit 3 at a depth of 1001 m in 2-8-8-29W1.*

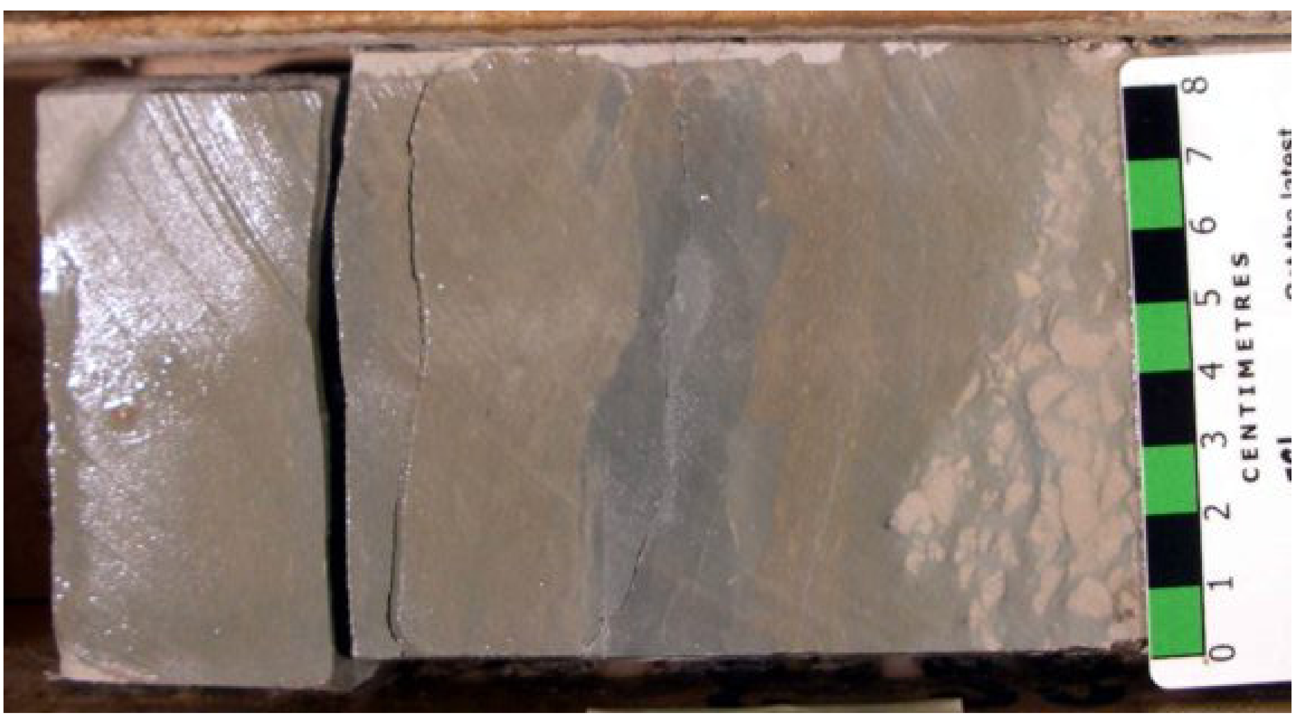


Figure 20: *Core photograph of subunit 4a at a depth of 1000 m in 2-8-8-29W1.*

Figure 21: *Core photograph of subunit 4b at a depth of 997 m in 2-8-8-29W1.*

Figure 22: *Core photograph of subunit 4c at a depth of 995 m in 2-8-8-29W1.*

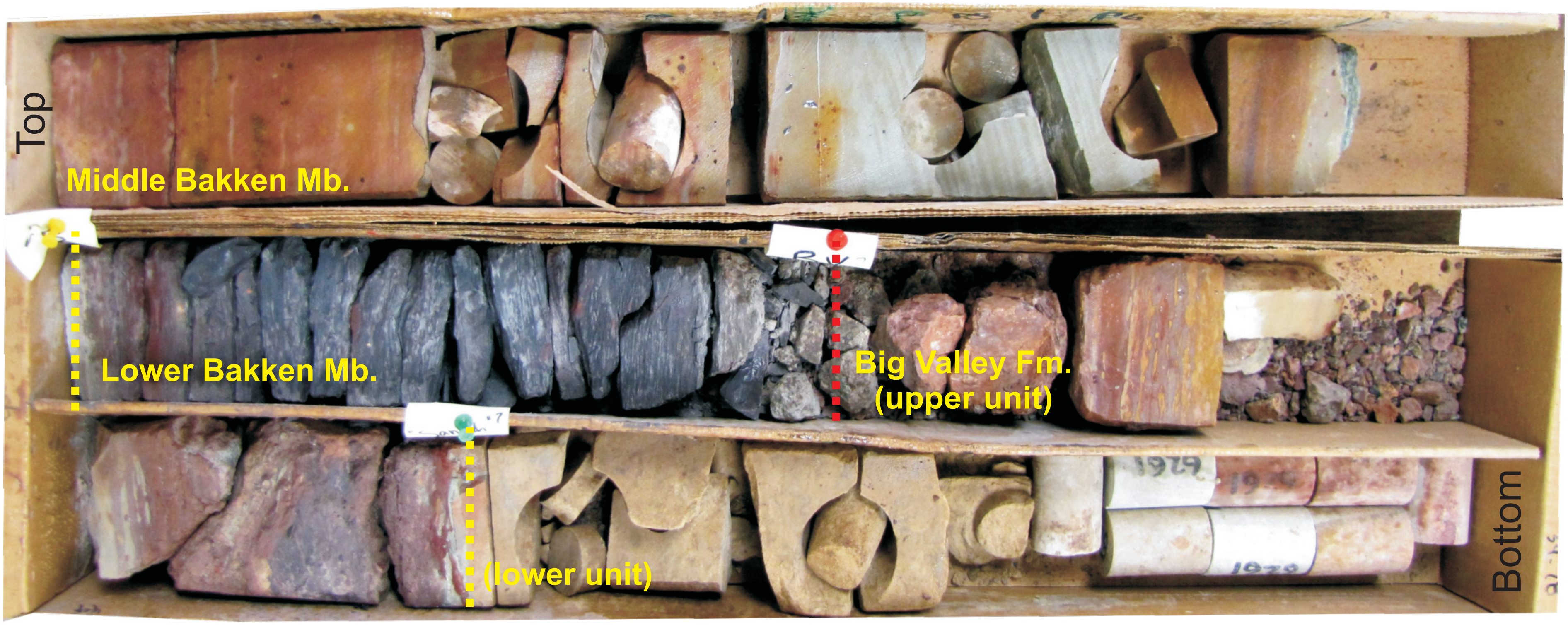


Figure 23: *Core photograph of the Big Valley Formation at a depth of approximately 835 to 837 m in 12-24-11-29W1.*

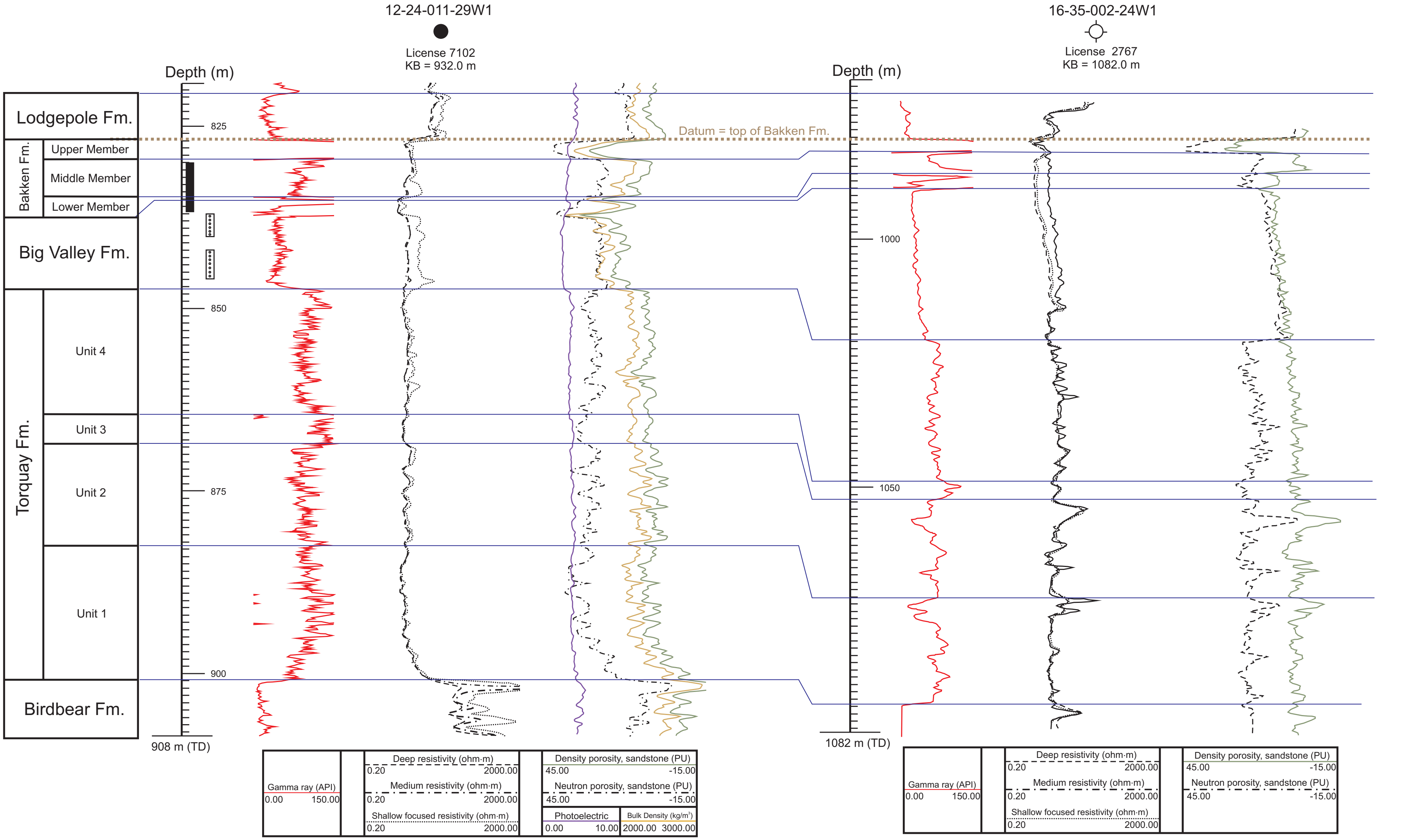


Figure 24: *Geophysical logs of the Big Valley Formation in 12-24-11-29W1, and 16-35-2-24W1. Abbreviations: Fm., Formation; PU, porosity units.*

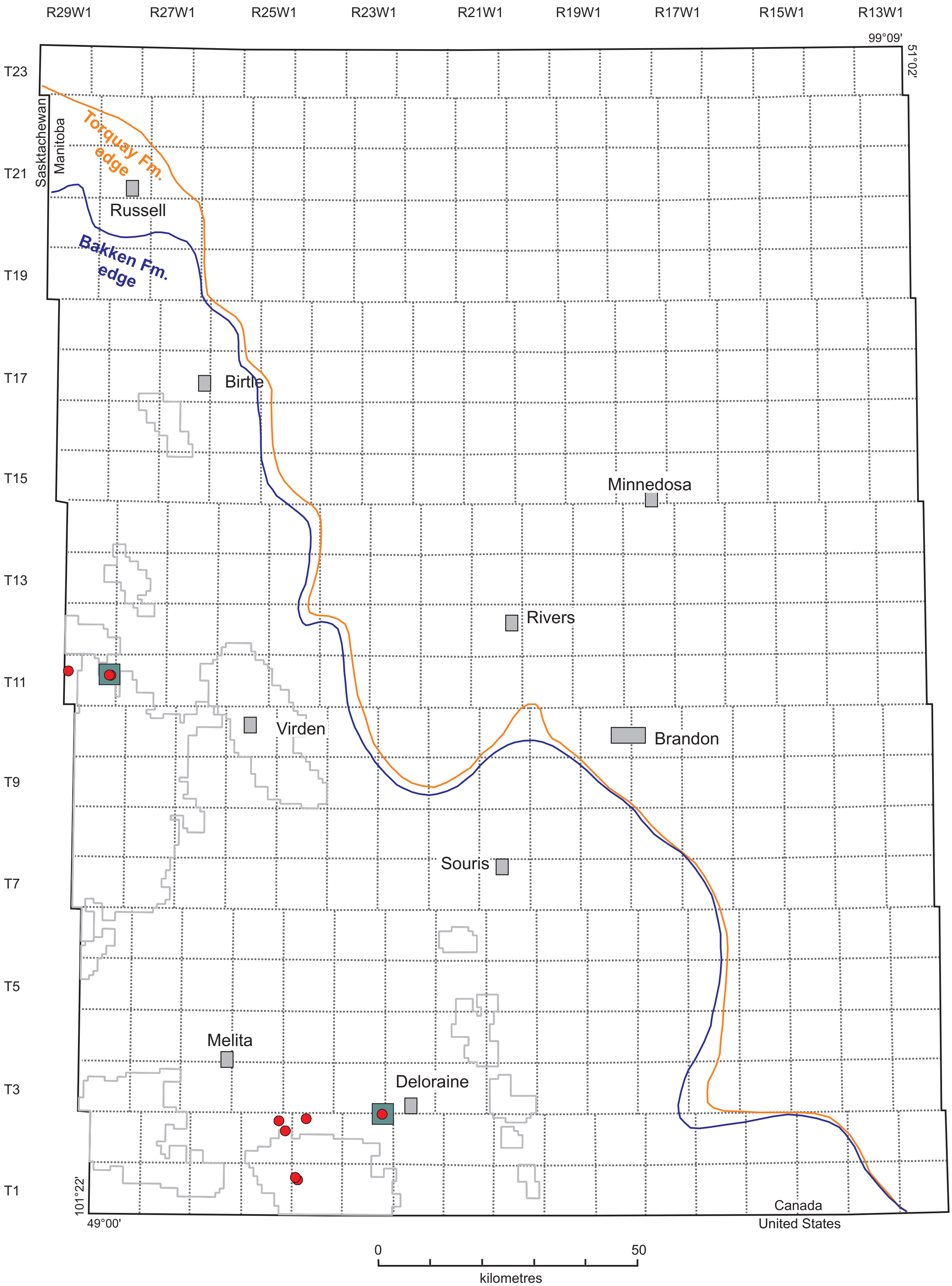


Figure 25: *Location of wells in southwestern Manitoba with Big Valley Formation (green squares) and Lower Member of the Bakken Formation (red dots) present. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names.*

a)

b)

Figure 26: *Core photographs of the Lower Bakken Member in 3-30-11-29W1:* ***a)*** *entire section from 864.3 to 865.3 m,* ***b)*** *close-up at a depth of 864.3 m.*

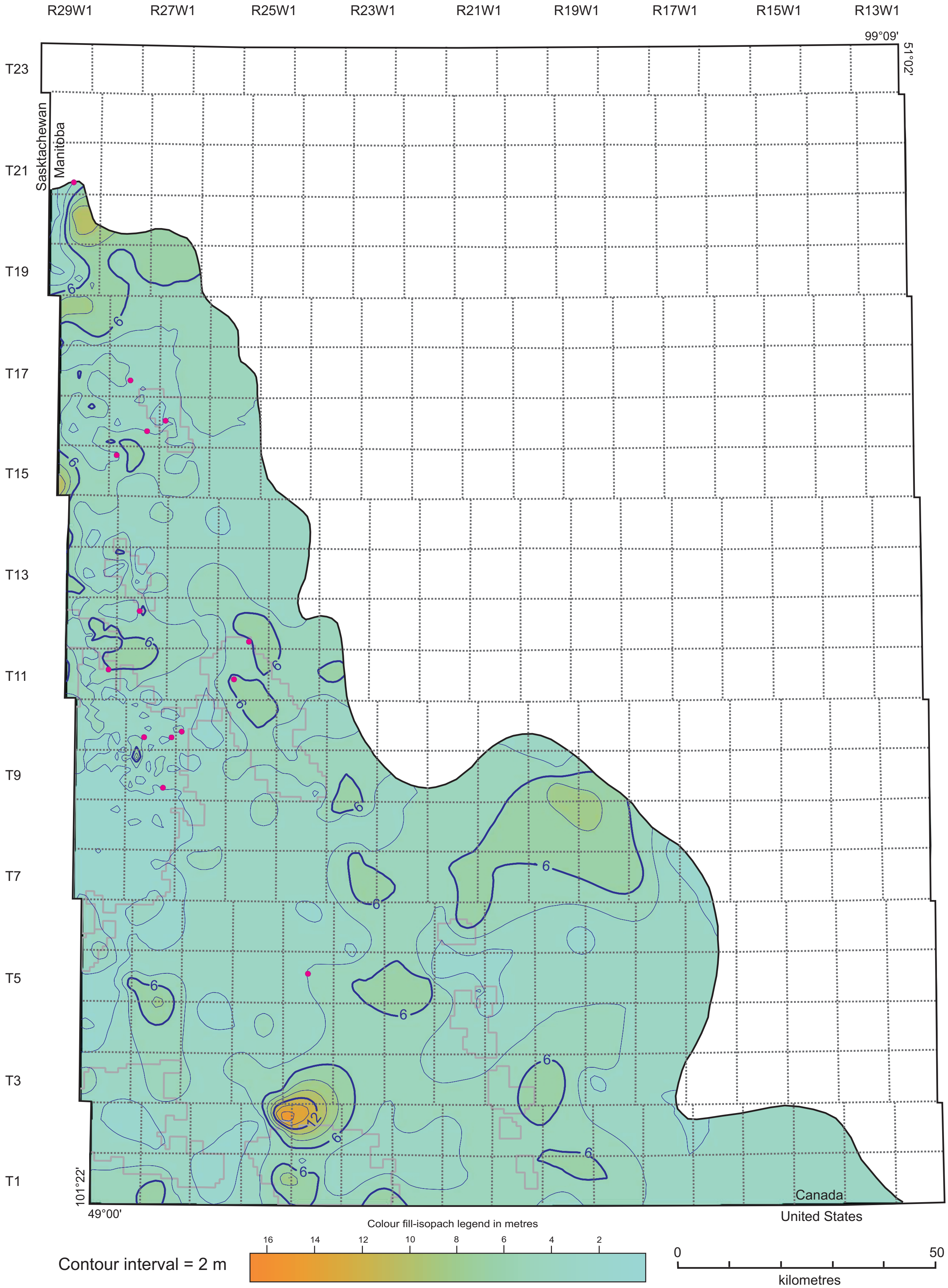


***Figure 27:** Isopach map of the Middle Bakken Member, with red dots showing the locations of wells in which the member has been identified; contour interval is 2 m. Computer generated using the kriging method at a grid-point density of 200. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names.*

		Christopher (1961)	LeFever et al. (1991)			Kreis and Costa (2006)	Angulo and Buatois (2010)	This report
		Saskatchewan	*Saskatchewan*	*North Dakota*	*Manitoba*	*Saskatchewan*	*FACIES Saskatchewan*	*Manitoba*
BAKKEN FORMATION	**Upper Member**						1	
	Middle Member	B4	C	7	4 3	C	3B, 10	3-4
		B3	B3	6 5		B3	8, 9	
		B2	B2	4 3	2 1	B2	6, 7	1-2
		B1	B1	2		B1	4, 5	
		A	A	1		A1 A	2, 3A	
	Lower Member						1	

Figure 28: *Lithostratigraphic subdivisions of the Bakken Formation by various authors, and facies assemblages by Angulo and Buatois (2010); shaded boxes refer to sections not represented in Manitoba.*

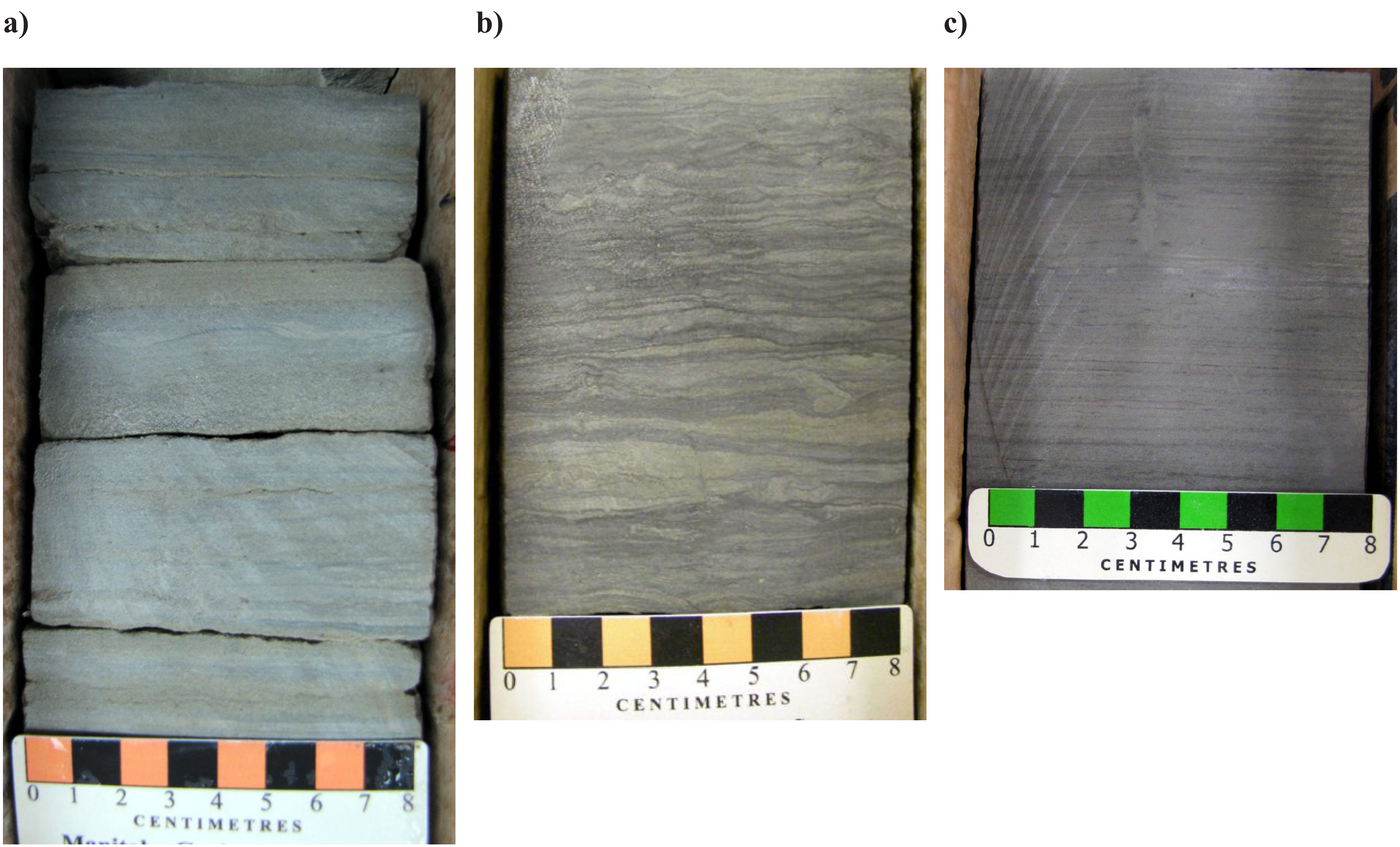


Figure 29: *Core photographs of lithofacies unit 1–2 of the Middle Bakken Member:* ***a)*** *coarse-grained sandstone lenses in a laminated fine-grained sandstone of lithofacies unit 1 at 817.2 m in 7-3-12-29W1;* ***b)*** *wavy-bedded, fine-grained sandstone of lithofacies unit 2 at 815.3 m in 7-3-12-29W1; and* ***c)*** *laminated fine-grained sandstone of lithofacies unit 2 at 522.5 m, 4-16-16-27W1.*

a) b) c)

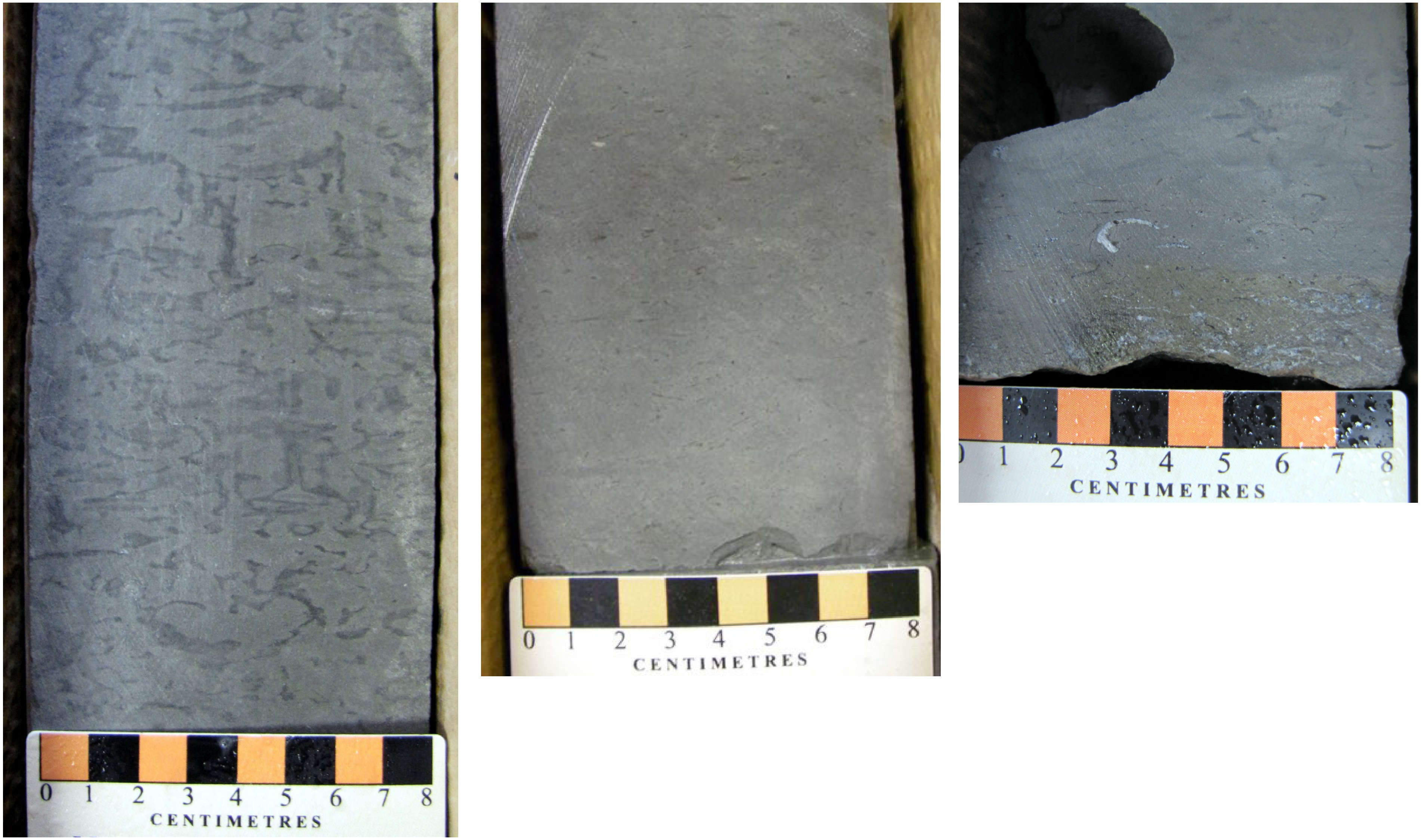
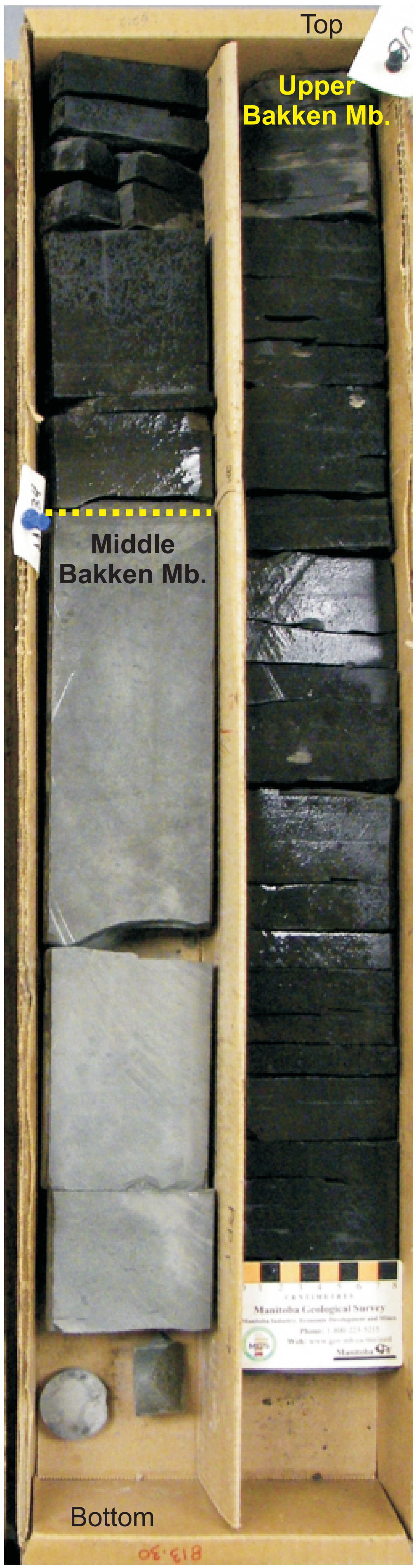


Figure 30: *Core photographs of lithofacies unit 3–4 of the Middle Bakken Member in 7-3-12-29W1:* ***a)*** *bioturbated, very fine grained sandstone of lithofacies unit 3 at 814.5 m;* ***b)*** *mottled, very fine grained sandstone of lithofacies unit 4 at 813.3 m, showing the* Nereites missouriensis *trace fossils that are common in this unit; and* ***c)*** *rare thin coquina bed at 814.6 m.*

a)



b)

c)

Figure 31: *Core photographs of the Upper Bakken Member showing variegation:* ***a)*** *normal black shale,* ***b)*** *dark purple shale, and* ***c)*** *grey-green shale.*

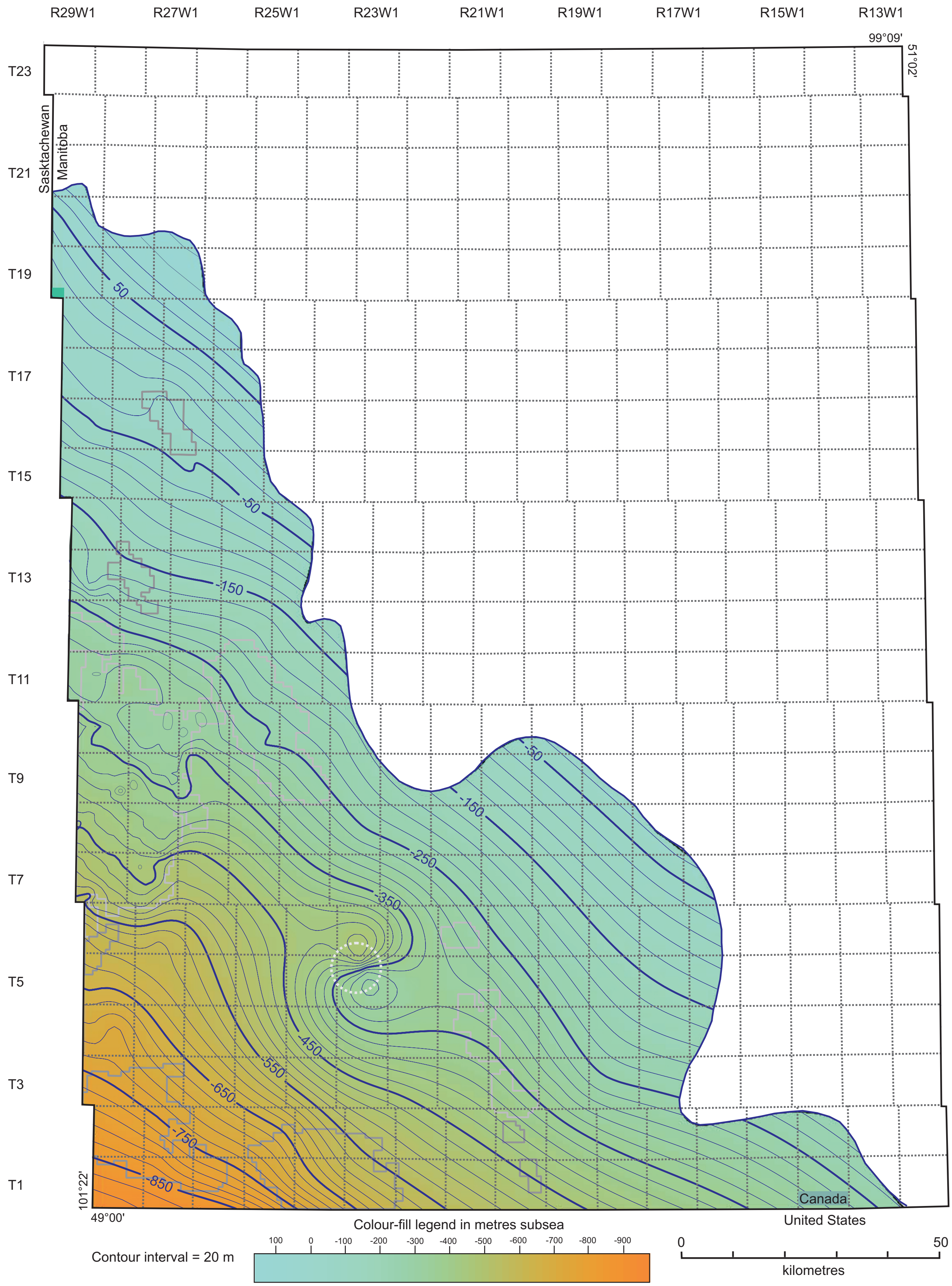


Figure 32: *Structure-contour map of the Upper Member of the Bakken Formation; contour interval is 20 m. Computer generated using the minimum-curvature method at a grid-point spacing of 1000 m. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

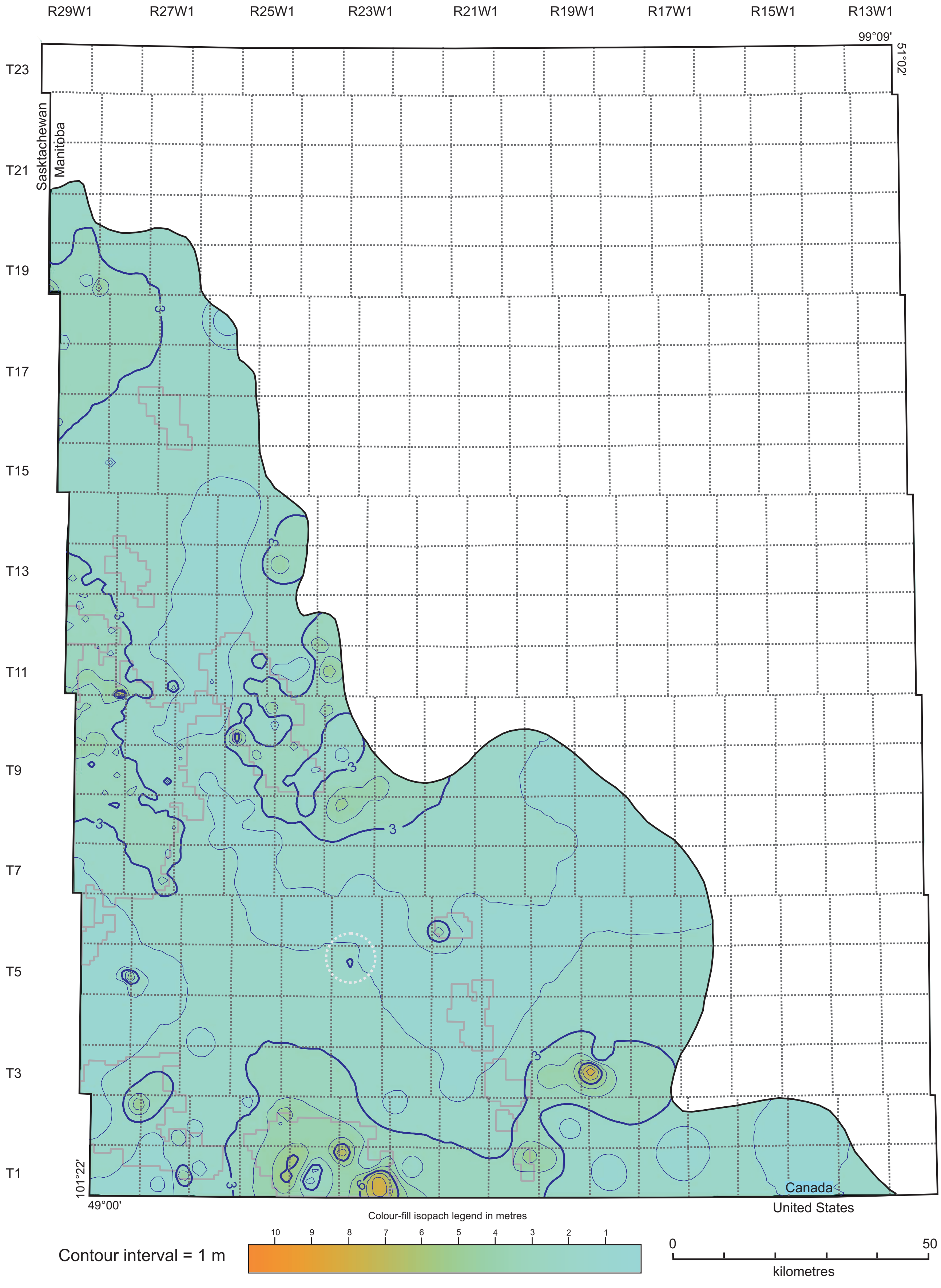


Figure 33: *Isopach map of the Upper Member of the Bakken Formation; contour interval is 1 m. Computer generated using the inverse-distance method at a grid-point density of 200. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

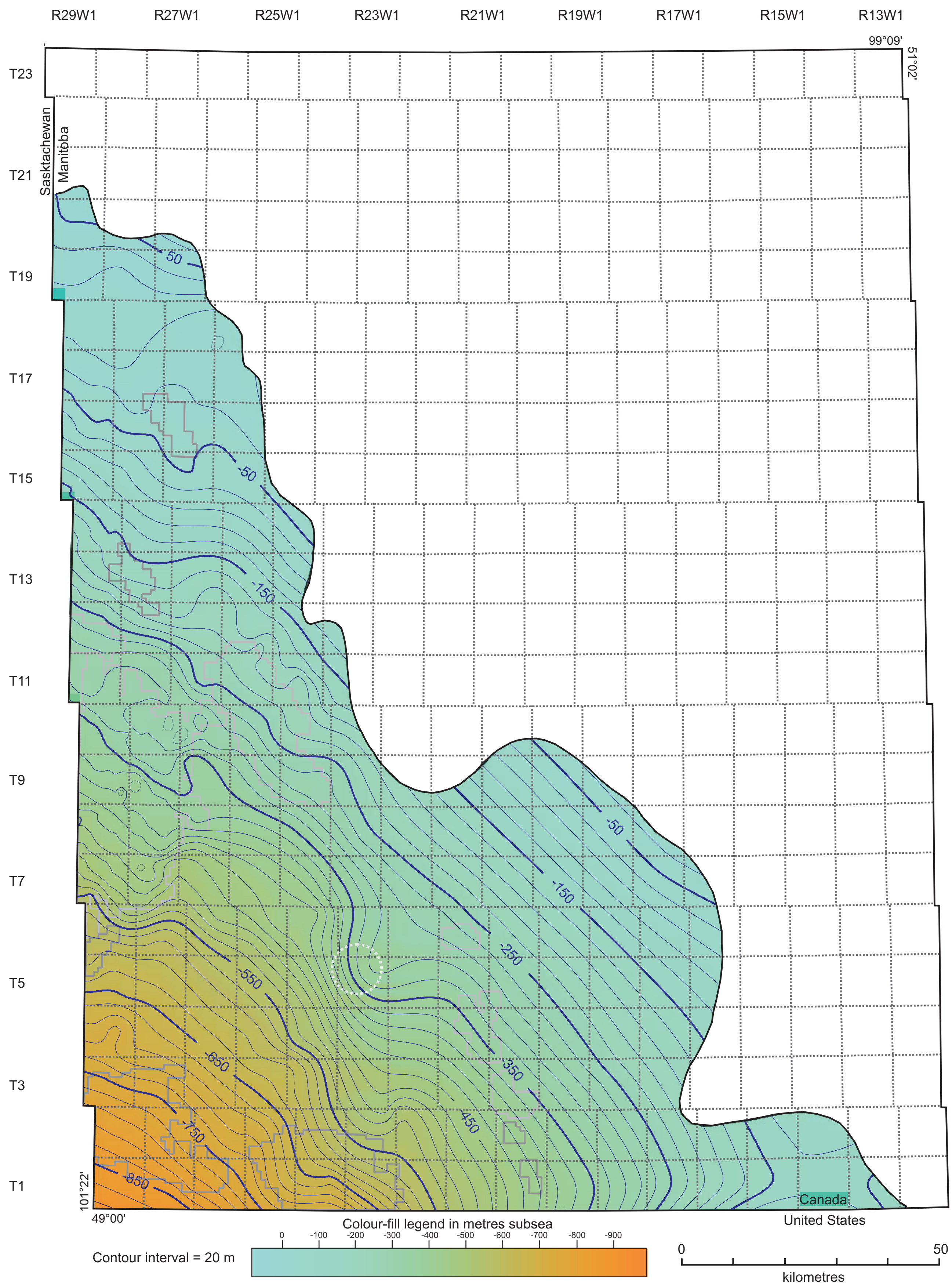


__Figure 34:__ Structure-contour map of the Middle Member of the Bakken Formation; contour interval is 20 m. Computer generated using the minimum-curvature method at a grid-point spacing of 1000 m. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.

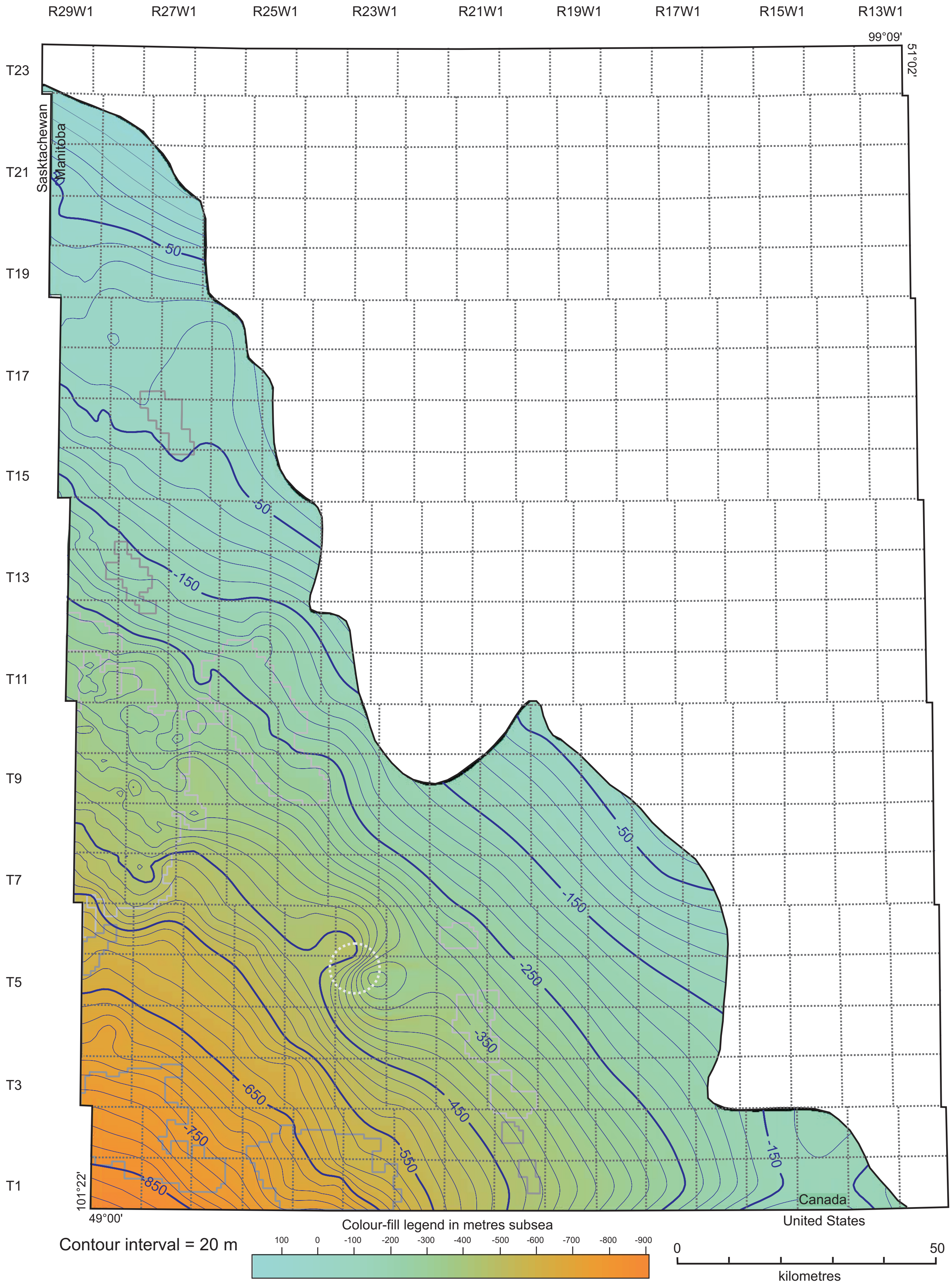


Figure 35: *Structure-contour map of the Torquay Formation; contour interval is 20 m. Computer generated using the minimum-curvature method at a grid-point spacing of 1000 m. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

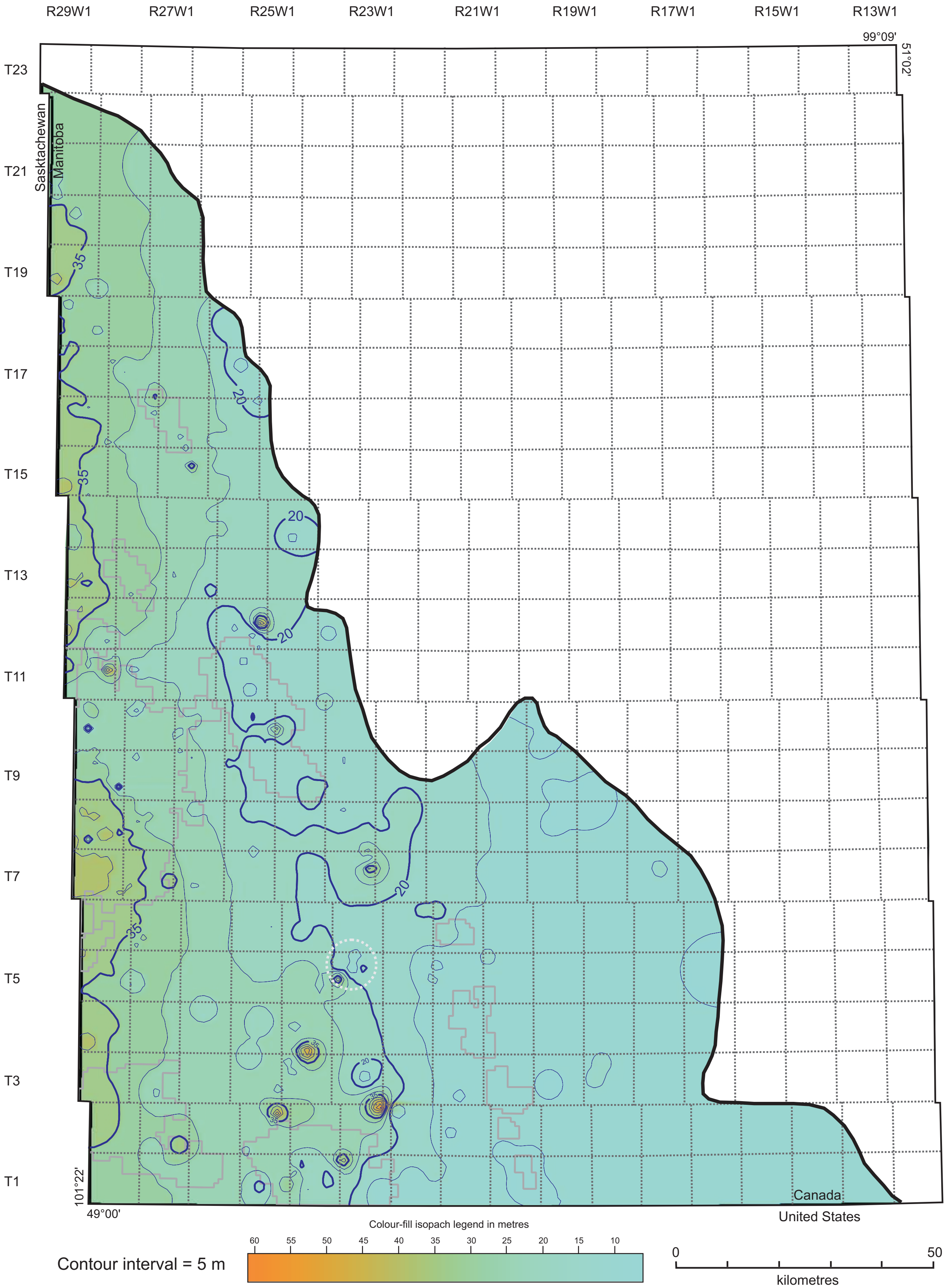


Figure 36: *Isopach map of the Torquay Formation; contour interval is 5 m. Computer generated using the inverse-distance method at a grid-point density of 200. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

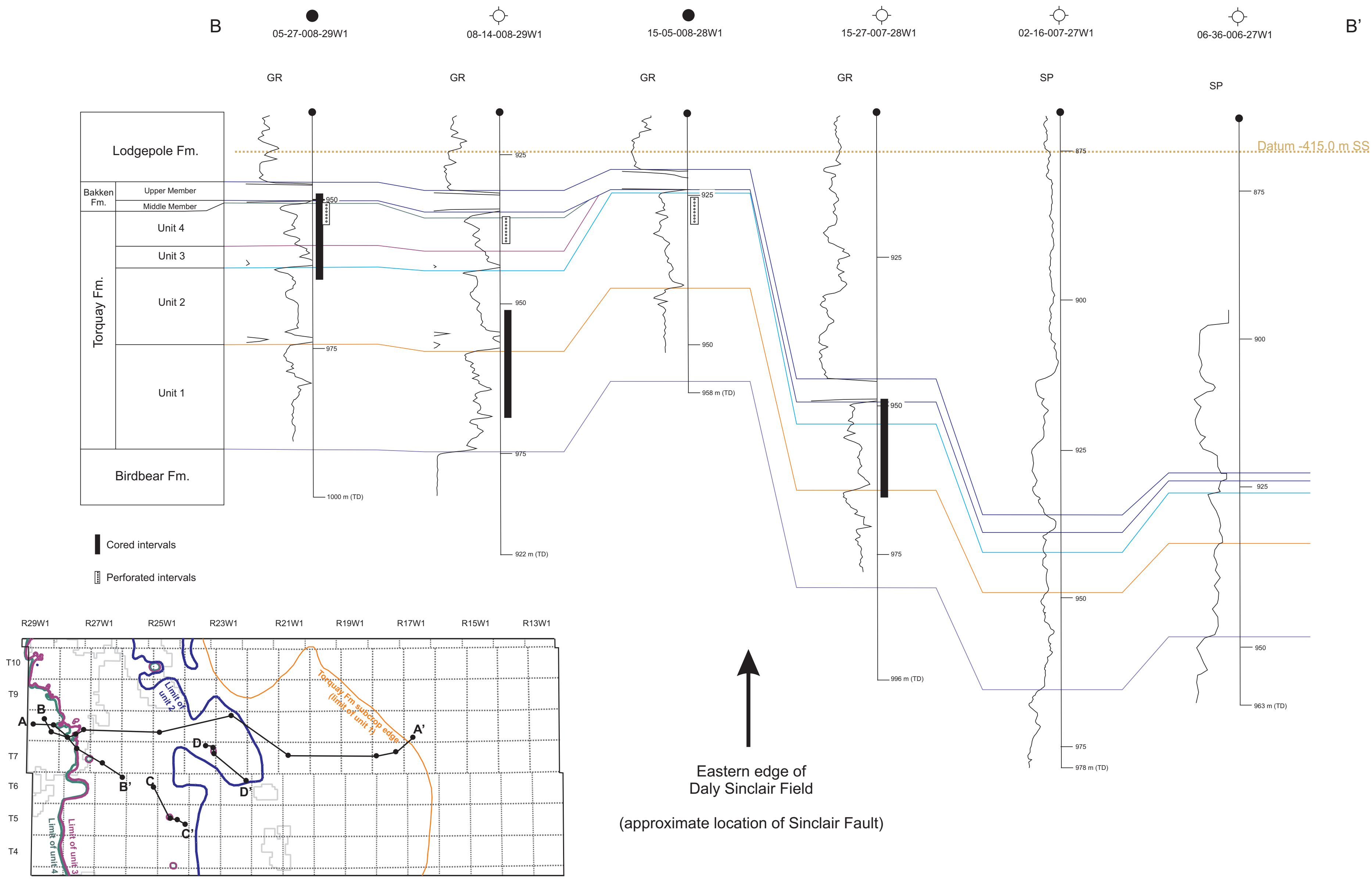


Figure 37: *West to east structural cross-section BB’ across the southern half of the Daly Sinclair Field and to the east. Abbreviations: Fm., Formation; GR, gamma ray.*

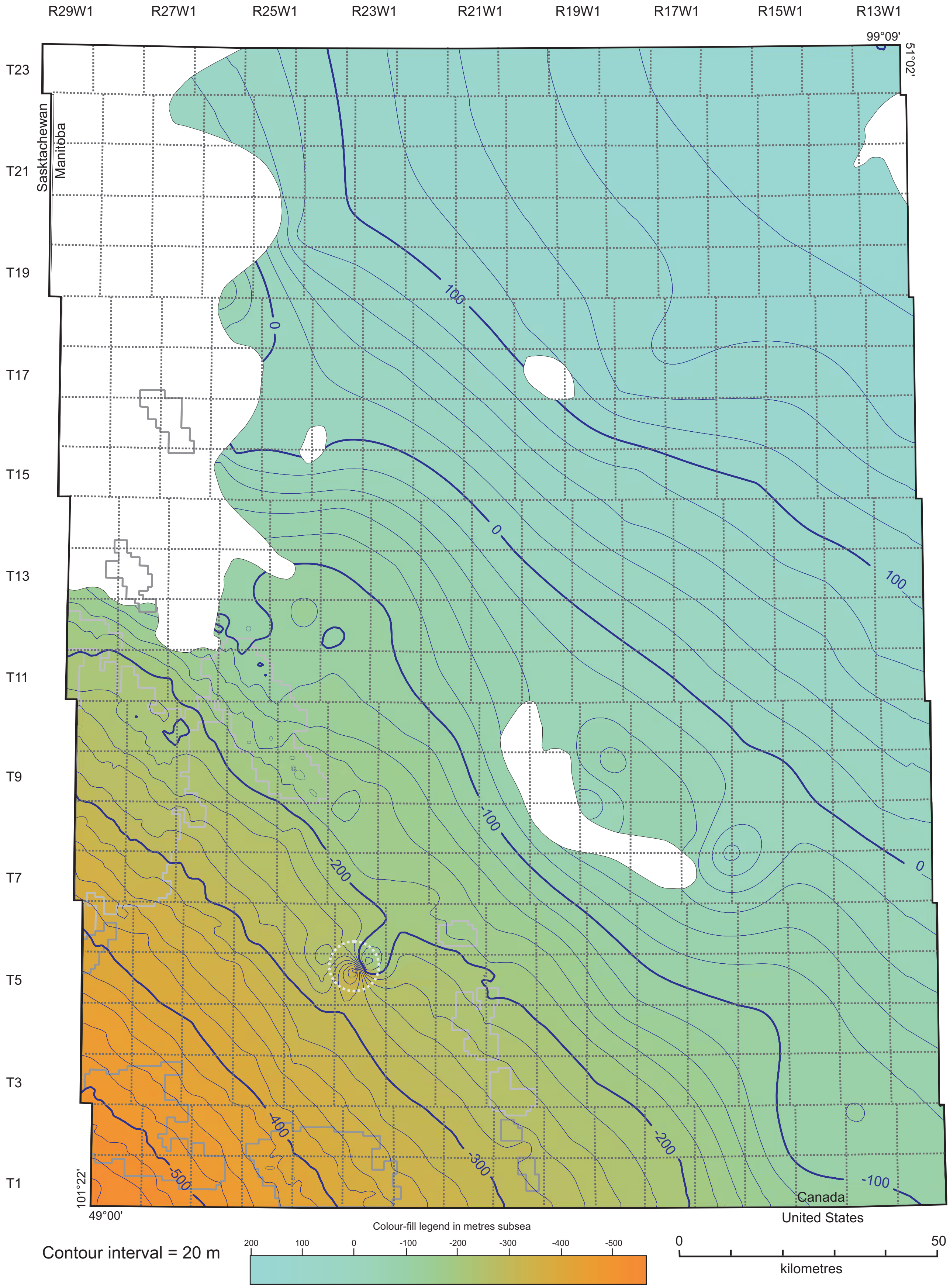


Figure 38: *Structure-contour map of the Amaranth Formation; contour interval is 20 m. Computer generated using the kriging method at a grid-point spacing of 1000 m. Oil-field boundaries are shown in grey outlines (Fulton-Regula, 2012); refer to Figure 1 for field names. Outline of the Hartney Structure is shown as a dotted white circle.*

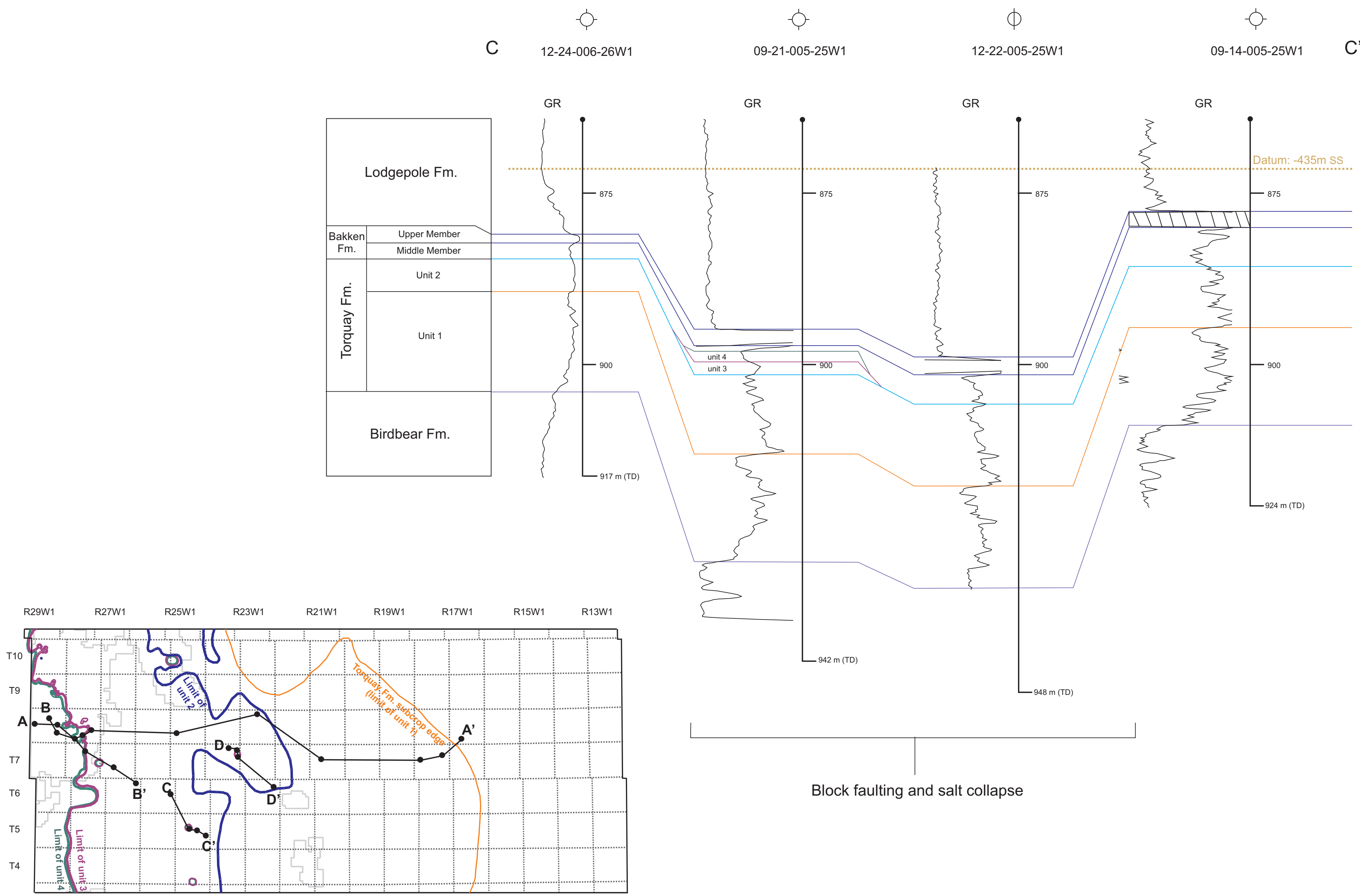


Figure 39: *Structural cross-section CC' through a salt-collapse structure and localized preservation of unit 4 in 9-21-5-25W1. Abbreviation: Fm., Formation; GR, gamma ray.*

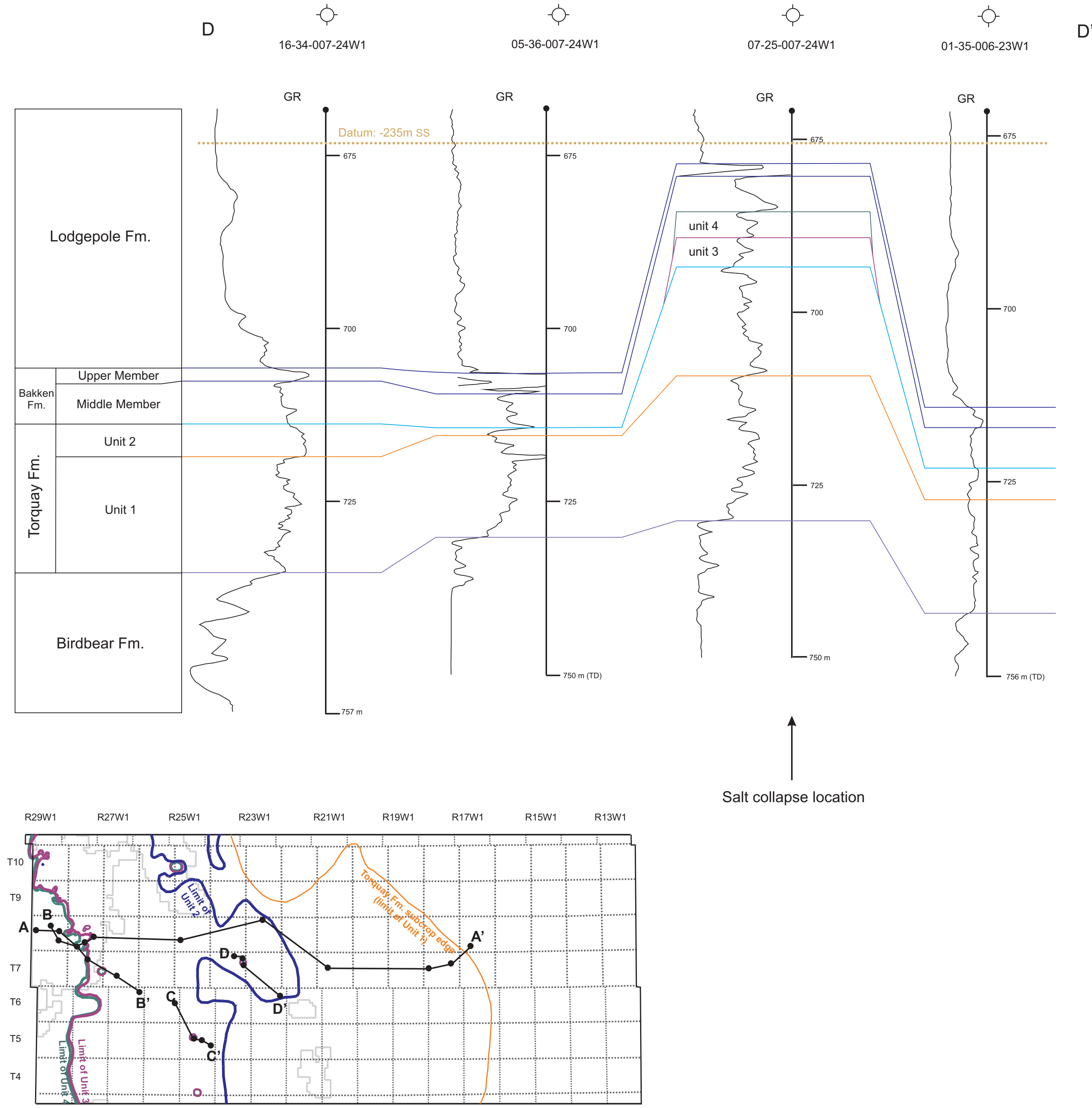


Figure 40: *Structural cross-section DD’ through a series of wells affected by block faulting and salt collapse, resulting in the extra preservation of unit 4 in 7-25-7-24W1. Abbreviation: Fm., Formation; GR, gamma ray.*

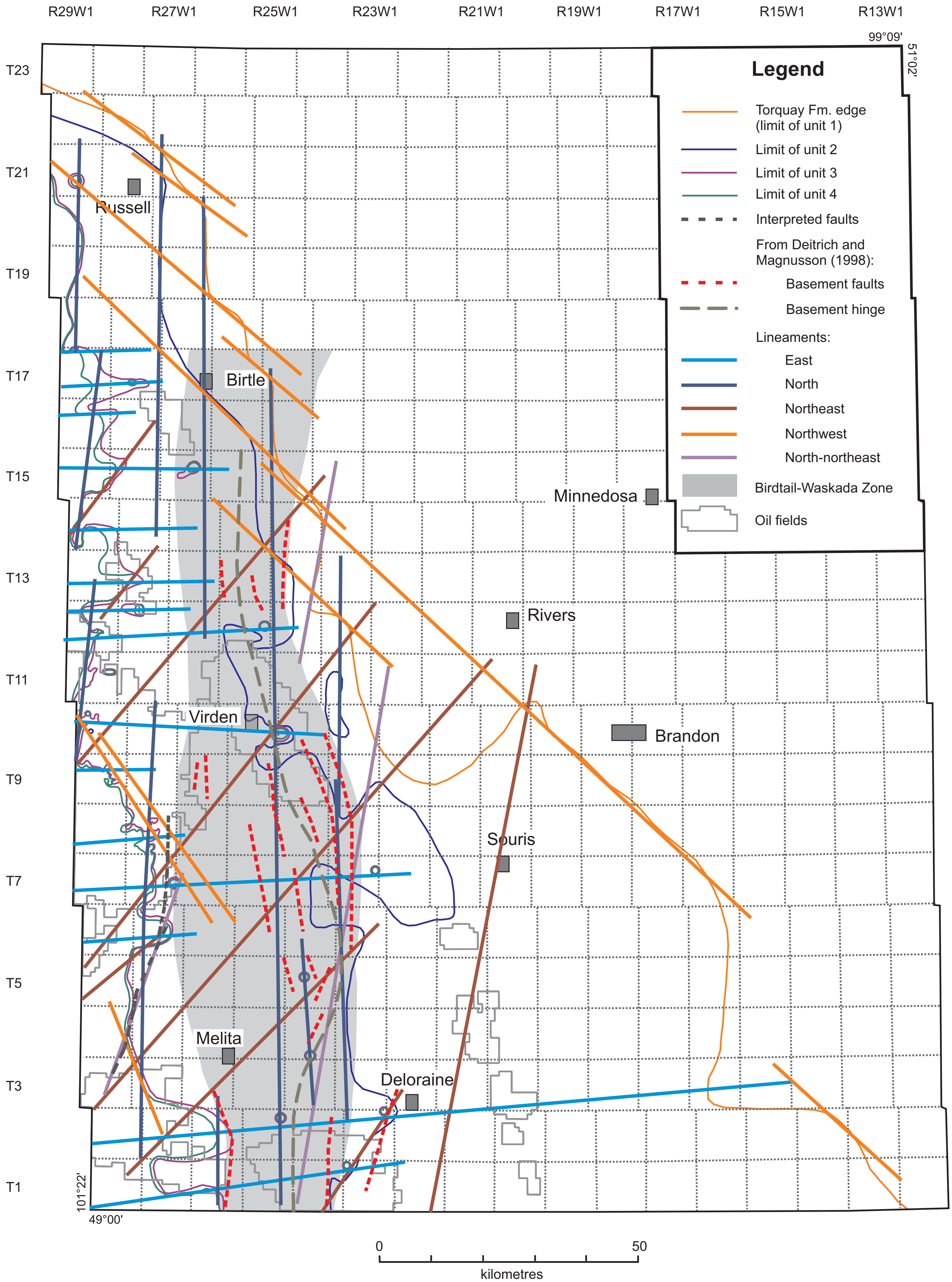


Figure 41: *Known and extrapolated faults and interpreted lineaments on the top of the Torquay Formation.*

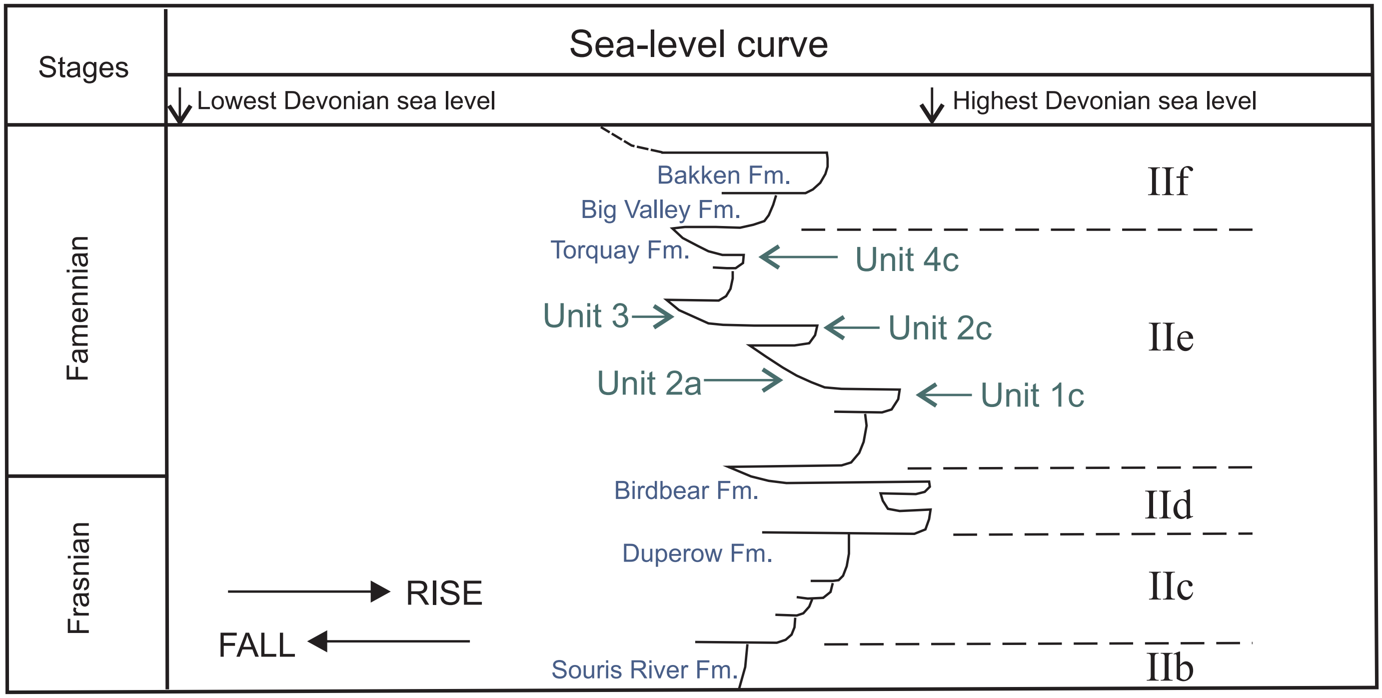


Figure 42: *Qualitative, eustatic sea-level curve for the Late Devonian (modified after Johnson et al., 1985); dashed lines indicate major transgressive-regressive (T-R) cycle breaks; Roman numerals indicate the T-R cycles as shown in Johnson et al. (1985). Abbreviation: Fm., Formation.*

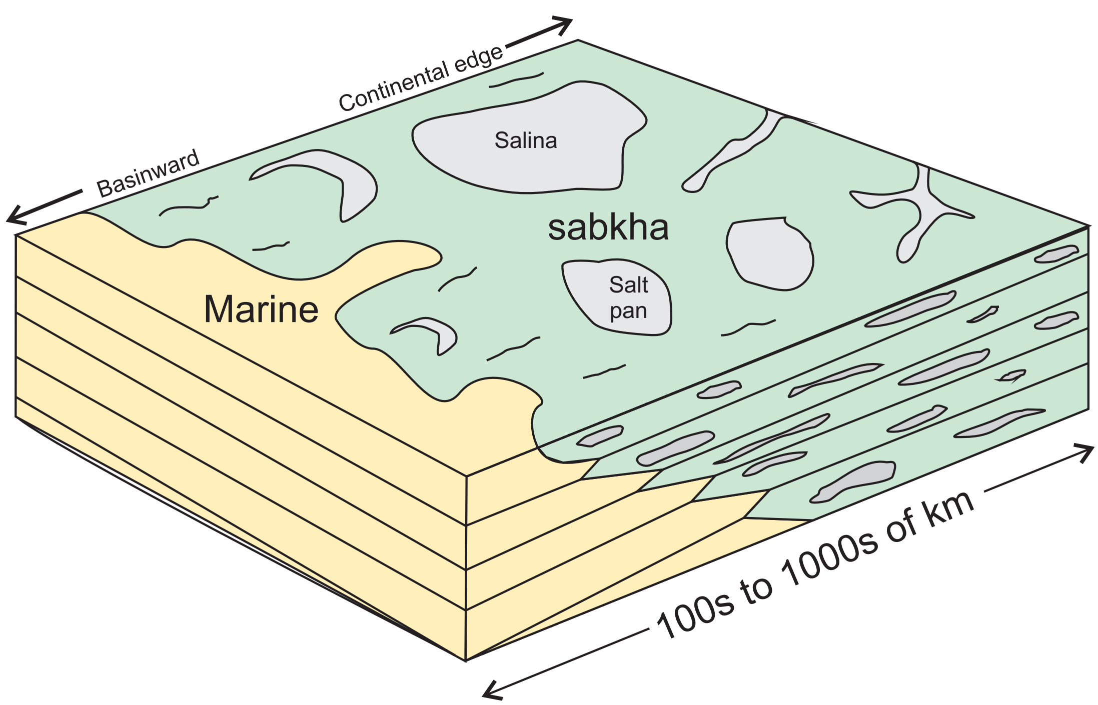


Figure 43: *Block diagram of the depositional model of a giant evaporitic mudflat platform representing the Torquay Formation.*

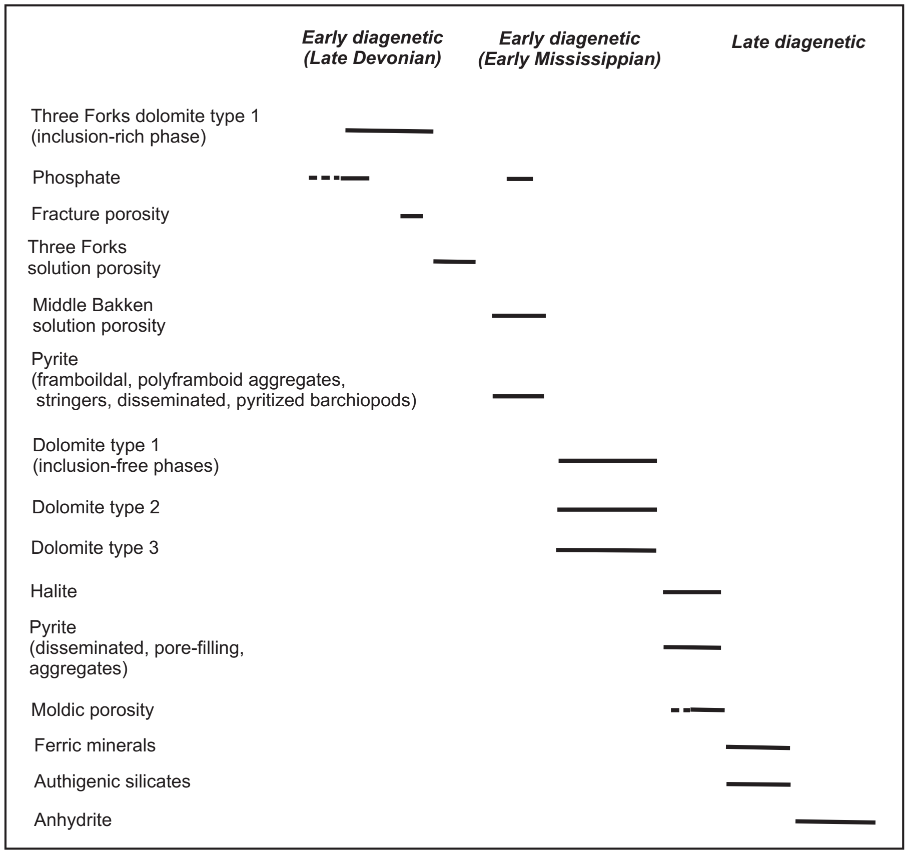


Figure 44: *Paragenetic sequence for the Torquay Formation and Middle Bakken Member in the Daly Sinclair Field area (modified from Karasinski, 2006).*

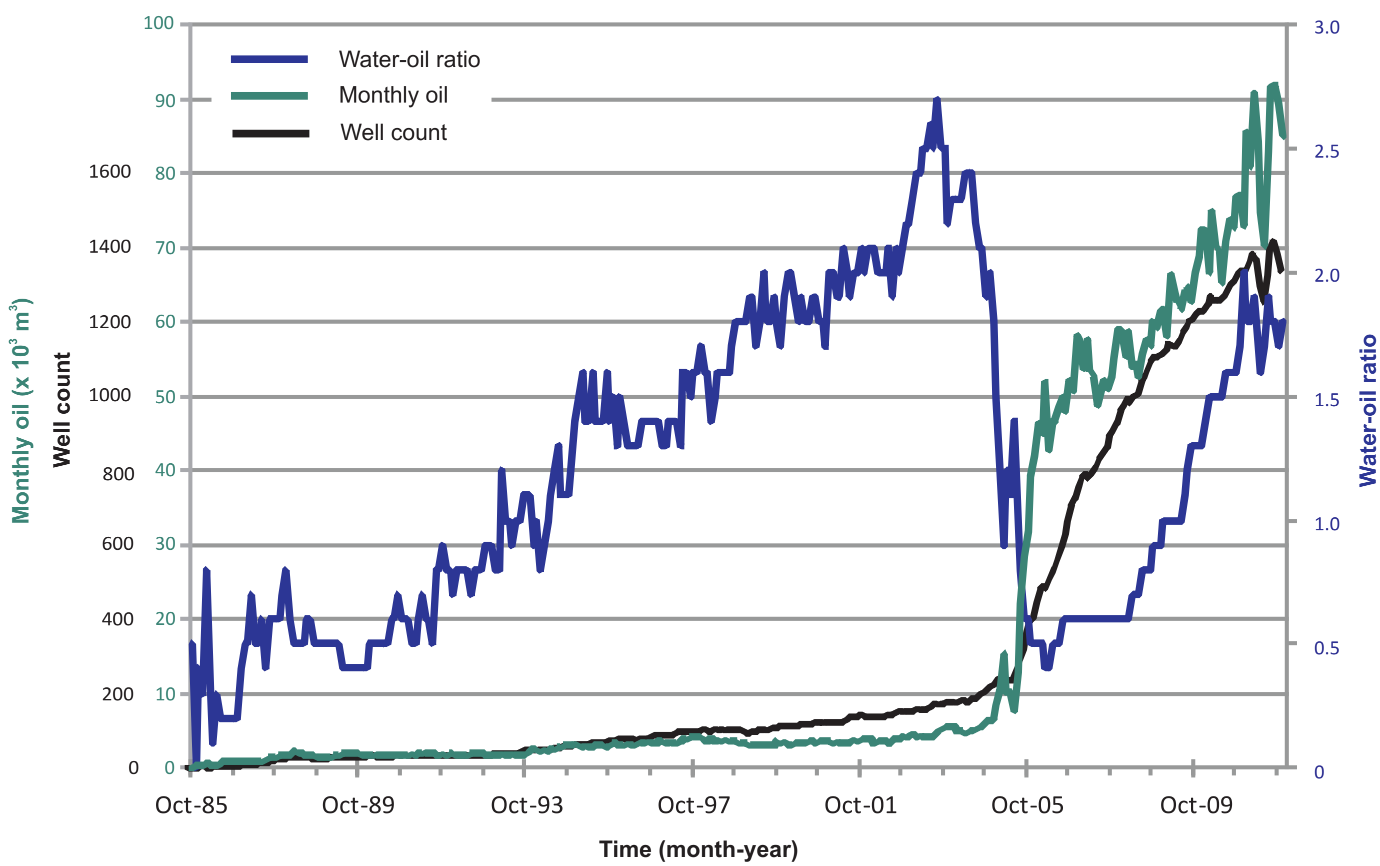


Figure 45: *Production graph of all Bakken and Bakken–Three Forks pools in Manitoba; information current to December 31, 2011.*

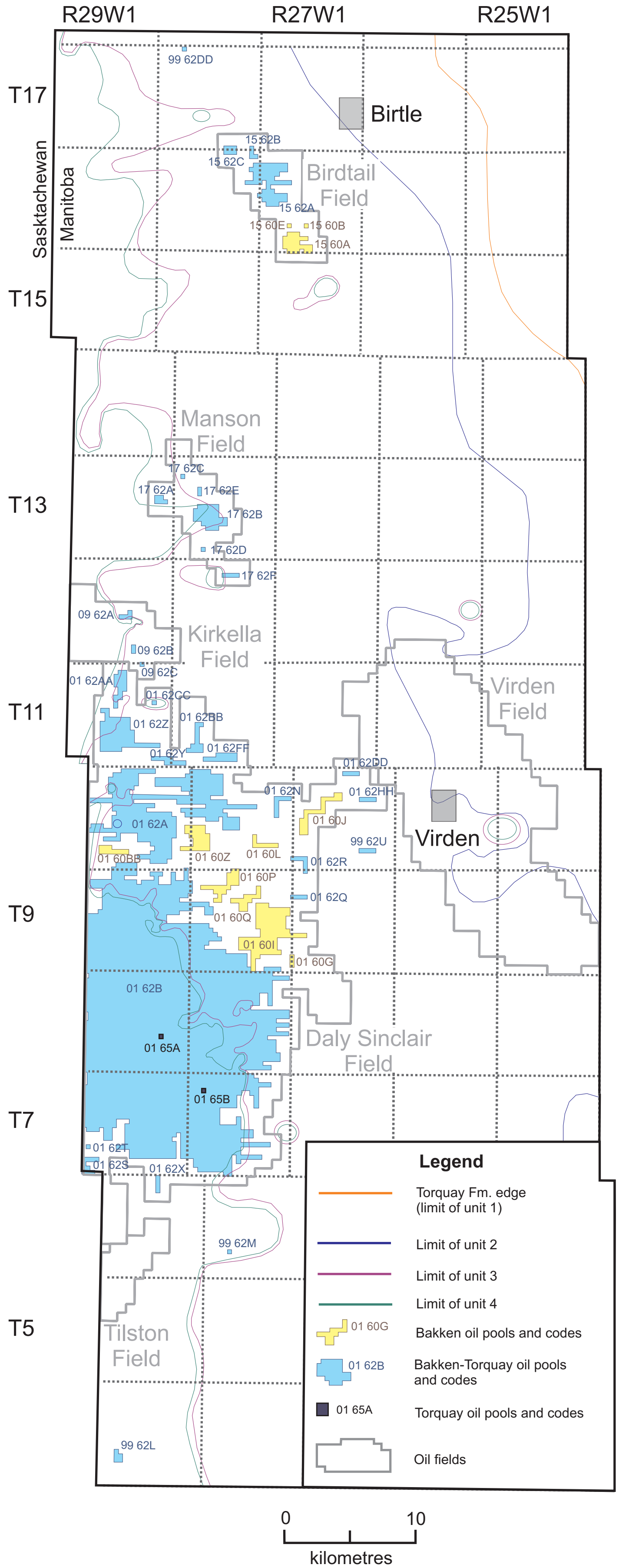


Figure 46: *Bakken, Bakken-Torquay and Torquay oil pools in southwestern Manitoba plotted with respect to the Torquay unit edges. Field-pool codes and field and pool boundaries are from Fulton-Regula (2012).*

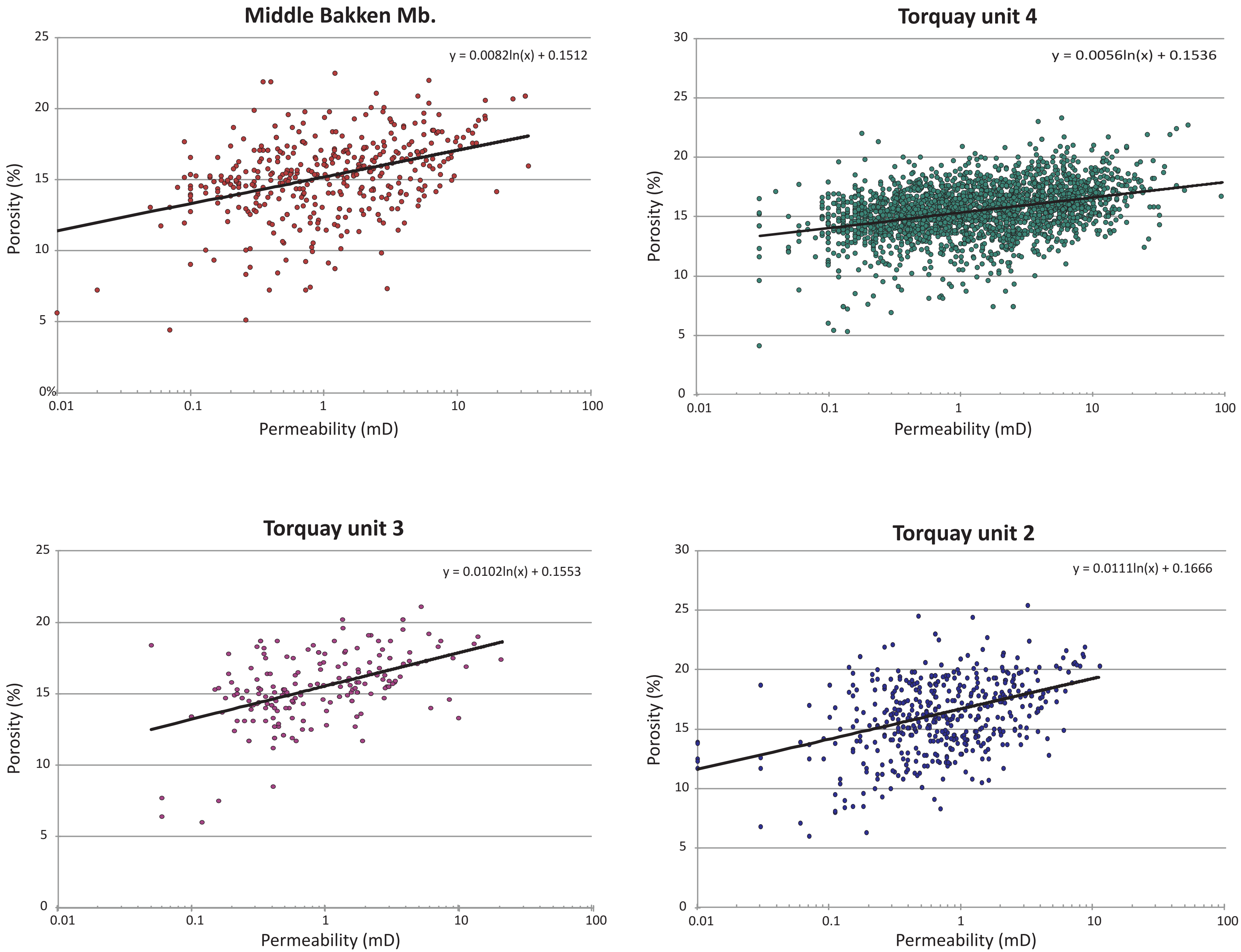


Figure 47: *Semilogarithmic plots of porosity versus permeability, showing the variation in these values for the Middle Bakken Member and Torquay units 4, 3 and 2.*

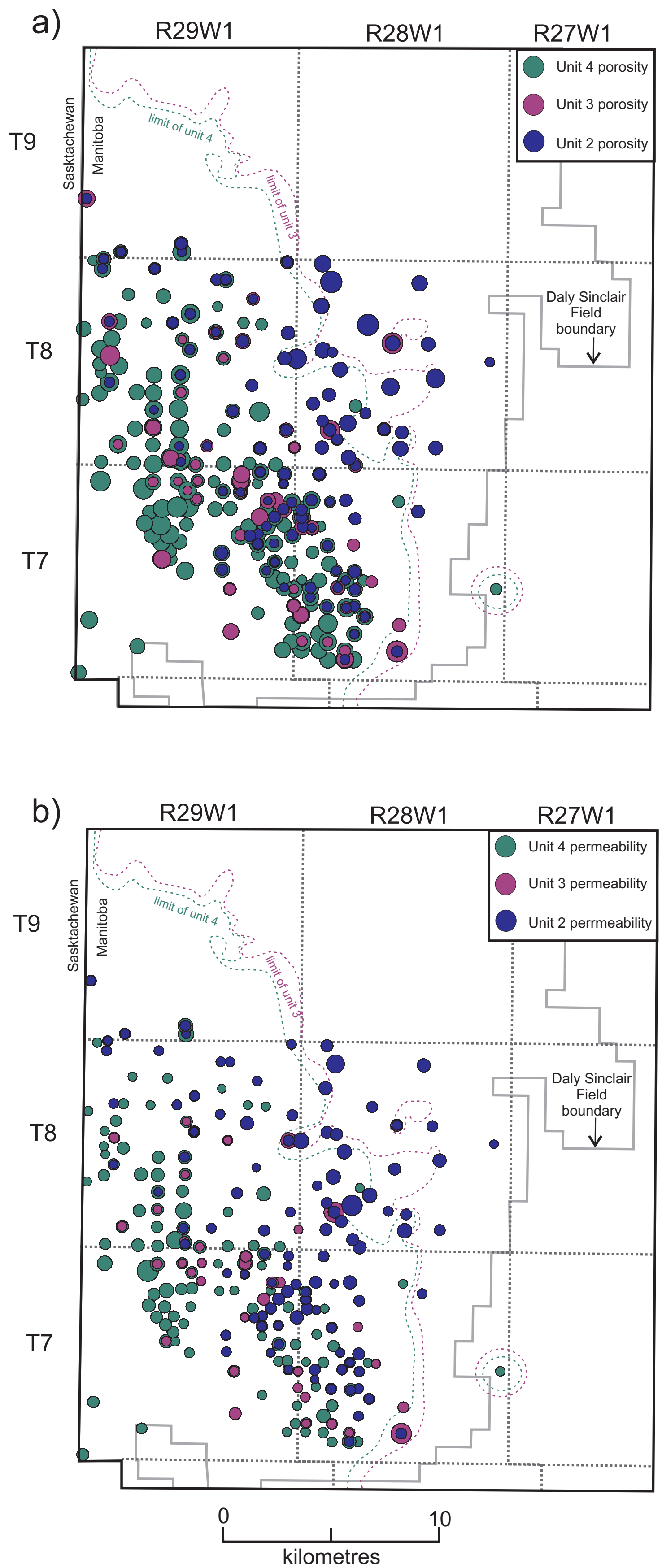


***Figure 48:** Distribution of porosity **(a)** and permeability **(b)** of the Torquay units in the Daly Sinclair Field at the unconformity surface relative to the unit subcrop edges; data are derived from core-analysis reports from all wells up to approximately December 31, 2009. The circle size indicates the relative porosity or permeability (i.e., larger circles represent higher values).*

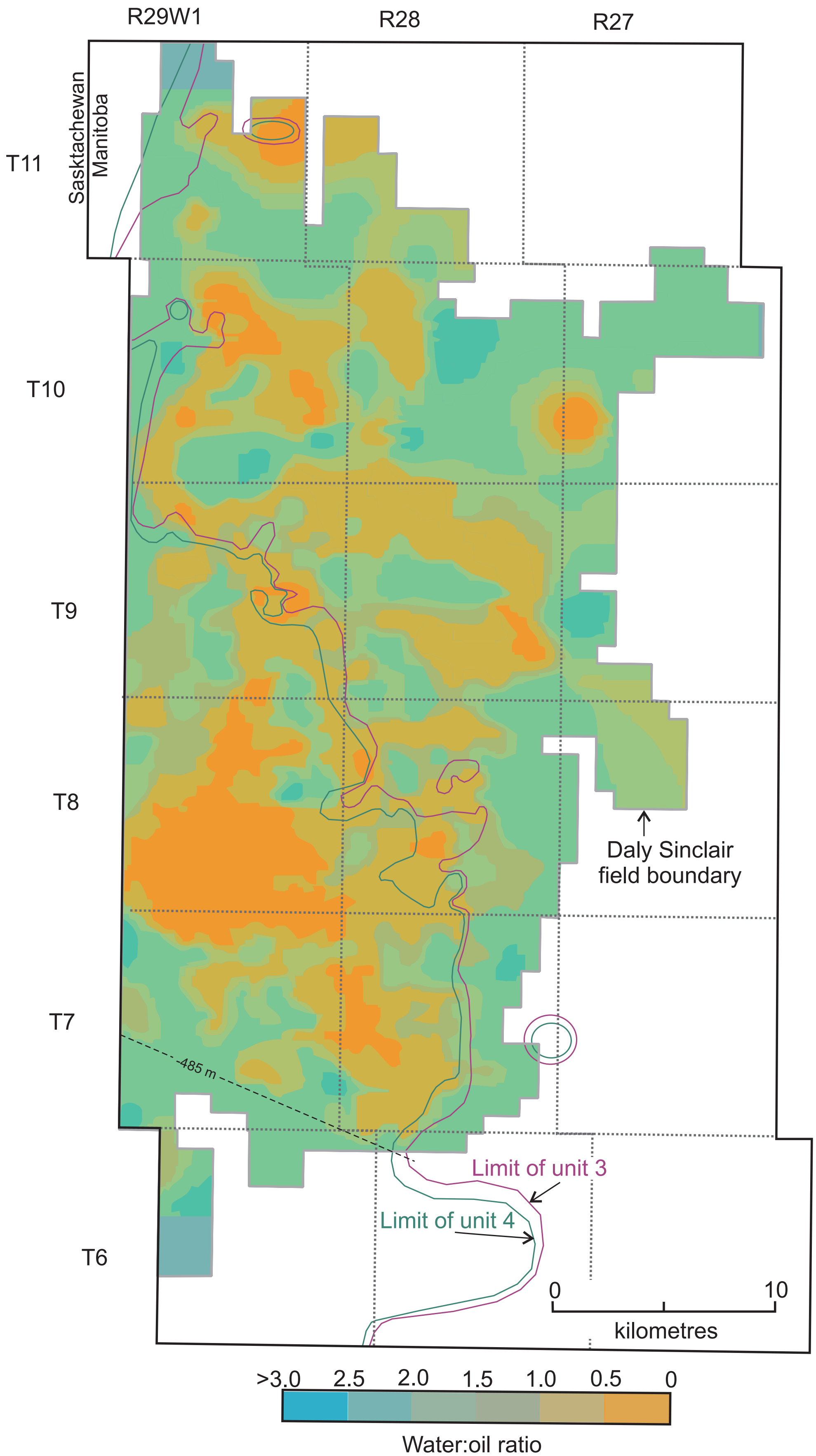


Figure 49: *Contour map of water:oil ratios calculated from the first 12 months of production for Bakken and Bakken-Torquay producing wells in the Daly Sinclair Field. The dashed line represents the –485 m subsea elevation of the Torquay Formation, which correlates with the water-oil contact.*

Appendix 1 – Core descriptions and mosaic core photographs

Selected core descriptions:

Author's note

The core descriptions on the following pages have been reproduced from the author's original descriptions. Very few edits were incorporated into these for inclusion here. The most significant difference between these descriptions and the main body of this report is the use of the terms 'shale' and 'silty shale'. In the report's core descriptions for the Torquay and Big Valley formations, the terms 'shale' and 'silty shale' have been changed to 'claystone' and 'mudstone', respectively, to better reflect the proper lithology and definition associated with these rock types. These changes were not made in the appendix so as to retain the original intent of the core descriptions at the time of logging. Some minor discrepancies occur between the depth of the cored interval indicated and the measured depth during core logging; these errors are due to loss of core and broken core. Core depths and thicknesses are given in the original units; for older wells, a conversion to metric units is included in parentheses.

The 15 core descriptions here were selected from the 82 cores logged for this study to best represent the formations geographically and lithologically. Since core logging was done over a 6-year period, and although every effort was made to maintain consistent descriptions between equivalent units, some slight differences in description style may be present.

Each core description is accompanied by a mosaic core photograph showing the entire core described. The scale card in the photographs is marked in centimetres.

06-21-001-19W1

Well: T.L. Cleary Turtle Mountain

Licence: 1149

KB: 2154 ft. (656.54 m)

Total depth: 3269 ft. (996.39 m)

Cored interval: 3196–3269 ft. (974.14–996.39 m)

Depth (ft.)	Thickness (ft.)	Description
3211.00–3213.72 (978.71–979.51 m)	2.72 (0.83 m)	**Bakken Formation, Upper Member** Shale: Black; blocky; massive to faintly laminated; tight; no oil shows; sharp lower contact
3213.72–3222.58 (979.51–982.24 m)	8.86 (2.70 m)	**Bakken Formation, Middle Member** **Lithofacies 3–4** Sandstone: light to medium grey; mottled; wispy black lenses (likely *Nereites missouriensis* trace fossils); brachiopods; shaly siltstone lenses and beds in places; burrows in places; porosity is 15%, pinpoint and intergranular; no oil shows; no ultraviolet (UV) fluorescence; gradational lower contact
3222.58–3232.60 (982.24–985.30 m)	10.10 (3.08 m)	**Lithofacies 1–2** Sandstone: light brown to maroon to orangish-brown; fine-grained; laminated throughout; occasional shaly laminae; medium-grained sandstone lenses throughout; porosity is 15%, pinpoint and intergranular; no oil shows; no UV fluorescence; sharp lower contact
3232.68–3248.17 (985.60–990.04 m)	15.4 (4.72 m)	**Torquay Formation** **Subunit 1c** Shaly siltstone: grey-green; massive; disseminated pyrite throughout; occasional coarse-grained sandstone lenses; has faint conchoidal fracture; poor porosity (<10%), pinpoint and intergranular; no oil shows; no UV fluorescence; sharp lower contact
3248.17–3254.24 (990.04–991.89 m)	6.07 (1.85 m)	**Subunit 1b** Silty shale: red-brown; massive; appears same as subunit 1c above, but oxidized; slight conchoidal fracture; poor porosity (<5%); no oil shows; sharp lower contact
3254.24–3258.31 (991.89–993.13 m)	4.07 (1.24 m)	Silty shale: red-brown, with reddish light brown siltstone clasts (angular, <5 mm in diameter); 60% shale, 40% siltstone; red-brown shale lenses and laminae throughout; all oxidized, except a few redox haloes of grey-green shale / light brown siltstone; wavy bedded; no oil shows; no UV fluorescence; sharp lower contact
3258.31–3262.44 (993.13–994.39 m)	4.13 (1.26 m)	Silty shale: red-brown; massive; poor porosity (<5%); appears same as subunit 1c above, but oxidized; slight conchoidal fracture; no oil shows; sharp lower contact; similar to interval 3254.24–3258.31 ft. in subunit 1b (above)
3262.44–3268.67 (994.39–996.29 m)	6.23 (1.90 m)	**Subunit 1a** Silty shale: red-brown, with reddish light brown siltstone clasts (angular, <5 mm); 60% shale, 40% siltstone; red-brown shale lenses and laminae throughout; 20% reduced, 80% oxidized; some redox haloes of grey-green shale / light brown siltstone; wavy-bedded; disseminated pyrite throughout; no UV fluorescence; no oil shows; sharp lower contact

06-21-001-19W1

Top

Bottom

Figure 50: *Composite core photograph of depth interval 3196–3269 ft. (974.14–996.39 m) in 6-21-1-19W1.*

14-24-001-25W1

Well: Seneca Waskada

Licence: 4723

KB: 477.3 m

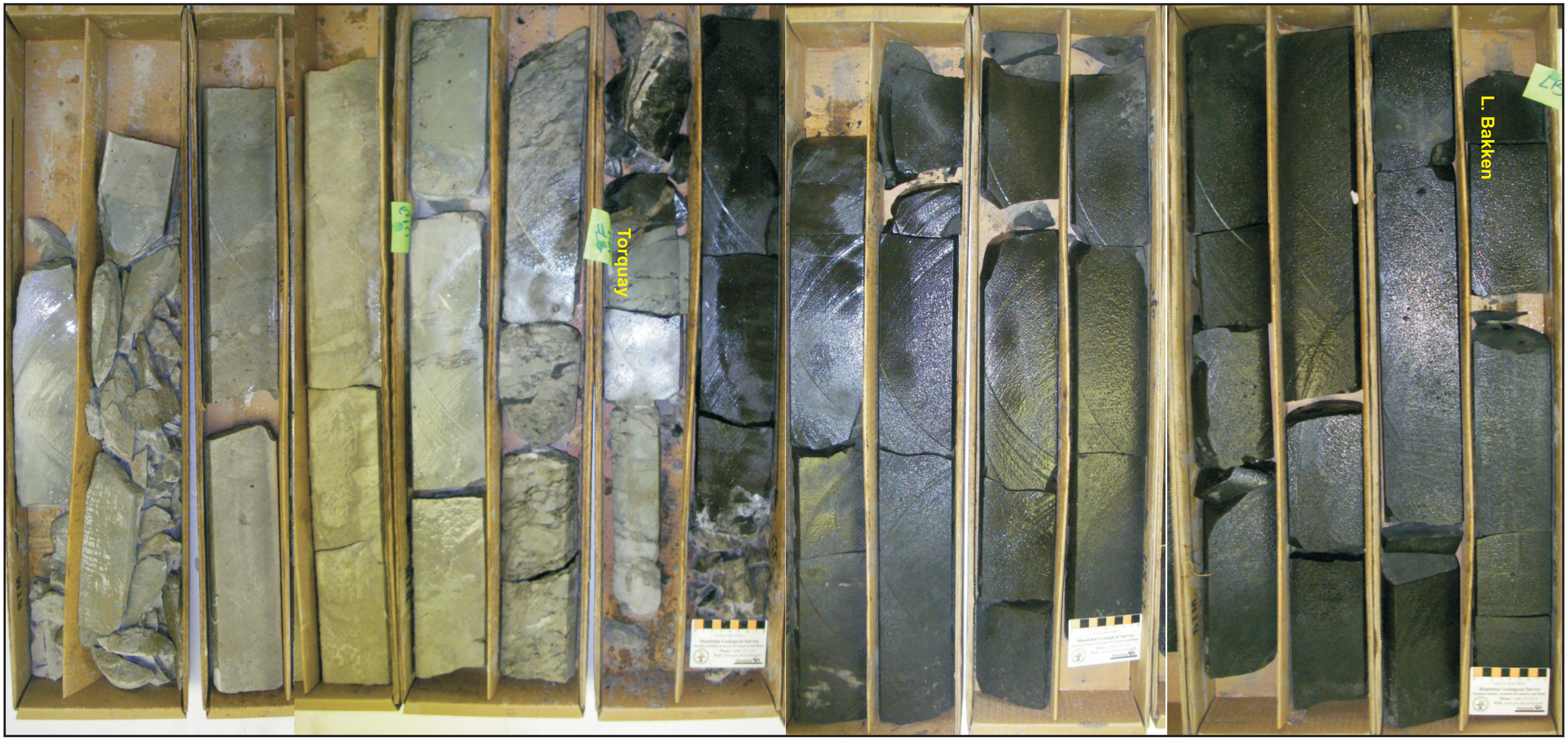
Total depth: 1195.5 m

Cored interval: 1129.0–1139.0 m

Depth (m)	Thickness (m)	Description
1129.0–1135.35	6.35	**Bakken Formation, Lower Member** Shale: dark brown to black; massive; faint dark brown lenses in places; conchoidal-like fracturing; micromicaceous; noncalcareous; basal ~50 cm is highly fractured with large anhydrite-filled fractures; disseminated and bleb pyrite in places, especially in lower 50 cm rubble; pyrite-filled fractures crosscutting lower contact; tight; no oil shows; sharp lower contact
1135.35–1136.69	1.34	**Torquay Formation** **Subunit 1b** Shale: grey-green; some black shale matrix between angular to subangular shale fragments; dolomitic; high-angle bedding juxtaposes lower angle (25°) bedding with a long anhydrite-healed vertical fracture; vertical movement along fracture; poor porosity (0%), pinpoint, intergranular; no shows; sharp lower contact
1136.69–1139.64	2.95	Silty shale: grey-green; mottled to bedded; occasional black shale lenses; dolomitic; disseminated pyrite in places, as blebs and along hairline fractures; soft-sediment deformation/brecciation of bedding toward base; base of core is very rubbly; alternating beds of faintly mottled silty shale with brecciated detrital siltstone clasts, high angle (36°) between these alternating beds; tight, porosity <5%; no oil shows

14-24-001-25W1

Top



Bottom

Figure 51: *Composite core photograph of depth interval 1129.0–1139.0 m in 14-24-1-25W1.*

06-07-004-21W1

Well: Tundra South Regent

Licence: 681

KB: 1647 ft. (502.01 m)

Total Depth: 2824 ft. (860.76 m)

Cored interval: 2799–2824 ft. (853.14–860.76 m)

Depth (ft.)	Thickness (ft.)	Description
2799.00–2805.14 (853.14–855.01 m)	6.14 (1.87 m)	**Torquay Formation** **Subunit 1c** Siltstone: maroon to light brown siltstone; 10% grey-green to red-brown silty shale matrix throughout; mottled with red-brown oxidation; redox haloes common; disseminated pyrite throughout; siltstone clasts are dolarenitic, subrounded; siltstone is massive (or difficult to see original fabric through redox discoloration) to bedded; basal 1 ft. (0.3 m) is shaly and more grey in colour (i.e., not reduced or oxidized); porosity 10–15%, pinpoint; faint yellow spotty UV fluorescence throughout; spotty oil staining; gradational lower contact
2805.14–2810.39 (855.01–856.61 m)	5.25 (1.60 m)	Siltstone: light brown to pinkish-brown; grey-green to red-brown silty shale as matrix, lenses and laminae; disseminated pyrite throughout; oxidation gives faint pink colour; soft-sediment deformation throughout; no signs of brecciation, but discontinuous bedding throughout; open and pyrite-healed vertical fractures; porosity 15%, pinpoint and small vugs; faint spotty yellow UV fluorescence in places; spotty oil staining; gradational lower contact
2810.39–2824.33 (856.61–860.86 m)	13.94 ft. (4.25 m)	Silty shale to shale: grey-green with red-brown redox haloes; 20% oxidized; disseminated pyrite throughout; massive and faint relict bedding with small angular siltstone clasts; open vertical fractures; tight; no oil shows

06-07-004-21W1

Top

Bottom

Figure 52: *Composite core photograph of depth interval 2799–2824 ft. (853.14–860.76 m) in 6-7-4-21W1.*

04-17-004-29W1

Well: Connaught South Tilston

Licence: 5938

KB: 497.9 m

Total depth: 1240.0 m

Cored interval: 1202.0–1220.0 m

Depth (m)	Thickness (m)	Description
1202.0–1202.36	0.36	**Lodgepole Formation, Scallion Member** Limestone: light brown to grey; wackestone; scattered crinoids; occasional brachiopods; fine black wispy laminae throughout; mottled; poor porosity (5%), pinpoint; no oil shows; sharp lower contact
1202.36–1203.21	0.85	**Bakken Formation, Upper Member** Shale: black; noncalcareous; blocky; occasional conodont fragments; tight; no oil shows; sharp lower contact
1203.21–1203.40	0.19	**Middle Member** **Lithofacies 3–4** Sandstone to siltstone; medium grey; very fine grained; quartz-rich; noncalcareous; mottled; bioturbated throughout; occasional black wispy lenses (likely *Nereites missouriensis* trace fossils); pyrite-rich sandstone lenses at top contact; lower 3 cm consists of a conglomeratic lag deposit with very fine grained sandstone to siltstone matrix, with rounded granules and pebbles of light grey sandstone; porosity 5–10%, pinpoint and intergranular; mottled pale yellow fluorescence; spotty oil staining; sharp lower contact
1203.40–1203.58	0.18	**Lithofacies 1–2** Sandstone: medium grey; very fine grained; quartz-rich; laminated throughout; blebs of pyrite throughout; noncalcareous; lower 5 cm has clasts of Torquay siltstone; porosity 5–10%, pinpoint and intergranular; spotty oil staining; spotty pale yellow UV fluorescence; sharp lower contact
1203.58–1208.96	5.38	**Torquay Formation** **Subunit 4c** Siltstone: 85% light brown to light grey siltstone, with 15% green-grey silty shale beds and matrix; laminated in places; near top is massive hummocky(?) to crossbedded in places; syneresis cracks; soft-sediment deformation in places; hairline vertical and horizontal fractures, partly to completely healed with pyrite in upper 1–1.5 m; disseminated pyrite throughout, with increased concentrations along bedding planes; occasional brecciated beds similar to subunit 4b; in one brecciated bed is a 5–7 mm transparent anhydrite bleb; open vertical fractures in brecciated zone; porosity 10–15%, pinpoint and fractures; even pale to bright yellow UV fluorescence, even at top and grading to mottled then spotty with increased depth; oil staining in siltstone, not in shale; gradational lower contact
1208.96–1211.80	2.84	**Subunit 4b** Siltstone: light brown to light grey siltstone clasts within 40% green-grey silty shale to shale matrix; brecciated; faint relict bedding seen by alignment of clasts; occasional pyrite as blebs and disseminated; one 15 cm zone toward the base is not brecciated, but consists of a light brown to light grey siltstone, bedded, laminated in places; soft-sediment deformation; rare open horizontal fractures along bedding planes; porosity 10–15 % in siltstone, 5% in shale, pinpoint and fractures; basal 1.4 m has yellow staining; bright yellow UV fluorescent bands and in siltstone clasts; gradational lower contact
1211.80–1212.57	0.77	**Subunit 4a** Silty shale: light green-grey to maroon; mottled; yellow staining over nonoxidized areas; faint relict siltstone clasts and faint remnant bedding; tight; no oil shows; gradational lower contact
1212.57–1214.22	1.65	**Unit 3** Silty shale: medium to light grey; unoxidized; faintly mottled; pyrite blebs in places and along vertical fractures; mottled with oxidation at base; tight; no oil shows; gradational lower contact to lower zone.
1214.22–1215.37	1.15	Silty shale: red-brown, occasionally medium to light grey; oxidized; faint relict siltstone clasts, matrix supported; tight, no oil shows; sharp lower contact
1215.37–1216.87	1.5	**Subunit 2c** Siltstone: 90% light brown siltstone with 10% green-grey silty shale laminae and lenses; some soft-sediment deformation; ripples; crossbedded; disseminated pyrite throughout and along bedding planes; open horizontal vertical fractures, mostly along bedding planes; porosity 10–15%, pinpoint and fractures; spotty oil staining; pale yellow UV fluorescence; sharp lower contact
1216.87–1221.08	4.21	**Subunit 2b** Siltstone to silty shale: red-brown oxidized to light brown siltstone beds and laminae, with dark red-brown silty shale interbeds and matrix; 70% of interval is oxidized, 30% is reduced; oxidized is massive to mottled, and preferentially occurs in shale and silty shale zones; soft-sediment deformation throughout; alternating zones of laminated siltstone and grey-green shale rhythmites, zones of massive silty shale to shale, and zone with occasional siltstone-clast relicts within a silty shale; ripples; crossbedded; lower 1.12 m is a massive red-brown oxidized silty shale with occasional siltstone relict clasts and laminations, mostly oxidized, rare redox haloes; porosity is variable, generally siltstone is 10–15% pinpoint and shale is tight; no oil shows

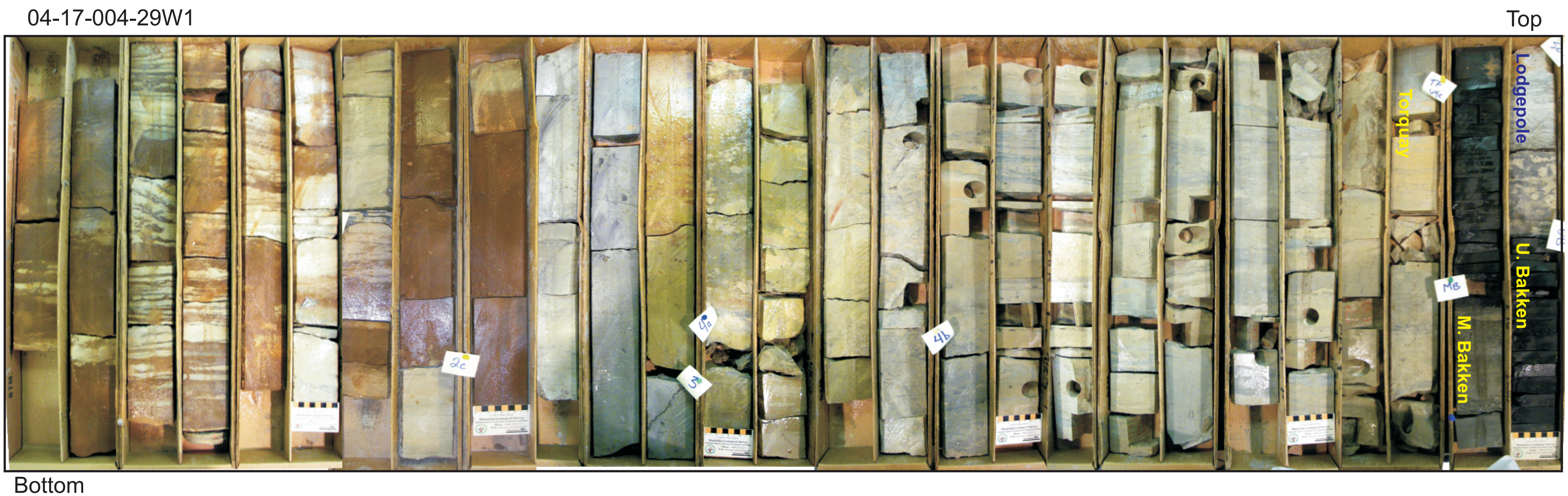


Figure 53: *Composite core photograph of depth interval 1202.0–1220.0 m in 4-17-4-29W1.*

12-22-005-25W1

Well: Clampett West Lauder

Licence: 7493

KB: 436.7 m

Total depth: 948.0 m

Cored interval: 898–933 m

Depth (m)	Thickness (m)	Description
898.00–900.87	2.97	**Lodgepole Formation, Scallion Member** Limestone: light grey to maroon; mottled; nodular; common argillaceous laminae and stringers; occasional crinoid fragments; more nodular in upper 1.5 m; small vugs and hairline vertical fractures infilled with anhydrite and/or pyrite-rich shale; open vertical fractures 40 cm long near base; poor porosity (5%), pinpoint and intercrystalline; no oil shows; sharp lower contact
900.97–902.82	1.85	**Bakken Formation, Upper Member** Shale: black to very dark purple-black; blocky to fissile; occasional conodonts; noncalcareous; tight; occasionally mottled with dark rusty blebs; no oil shows; sharp lower contact
902.82–905.30	2.48	**Middle Member** **Lithofacies 3–4** Siltstone to sandstone: medium grey to red-brown to maroon; shaly siltstone to siltstone to very fine grained sandstone; mottled; mostly oxidized; bioturbated throughout; occasionally massive; occasional small brachiopods; moderate porosity (8–10%), pinpoint and intergranular; light spotty oil staining; pale yellow UV fluorescence; gradational lower contact
905.30–906.81	1.51	**Lithofacies 1–2** Siltstone to sandstone: red-brown to maroon, some light green-grey to light grey; very fine grained; laminated throughout; mostly all oxidized; wavy-bedded; occasional very small burrows; shaly lenses common; porosity 5–8%, pinpoint and intergranular; no oil shows Note: lower contact missing; 9 m of core lost (907–916 m)
916.00–918.71	2.71	**Torquay Formation** **Subunit 2a** Silty shale: red-brown; 95% oxidized; occasional redox haloes are grey-green; occasional thin beds with relict angular siltstone fragments/clasts; occasional shale-filled hairline vertical fractures; poor porosity (<5%), pinpoint and intergranular; sharp lower contact; no oil shows; sharp lower contact
918.71–921.90 m	3.19	**Subunit 1c** Shaly siltstone to siltstone: light brown and grey-green, red-brown; 70% oxidized; redox haloes common; upper 0.57 m is dominantly siltstone with grey-green shale laminae, lenses and matrix; soft-sediment deformation common; remainder of unit is shaly siltstone with disturbed bedding; occasional ripple marks; moderate porosity (10% in upper 0.57 m, 5% in rest of unit); no oil shows; gradational lower contact
921.90–930.14	8.24	**Subunit 1b** Silty shale: red-brown; 95% oxidized, occasional grey-green redox haloes; occasional dark grey anhydrite nodules, occurrence and size of nodules increase with increased depth; occasional relicts of angular to subangular siltstone clasts/fragments; anhydrite-healed vertical fractures at 924.16–924.7 m and at base of unit; between 924.7 and 928 m, there are elongated, subangular to angular siltstone clasts in shaly matrix, wavy-bedded; anhydrite nodules; poor porosity (<5%), pinpoint and intergranular; no oil shows; gradational lower contact
930.14–933.0	2.86 m	**Subunit 1a** Silty shale: red-brown; 98% oxidized; 20% dark grey nodular anhydrite, argillaceous; very similar to middle part of subunit 1b, but more anhydrite in this unit; anhydrite content increases with depth; occasional siltstone laminae and thin beds; soft-sediment deformation throughout; faintly bedded, as evidenced by parallel alignment of siltstone clasts; poor porosity (<5%); no oil shows

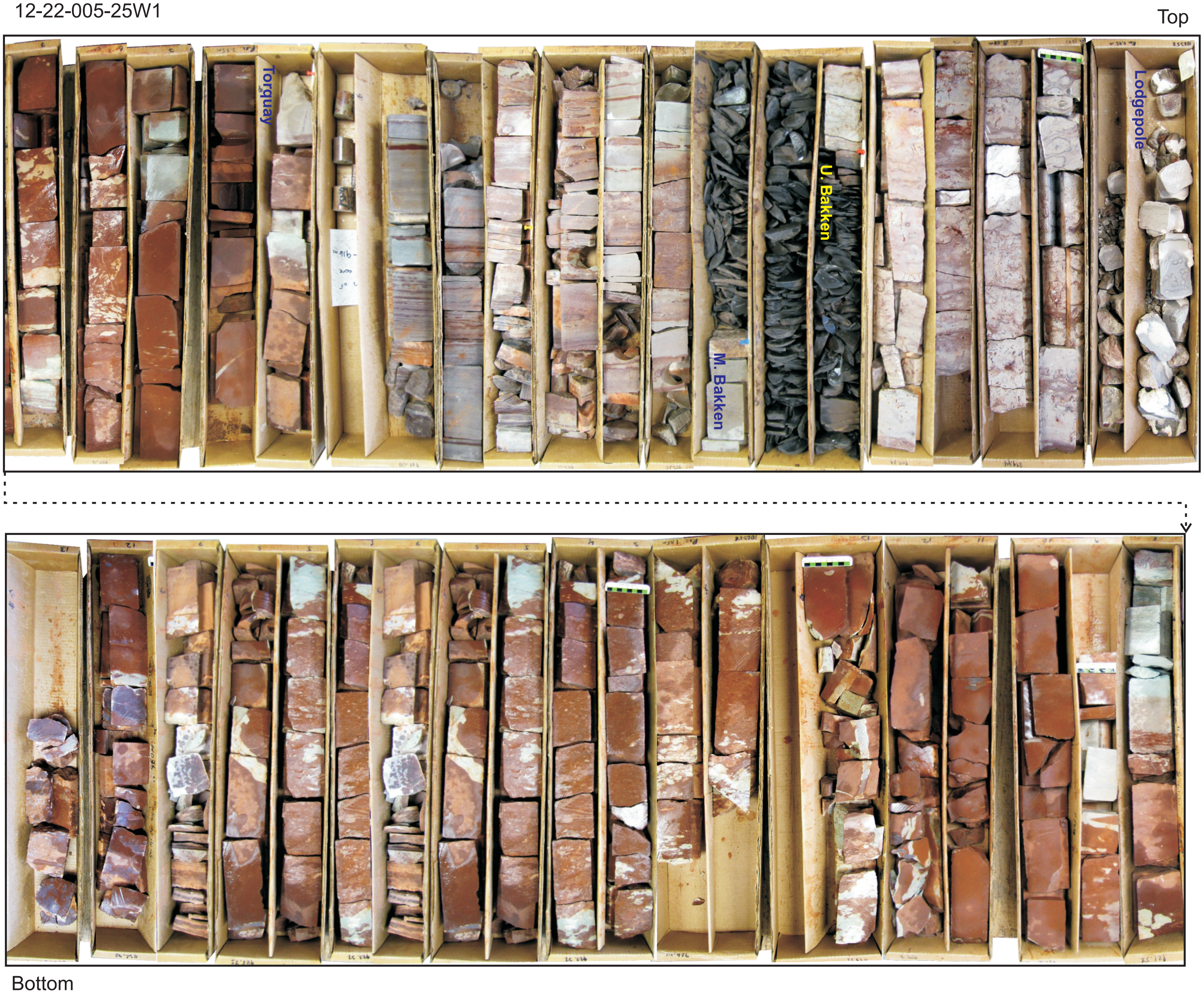


Figure 54: *Composite core photograph of depth interval 898–933 m in 12-22-5-25W1.*

04-28-007-29W1

Well: Tundra Sinclair Prov.

Licence: 5303

KB: 518.7 m

Total depth: 1045.0 m

Cored interval: 1002.0–1020.0 m

Depth (m)	Thickness (m)	Description
1002.0–1002.79	0.79	**Bakken Formation, Upper Member** Shale: black; blocky, hockey pucks; noncalcareous; occasional conodonts; tight; no oil shows; sharp lower contact
1002.79–1003.41	0.62	**Middle Member** **Lithofacies 3–4** Siltstone: medium grey; noncalcareous; burrow-mottled throughout; black wispy lenses throughout (likely *Nereites missouriensis* trace fossils); brachiopod-rich beds in places; open hairline horizontal fractures in places; occasional disseminated pyrite; white anhydrite blebs and fossil replacements; good porosity (10–15%), pinpoint, intergranular and fractures; no oil shows; gradational lower contact
1003.41–1004.31	0.90	**Lithofacies 1–2** Sandstone: medium to dark grey to medium brown; very fine grained; finely laminated throughout; occasional wavy bedding; occasional disseminated pyrite, especially along basal contact; good porosity (10–15%), pinpoint and intergranular; no UV fluorescence; no oil shows; sharp lower contact
1004.31–1008.36	4.05	**Torquay Formation** **Subunit 4c** Siltstone: 85% light brown siltstone with 15% grey-green shale as interbeds, laminae, flasers, lenses and matrix; noncalcareous; soft-sediment deformation in places; siltstone has ripples, cross-bedding, massive to hummocky bedding in places; thin haloturbated beds common; noncalcareous; occasional anhydrite blebs and dolomite replacement blebs; disseminated pyrite throughout, and concentrated along preferential bedding planes; occasional open horizontal fractures along preferential shale-siltstone bedding-plane contacts; two 15 cm zones of nonreduced, nonoxidized grey shale are highly haloturbated; good porosity (12–15%), pinpoint and intergranular; straw pale to bright yellow UV fluorescence in places, especially in ripple and crossbeds; spotty to even oil staining; sharp lower contact
1008.36–1011.65	3.29	**Subunit 4b** Shale: 75% grey-green to medium dark grey shale; 25% light brown siltstone fragments; noncalcareous; siltstone occurs as fragments of disturbed bedding with internal sedimentary structures preserved; some zones have large fragments of siltstone and other zones have siltstone more as a matrix or small faint lenses and fragment relicts; boundaries between zones of large fragments and small fragments are sharp; occasional zones are not reduced or oxidized, and shale is medium to dark grey; zones with large siltstone fragments are angular and poorly sorted, shale zones with small faint siltstone fragments are subrounded and moderately sorted; zones of small fragments are probably heavily haloturbated; occasional red-brown shale lenses (reduced) in places; contacts between zones of large fragments and small fragments indicate that fragmentation of a bed below occurred before deposition of the top bed; good porosity in siltstone (10–15%), pinpoint and intergranular; poor porosity in shale (<5%); even pale yellow to straw yellow UV fluorescence throughout siltstone; light oil staining; sharp lower contact
1011.65–1011.89	0.24	**Subunit 4a** Shale: 60% grey-green shale; 40% light brown siltstone; shale occurs as matrix and occasional laminae and lenses within siltstone; haloturbated; most internal structures are missing; noncalcareous; porosity 10%, pinpoint and intergranular; no UV fluorescence; no oil shows; sharp lower contact
1011.89–1015.66	3.77	**Unit 3** Silty shale: red-brown; massive to faintly mottled; occasional elongate, subrounded siltstone clasts aligned parallel to bedding direction; noncalcareous; all oxidized; occasional pinpoint green redox haloes; poor porosity (<10%), intergranular; no UV fluorescence; no oil shows; sharp lower contact
1015.66–1015.81	0.15	**Subunit 2d** Silty shale: grey-green; massive to faintly mottled; noncalcareous; poor porosity (5%), intergranular; no oil shows; sharp lower contact
1015.81–1016.31	1.40	**Subunit 2c** Siltstone: 85% light brown siltstone; 15% grey to grey-green shale as laminae, lenses, flasers and matrix; siltstone commonly has ripples, crossbedding, hummocky cross-stratification; noncalcareous; sedimentary structures in siltstone repeat throughout section in cycles of (bottom to top): hummocky, crossbedding, ripples, distorted bedding; escape structures are concentrated in particular 40 cm zones from 1016.26 to 1016.66 m; occasional burrow mottling; good porosity (12–15%), pinpoint and intergranular; no UV fluorescence; no oil shows; sharp lower contact

Depth (m)	Thickness (m)	Description
1016.31–1020.13	2.92	**Subunit 2b** Siltstone to shale: 50% light brown siltstone as laminae, thin beds and distorted fragments; 50% grey-green shale as laminae, flasers, thin beds and matrix; noncalcareous; two thick zones within units of rhythmites (alternating beds of 5 mm of massive siltstone and shale with ripples and flasers in places); occasional thick zones of distorted beds where internal structures of siltstone fragments are destroyed; 50% oxidized; redox haloes common throughout, with oxidation most pervasive in shale; some thin distorted beds with rhythmite zones; good porosity in siltstone (10–12%), pinpoint and intergranular; poor porosity in shale (<5%); no oil shows

04-28-007-29W1

Top

Bottom

Figure 55: *Composite core photograph of depth interval 1002.0–1020.0 m in 4-28-7-29W1.*

09-14-008-28W1

Well: Tundra Sinclair Prov.

Licence: 6032

KB: 482.6 m

Total depth: 917.0 m

Cored interval: 874.0–890.0 m

Depth (m)	Thickness (m)	Description
874.0–875.68	1.68	**Bakken Formation, Upper Member** Shale: black; noncalcareous; blocky; occasional conodonts; pyrite disseminated and as small blebs; tight; no oil shows; sharp lower contact
875.68–876.85	1.17	**Middle Member** **Lithofacies 3–4** Siltstone: medium grey; burrow-mottled throughout; noncalcareous; black wispy lenses throughout (likely *Nereites missouriensis* trace fossils); occasional brachiopods; disseminated pyrite throughout; porosity 10%, pinpoint and intergranular; no UV fluorescence; no oil shows; gradational lower contact
876.85–878.15	1.30	**Lithofacies 1–2** Sandstone: medium to dark grey to brown; siltstone to very fine grained sandstone; finely laminated throughout; some wavy bedding; occasional small-scale bioturbation; occasional burrows; good porosity (10–15%), pinpoint and intergranular; no UV fluorescence; no oil shows; sharp lower contact
878.15–879.67	1.52	**Torquay Formation** **Subunit 2b** Siltstone to shale: 50% beige to light brown siltstone, 50% grey-green shale to silty shale; rhythmites of massive to haloturbated thin beds of shale and siltstone; porosity 10%, pinpoint and intergranular; no oil shows; sharp lower contact
879.67–888.56	8.89	**Subunit 2a** Silty shale: brownish grey-green; massive to faintly bedded; disseminated and small blebs of pyrite throughout; two zones of increased shaliness, where laminated, distorted/brecciated siltstone beds occur, top bed is 30 cm thick, and lower bed is 1.10 m thick; lower part of unit is more oxidized, mostly as haloing and preferential oxidation of shale and long hairline vertical fractures; redox (green) haloes along a 70 cm long, partly open vertical hairline fracture in basal oxidized zone; poor porosity (<10%), intergranular and pinpoint; no oil shows; gradational lower contact; lower contact difficult to determine due to extensive oxidation overprint
888.56–889.58	1.02	**Subunit 1c** Silty shale: red-brown shale to silty shale, with light brown to beige siltstone as thin beds, laminae and small fragments; alternating zones of massive to faintly bedded silty shale, and fragmented siltstone within shale matrix; porosity 15%, pinpoint and intergranular; no oil shows

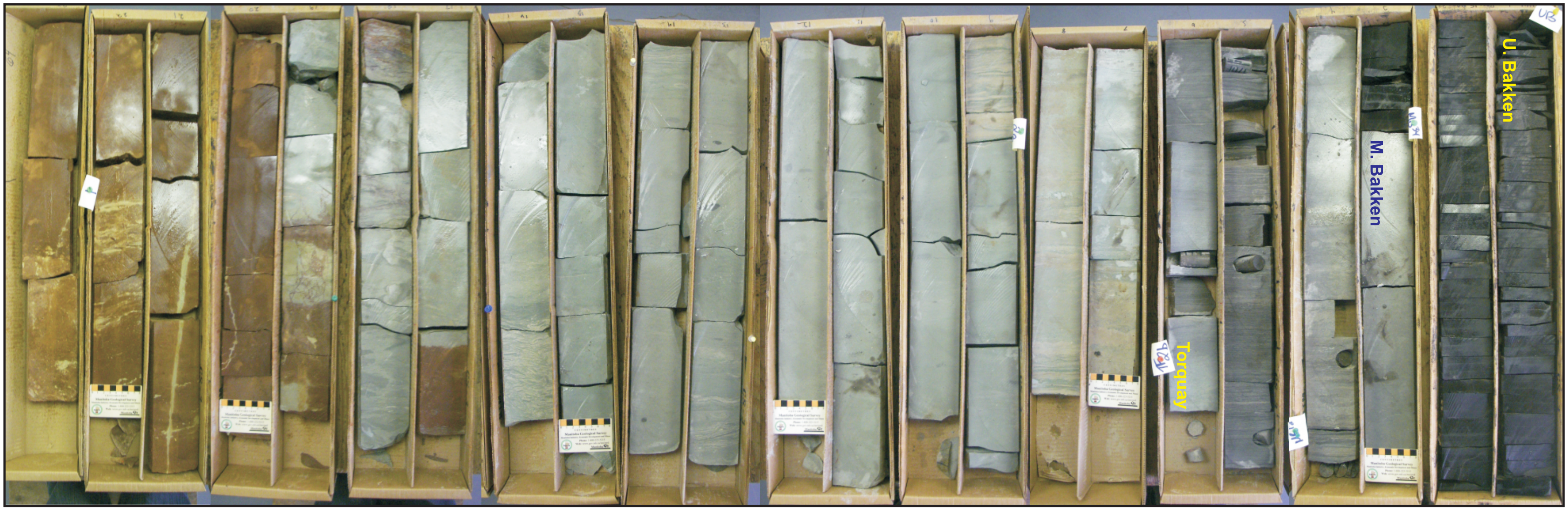


Figure 56: *Composite core photograph of depth interval 874.0–890.0 m in 9-14-8-28W1.*

04-23-008-29W1

Well: Tundra Sinclair

Licence: 5590

KB: 515.9 m

Total depth: 995.0 m

Cored interval: 939.5–950.2 m

Depth (m)	Thickness (m)	Description
939.50–940.62	1.12	**Bakken Formation, Upper Member** Shale: black; fissile to blocky; planar laminations; traces of disseminated pyrite; noncalcareous; dolomite replacement of fossils in some beds; tight porosity; no oil shows; sharp lower contact
940.62–941.13	0.51	**Middle Member** Sandstone: dark grey; faint wavy bedding to massive in places; pyrite disseminated throughout and as replacement of clasts near base of unit; noncalcareous; 15–20% pinpoint and intergranular porosity; no UV fluorescence; no oil shows; sharp lower contact 940.62–940.85: lithofacies 3–4 940.85–941.13: lithofacies 1–2
941.13–944.46	3.33	**Torquay Formation** **Subunit 4c** Siltstone: 70% light brown to tan siltstone with 30% grey shale laminae and interbeds; ripple marks; occasional soft-sediment deformation; occasional rip-up clasts; anhydrite as occasional blebs and as a replacement product; dolomitic; 15% pinpoint and intergranular porosity; bright yellow UV fluorescence throughout siltstone; light oil staining throughout; sharp lower contact
944.46–946.71	2.25	**Subunit 4b** Breccia: 70% greenish grey shale with 30% light tan to light brown angular siltstone clasts; shale content increases with depth; contorted bedding; upper half has contorted bedding and clasts that average <1 cm in diameter; hairline horizontal and vertical fractures occasionally filled with anhydrite; disseminated pyrite throughout; noncalcareous; shale has tight porosity and siltstone has 15% porosity; bright yellow UV fluorescence in occasional siltstone clasts; spotty oil staining throughout
946.71–947.84	1.13	Breccia: 70% medium to light grey shale with 30% light brown to light grey siltstone clasts ranging up to 8 cm and averaging 1 cm in diameter; highly contorted bedding near top of unit, grading to slightly contorted bedding near base; occasional faint laminations; disseminated pyrite in places; noncalcareous; tight porosity in shale and 15% porosity in siltstone; no oil shows; gradational lower contact
947.84–948.38	0.54 m	**Subunit 4d** Shale: 75% light grey, massive to faintly bedded shale with 25% small, light brown subangular siltstone clasts less than 0.5 cm in diameter; hairline vertical fractures filled in places with anhydrite; pinpoint anhydrite located preferentially near vertical fractures; dolomitic; tight porosity in shale and 15% porosity in siltstone; no UV fluorescence; no oil shows; sharp lower contact
948.38–950.45	2.07	**Unit 3** Shale: 70% rusty-brown, massive to faintly bedded shale with 30% small, light brown, subangular siltstone clasts less than 0.5 cm in diameter; noncalcareous; clasts less than 0.3 cm appear to have rotted hairline vertical fractures filled in places with anhydrite; pinpoint anhydrite located preferentially near vertical fractures; starting at 949.04 m is a large vertical fracture within the rusty-brown shale, 25 cm long with a green halo rimming the fracture; tight porosity; no UV fluorescence; no oil shows

04-23-008-29W1

Top

Bottom

Figure 57: *Composite core photograph of depth interval 939.5–950.2 m in 4-23-8-29W1.*

11-08-009-25W1

Well: Enerplus Virden

Licence: 4011

KB: 435.4 m

Total depth: 770.0 m

Cored interval: 720.0–723.55 m

Depth (m)	Thickness (m)	Description
720.0–723.55	3.55	**Lodgepole Formation, Routhledge Shale facies** Shale: black; blocky; massive to faintly bedded; disseminated pyrite along bedding planes; tight; no oil shows; sharp lower contact
723.55–727.92	4.37	**Bakken Formation, Upper Member** Shale: black; blocky; massive; pyrite nodules throughout; tight; no oil shows; sharp lower contact
727.92–728.75	0.83	**Middle Member** **Lithofacies 3–4** Siltstone: light to medium grey; siltstone to very fine grained sandstone; noncalcareous; black wispy lenses (likely *Nereites missouriensis* trace fossils) throughout; mottled throughout; no UV fluorescence; no oil shows; sharp lower contact
728.75–731.52	2.77 m	**Lithofacies 1–2** Sandstone: light to medium grey; fine to very fine grained; noncalcareous; laminated throughout; brachiopod-rich beds in places; no UV fluorescence; no oil shows; sharp lower contact
731.52–734.14	2.62 m	**Torquay Formation** **Subunit 2a** Silty shale: grey-green; finely bedded with grey-green shale; noncalcareous; faint wavy bedding in places; soft sediment deformation; pyrite disseminated and as blebs throughout; porosity in silty shale is 5–10%, pinpoint and intergranular; tight in shale; no UV fluorescence; no oil shows; gradational lower contact
734.14–7356.21	1.07	**Subunit 2a** Silty shale: green-grey; less silty than subunit 2a above; massive to faintly bedded; noncalcareous; disseminated pyrite throughout; highly fractured in basal 43 cm; open horizontal and vertical fractures; porosity 10%, pinpoint and intergranular; porosity increases with fracturing; no UV fluorescence; no oil shows; gradational lower contact
735.21–737.06	1.85 m	**Subunit 1c** Silty shale: grey-green; 45% silty shale to 45% shaly siltstone with 10% siltstone clasts; noncalcareous; faintly bedded; occasional wavy bedding; disseminated pyrite throughout; porosity 10%, pinpoint and intergranular; no oil shows; gradational lower contact
737.06–737.67	0.61 m	Shaly siltstone: grey-green; 50% silty shale to 30% shaly siltstone with 20% siltstone clasts; noncalcareous; faintly bedded; occasional wavy bedding; disseminated pyrite throughout; porosity 10–15%, pinpoint and intergranular; no oil shows; gradational lower contact
737.67–738.9	1.23 m	**Subunit 1b** Silty shale: 60% grey-green, wavy-bedded silty shale; 30% light brown, laminated siltstone; 10% grey-green shale; occasional siltstone clasts, subangular to subrounded (mostly in top half); bottom half of zone has fewer siltstone clasts and beds than in upper half (<10%); disseminated pyrite throughout; porosity 10–15% in siltstone and silty shale, tight in shale, and overall decrease in porosity with depth; no oil shows

Figure 58: *Composite core photograph of depth interval 720.0–723.55 m in 11-8-9-25W1.*

01-23-010-29W1

Well: Tundra North Ebor Unit No. 1

Licence: 3991

KB: 525.2 m

Total depth: 880.0 m

Cored interval: 849.0–867.5 m

Depth (m)	Thickness (m)	Description
849.0–849.60	0.60	**Bakken Formation, Upper Member** Shale: black; blocky; noncalcareous; occasional conodonts; tight; no oil shows; sharp lower contact
849.60–851.44	1.84	**Middle Member** **Lithofacies 3–4** Siltstone: light grey to red-brown; burrow-mottled; black wispy trace fossils throughout; some redox haloing in bottom half; noncalcareous; good porosity (10–15%), pinpoint and intergranular; no oil shows; gradational lower contact
851.44–853.49	2.05	**Lithofacies 1–2** Sandstone: purple to maroon; very fine grained; thinly laminated throughout; good porosity (10–15%), pinpoint and intergranular; pale yellow UV fluorescence; spotty light oil staining; sharp lower contact
853.49–854.83	1.34	**Torquay Formation** **Subunit 2c** Sandstone: 90% light brown to maroon, fine- to very fine grained sandstone; 10% grey-green to maroon silty shale; sandstone massive to faintly bedded; noncalcareous; occasional white anhydrite as blebs and cement; excellent porosity (15–20%), pinpoint, intergranular and small to medium vugs; spotty yellow UV fluorescence; spotty oil staining; gradational lower contact
854.83–857.78	2.95	**Subunit 2b** Siltstone to silty shale: 50% light brown to red-brown siltstone; 50% grey-green to red-brown silty shale to shale; noncalcareous; 60% oxidized, some haloing and preferential shale oxidation; mini-cycles of thinly laminated, rippled and haloturbated beds; some crossbedding and/or hummocky cross-stratification; soft-sediment deformation throughout; some bed brecciation in places, fragments are angular and elongate; good porosity (10–15%), pinpoint, intergranular and small vugs; no oil shows; gradational lower contact
857.78–860.82	3.04	**Subunit 2a** Shale to silty shale: grey-green to red-brown; oxidation increases with depth; occasional light brown to red-brown siltstone clasts and lenses; faintly bedded; bioturbated in places; tight; no oil shows; gradational lower contact
860.82–864.09	3.27	Silty shale to shale: 60% red-brown silty shale to shale; 40% red-brown siltstone as laminae and lenses; ripple marks; haloturbated; crossbedded; hummocky cross-stratification; occasional disturbed bedding; oxidized throughout with rare redox haloes as pinpoint spots in places; poor porosity (<5%), pinpoint and intergranular; no oil shows; gradational lower contact
860.09–866.66	2.57	Silty shale to shale: same as subunit 2a, zone 1 above; upper 0.70 m is reduced and lower part is oxidized to rusty-red; occasional redox haloing; tight; no oil shows; gradational lower contact
866.66–867.25	0.59	**Subunit 1c** Siltstone to silty shale: rusty-brown; faintly bedded; some haloturbation in places; siltstone clasts and lenses within silty shale; porosity 10%, pinpoint, intergranular and small vugs; no oil shows

01-23-010-29W1

Top

Bottom

Figure 59: *Composite core photograph of depth interval 849.0–867.5 m in 1-23-10-29W1.*

12-24-011-29W1

Well: Reliable South Kirkella

Licence: 7102

KB: 524.7 m

Total depth: 932.0 m

Cored interval: 830.0–839.8 m

Depth (m)	Thickness (m)	Description
830.0–830.59	0.59	**Bakken Formation, Upper Member** Shale: black; massive; tight; blocky; hard; occasional conodonts; hairline horizontal fractures common; noncalcareous; sharp lower contact
830.59–832.69	2.10	**Middle Member** **Lithofacies 3–4** Siltstone to sandstone: grey to purple, occasionally green-grey and red-brown; very fine grained sandstone; mottled; extensively burrow-mottled throughout; noncalcareous; quartz-rich; occasional hairline horizontal green-grey redox haloes within purple sections; grey-green shale matrix and lenses increase with depth; occasional dark purple wisps (likely *Nereites missouriensis* trace fossils); mostly oxidized; spotty oil stain, commonly along open fractures and parallel to bedding planes; moderate porosity (5–10%), pinpoint and intergranular; sharp lower contact
832.69–835.76	3.07	**Lithofacies 1–2** Sandstone: dominantly red-brown to purple, with some grey to light brown intervals; very fine to medium-grained; noncalcareous; mostly oxidized; laminated throughout; wavy bedding common in upper 1 m; small burrows; bioturbated; one 1 cm bed is bioturbated with tiny burrows, then eroded with quiet deposition on top and filling in lows; upper 1 m is bioturbated, below is scarcely bioturbated; sandstone lenses occasionally have rusty spots (oxidized pyrite blebs); good porosity (10%), pinpoint and intergranular; occasional open hairline horizontal fractures; patchy oil stain in lower 2 m, mostly common in coarser grained sandstone lenses, laminae and beds; erosional lower contact, some wisps of shale within basal 2 cm, occasional small and angular fragments (erosional lag?); sharp lower contact
835.76–836.16	0.40	**Lower Member** Shale: dark grey to black, red-brown in places along open or partly open vertical fractures; noncalcareous; occasional lenses and fine laminae of dark grey siltstone; faintly bedded; shale is bright green at Middle Member contact, then grades down quickly to rusty red-brown then black shale; tight; no oil shows; breaks apart easily; sharp lower contact, with erosional lag
836.16–836.61	0.45	**Big Valley Formation** Silty shale to shale: varicoloured; middle 15 cm is green shale interbedded with light brown siltstone (very similar to Torquay), heavily oxidized to red-brown; lower 12 cm is very erosional with angular, poorly sorted clasts in green to red-brown shale matrix; clasts vary in lithology, including large black shale clasts 10 cm in diameter, sandstone, siltstone, granitic; upper and lower contacts are sharp and erosional; upper contact is red-brown, shale-rich and breaks apart easily (very crumbly); poor state of core near upper contact makes it difficult to characterize properly, but probably a shale-rich erosional lag; poor porosity (5%), pinpoint and intergranular; no oil shows; sharp contact with sandstone below
836.61–836.89	0.28	Sandstone: light brown with faint darker brown mottling; fine-grained; bioturbated throughout; quartz-rich, rare black grains; noncalcareous; moderately well sorted; frosted grains; subangular to mostly subrounded; fine dolomitic silty matrix; strong petroliferous odor; excellent porosity (>15%), pinpoint and intergranular; even light oil stain and yellow UV fluorescence throughout

12-24-011-29W1

Top

Bottom

Figure 60: *Composite core photograph of depth interval 830.0–839.8 m in 12-24-11-29W1.*

01-10-012-26W1

Well: Dome Cox Harmsworth

Licence: 541

KB: 1497 ft. (456.29 m)

Total depth: 2278 ft. (694.33 m)

Cored interval: 2176–2201 ft. (663.24–670.86 m)

Depth (ft.)	Thickness (ft.)	Description
2176.00–2176.79 (663.24–663.49 m)	0.79 (0.24 m)	**Bakken Formation, Upper Member** Shale: dark purple; blocky; noncalcareous; all oxidized; tight; no oil shows; sharp lower contact
2176.79–2185.98 (663.49–666.29 m)	9.19 (2.80 m)	**Middle Member** **Lithofacies 3–4** Sandstone: purple to pinkish-brown; very fine grained; mottled throughout; occasional laminae with occasional burrows; dark purple to black wispy trace fossils throughout (likely *Nereites missouriensis*); some yellow-brown mottled siltstone in places; all oxidized; porosity 10%, pinpoint and intergranular; no oil shows; gradational lower contact
2185.98–2194.58 (666.29–668.91 m)	8.60 (2.62 m)	**Lithofacies 1–2** Sandstone: purple to pinkish-brown; very fine to fine-grained sandstone; occasional medium-grained sandstone beds, laminae and lenses; laminated throughout; occasional burrows; noncalcareous; occasional white anhydrite lenses; all oxidized; some redox haloing toward base; basal 10 cm marked by a finely bedded / crossbedded / ripple-marked siltstone (may be Three Forks?); porosity 10%, pinpoint and intergranular; no oil shows; gradational lower contact
2194.58–2196.45 (668.91–669.48 m)	1.87 (0.57 m)	**Torquay Formation** **Subunit 2a** Silty shale: purple to red-brown; massive; oxidized with some redox haloing near top; tight; no oil shows; sharp lower contact
2196.45–2200.16 (669.48–670.61 m)	3.71 (1.13 m)	**Subunit 1c** Siltstone: 60% red-brown siltstone fragments and laminae; 40% red-brown silty shale matrix and laminae; 95% oxidized, some redox haloing; difficult to see original sedimentary fabric due to oxidation overprint; faint relict of alternating beds similar to Three Forks subunit 2b at 9-28-12-28W1; porosity 5–10%, pinpoint and intergranular; no oil shows

01-10-012-26W1 Top

Bottom

Figure 61: *Composite core photograph of depth interval 2176 –2201 ft. (663.24–670.86 m) in 1-10-12-26W1.*

09-09-014-29W1

Well: CDCOG et al. Manson

Licence: 2556

KB: 1659 ft. (505.66 m)

Total depth: 2315 ft. (705.61 m)

Cored interval: 2191–2245 ft. (667.82–684.28 m)

Depth (ft.)	Thickness (ft.)	Description
2191.00–2191.62 (667.82–668.01 m)	0.62 (0.19 m)	**Bakken Formation, Upper Member** Shale: black, grades to dark green toward base; blocky; noncalcareous; tight; no oil shows; sharp lower contact
2191.62–2195.49 (668.01–669.19 m)	3.87 (1.18 m)	**Middle Member** **Lithofacies 3–4** Siltstone: grey-green; siltstone to very fine grained sandstone; mottled throughout; occasional black shale lenses; noncalcareous; black wispy trace fossils throughout; pyrite disseminated and as blebs throughout; porosity 10%, pinpoint and intergranular; gradational lower contact
2195.49–2196.50 (669.19–669.49 m)	1.01 (0.17 m)	**Lithofacies 1–2** Sandstone: grey-green; very fine to medium-grained; laminated throughout; noncalcareous; porosity >10%, pinpoint and intergranular; spotty yellow UV fluorescence; spotty light brown oil staining; sharp lower contact
2196.50–2203.91 (669.49–671.75 m)	7.41 (2.26 m)	**Torquay Formation** **Subunit 4c** Siltstone: 90% light brown siltstone; 10% grey-green silty shale as matrix and laminae; typical subunit 4c lithology; crossbedding and ripple marks common; disseminated pyrite in places; noncalcareous; porosity 12–15%, pinpoint, intergranular and small vugs; spotty pale yellow UV fluorescence; light to dark brown, even to mottled oil staining; sharp lower contact
2203.91–2212.6 (671.75–674.40 m)	8.69 (2.65 m)	**Subunit 4b** Sandstone: 60% light brown sandstone fragments; 40% grey-green silty shale to shale matrix; shale content increases with depth; typical subunit 4b lithology, but sandstone instead of siltstone; highly distorted/brecciated bedding throughout; noncalcareous; disseminated pyrite throughout shale; porosity 10–15%, pinpoint and intergranular; porosity best in sandstone fragments; spotty pale yellow UV fluorescence; spotty light brown oil staining; gradational lower contact
2212.6–2218.24 (674.40–676.12 m)	5.64 (1.72 m)	**Subunit 4a** Silty shale: grey-green; typical subunit 4a lithology; faintly bedded; noncalcareous; pyrite disseminated and as blebs throughout; porosity 5%, pinpoint and intergranular; no oil shows; sharp lower contact
2218.24–2225.33 (676.12–678.28 m)	7.09 (2.16 m)	**Unit 3** Silty shale: red-brown; typical unit 3 lithology; massive to faintly bedded; noncalcareous; porosity <5%, pinpoint and intergranular; no oil shows; sharp lower contact.
2225.33–2229.37 (678.28–679.51 m)	4.04 (1.23 m)	**Subunit 2c** Siltstone: 60% light brown siltstone; 40% grey-green silty shale to shale as interbeds and matrix; noncalcareous; massive to bedded in places; laminated siltstone and shale in places; crossbedding and ripple marks in places; no escape structures; 10% oxidized to red-brown; porosity 10–15%, pinpoint, intergranular and small vugs; pale yellow UV fluorescence; light brown, spotty to localized oil staining; gradational lower contact
2229.37–2238.98 (679.51–682.44 m)	9.61 (2.93 m)	**Subunit 2b** Siltstone to silty shale: 50% light brown siltstone; 50% grey-green silty shale to shale; shale commonly waxy and bright green; noncalcareous; alternating beds of siltstone–silty shale laminations, massive silty shale to shale, distorted bedding, crossbedding and ripple-marked siltstone; 50% oxidized to red-brown; porosity 10% in siltstone, pinpoint and intergranular; bright yellow localized UV fluorescence; gradational lower contact
2238.98–2246.72 (682.44–684.80 m)	7.74 (2.36 m)	**Subunit 2a** Silty shale: red-brown; massive with occasional angular siltstone fragments; noncalcareous; soft-sediment deformation; mostly oxidized, occasional redox haloes; tight; no oil shows

Figure 62: *Composite core photograph of depth interval 2191–2245 ft. (667.82–684.28 m) in 9-9-14-29W1.*

04-16-016-27W1

Well: Tundra Birdtail

Licence: 4172

KB: 483.7 m

Total depth: 540.0 m

Cored interval: 515.0–533.0 m

Depth (m)	Thickness (m)	Description
515.00–518.00	3.00	**Lodgepole Formation, Basal Limestone facies** Limestone: light grey; wackestone to packstone; nodular; fossiliferous (crinoids mostly); grey argillaceous partings between calcareous nodules; rubbly core in places due to large vugs and vertical fractures; open vertical fractures lined with pyrite; no oil shows; sharp lower contact
518.00–520.00	2.00	**Bakken Formation, Upper Member** Shale: green with occasional red-brown patches in places; faintly laminated; noncalcareous; waxy; pyrite nodules in places; 26 cm long partly healed vertical fracture in basal 30 cm of unit; red oxidation occurs near top of fracture where it intersects a thick oxidized interval; tight; no oil shows; sharp lower contact
520.00– 521.00	1.00	**Middle Member** **Lithofacies 3–4** Sandstone: pinkish grey-brown; noncalcareous; pink colouration increases with depth; mottled; bioturbated throughout; remnant black wispy laminae (likely *Nereites missouriensis* trace fossils), often associated with pyrite; pyrite occasionally replaces shell fragments; good porosity (10–15%), pinpoint and intergranular; even to mottled light oil staining in places; sharp lower contact
521.00–522.84	1.84	**Lithofacies 1–2** Sandstone: medium grey to medium brown; fine- to coarse-grained; laminated throughout; wavy-bedded; occasionally bioturbated (burrows); minor soft-sediment deformation; noncalcareous; disseminated and blebby pyrite throughout; lower 1 m has well-developed coarse sand beds and lenses with even oil staining throughout; good porosity (15%), pinpoint and intergranular; sharp lower contact, abundant pyrite nodules/blebs and brecciation, erosional lag with in situ fragments
522.84–533.32	10.48	**Torquay Formation** **Subunit 2b** Silty shale: 60% grey-green silty shale; 40% light brown dolomitic siltstone beds, lenses and clasts; silty shale is massive to faintly bedded; siltstone is laminated, ripple marked and brecciated, amount of distorted/brecciated beds increases with depth, nodular in places; brecciation of siltstone ranges from tiny angular fragments to large elongate/oval fragments; wavy-bedded in places, rhythmites in places; upper 4.06 m unoxidized and lower 6.42 m mostly oxidized with occasional reduced patches; oxidized parts are red-brown to pink or orangish-brown; porosity is good in siltstone (>10%) but poor in silty shale (<10%), pinpoint and intergranular; disseminated pyrite throughout unoxidized parts; no oil shows Thick shale breaks occur at: 523.70–526.87 m 530.36–531.06 m 532.31–532.65 m

04-16-016-27W1 Top

Bottom

Figure 63: *Composite core photograph of depth interval 515.0–533.0 m in 4-16-16-27W1.*

04-17-019-29W1

Well: Francana Millwood Prov.

Licence: 2162

KB: 1606 ft. (489.51 m)

Total Depth: 3302 ft. (1006.45 m)

Cored interval: 1601–1641 ft. (487.98–500.17 m)

Depth (ft.)	Thickness (ft.)	Description
1601.00–1604.24 (487.98–488.97 m)	3.24 (0.99 m)	**Bakken Formation, Middle Member** **Lithofacies 3–4** Sandstone: red-brown to light pinkish-brown; very fine grained; mottled; bioturbated; grey-green shaly siltstone in places and as matrix; occasionally laminated and finely bedded; noncalcareous; pyrite blebs in places; porosity 10–12%, pinpoint, intergranular and small vugs; possible faint, brown, spotty oil stain; no UV fluorescence; gradational lower contact Note: not a typical lithofacies 3–4 lithology, like that seen south of Twp. 16
1604.24–1616.77 (488.97–492.79 m)	12.53 (3.82 m)	**Lithofacies 1–2** Sandstone: very fine to fine-grained; pink-brown grading to light brownish-grey and greenish-grey with depth; laminated throughout; occasional soft-sediment deformation and bioturbation; occasional thin light brown siltstone beds/laminae (similar to Torquay lithology); occasional ripple marks; noncalcareous; pyrite blebs in places; shaly siltstone laminae in upper half are slightly oxidized; open vertical fracture, ~20 cm long, in middle of section; good porosity (10–15%), pinpoint, intergranular and small vugs; no oil shows; sharp lower contact
1616.77–1620.55 (492.79–493.94 m)	3.77 (1.15 m)	**Torquay Formation** **Subunit 4c** Siltstone: light orange-brown; 90% dolomitic siltstone, 10% grey-green shale to silty shale; massive to faintly bedded; some soft-sediment deformation; disseminated pyrite throughout; noncalcareous; open vertical fractures in middle of section, ~15 cm long; occasional flasers; good porosity (10–15%), pinpoint, intergranular and small vugs; no oil shows; sharp lower contact
1620.55–1634.98 (493.94–498.34 m)	14.44 (4.40 m)	**Subunit 4b** Siltstone: 65% light orange-brown siltstone; 35% green-grey silty shale; shale concentration increases with depth; brecciated throughout; soft-sediment deformation throughout; fragmented beds; occasional laminae preserved; small pyrite blebs in places; oxidized to red-brown in middle of unit; porosity best in siltstone (10–15%), pinpoint and intergranular; no oil shows; sharp lower contact
1634.98–1636.79 (498.34–498.89 m)	1.80 (0.55 m)	**Subunit 4a** Silty shale: light grey-brown; massive; noncalcareous; pyrite blebs in places; poor porosity (5%), pinpoint and intergranular; no oil shows; sharp lower contact
1636.79–1640.73 (498.89–500.09 m)	3.94 (1.20 m)	**Unit 3** Silty shale: dark rusty red-brown; massive; noncalcareous; poor porosity (<5%), pinpoint and intergranular; similar to subunit 4a above but extensively oxidized; no oil shows

Figure 64: *Composite core photograph of depth interval 1601–1641 ft. (487.98–500.17 m) in 4-17-19-29W1.*