

Geological Mapping of Mississippian Strata in Southeastern Saskatchewan, Northwestern North Dakota, and Northeastern Montana (IEA Weyburn CO₂ Monitoring and Storage Project)

Don M. Kent¹, Patty L. Thomas², and Tom Heck³

Kent, D.M., Thomas, P.L., and Heck, T. (2004): Geological mapping of Mississippian strata in southeastern Saskatchewan, northwestern North Dakota, and northeastern Montana (IEA Weyburn CO₂ Monitoring and Storage Project); in Summary of Investigations 2004, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2004-4.1, CD-ROM, Paper A-7, 22p.

Abstract

This regional geological mapping of Mississippian strata, part of the Geoscience Framework component of the International Energy Agency Weyburn CO₂ Monitoring and Storage Project, provides the first cross-border maps in the northeastern portion of the Williston Basin and the first update to Fuzesy's 1960 report on the Mississippian rocks of Saskatchewan. Two styles of deposition are recognized from examination of individual isopach maps and distribution of lithofacies. The first, a progradational phase, is represented by evidence for clinoform sedimentation in the Souris Valley Beds, followed by widespread open-marine sedimentation in the overlying Tilston and Alida beds. The second style, an aggradational phase, encompasses the Frobisher, Midale, Ratcliffe, and Poplar beds, where each unit is marked by one or more shallowing- or brining-upward cycles interpreted to represent deposition under conditions of limited accommodation space. Correlation of some isopach trends with structural lineaments identified using seismic and other remote-sensing techniques suggests possible structural controls on sedimentation. This mapping project has identified areas in which detailed studies are needed to increase knowledge and understanding of facies relationships, depositional environments, and structural controls on sedimentation.

Keywords: *Regional, isopach maps, marker-defined units, Souris Valley Beds, Tilston Beds, Alida Beds, Kisbey(K2) Beds, Frobisher Beds, Midale Beds, Oungre Unit, Poplar Beds, Big Snowy Group, structural controls, lineaments, IEA Weyburn CO₂ Monitoring and Storage Project.*

1. Introduction

This paper and accompanying map series are an outcome of the International Energy Agency Weyburn CO₂ Monitoring and Storage Project (IEA Weyburn CO₂ Project). The project area is centred on the Weyburn Oil Field, and covers 24 ranges west of the second meridian, 17 townships north of the Canada–U.S. border, and six townships south of this border into North Dakota and Montana. The majority of the oil pools in this prime producing area are located in Mississippian and older Paleozoic strata. This paper presents observations made during the preparation of a database of stratigraphic tops and the creation of isopach maps of major Mississippian stratigraphic units. Further outcomes of this mapping project are expected to be papers that more fully explain advances in general understanding of the facies relationships and depositional histories of the stratigraphic units identified in these notes. Figure 1 illustrates the regional extent of the study area, and the revised distribution of subcropping Mississippian units resulting from this study.

2. Mississippian Stratigraphic Framework of the Project Area

Oil shows discovered in Mississippian rocks in the early days of drilling in the late 1940s made these strata the favoured targets for hydrocarbon exploration. The lithostratigraphic terminology applied to these rocks was based on that of the most proximal outcrops located in South Dakota and Montana. An increase in available subsurface information and the discovery of oil in various intervals that were delimited by correlatable geophysical well-log signatures resulted in the identification of a succession of marker-defined units. A plethora of names as well as combinations of alphabetical and numerical terms were applied to these units (Thomas, 1954; Fuller, 1956) until the nomenclature committee of the Saskatchewan Geological Society (1956) standardized the names and gave them a quasi-formal status with the suffix “Beds”. It was implied that the marker-defined units were isochronous and

¹ D.M. Kent Consulting Geologist Ltd., 86 Metcalfe Road, Regina, SK S4V 0H8.

² Consulting Geologist, R.R. 2, Regina, SK S4P 2Z2.

³ Formerly of North Dakota Geological Survey, Bismarck, ND.

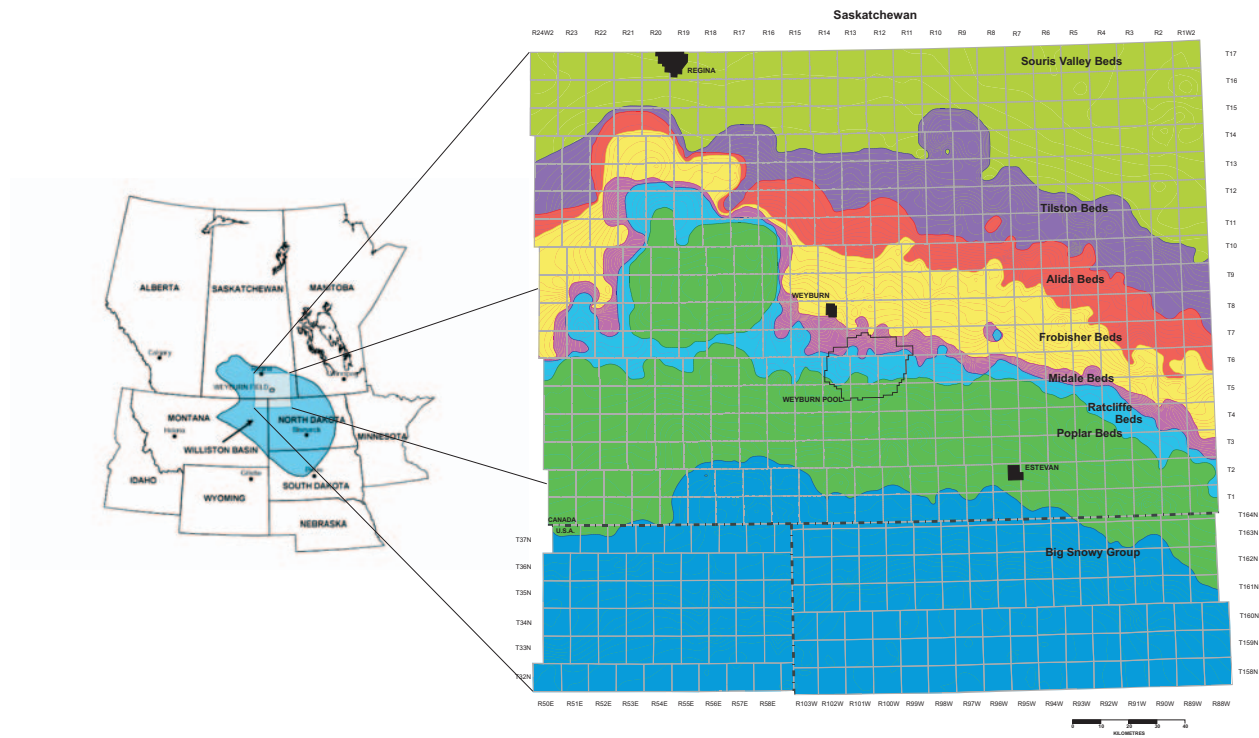


Figure 1 - Regional extent of mapping project showing revised distribution of subcropping Mississippian units.

included the lithologies of the outcropping lithostratigraphic units as facies (Edie, 1958; Cumming *et al.*, 1959; Brindle, 1960; Fuzesy, 1960; Kent, 1974). Adherence to the names and boundaries of these marker-defined units has been maintained in the preparation of the maps presented in this paper (Figure 2).

3. Lithologic Composition and Styles of Sediment Accumulation

a) Souris Valley, Tilston, and Alida Beds

Souris Valley Beds

Cores of the Souris Valley Beds are both rare and non-representative inasmuch as they are from either the lower 30 m or less of this stratigraphic unit, or the upper 6 m. Consequently, the regional lithological complexities of the Souris Valley are described primarily in terms of the unit's variable gamma-ray log signature.

The Souris Valley rests on the Devonian-Mississippian Bakken Formation in sharp, conformable contact with the upper shale member of the Bakken. The basal beds of the Souris Valley have a significant argillaceous content and exhibit an upward gradation from mudrock to argillaceous and non-argillaceous carbonate rock. The transitional upper contact is represented by a downward gradation from non-argillaceous, interbedded skeletal grainstones and lime mudstones of the overlying Tilston Beds, to light red, skeletal grainstones and lime mudstones interlaminated with organic-bearing argillaceous seams of the uppermost Souris Valley.

Gamma-ray signatures from geophysical well logs show that compositional variations in the Souris Valley are regionally complex and deserving of detailed analysis beyond the scope of this paper. Across most of the central portion of the map area where thicknesses uniformly range from 100 to 150 m in thickness (Figure 3), low gamma-ray signatures suggest that 80 to 100 m of the Souris Valley succession comprises non-argillaceous to intermittently argillaceous carbonate. The thickest Souris Valley section, up to 225 m in parts of North Dakota, is associated with an additional section of argillaceous carbonate in the lowermost portion of the section, below the non-argillaceous carbonate. Significant thinning to 70 m in the northeast corner of the map area reflects the loss of Tilston Beds cover and truncation of the Souris Valley at the sub-Mesozoic unconformity. The thin southwest of the Weyburn Field coincides with a thick in the overlying Tilston Beds. In the absence of further study, this relationship is presumed to reflect either a genetic relationship or correlation difficulties.

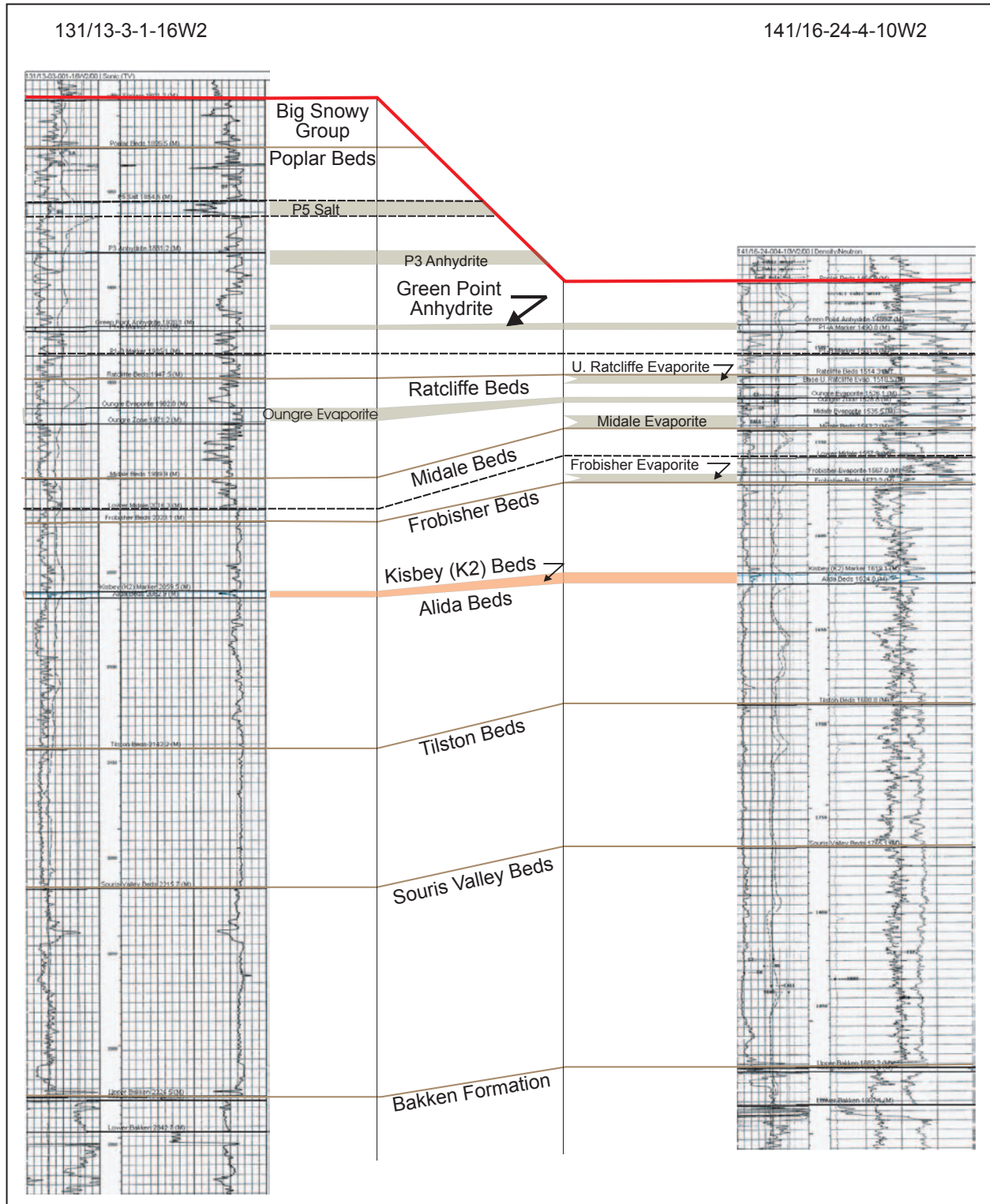


Figure 2 - Correlation of Mississippian stratigraphic units in two wells in southeastern Saskatchewan based on geophysical well-log signatures. Evaporite units and the Kisbey (K2) marker bed are also delineated.

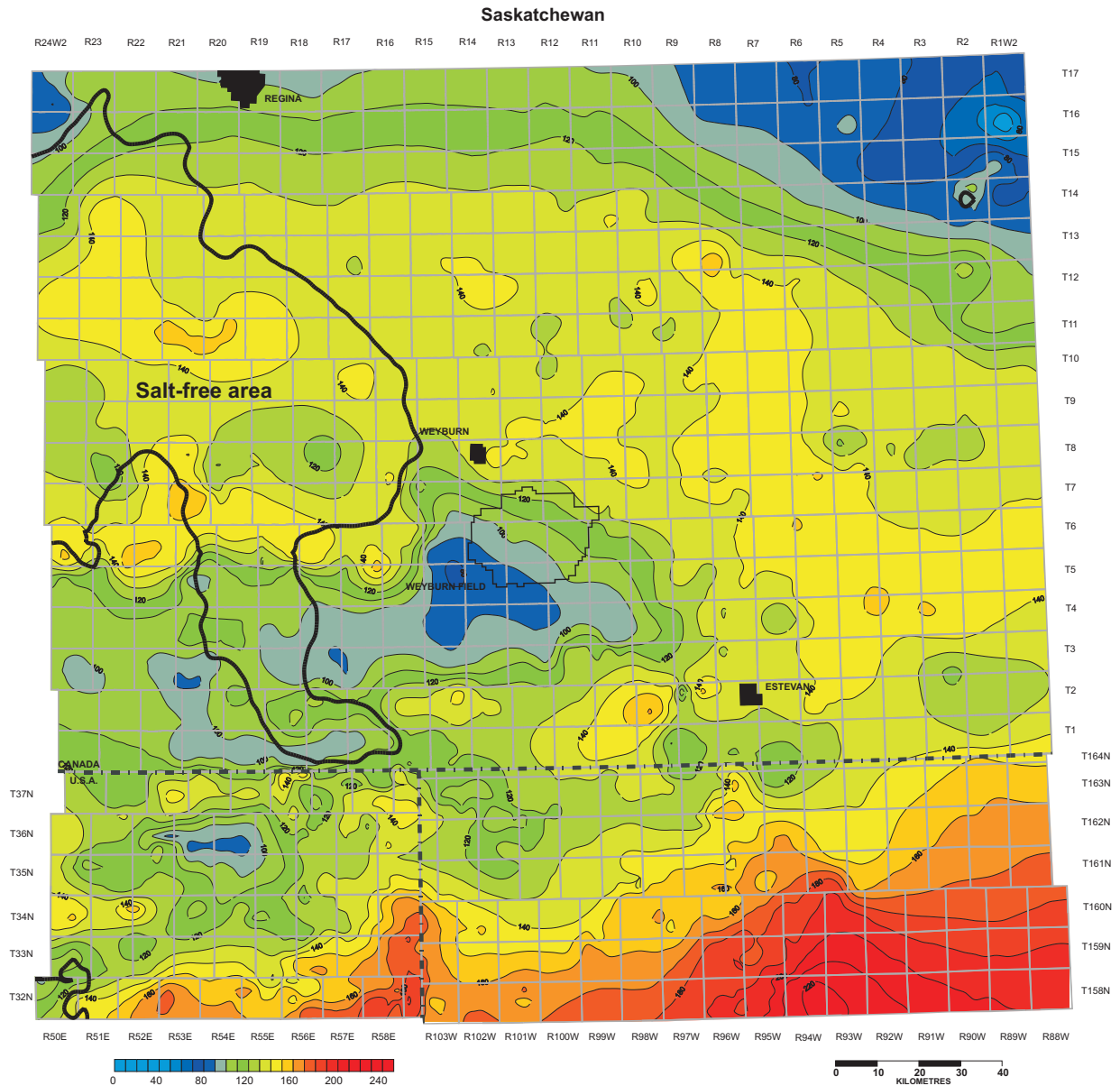


Figure 3 - Isopach map of the Souris Valley Beds. Note erosional thinning to the north and a depositional thick to the south. Solid heavy lines delineate areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent. Contour interval is 10 m.

Tilston Beds

The Tilston Beds conformably overlie the Souris Valley Beds. Both the basal and upper contacts are placed at the top of an increase in gamma-ray log response. The upper marker is commonly referred to as the MC2 marker. Cores that include the marker show that it has variable characteristics: its colour ranges from light grey-brown or green to light brick-red; it is an argillaceous dolomicrite, in places interlaminated with claystone partings that are commonly imprinted with plant debris; and it may be underlain by an intraformational breccia of pebble-size dolomicritic particles. Within the study area, the Tilston is dominantly micritic with variable proportions of skeletal allochems that include crinoid columnals, brachiopod-valve fragments, fenestrate and ramose bryozoans, and rugose horn corals. Observation of gamma-ray log response suggests that regionally the Tilston Beds are comparatively uniform in character.

The isopach map (Figure 4) of the Tilston Beds shows that these strata generally thin northeastward from their maximum stratigraphic thickness of 100 m in the U.S. portion of the study area to zero thickness at the subcrop edge. The areas southwest of the Weyburn Field and just south of the Canada–U.S. border are exceptions to this trend and reveal reciprocal thickness changes associated with thickness changes in the underlying Souris Valley Beds, suggesting either differing correlation of the contact between the two units, or, more likely, a genetic relationship between the two units (investigation of this is beyond the scope of this paper). Anomalous thickening of the subcropping Tilston in Township 14, Ranges 9 and 10W2 corresponds to a significant thinning in the Prairie Evaporite isopach (Kreis *et al.*, 2003) in the same locality, suggesting that salt solution may have started prior to development of the sub-Mesozoic unconformity.

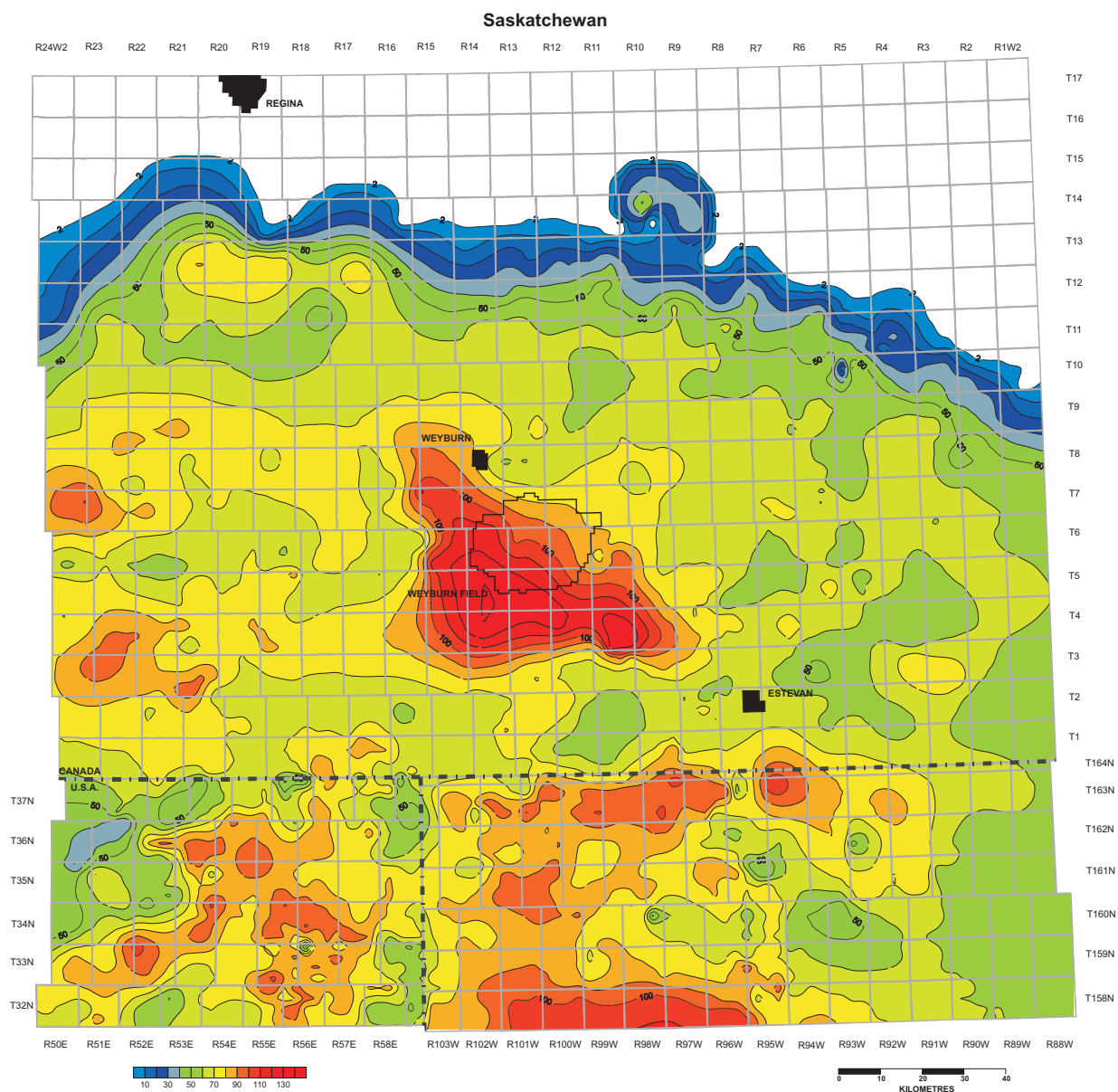


Figure 4 - Isopach map of the Tilston Beds. Note erosional thinning to the north. Contour interval is 10 m.

Alida Beds

Carbonates of the Alida Beds lie with apparent conformity on the Tilston Beds, whereas their contact with the overlying Kisbey (K2) is disconformable over a considerable portion of the project area. Read and Dorobeck (1993) correlate the Kisbey (K2)–Alida contact with a third order sequence boundary in the Madison rocks of the Cordilleran region of Montana. In core, this upper contact may exhibit an irregular or sharp, planar surface (Kent, this volume). Alida Beds below the contact are commonly pale red-brown to grey-green argillaceous dolostone.

Alida Beds immediately south of the subcrop edge comprise an assortment of particle and textural types including ooids, crinoid columnals, brachiopod-valve fragments, fenestrate bryozoa, rugose horn corals, and algal debris in wackestones and grainstones. Throughout the remaining project area, the rocks are predominantly micritic with crinoid, brachiopod, and bryozoan debris in lime mudstones, wackestones, and wackepackstones.

The wide range in thickness of the Alida Beds from about 25 to 100 m may be in part a reflection of the relief on the sub-Kisbey (K2) unconformity marking the top of the unit (Figure 5). Several of the local thickness anomalies, up

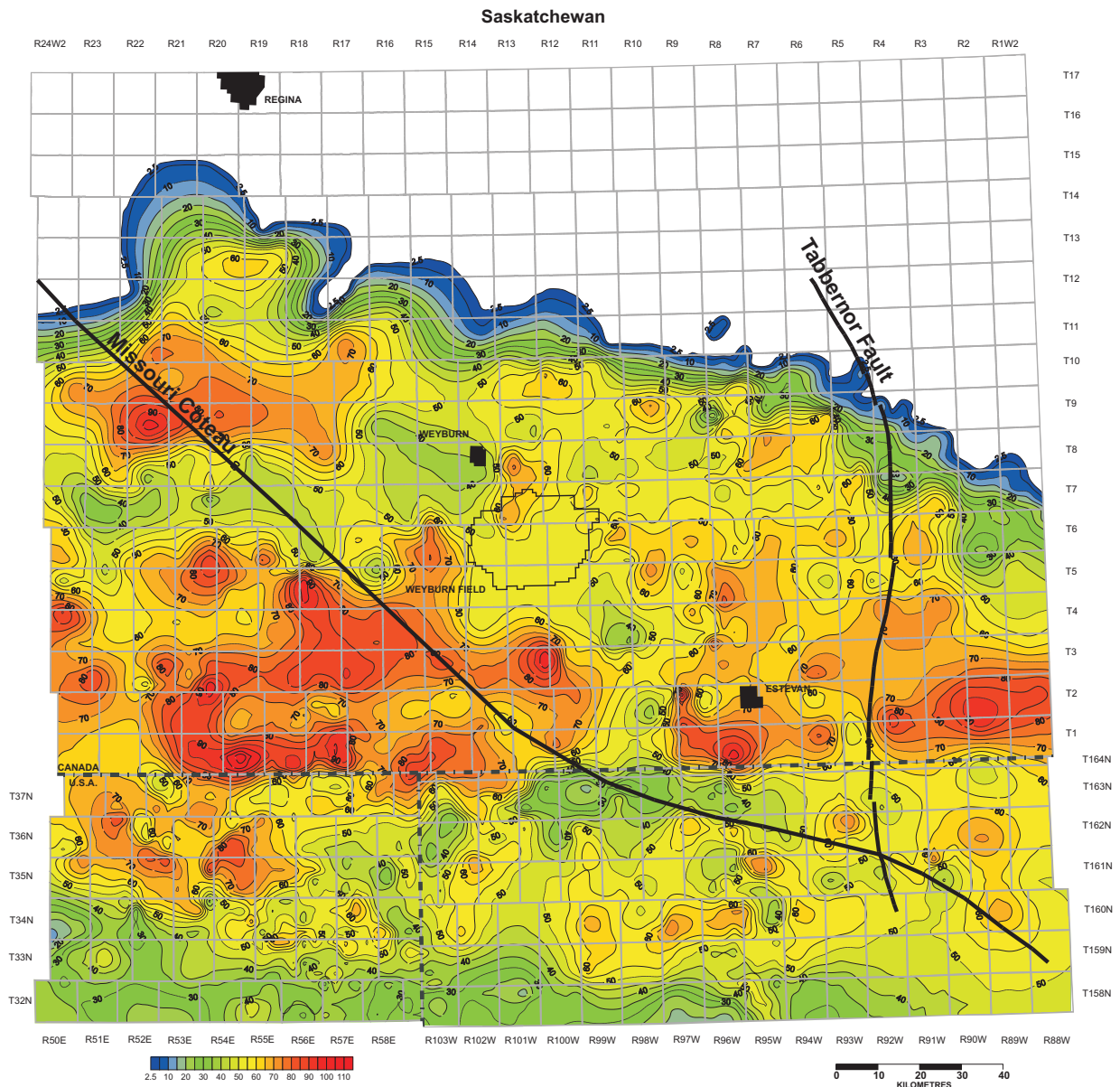


Figure 5 - Isopach map of the Alida Beds. Note erosional thinning to the north. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 5 m.

to 105 m thick, coincide with thin areas in the underlying Tilston Beds. Unlike the underlying units, the Alida Beds thin to the southwest and to the north at their subcrop edge.

Interpretation of Depositional Setting

A thick, non-argillaceous body of Souris Valley Beds in the north-central part of the project area appears to have been the nucleus of normal marine carbonate sedimentation. Carbonate sediments could have been generated and subsequently distributed to proximal regions where they mixed with argillaceous material. Thinner, non-argillaceous beds may have been spillover lobes created during storms. Biota from the only core of a non-argillaceous body suggests some may be bryozoan-crinoidal mud-mounds that have potential to be good reservoirs. The argillaceous, basal interval in the Souris Valley Beds probably represents deeper, less oxygenated basinal deposits. Both the Tilston and Alida beds appear to have been deposited in subtidal environments below fair-weather wave-base conditions. Overall, the combined succession of Souris Valley, Tilston, and Alida beds probably represents progradational basin-fill deposits.

b) Kisbey (K2) Beds

Kisbey (K2) Beds

The Kisbey Beds are unique in the Mississippian succession of the Williston Basin in that they may contain a significant component of relatively coarse siliciclastics. East of the study area, three quartz sand-rich intervals (K1, K2, and K3) are present at the stratigraphic level of the Frobisher-Alida Beds but, within the project area, only the regional Kisbey (K2) can be mapped. The lower contact of the Kisbey (K2) interval with the underlying Alida Beds may be sharp, or marked by a gradation from variably coloured argillaceous dolostone, to red-brown arenaceous and argillaceous dolostone, to dolomite-cemented quartz arenite. The basal beds of the sandstone commonly have a patterned appearance made up of dark grey and grey-white areas similar to patterned carbonate, or purple-red swirls that resemble distorted layering. The contact with the overlying Frobisher Beds is commonly gradational from dolomite-cemented sandstone to arenaceous limestone.

Quartz sand accumulations are common to the Kisbey (K2) in the eastern part of the project area and extend along the subcrop edge westward as far as Range 13W2. The rocks of this unit include argillaceous dolostone in thinner isopach areas, and calcite-cemented quartz arenite and sandy dolostone in thicker isopach areas. In the Lost Horse Hill area (Range 8W2, Townships 9 and 10), Perras (1990) sub-divided quartz sand-rich rocks of the Kisbey (K2) into three subfacies: a) virtually allochem-free and non-stratified; b) containing 35 to 50% or more ooids and peloids with fine laminae and low-angle cross-lamination; and c) containing 5 to 40% ooids and peloids with current ripples. Outside of this area, the rocks are commonly structureless, but in places contain 1 to 5% allochem concentrations that include crinoid columnals, brachiopod-valve fragments, and ooids. The quartz grains are consistently very fine to fine grained, subangular to subrounded, and vitreous or, rarely, frosted. Where the quartz grains occur within an argillaceous, microcrystalline dolomite matrix, they form trace amounts to about 30% of the rock.

Interpretation of the Kisbey (K2) isopach map (Figure 6) is constrained to well information that permits recognition of quartz, such as the PE curve on geophysical well logs, and by limited well penetrations. Where possible, the presence of quartz sandstone was verified through lithological log descriptions of rare cored intervals. From the isopach map, the sand bodies appear to be elongated, having a shoestring-like pattern; some seem to be aligned parallel to the trace of the Tabernor Fault. Kent (this volume) has suggested that, in places, the elongated sand bodies may have accumulated as aeolian dune deposits.

Interpretation of Depositional Setting

The Kisbey succession appears to have been formed in phases. The argillaceous dolostone may represent a weathered residue beneath an exposure surface, with quartz sands subsequently distributed over the exposure surface. Perras (1990) interpreted the Kisbey (K2) sandstones observed in the Lost Horse Hill area to be subtidal sand waves and beach deposits, and from the absence of sedimentary structures concluded that the sediments were subsequently reworked. Sand accumulations outside this area have uncertain origin, but they have been interpreted as channel-fill deposits by many geologists familiar with them. However, stratification and other sedimentary structures are rare in the cores examined during this study. The presence of skeletal debris intermixed with quartz grains suggests sedimentation in a marine environment, possibly as sandbars. The Kisbey has good potential as a hydrocarbon reservoir but more regional work needs to be done to separate its various sand bodies and to determine their geometries and distributions.

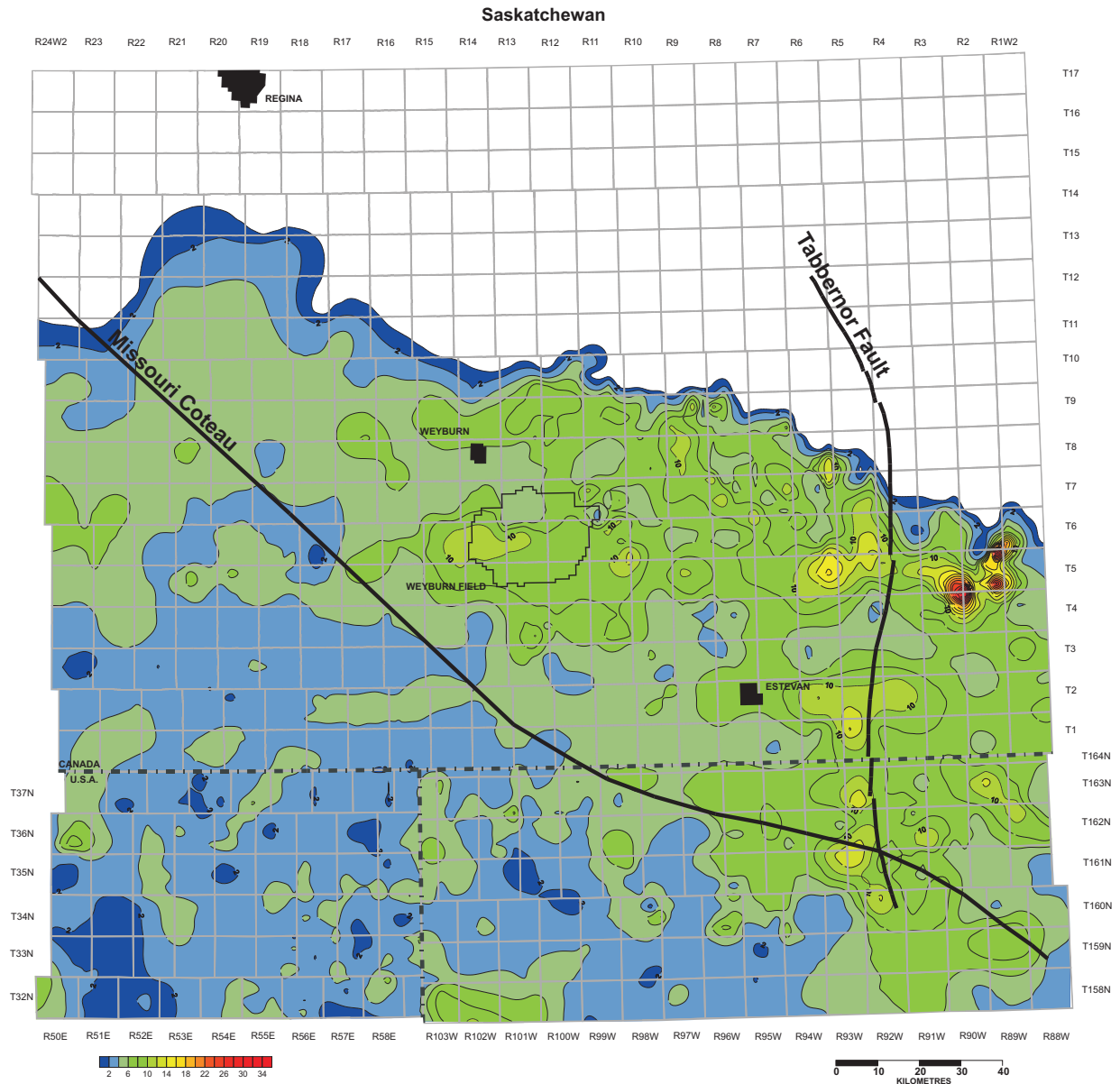


Figure 6 - Isopach map of the K2 Beds. Note depositional thick in the eastern and northeastern parts of the Kiseby. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 2 m.

c) Frobisher, Midale, and Ratcliffe Beds

The Saskatchewan Geological Society's nomenclature committee (1956) concluded that evaporites in the Mississippian succession should be placed at the base of each of the marine cycles, so that the Frobisher Evaporite is included with the Midale Beds and the Midale Evaporite with the Ratcliffe Beds. Current understanding is that the marine cycles have a history of sedimentation in limited accommodation space that brings on restricted circulation. Therefore, the evaporites would be genetically more related to the underlying rather than overlying marine succession (Marsh and Qing, 2002; Kent, 2003). For discussion in this paper, the evaporites will be considered as the final stage of the underlying marine unit. However, Mississippian isopach maps prepared for the IEA Weyburn CO₂ Project and used to illustrate this paper retain the traditional nomenclature. Future work will be directed to the revising stratigraphic nomenclature of these rocks.

Frobisher Beds and Frobisher Evaporite

Carbonate rocks of the Frobisher Beds are in gradational contact with the underlying Kisbey (K2) Beds and overlying Frobisher Evaporite, and are disconformable with the overlying Midale Beds (Kent 2001; Kent and Nimegeers, 2002; and Nimegeers and Qing, 2002).

The isopach map of the Frobisher Beds (Figure 7) reflects the ramp depositional model proposed for these rocks (Kent, 1999). Thick accumulations of coated-grain grainstones, packstones, and wackepackstones interbedded with lime mudstones of the inner ramp pass southward, approximately along the surface trace of the Missouri Coteau's northeastern edge, into thinner accumulations of skeletal wackestones and lime mudstones of the outer ramp. Vertically, the ramp succession includes four basic lithologies based on differing component content and mineralogical composition. The basal interval includes micritic rocks ranging from lime mudstones and wackestones through to less common packstones. In places, the micritic intervals alternate with packstone and wackestone, but generally pass upward into wackestone. The widespread occurrence of skeletal fragments,

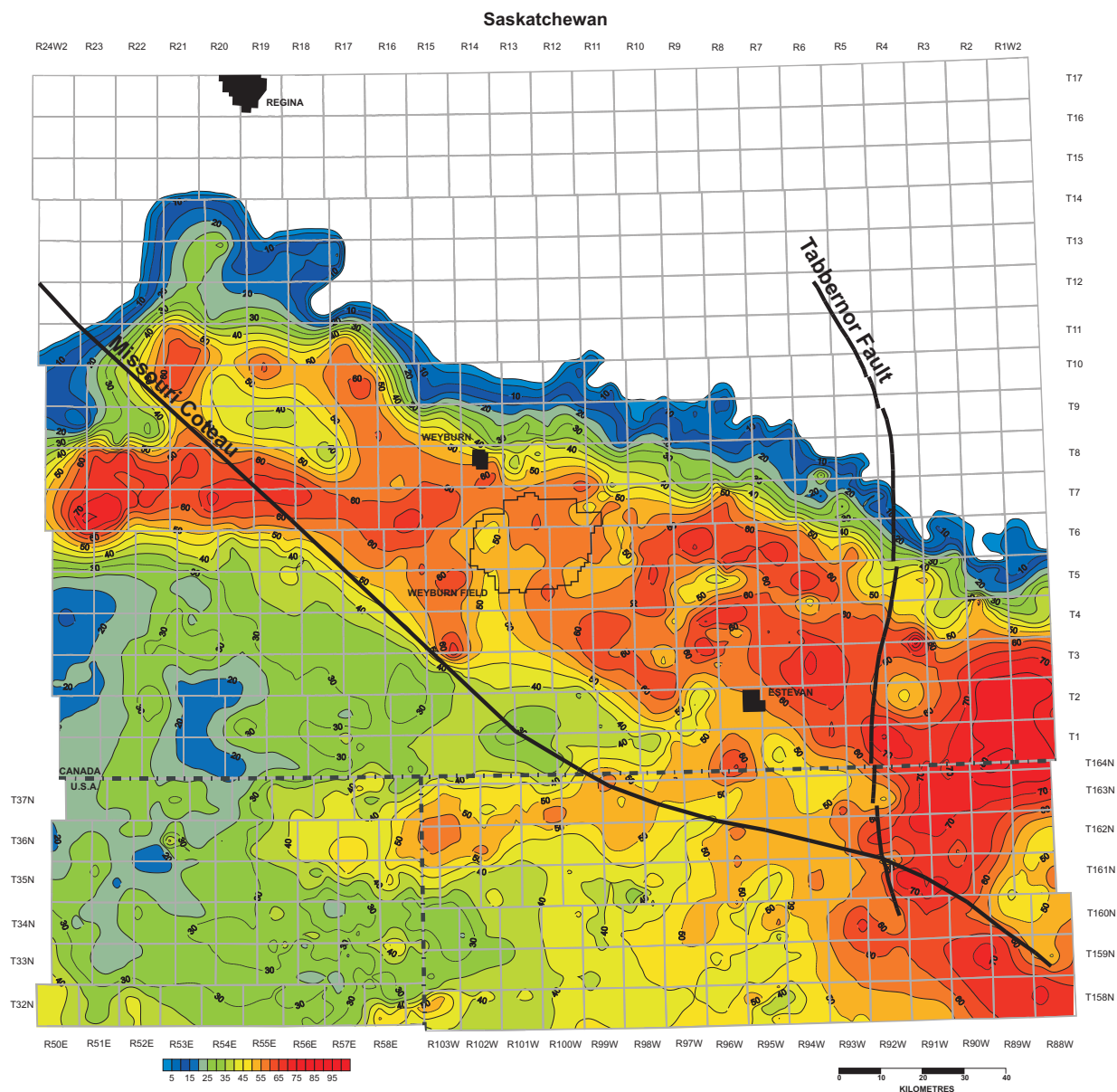


Figure 7 - Isopach map of the Frobisher Beds. Note erosional thinning to the north. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 5 m.

particularly the calcareous alga *Ortonella*, is characteristic. Other particles include fragments of brachiopod and ostracod valves, rugose horn coral thecae, crinoid columnals, ooids, peloids, and pisolites. The micrite matrix is fine crystalline, <7 µm, but where dolomitized is coarser, 10 to 25 µm. Kent and Curry (2002) show the micritic rocks are overlain by a unit with very fine sand-size to pebble-size particles that are dominantly ooids, pisolites, and intraclasts of aggregated ooids, but also include brachiopod-valve fragments, high-spined gastropods, fragments of rugose horn coral thecae, and oncolites.

A dolostone commonly referred to as the State 'A' Marker lies immediately subjacent to the Frobisher Evaporite, and includes dolomicrite and dolomitized, coated-grain-bearing wackestones to packstones, as well as non-dolomitized carbonates with similar textural compositions. Some of the coated-grain components of the State 'A' are recognizable as dolomicrite without the aid of a microscope. Poor preservation of coated grains is attributed to alteration of rocks, possibly induced by mixing highly saline marine and fresh waters beneath the Frobisher Evaporite sabkha. In places, the dolomicrites are laminated with partings of finely disseminated organic material, and may contain skeletal components including crinoid columnals, brachiopod valves, and rugose corals. Elsewhere, they contain a limited ichnofauna of *Planolites* and *Chondrites*. Marsh and Qing (2002) report occurrences of the calcareous alga *Ortonella*.

The Frobisher Evaporite (Figure 8) contains both isolated and coalescing nodular anhydrite and rare occurrences of vertical elongate, horizontal elongate, and massive anhydrite. The nodular anhydrite is in diversely coloured host rocks that include red-stained, lateritic-appearing dolostone, light green-grey argillaceous dolostone, and medium grey-brown dolostone.

Interpretation of Depositional Setting

The Frobisher Bed succession is considered to have been deposited under conditions of limited accommodation space in which sediment accumulation was more by aggradation than progradation. The limited accommodation space is reflected in repetitions of shallowing-upward or brining-upward cycles in this part of the succession.

There may be an assortment of origins for the State 'A' Marker depending on the topographic expression of the upper surface of the Frobisher coated-grain banks. *Ortonella*-rich micrites and burrowed dolomicrites may have been deposited in topographic lows on the bank that could have been accessed by marine waters. In contrast, other lows that were intermittently flooded may have been the sites of penesaline conditions resulting in the deposition of laminated dolomicrite. Conversely, oolites and other coated-grains may have formed in areas of positive relief and been distributed in other depositional settings by storm waves. The textural characteristics of the Frobisher Evaporite strongly support a sabkha formation (Kent, 2003).

Midale Beds and Midale Evaporite

Traditional sub-division of the Midale carbonate has been based on petrophysical properties and geophysical log signatures with the term 'Vuggy' applied to the lower part and 'Marly' to the upper. However, in this regional study it has become evident that accurate use of these descriptive terms is areally limited to the Midale trend of producing oil pools. Outside this locality, the lower part of the Midale carbonate is compositionally and petrophysically variable, not necessarily 'vuggy'. Similarly, whereas the 'Marly' is commonly a microdolostone inside the pool area, regionally it is more calcitic (Kent and Nimegeers, 2002). The terms upper Midale and lower Midale are substituted for 'Marly' and 'Vuggy', respectively, in this report.

Carbonate rocks of the lowermost Midale Beds rest on an exposure surface marking the top of the Frobisher Evaporite. The contact appears relatively sharp on geophysical logs, but is not always as well defined in core. Erosion has clearly taken place where anhydrite-nodule-bearing clasts are incorporated in the overlying basal Midale rocks, or where red or greenish grey argillaceous dolostone presents a sharp contrast between underlying and overlying units. A gradational contact is evident from some cored intervals where distorted rock occurs between underlying nodular anhydrite and overlying Midale carbonate. The basal rocks of the Midale Beds show some variability in their textural and allochemic aspects, and generally contain a significant micritic matrix component. Non-skeletal allochems, ooids, and intraclasts as well as skeletal particles and debris from calcareous algae, ortonellids and kamenids, brachiopod- and ostracod-valve fragments, and crinoid columnals are characteristic.

The Midale Evaporite includes laminated dolomicrites and pattern carbonates in the lower portion and an assemblage of anhydrite textural types including layered, horizontal elongate, vertical elongate, and isolated nodular.

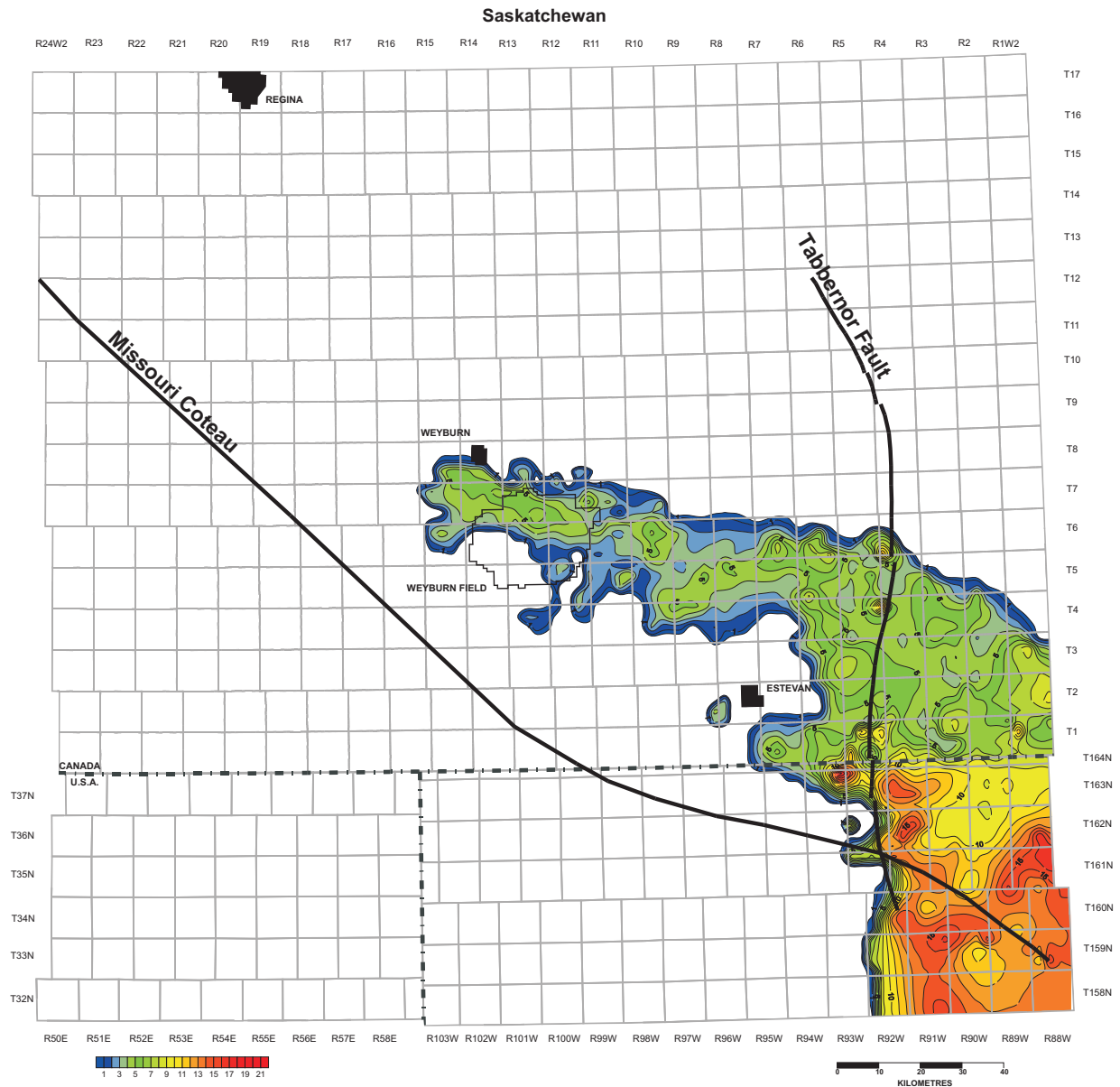


Figure 8 - Isopach map of the Frobisher Evaporite. Note erosional thinning to the north and depositional thickening in the North Dakota portion of the map area. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 1 m.

Interpretation of Depositional Setting

The Midale Beds isopach map (Figure 9) appears to reflect the shallow-ramp depositional setting of the unit (Kent, 1984, 1999) in a similar manner to that of the Frobisher Beds. However, this ramp has inner ramp, ramp crest, and outer ramp facies. The ramp crest appears to form the thickest areas of the lower Midale (Figure 10), with the inner ramp to the north and the outer ramp to the south. The upper Midale isopach map (Figure 11) is a reverse image of its lower Midale counterpart. It is thinner over the coated-grain shoals of the ramp crest and thicker in the outer ramp environment. The surface trace of the Missouri Coteau appears to delineate the southward transition from ramp crest to outer ramp, or the transition from where the lower Midale thins to where the upper Midale thickens.

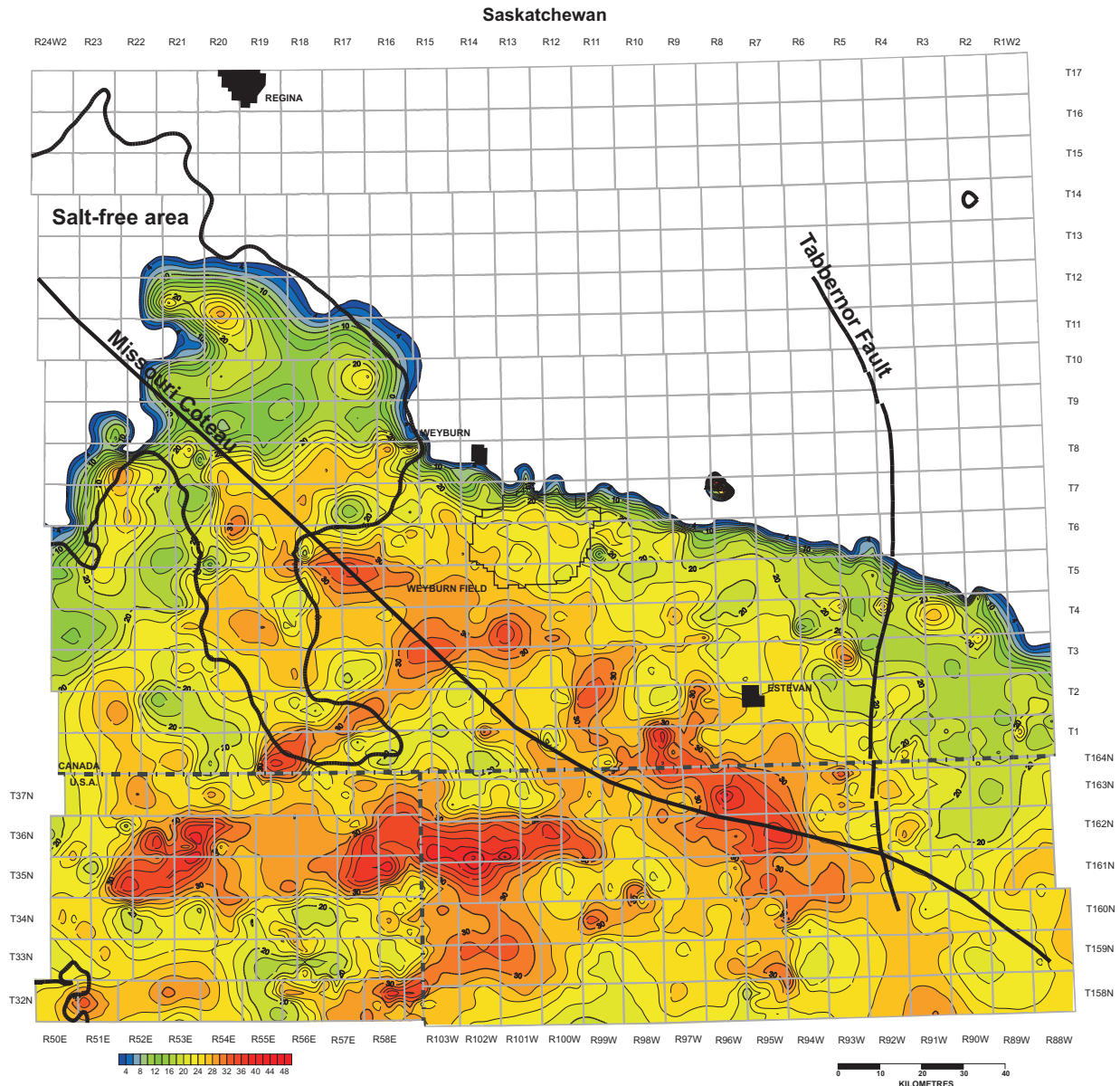


Figure 9 - Isopach map of the Midale Beds. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement, the areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent, and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 2 m.

The ramp crest facies is made up of local accumulations of alternating wackestone, wackepackstone and packstone, and grainstones with a range of particles including ostracod and brachiopod-valve fragments, and more abundant ooids, pisoids, and peloids. These coated-grain accumulations are interpreted to represent shoals and shoal complexes (Charbonneau, 1993; Lubey and Charbonneau, 1995). Each shoal consists of an inner shoal environment dominated by grain-supported rocks; a proximal shoal environment in which more abundant, grain-supported intervals alternate with matrix-supported layers; and a distal shoal setting dominated by lime mudstone and matrix-supported rock. The geometry of the shoals may be equidimensional, irregularly shaped (Charbonneau, 1993; Lubey and Charbonneau, 1995), or elongate along a southwest-northeast axial trend (Edmunds *et al.*, 1994).

There are two subfacies, proximal and distal, in the outer ramp setting. Kent (1999) shows that the coated-grain shoal complexes pass into well developed bioclastic banks in the proximal outer ramp position. Crinoidal remains dominate the bioclastic banks but abundant fenestral bryozoan debris are also present as well as the remains of brachiopods, solitary rugose horn corals, syringoporida corals, and calcareous algae. The rocks range from coarsely

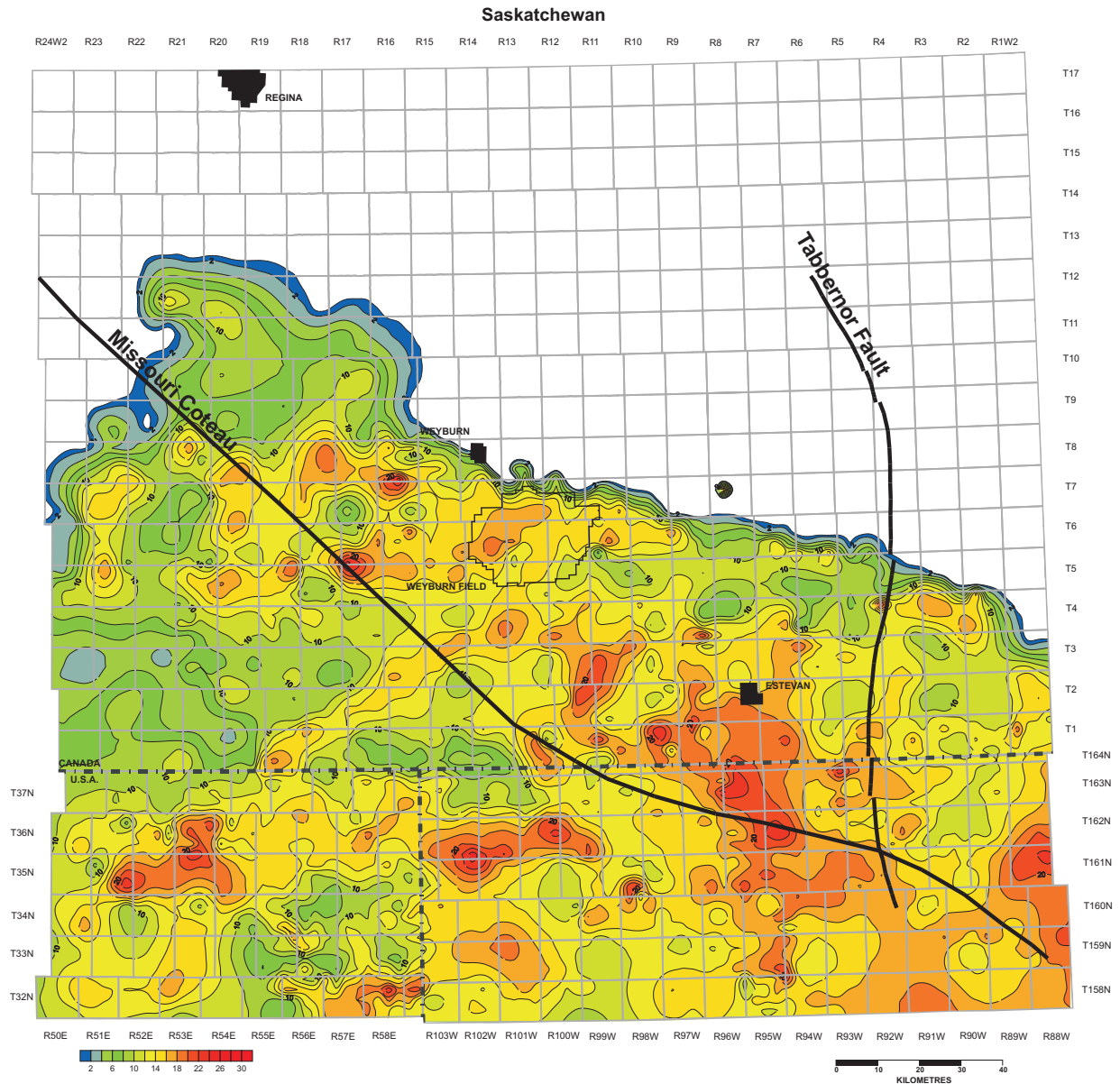


Figure 10 - Isopach map of the lower Midale. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 2 m.

calcarenitic grainstones and packstones to those that are micritic matrix-supported, the combination of which may reach 30 m in thickness. The distal outer ramp rocks are dominantly lime mudstone or dolomiticrites that are extensively burrowed and interpreted as typical of the *Cruziana* ichnofacies (Keswani and Pemberton, 1993). Local storm deposits of skeletal debris are also present. Cores of the upper Midale visually demonstrate the waning of accommodation space over a narrow transition interval from rocks deposited in a marine environment to those that represent a penesaline setting. The marine rocks typically containing *Planolites* and *Chondrites* ichnogenera are separated by a few decimetres of structureless dolomiticrite from laminated dolostones with organic-rich interlaminae. The remainder of the upper Midale includes dolomiticrites as well as undolomitized lime mudstones and a textural spectrum of skeletal-bearing rock from wackestones to grainstones. Harvey *et al.* (2004) note that the unit becomes increasingly less dolomitic in the outer ramp setting.

The inner ramp rocks include lime mudstones, skeletal wackestones, and dolomiticrites. The dolomiticrites and lime mudstones contain a similar ichnofauna to that of the outer ramp. Kent (2003) designated the vertical sequence of

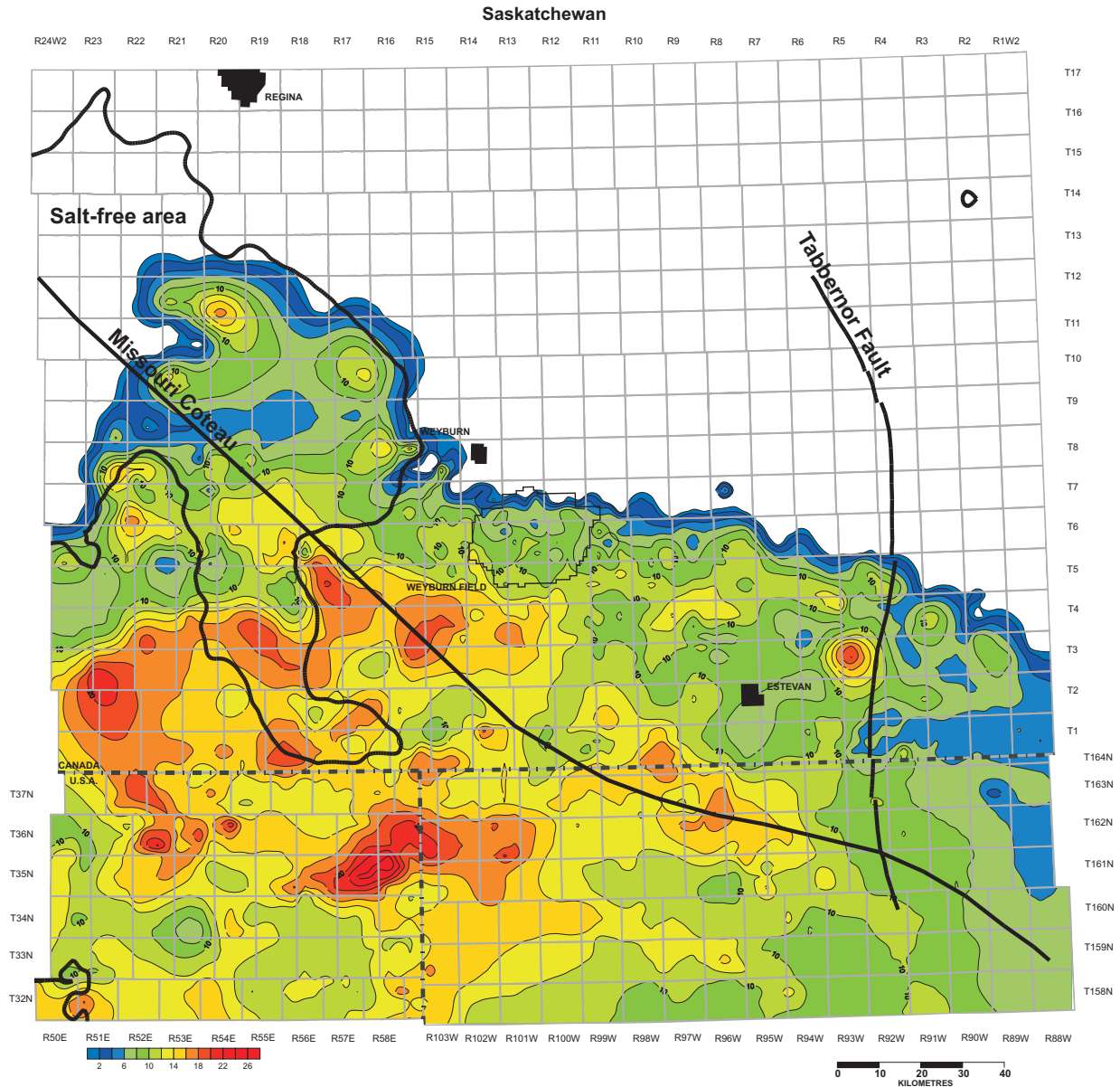


Figure 11 - Isopach map of the upper Midale. Note depositional thick in the west-central map area. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement, the areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent, and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 2 m.

anhydrite textures in the Midale Evaporite as a desiccating-upward salina cycle. Figure 12 illustrates the southwestern edge of the evaporite in Canada is spatially related to the trace of the Missouri Coteau.

Ratliffe Beds and Oungre Evaporite

The Ratcliffe Beds sit conformably on the underlying Midale Evaporite, or, where this unit is absent, the Midale Beds. They are dominantly evaporitic north of the trace of the Missouri Coteau, and are lime mudstones or wackestones to the south. Coated-grain developments, such as in the Hummingbird Pool, are localized (Fuzesy, 1973).

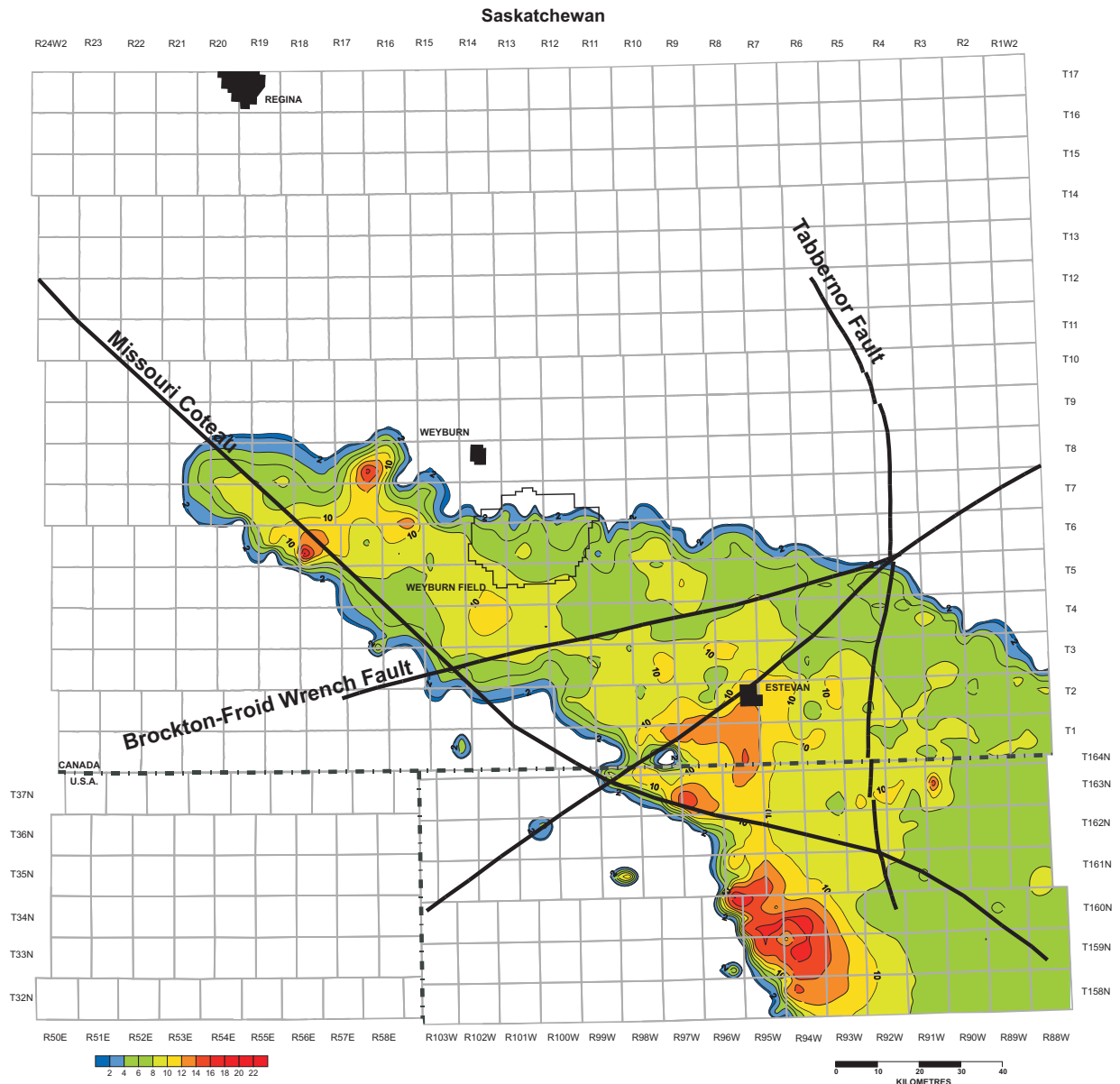


Figure 12 - Isopach map of the Midale Evaporite. Vertically projected traces of the Tabbernor Fault Zone as identified in the Precambrian basement, the Brockton-Froid Wrench Fault, and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 2 m.

The isopach trend of the Ratcliffe Beds (Figure 13) resembles those of the Midale Beds. The unit thickens to the west and southwest and thins to the northeast, the main change taking place approximately along the trace of the Missouri Coteau. Where the lower Ratcliffe, or Oungre unit, is thin, it is dominantly dolomicrite with an ichnofossil assemblage suggesting the *Cruziana* facies. Elsewhere, both the lower and upper Ratcliffe have a mixed assemblage of rock types including coated-grain wackestones to packstones, 6 to 21 m thick, respectively.

The most prominent evaporite in the Ratcliffe Beds is the Oungre Evaporite. Its sequence of anhydrite textural types is similar to that of the Midale Evaporite (layered, horizontal elongate, vertical elongate, and isolated nodular), and therefore represents a desiccating-upward cycle.

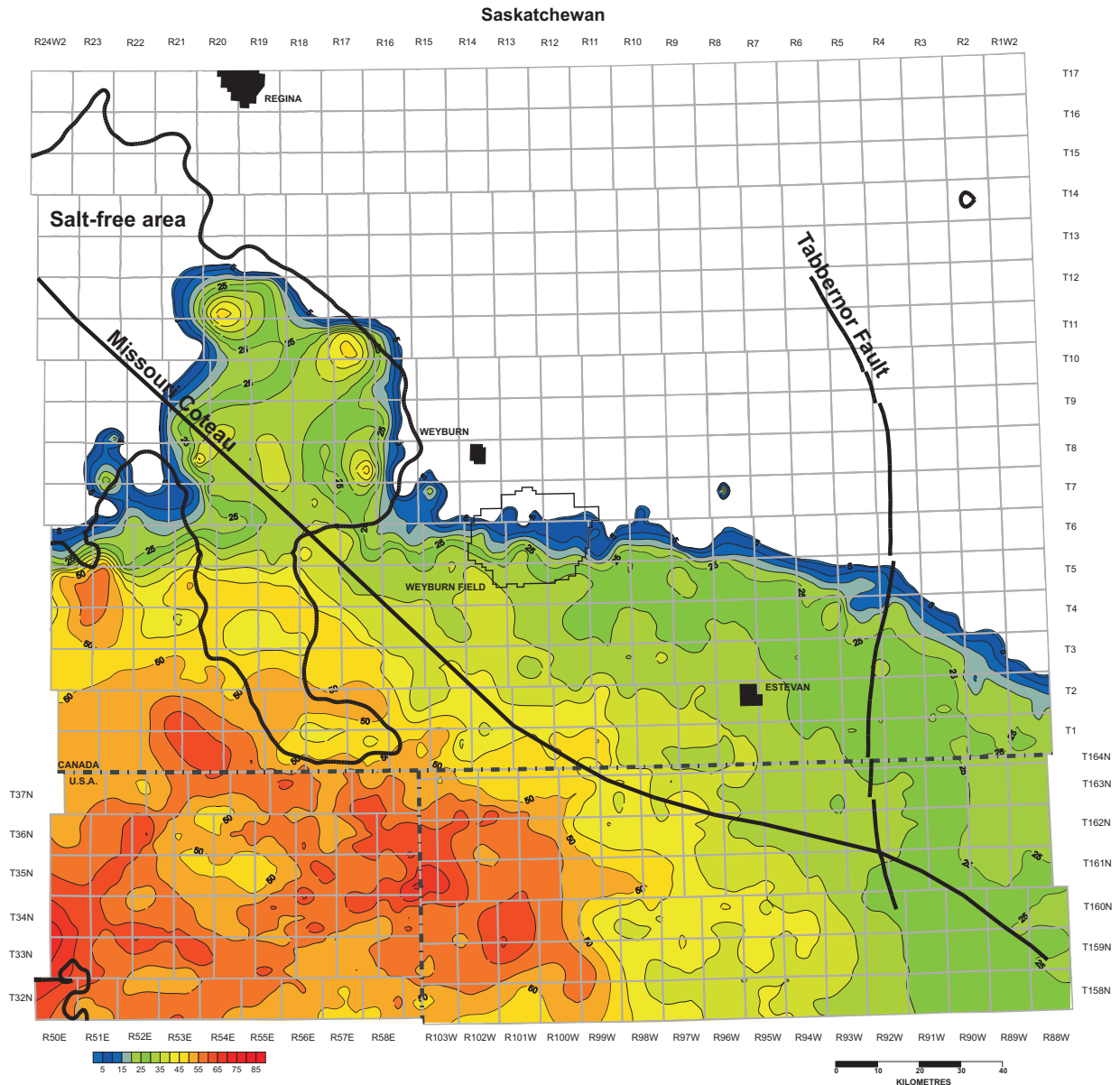


Figure 13 - Isopach map of the Ratcliffe Beds. Note erosional thinning to the northeast and depositional thickening to the southwest. Vertically projected traces of the Tabernor Fault Zone as identified in the Precambrian basement, the areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent, and the northeastern edge of the present-day Missouri Coteau are shown. Contour interval is 5 m.

Interpretation of Depositional Setting

The Ratcliffe comprises repetitions of marine sediments demonstrating diminishing accommodation space upward, and desiccated salina deposits.

d) Poplar Beds and Big Snowy Group

Poplar Beds and Green Point Anhydrite

The isopach map of the Poplar Beds (Figure 14) indicates that the unit is thickest in the U.S. portion of the study area, and extends northwards only six townships into Saskatchewan, except for an isolated remnant in the

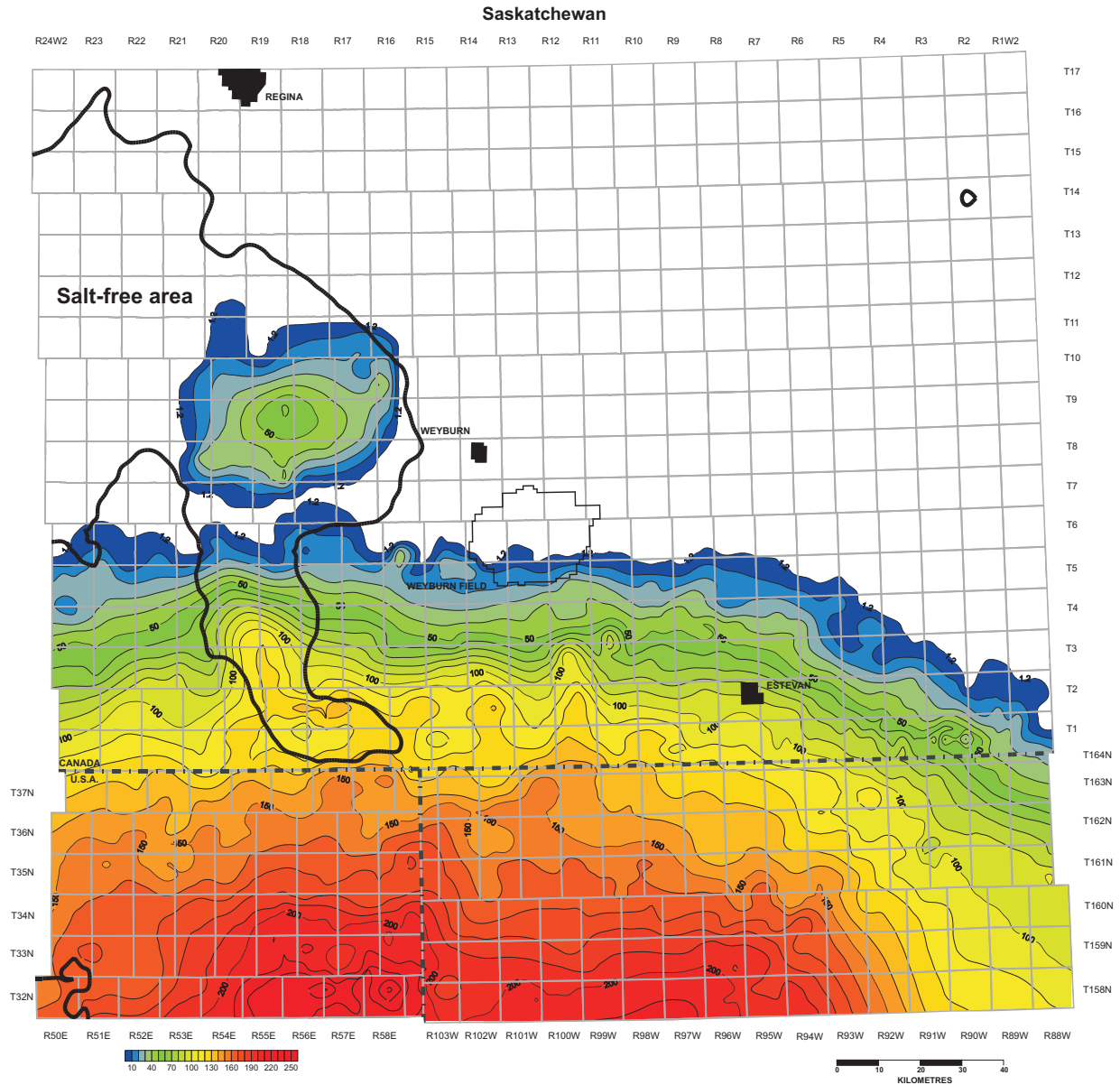


Figure 14 - Isopach map of the Poplar Beds. Solid heavy lines delineate areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent. Contour interval is 10 m.

Hummingbird Trough, a Prairie Evaporite salt-solution feature (Kreis *et al.*, 2003). In the Saskatchewan portion of the study area, the Poplar is truncated by the sub-Mesozoic unconformity except in an area close to the Canada–U.S. border between Range 6 and Range 20 where rocks of the Big Snowy Group are preserved. The basal contact of the Poplar Beds is at the top of the Ratcliffe Beds. In the 8-22-2-17W2 well that Fuzesy (1960) established as a reference well for the Poplar, the unit’s upper contact is at the base of a positive gamma-ray signature of about 50 API units.

Core from the 1-31-1-20W2 well indicates that the Poplar consists of repetitions of lime mudstones, dolomiticrites, rare oolitic grainstones, argillaceous dolostones, and anhydrites. In places, two salt deposits are present in the succession; one occurs 10 to 15 m above the base and the other is about 30 m below the top of the Poplar Beds. Based on a marine megafaunal assemblage (Brindle, 1960), that portion of the Poplar lying below the upper salt bed, or its equivalent rocks, is made up of repeated combinations of evaporites, mainly anhydrite, and marine carbonates. The rocks overlying the upper salt equivalent in the 1-31-1-20W2 well are increasingly more argillaceous and appear to be characteristic of peritidal rocks.

The Green Point Anhydrite (Figure 2) occurs 40 to 60 m above the top of the Ratcliffe Beds, has distinctive gamma-ray and porosity log signatures, and therefore was used as a means of correlating the upper portion of the Mississippian succession. The isopach map of the Green Point Anhydrite shows that it is more extensive than the Frobisher, Midale, and Oungre evaporites, and its wide areal extent in the U.S. portion of the project area makes it a good correlation datum. Cores of the anhydrite are rare, but those that were observed have the same textural components as the Oungre and Midale evaporites.

Big Snowy Group

The Kibbey Formation is the basal unit of the Big Snowy Group in the U.S. portion of the project area, and, in Canada, subcrops at the sub-Mesozoic unconformity in Townships 1 and 2, Ranges 6 to 20W2. The isopach map of the Big Snowy Group (Figure 15) shows that the unit is less than 20 m thick in most of its subcropping area, but reaches 60 m in Township 1, Ranges 17 and 18W2. According to Fuzesy (1960), the Kibbey includes red, sometimes argillaceous sandstones and siltstones with interbedded red shales, anhydrite, limestones, and dolostones. Determining the top of the Kibbey in drill cuttings or core, if available, is difficult. Fuzesy (1960) states that the

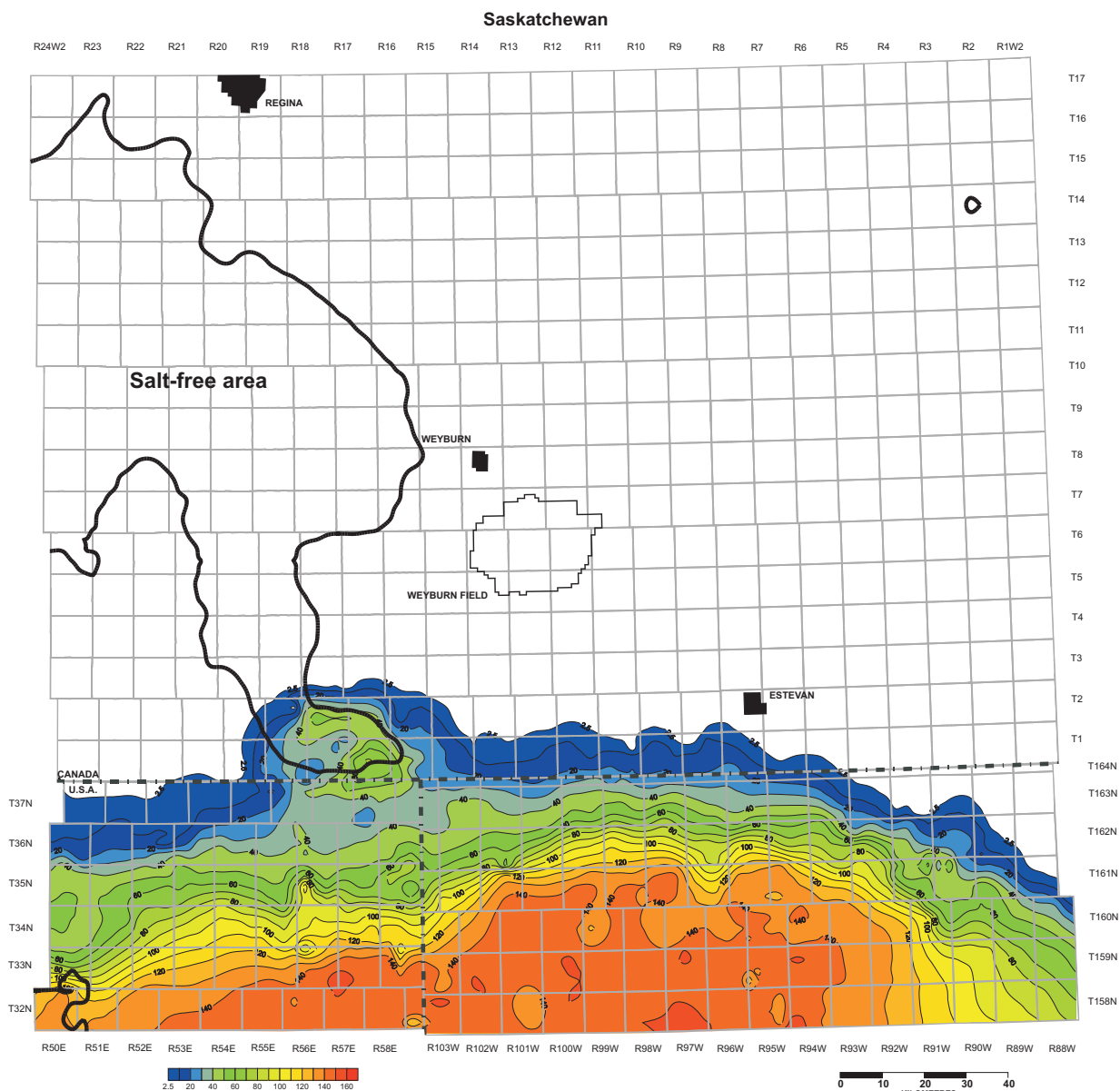


Figure 15 - Isopach map of the Big Snowy Group. Solid heavy lines delineate areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent. Contour interval is 10 m.

distinction lies in the difference in colouration of the rocks. He described the Lower Watrous as “orange to brick-red” and considered the Kibbey to be “vermilion”. Where the Kibbey is greater than 30 m thick, a persistently occurring 10 to 15 m thick limestone, the Kibbey Limestone, may also aid in the identification of the unit.

Interpretation of Depositional Setting

The Poplar Beds and Big Snowy Group are the epilogue to Mississippian sedimentation in the Williston Basin as they show a decrease in marine sediment types and an increase in continental deposits. Very little detailed work has been done on these units.

4. Structural Controls on Sedimentation

The most obvious structural feature on structure-contour maps of all the Mississippian units is the Hummingbird Trough. It is recognizable as a synform extending from Township 1, Ranges 16 to 19W2 to Township 7, Ranges 19 to 21W2 (Figure 16). It is an area totally devoid of the Middle Devonian Prairie Evaporite Formation and other

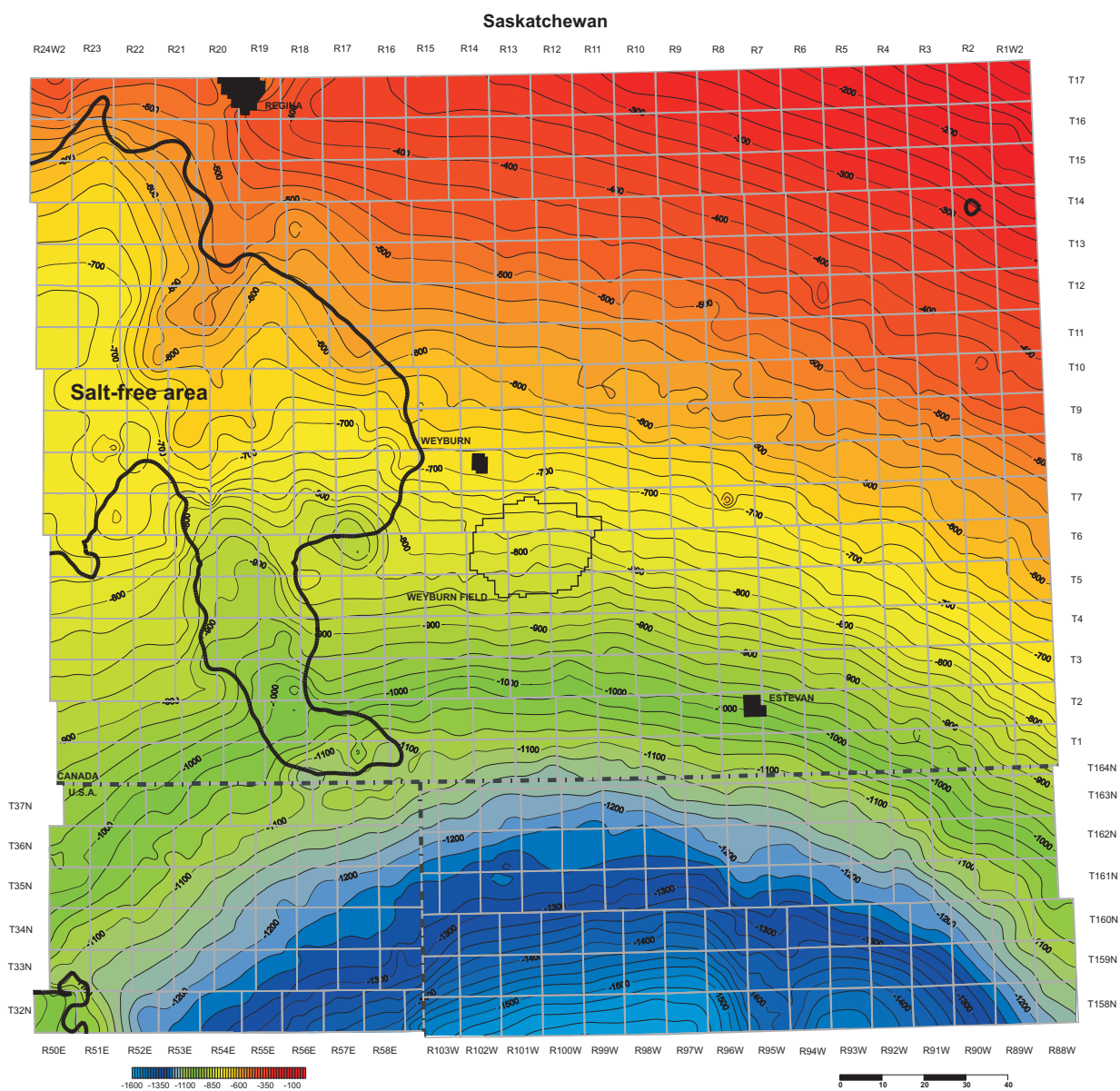


Figure 16 - Structure map of the sub-Mesozoic unconformity surface. Solid heavy lines delineate areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent. Contour interval is 25 m.

younger Devonian salt beds. The Hummingbird Trough opens into a salt-free area centred on Township 9, Range 19 W2M. The isopach maps of all units from the Alida to Poplar beds show that these strata are more widely preserved in this salt-free area. This suggests that solution of the Prairie Evaporite Formation in that region must have taken place prior to erosion of those Mississippian units. Isopach maps of the Lower Watrous (Figure 17) indicate thickening of the unit in both the Hummingbird Trough and the larger salt-free area that may have resulted from a second phase of salt removal during the time of Lower Watrous sedimentation. Salt beds removed at that time may have been the younger Devonian salt units, the Davidson and Flat Lake evaporites.

Some correlation is evident between observed structural lineaments and isopach anomalies within Mississippian strata. For example, several thickness anomalies on the Kisbey isopach map (Figure 6) along the eastern side of the project area appear to be in some way related to the Tabernor Fault. The general isopach trends of the Frobisher (Figure 7), Midale (Figures 9, 10, and 11), and Ratcliffe (Figure 13) beds and their related evaporites (e.g., Figures 8 and 12) show strong spatial relationship to the trace of the Missouri Coteau. In addition, these units appear to change strike at the trace of the Tabernor Fault, taking on a more southerly trend on the east side of the fault in

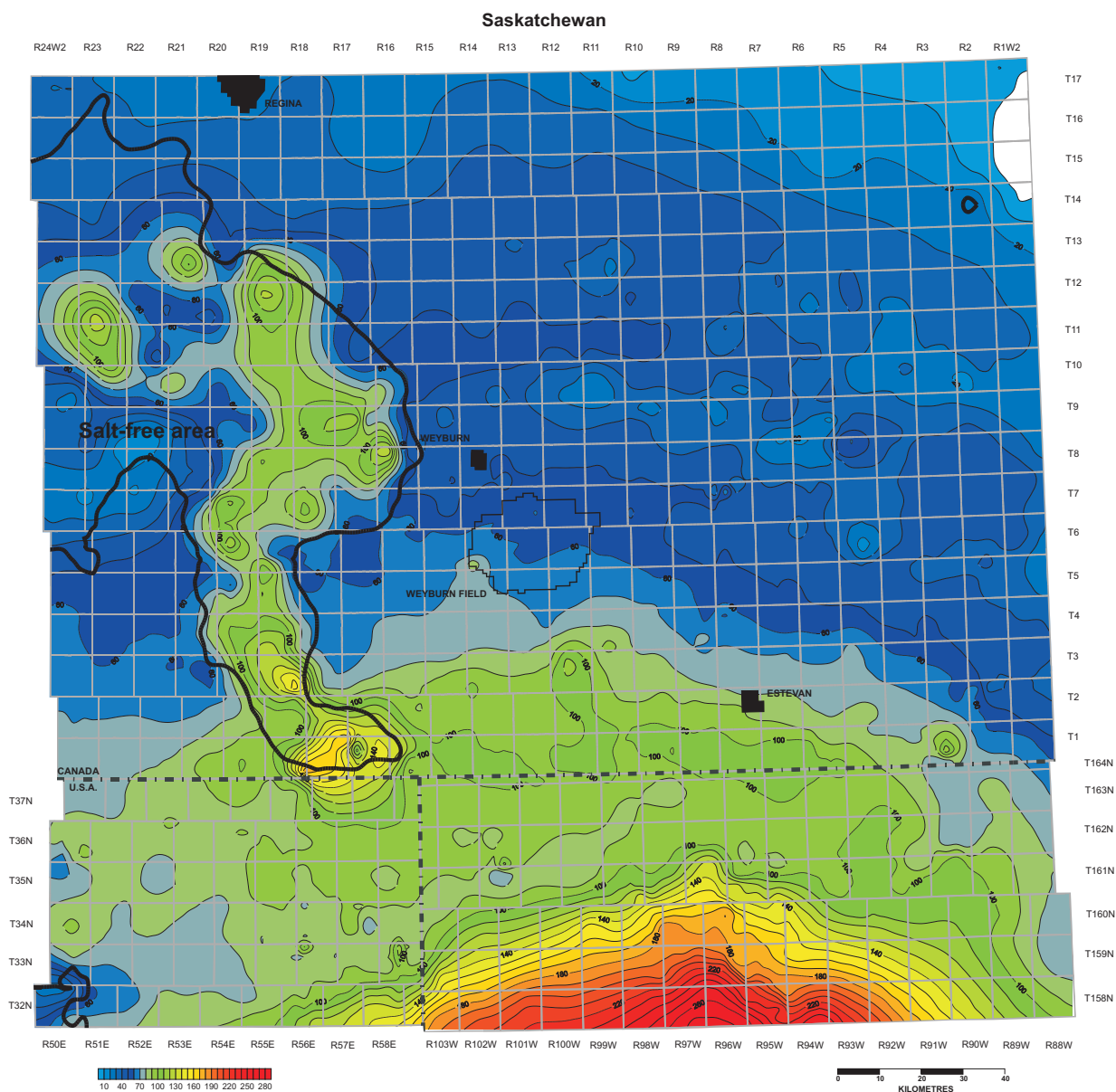


Figure 17 - Isopach map of the Lower Watrous. Solid heavy lines delineate areas under which the underlying Middle Devonian Prairie Evaporite Formation is absent. Contour interval is 10 m.

contrast to a northwesterly trend west of the fault. The Midale Evaporite (Figure 12) appears to thin along the left-lateral Brockton-Froid Wrench Fault.

5. Acknowledgments

The authors gratefully acknowledge the financial support given to this mapping project by the IEA Weyburn CO₂ Monitoring and Storage Project. The Lower Watrous map was created from data generated by J.E. Christopher, J. LeFever, A. Marsh, M. Yurkowski, and P. Thomas for preparing Mesozoic maps, also for the IEA Weyburn CO₂ Project. The authors thank Tom Love for help with the map production, and Chris Gilboy and Fran Haidl for their review of this paper.

6. References

- Brindle, J.E. (1960): Mississippian megafaunas in southeastern Saskatchewan; Sask. Dep. Miner. Resour., Rep. 45, 107p.
- Charbonneau, S. (1993): Advancement of horizontal wells in the Midale Unit; First International Williston Basin Horizontal Well Workshop, N. Dak. Geol. Surv./Sask. Energy Mines, pE1-E13.
- Cumming, A.D., Fuller, J.G.C.M., and Porter, J.W. (1959): Separation of strata: Paleozoic limestones of the Williston Basin; Amer. J. Sci., v257, p722-733.
- Eddie, R.W. (1958): Mississippian sedimentation and oil fields in southeastern Saskatchewan; *in* Goodman, A.J. (ed.), Jurassic and Carboniferous of Western Canada, John Andrew Allan Memorial Volume, Amer. Assoc. Petrol. Geol., p331-363.
- Edmunds, A.C., Millane, T.J., Churcher, P.L., and Tottrup, P. (1994): Factors affecting horizontal well performance in the Weyburn Unit Saskatchewan; Second International Williston Basin Horizontal Well Workshop, N. Dak. Geol. Surv./Sask. Energy Mines, pB2-1 to B2-24.
- Fuller, J.G.C.M. (1956): Mississippian Rocks and Oilfields of Southeastern Saskatchewan; Sask. Dep. Miner. Resour., Rep. 19, 72p.
- Fuzesy, L.M. (1960): Correlation and Subcrops of the Mississippian Strata in Southeastern and South-central Saskatchewan; Sask. Dep. Miner. Resour., Rep. 51, 63p.
- _____ (1973): The Geology of the Mississippian Ratcliffe Beds in South-central Saskatchewan; Sask. Dep. Miner. Resour., Rep. 163, 63p.
- Harvey, D., Kent, D.M., and Qing, H. (2004): Limited accommodation space an important factor in the formation of early dolomites in Mississippian Midale and Ratcliffe Beds of southeast Saskatchewan, reservoir rocks for an estimated 5×10^9 barrels of oil-in-place; Dolomites – The Spectrum: Mechanisms, Models, Reservoir Development; Can. Soc. Petrol. Geol., Seminar and Core Conference, CD-ROM, 15p.
- Kent, D.M. (1974): A Stratigraphic Analysis of the Mississippian Madison Formation in Southwestern Saskatchewan; Sask. Dep. Miner. Resour., Rep. 141, 85p.
- _____ (1984): Depositional setting of Mississippian strata in southeastern Saskatchewan: A conceptual model for hydrocarbon accumulations; *in* Lorsong, J.A. and Wilson, M.A. (eds.), Oil and Gas in Saskatchewan, Sask. Geol. Soc., Spec. Publ. No. 7, p19-30.
- _____ (1999): A re-examination of the processes of formation and diagenesis of coated-grain accumulations and contiguous facies in the Mississippian of southeastern Saskatchewan; *in* Summary of Investigations 1999, Volume 1, Saskatchewan Geological Survey, Sask. Energy Mines, Misc. Rep. 1999-4.1, p17-26.
- _____ (2001): A regressive discontinuity in the Midale Beds succession: A cause for two diagenetic events; *in* Ninth Williston Basin Horizontal Well and Petroleum Conference, N. Dak. Geol. Surv./Sask. Energy Mines, ext. abstr.
- _____ (2003): Some thoughts on the calcium sulphate deposits in the Paleozoic rock record of southern Saskatchewan; *in* Summary of Investigations 2003, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2003-4.1, CD-ROM, Paper A-8, 12p.

- Kent, D.M. and Curry, C. (2002): Characterization of reservoir rocks in the Mississippian Frobisher Beds of the South Heward Pool, Southeastern Saskatchewan; *in* Summary of Investigations 2002, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2002-4.1, p24-36.
- Kent, D.M. and Nimegeers, A.R. (2002): Intrastratal deposition breaks in the Mississippian Midale Beds of southern Saskatchewan; their roles in reservoir rock creation and hydrocarbon accumulation; Can. Soc. Petrol. Geol., Diamond Jubilee Convention, core convention, abstr. vol., p47.
- Keswani, A.D. and Pemberton, S.G. (1993): Sedimentology, ichnology, and paleoecology of the Mississippian Midale carbonates in the Williston Basin, Radville area, Saskatchewan: Preliminary interpretation; *in* Haan, J.D., Jang, K., and Webb, T. (eds.), Carboniferous to Jurassic-Pangea, Can. Soc. Petrol. Geol., Calgary, core workshop guidebook, p206-228.
- Kreis, L.K., Thomas, P.L., Burke, R.B., and Whittaker, S.G. (2003): Devonian isopach and structure maps, IEA Weyburn CO₂ Monitoring and Storage Project Area (Test Version CD-ROM).
- Lubey, P. and Charbonneau, S. (1995): Lougheed Midale Beds exploitation case study: Success through technology and innovation; Third International Williston Basin Horizontal Well Workshop, N. Dak. Geol. Surv./Sask. Energy Mines, B7-2 to B7-22.
- Marsh, K.A. and Qing, H. (2002): Transgressive-regressive cycles of the Mississippian Frobisher carbonate-evaporite succession in the Steelman area, southeastern Saskatchewan; *in* Summary of Investigations 2002, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2002-4.1, p37-46.
- Nimegeers, A.R. and Qing, H. (2002): Depositional model of Midale Beds, Steelman Field, southeastern Saskatchewan; *in* Summary of Investigations 2002, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2002-4.1, p47-67.
- Perras, G.L. (1990): Sedimentological and reservoir characteristics of the Frobisher-Alida Beds, Lost Horse Hill Field, southeastern Saskatchewan; unpubl. M.Sc. thesis, Univ. Regina, 212p.
- Reid, S.K. and Dorobek, S.L. (1993): Sequence stratigraphy and evolution of a progradational, foreland carbonate ramp, lower Mississippian Mission Canyon formation and stratigraphic equivalents, Montana and Idaho; *in* Loucks, R.G., and Sarg, J.F. (eds.), Carbonate Sequence Stratigraphy, Amer. Assoc. Petrol. Geol., Mem. 57, p327-352.
- Saskatchewan Geological Society (1956): Report of the Mississippian names and correlations committee; Sask. Geol. Soc.
- Thomas, G.E. (1954): Mississippian of the northeastern Williston Basin; Can. Min. Metall. Bull., v47, p136-142.