

Geological Mapping of Mesozoic Strata in Southeastern Saskatchewan, Northwestern North Dakota, and Northeastern Montana, and Regional Effects of Deformation by Glacial-Ice Loading (IEA Weyburn CO₂ Monitoring and Storage Project)

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Abstract

Recent subsurface geological mapping of Mesozoic strata, part of the IEA Weyburn CO₂ Monitoring and Storage Project, has indicated that deformation under loading by Pleistocene continental ice sheets may have impacted clay-rich and sandy, weakly consolidated formations as deep as 350 m below ground level. Because of post-Eocene erosion across the southward-dipping sedimentary strata, the formations affected are younger toward the south. Thus Colorado Group formations are affected in east-central Saskatchewan, and the Lea Park and Bearpaw formations farther south. Antecedent landforms probably influenced glacial-ice flow, erosion and deposition, and topographic highs likely impeded and deflected basal ice motion until sufficient ice mass developed to overcome them. Factors contributing to deformation were: 1) the weight of the ice (which was approximately 1.5 km thick), 2) repetitive glaciation and accompanying meteoric formation-water over-pressures, and 3) permafrost and thawing. Bentonite may have acted as a lubricant in the deformation process under loading. However, for the rocks to have deformed at depth, even by plastic flowage, accommodation space would have been required. Under glacial-ice loading, there would have been little free space. Formations below the Lea Park are increasingly indurated with depth, and the Jurassic and Paleozoic beds are all competent, except for the Middle Devonian salt beds of the Prairie Evaporite Formation at a depth of about 2400 m, which could have yielded to differentially applied compressional stress. This is suggested to have occurred.

Keywords: *Upper Cretaceous, sub-Pierre Shale unconformity, Pleistocene, sub-glacier rock deformation, salt tectonics.*

1. Background

Byers (1959) identified deformation of the Maastrichtian Eastend, Whitemud, and Bearpaw formations cropping out near Claybank on the Missouri Coteau, approximately 30 km south-southeast of Moose Jaw in southeastern Saskatchewan. The author noted that these formations are “isoclinally folded and thrust faulted into a series of subparallel, overturned folds and thrust blocks”, and affect strata that are 63.4 m (208 ft) thick. This deformation is attributed to glacial ice thrusting against the Missouri Coteau from the lowland to the northeast (Figure 1). On the lowland south of Esterhazy, in the SRC Esterhazy NE9-26-18-2W2 test hole, Christiansen (1971) reported the presence of 79.3 m (260 ft) of “brecciated, slickensided and mylonitic” Campanian Odanah Shale, overlying 1.8 m (6 ft) of glacial till. Similarly deformed Odanah and Lea Park shale beds crop out in the adjacent Qu’Appelle Valley farther south, and were also encountered in test holes south of the valley. About 60 km to the north of Yorkton, Wickenden (1945) reported mass displacement of Colorado shale by glacial ice action. There, in the Thunder Hill Lsd 1-25-35-30W1 test hole (Figure 1), 66.4 m (218 ft) of the Ashville (Lower Colorado) formation were encountered above 37.2 m (122 ft) of glacial drift interlayered with Upper Colorado Favel (Niobrara) strata. These overlie the regionally developed Ashville Formation (about 145 m [475 ft] thick), which rests upon the Swan River (Mannville) Formation. Severe faulting and brecciation extend downward in the Swan River to a depth of 280 m (920 ft). Bluemle and Clayton (1984), in a survey of glacier-deformation phenomena on the interior plains of Saskatchewan and North Dakota, observed that masses of glacial and sedimentary rock up to several hundred metres thick and 150 km² in area are affected. They proposed a major contributing factor in glacial deformation to be high pore-water pressure in sandy bodies at the ice-rock interface which act to create upward shear beneath the front of the glacier. As these sandy bodies are in unconfined strata, the deformation is largely an expression of horizontal shear in unconfined strata. Unanswered is the question of what would be the response of confined

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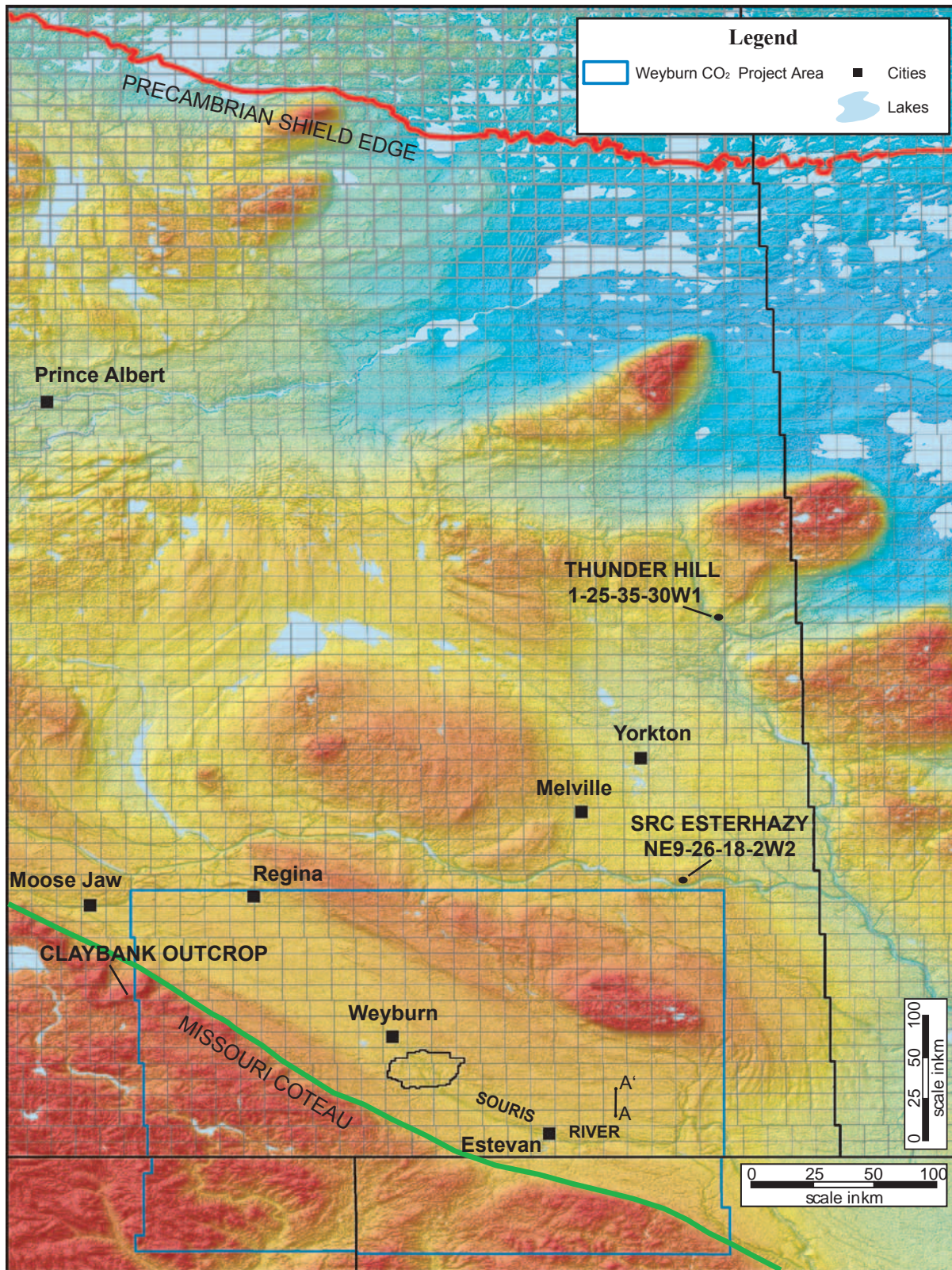


Figure 1 - Digital elevation model of southeastern Saskatchewan, southwestern Manitoba, northwestern North Dakota, and northeastern Montana. Locations are shown for two wells in which glacial till underlying strata of Cretaceous age has been reported, the Claybank outcrop, and the cross-section A-A' shown in Figure 4.

sediments deep in the subsurface of these regions impacted by glacier loading. Were the Upper Cretaceous strata of southeastern Saskatchewan an isotropic medium for the transmission of stress, the answer would probably be no response. However, isopach maps of these formations indicate patterns not wholly attributable to depositional agents or lithological homogeneity.

2. The Stratigraphic and Structural Setting

The area of study is bounded by Ranges 1 and 24W2, and Townships 1 and 17 in Saskatchewan; Ranges 50 and 58E, and Townships 32 and 37N in Montana; and Ranges 88 and 103W, and Townships 158 and 164N in North Dakota (Figure 1). In general, Mesozoic strata of the map area steadily increase in thickness from 675 m in the northeast to 2300 m at the southern edge south of Estevan (Figure 2). The loss of section to the east is attributable to erosion of Mesozoic strata associated with the Campanian sub-Pierre Shale (Lea Park) and post-Eocene, pre-Pleistocene unconformities. The Mesozoic stratigraphic sequence is partitioned by four major unconformities. These are (oldest to youngest): the sub-Mesozoic, the sub-Cretaceous, the Late Cretaceous (Campanian) sub-Lea Park

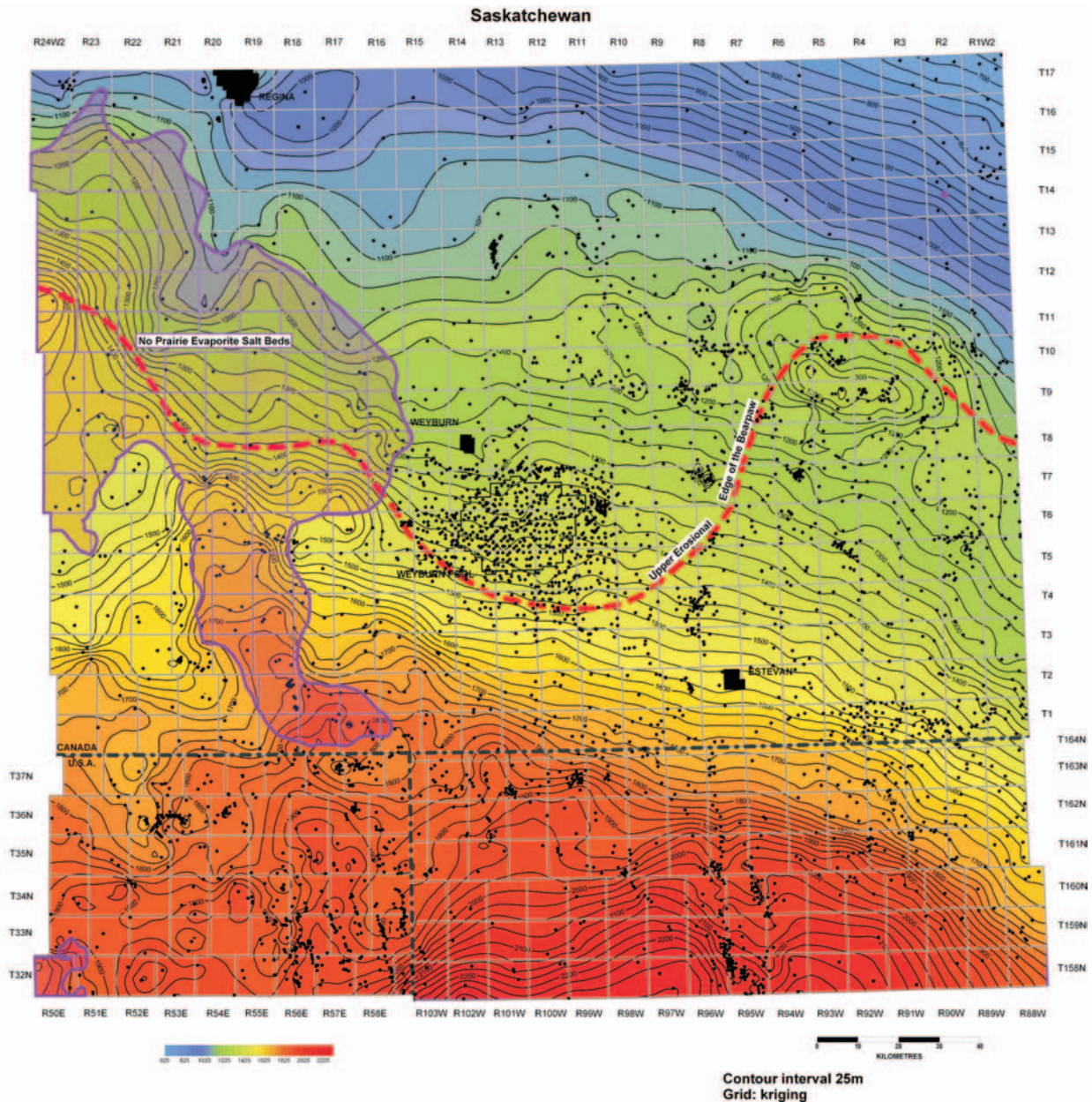


Figure 2 - Isopach map of Mesozoic strata. Solid heavy line shows edge of the Middle Devonian Prairie Evaporite salt beds; dashed heavy line delineates the upper erosional edge of the Bearpaw Formation.

(sub-Pierre Shale), and the mid-Tertiary. Major changes in basin configuration are associated with the lithostratigraphic units above each unconformity. The Paleocene Ravenscrag Formation, largely made up of quartzose sandstone, shale, and coal beds, lies at the top of the pre-mid-Tertiary sequence. It thickens southward from 300 m near Estevan to 470 m in the Williston Basin of western North Dakota, where it is named the Fort Union Formation. Paleocene strata are commonly better indurated than those of the underlying later Maastrichtian Eastend, Whitemud, and Frenchman formations, which are more indurated than earlier Maastrichtian through Early Campanian strata (Bearpaw, Belly River and Lea Park formations), probably as a result of secondary cementation by meteoric ground water. With further increase in depth, Mesozoic strata from those of Santonian–Early Campanian (Milk River) to Triassic (Lower Watrous) age become gradually more indurated. With respect to thickness and areal extent, shales in the Mesozoic succession are dominant.

The configuration of the contours shown in the structure map on the top of the Jura-Triassic Lower Watrous Member (Figure 3) is similar to the isopach morphology of the Mesozoic succession (Figure 2). The Lower Watrous surface dips at about 4 m/km, i.e., with respect to mean sea level (msl), from -75 m in the northeast to -750 m in the

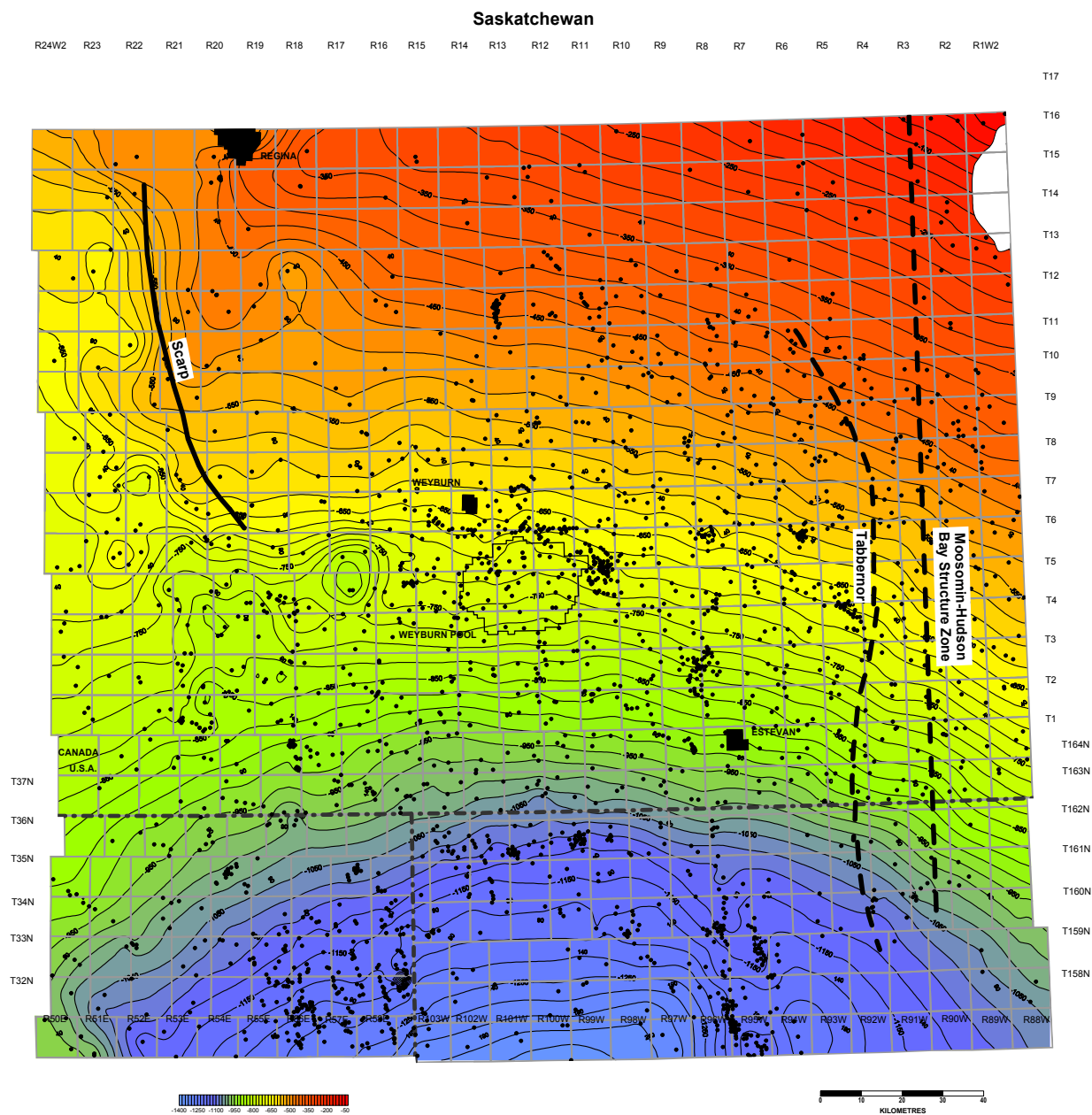


Figure 3 - Structure map on the top of the Jura-Triassic Lower Watrous Member.

south across the Weyburn Oil Field, to -1350 m in western North Dakota. A west-facing scarp along Range 22W2, which at Township 6 evolves eastward into a trough toward the Weyburn Oil Field, offsets the Saskatchewan Monocline to the west. This structural configuration is common to all the Mesozoic formations and is thus post-Cretaceous in age. In contrast, the northern extension along Range 95W of the Nesson Anticline is evident only as high as the sub-Lea Park erosion surface, apparently representing an episodically reactivated Paleozoic structure. Other structural activities are indicated by the isopach maps, especially in the region east of Range 6W2, where northerly aligned repetitive thickening and thinning, believed to represent basement reactivation of lineaments associated with the Tabernor Fault Zone and the western boundary zone of the Superior Precambrian Province (Moosomin–Hudson Bay Structural Zone, Waskada High), occur throughout the succession.

3. The Upper Cretaceous Stratigraphic Succession

In the Steelman area, stratigraphic units above the datum of the Greenhorn (Second White Specks) Formation (Figure 4) include the Carlile Formation, the Niobrara Formation and its Govenlock Member, the Lea Park Formation, the Belly River (Oldman Member), and the members of the Bearpaw Formation as adapted to the map area by the authors from Caldwell (1968). The wells in Figure 4 span a distance of 30 km south to north between Lsd 131/5-28-3-5W2 and 131/14-27-5-5W2, northeast of Estevan. The layout of the stratigraphic units is typical of the study area, although the Milk River Formation, which is present to the west, has been completely eroded along the sub-Lea Park unconformity at this location. This erosion surface in the cross section is essentially sub-parallel to the Greenhorn stratigraphic datum. Higher in the section, however, stratigraphic correlation offsets between wells increase from relatively small in the Lea Park Formation to substantial (up to about 70 m) in the Belly River and Bearpaw formations. The offsets are not a function of distance between wells, which ranges from 0.78 km to 9.6 km; nor are they a strict function of lithological variation in that all units, at one site or other, are affected by relative thickening, thinning, and absence. It is, rather, a pattern of post-depositional stratigraphic distortion – a type of boudinage on a large lateral scale.

a) The Greenhorn Formation

The Turonian Second White Specks Formation of Saskatchewan (Figure 5) is stratigraphically equivalent to the Greenhorn Formation in the Williston Basin of North Dakota. It is made up of dark and light grey, laminated, calcareous shale and argillaceous limestone, and includes ubiquitous white coccoliths. Bentonitic marker beds at the top, benthic and planktonic foraminifera, fragments of inoceramid and other pelecypods, fish scales and bones, and ammonites are common. Basal contact on the Belle Fourche Formation is marked in places by a bed of coarse bioclastic debris up to 5 cm thick (Gilboy, 1996), and by coal on kaolinitic seat earth in the northeast of the study area. The formation thins from 50 m at its depocentre in North Dakota and Montana to a widespread 35 m in Saskatchewan around Estevan. Farther north, there is a 10 m decline in thickness across a northeast-trending slope that extends from northern Montana to south of the Weyburn Oil Field, where at Range 8W2, it grades into the northerly aligned, 14 m-thick flat of the eastern region. From the thick front south of the Weyburn Oil Field, the formation thins to 11 m in the northwest near Regina. The isopach pattern overall resembles broad terraces with north- and northwest-facing scarps. These, in addition to the large southward re-entrants around Regina and the southeasterly re-entrant incorporating the Weyburn Oil Field and vicinity, have the morphological makeup of an erosion surface. Uplift would have been accentuated in the northwest, with southward back stripping toward a subsiding Williston Basin.

b) The Carlile Formation

The dominantly black, bituminous (Morden) shale and overlying calcareous shale and argillaceous limestone constituting the Carlile Formation thin from 90 m in North Dakota to 18 m east of Regina. South of the border, the isopachs conform, more or less, to the curvature of the Williston Basin. Carlile deposition appears to have been progradational on the Greenhorn surface from the south across a nearly filled Williston Basin. However, its isopach pattern, like those of the Greenhorn, Joli Fou, and Newcastle formations, indicate onlap or back step from an arch or dome to the north.

c) The Niobrara Formation

The Turonian to Coniacian Niobrara Formation is the uppermost unit of the Colorado Group. It is divided into three members: Govenlock (black, bituminous shale and calcareous shale), Medicine Hat (grey-black shale, and silty to sandy mudstone), and the First White Speckled Shale (medium grey to light grey, speckled, calcareous mudstone and shale). The 140 m-thick Niobrara Formation is present in its entirety only where it is overlain by the Campanian Milk River Formation in the southwestern part of the map area. To the northwest, the Niobrara is variably truncated by a post-Milk River erosion surface which features a valley that cuts to within 60 m of the base of the Niobrara, and terminates the Milk River Formation (Figure 6). East of this valley and around its northern end, an outlying welt of full-section Niobrara extends from the vicinity of Regina to the Weyburn Oil Field, and overlooks a northeastern

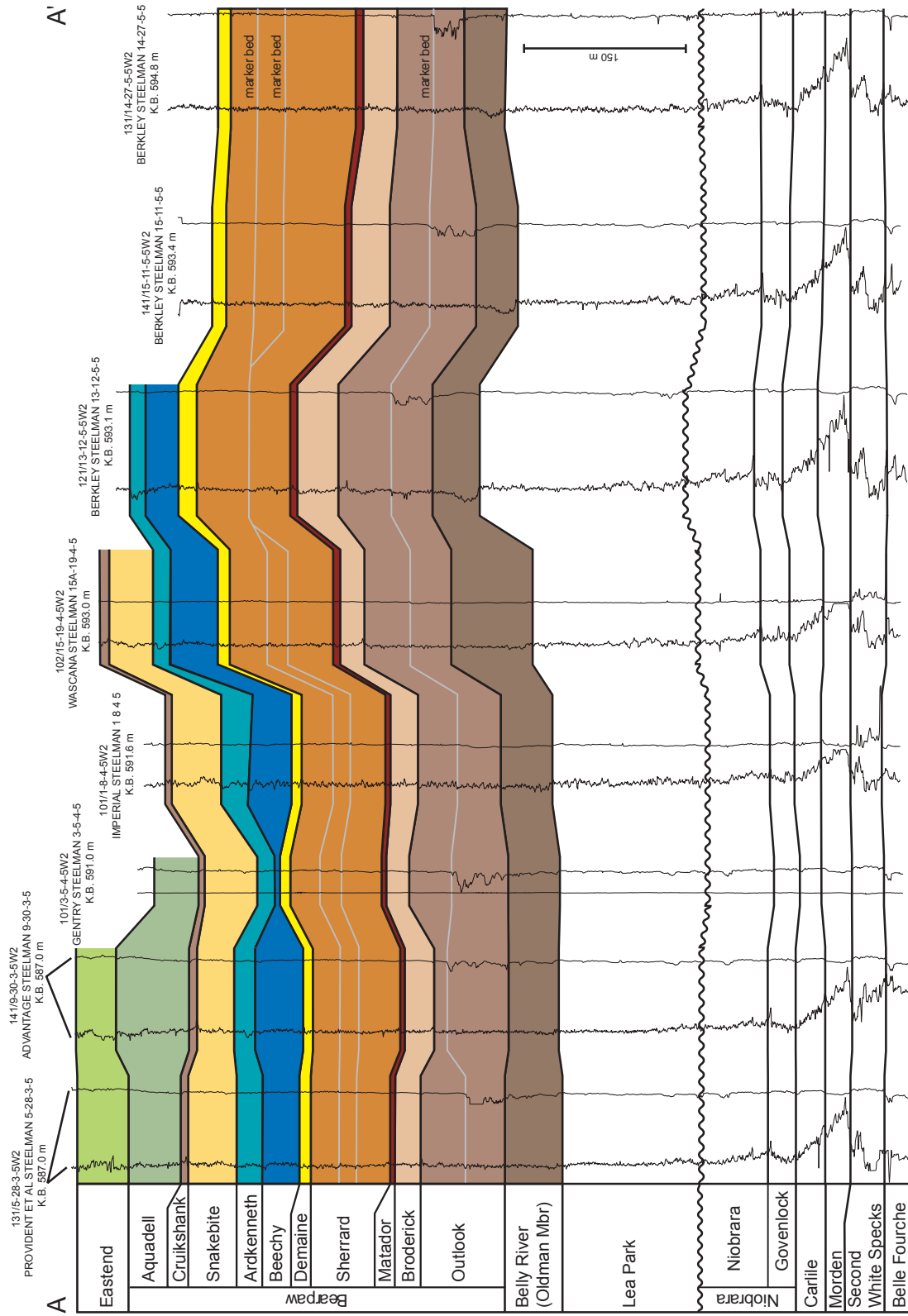


Figure 4 - Stratigraphic cross section (see Figure 1 for location) of post-Greenhorn formations east of Estevan, Saskatchewan. In places, correlation offsets in shallower formations are pronounced.

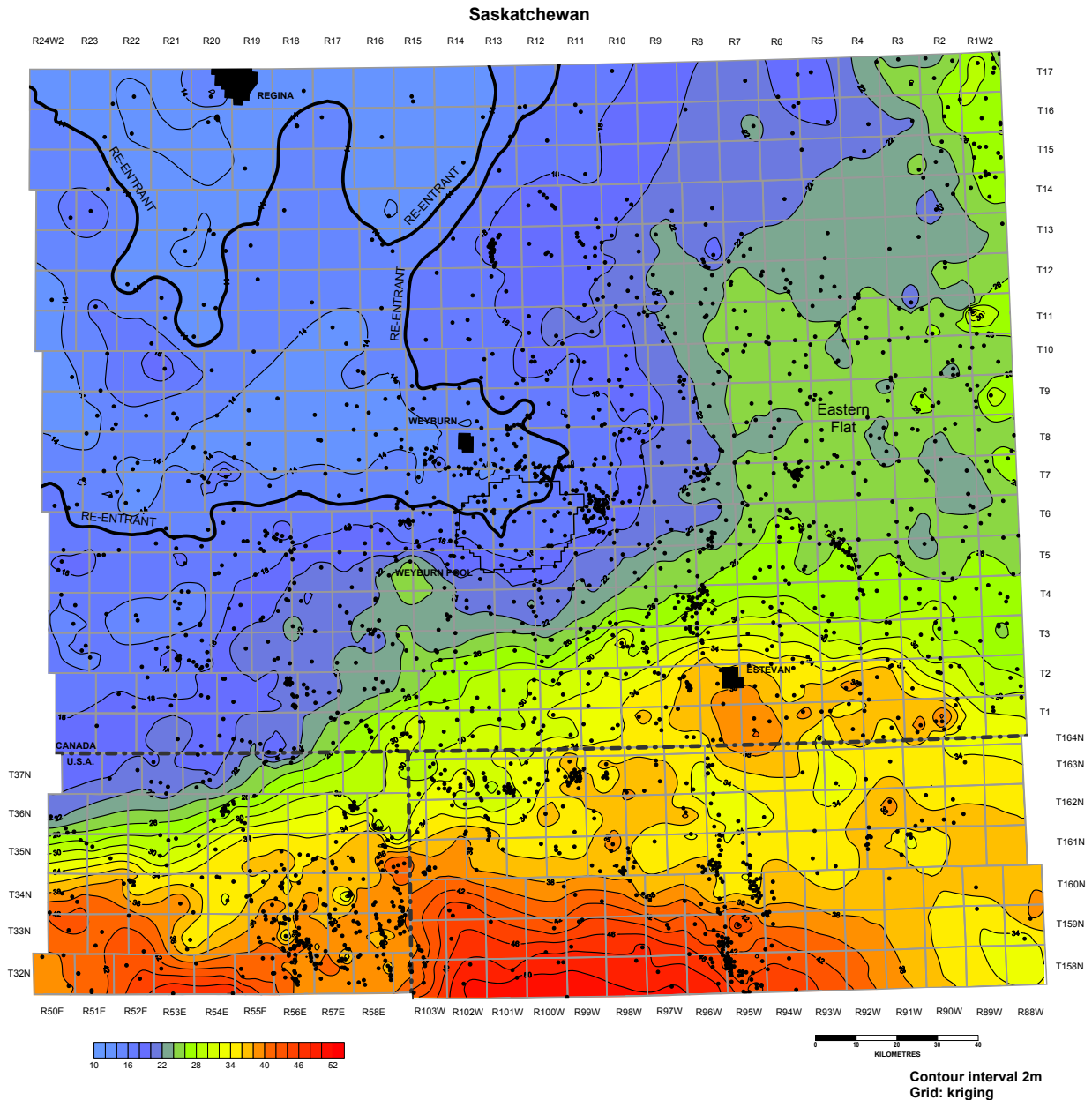


Figure 5 - Isopach map of the Greenhorn (Second White Specks) Formation.

region of relatively thin Niobrara. Thus from the edge of the Milk River Formation to the east an isopach map of the combined Upper Colorado post-Greenhorn strata should reflect sub-Lea Park (sub-Pierre Shale) relief (Christopher and Yurkowski, 2003). This effect is depicted in Figure 6.

d) The Milk River Formation

The Milk River is present only in the west of the study area, where it attains a thickness of 137 m in the southwestern corner. It thins gently northeasterly to 120 m, beyond which the slope to the zero edge increases to 120 m over 50 km, i.e., 2.4 m/km. The zero edge more-or-less delineates a topographic escarpment parallel to the structural Elbow-Weyburn lineament, and is a Campanian precursor of the present day Missouri Coteau. Though little is known physically of the Milk River Formation in the area, the log suites indicate it to be like the Colorado Group: predominantly formed of fairly well indurated, cyclic shale and muddy siltstone.

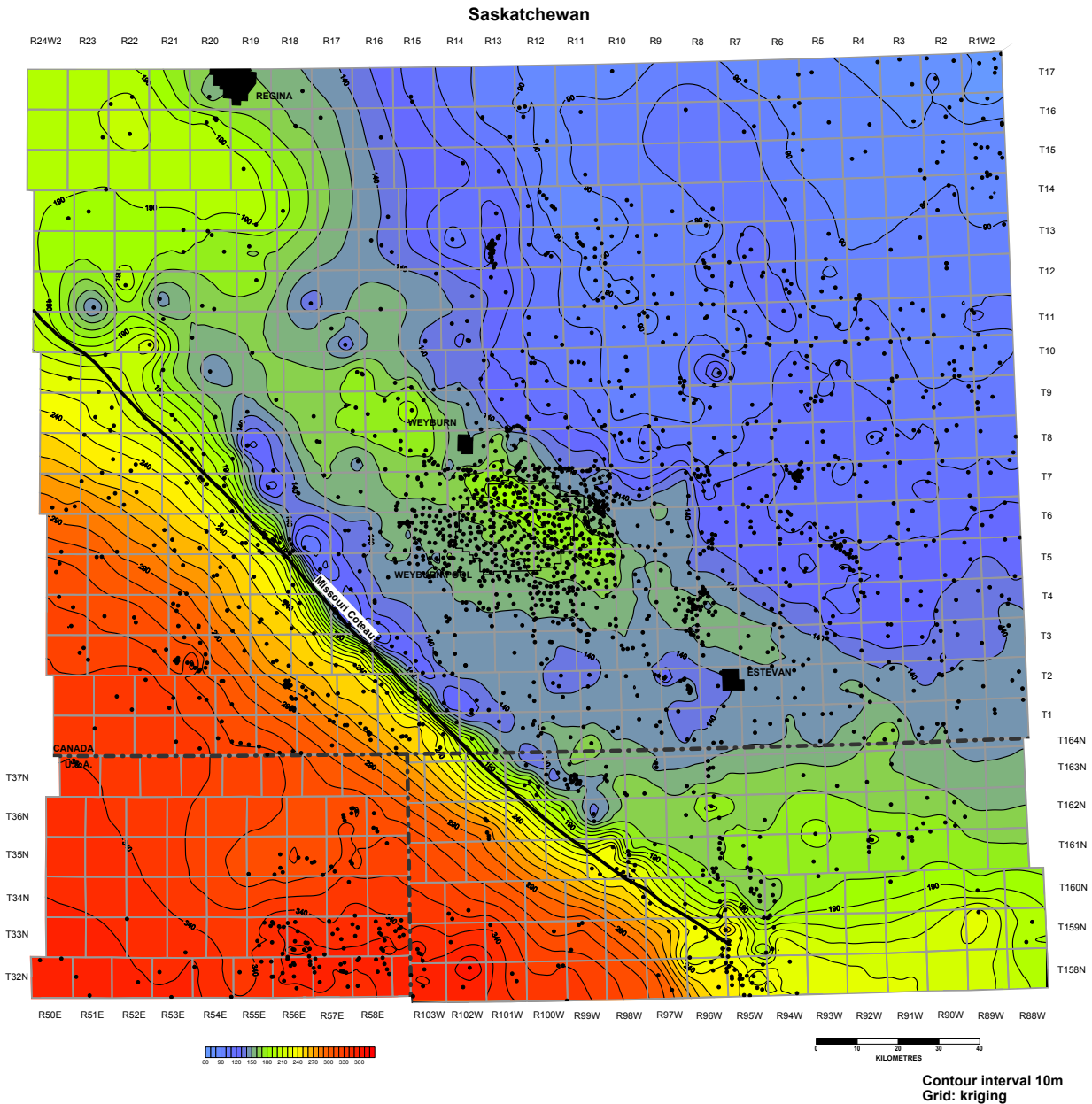


Figure 6 - Isopach map of the stratigraphic interval between the Greenhorn Formation and the sub-Pierre Shale erosion surface.

e) The Sub-Lea Park Unconformity

The sub-Lea Park unconformity (Christopher and Yurkowski, 2003) of the study area is considered the equivalent of the sub-Pierre Shale unconformity which is at the base of the Pierre Shale and can be traced throughout the eastern Cretaceous Campanian basin from Nebraska and eastern Wyoming (McGraw, 1975), through South and North Dakota (Shurr and Rieskind, 1984), into Manitoba and eastern Saskatchewan (McNeil and Caldwell, 1981). The sub-Pierre Shale erosion surface is described as cut on the Niobrara Formation. In the study area, it is also cut on the Niobrara as described above, but rises on to the Milk River Formation at the escarpment east of the Weyburn Oil Field. Using the Greenhorn Formation as stratigraphic datum, an isopach map of strata up to the unconformity presents a topographic counterpart of the sub-Pierre Shale erosion surface, whereon isopach thicks and thins correspond to topographic highs and lows, respectively (Figure 6). To the west, the escarpment rises 230 m above the adjacent valley floor. East of the escarpment the topographic expression is similar to that on the Niobrara. To the west, the 5.6 m/km rise of valley wall is in the Niobrara Formation. Across the Milk River Formation, the slope of the unconformity decreases from 3 m/km to 1.25 m/km over a distance of 80 km. The surface to the west flattens to

less than 10 m of relief. On the eastern side of the valley a ridge, 70 m high and several townships wide, trends southeastward through the Weyburn Oil Field to Estevan. Northeast of the ridge, the region, though comparatively low in relief, features a central depression, 50 m deep, between Ranges 15W2 and 7W2. The isometric block diagram of the erosion surface (Figure 7) depicts a southwestern plateau overlooking to the east a dissected terrace above a rolling lowland in the distance. The morphology is similar to that of the present day (Figure 1), whereby the Missouri Coteau from a similar height overlooks lower ground to the northeast. However, the sub-Pierre Shale valley has been filled in, and the modern Souris River overlies the sub-Lea Park ridge that trends northeast through the Weyburn Oil Field and Estevan. The counterpart eastern sub-Pierre Shale depression now underlies a broad topographic divide that includes Moose Mountain.

f) The Campanian Pierre Shale

The Pierre Shale is a vast, mostly calcareous, grey shale lithosome indigenous to the eastern Campanian marine basin that extended from Saskatchewan and Manitoba in the north to Nebraska in the south. It is the eastern correlative of the Montana Group in the Western Interior Basin and is stratigraphically subdivided (oldest to youngest) into the Pembina, Millwood, Odanah, and Bearpaw formations (McNeil and Caldwell, 1981). These formations equate with the Pakowki, Belly River, and Bearpaw formations of western Saskatchewan. Because of the eastward feathering out of Belly River sandstone units into the Lea Park shale of south-central Saskatchewan (Caldwell, 1968; McLean, 1971), the Lea Park of the study area comprises the Pakowki Shale and the lower sandstone (Foremost) transitional shale facies of the Belly River. The Upper Belly River Oldman Member is carried across the study area as an attenuated Belly River Formation, and tied into the Odanah Formation outcrop in the Qu'Appelle Valley of eastern Saskatchewan. This stratigraphic schema is depicted in Figure 2 of Christopher and Yurkowski (2003). The Pembina Member occupies the lower part of the Lea Park shale and includes the basin-wide Ardmore bentonite seen in core from the Bobjo Alameda No.1 (Lsd 16-4-4-2W2) and the International Yarbo 17S (Lsd 1-24-20-33W1) wells.

g) The Lea Park Formation

The Lea Park shale in the study area is dark grey, calcareous, abundantly fossiliferous, and includes locally developed, 10 to 20 m-thick bodies of clayey quartzose siltstone and very fine-grained sandstone, which appear to be deeper water facies of western sandstones belonging to the Belly River Formation. However, in the lower quarter of the formation, the Pembina facies of grey-black shale and bentonites grading downward into deeper water, black, carbonaceous shale is present. These shales are apparently the stratigraphically highest potential hydrocarbon source beds as exemplified by underlying black shale of the Carlile, Greenhorn, and Belle Fourche formations. Because the Lea Park blankets the sub-Pierre Shale erosion surface, its isopach map is a near inversion of that surface (Figure 8). In the southwest, where the Lea Park overlies the Milk River Formation, thickness is 85 to 100 m, but increases at the western escarpment of the trough by another 100 m. In the trough, where thickness ranges between 150 and 245 m over a width of 20 to 35 km and a length greater than 150 km, is a complex erosional valley with a deep thalweg along the western side. The valley extends well into North Dakota, where it is deflected into a southerly alignment alongside the Nesson Anticline. In Saskatchewan, it extends beyond the study area to the northwest. In the thalweg, the presence of two fining-upward basal argillaceous sandstone sequences with a total thickness of 20 m supports the possibility of an initial fluvial infill. However, overlying black shale, 5 to 30 m thick, indicates a succeeding widespread marine invasion with stagnant bottom conditions. The Lea Park thins to 120 m over the 35 km wide medial ridge (Weyburn Oil Field–Estevan trend) of the sub-Lea Park erosion surface. This ridge, like the trough, is aligned northwesterly, but is nearly pinched off in Range 14W2 Township 8, southwest of the City of Weyburn. The southern portion of the ridge encompasses the Weyburn Oil Field and extends southeast past Estevan, beyond which it thins axially as it widens into the southeastern corner of Saskatchewan. The same pattern is exhibited northwest of the City of Weyburn to the northern edge of the area. The morphology of the ridge resembles that of the valley, but inverted. To the northeast of the Weyburn Oil Field, the ridge overlooks a vast U-shaped area of Lea Park thickening which, at its maximum of 190 to 210 m (i.e., about 90 m thicker than in the ridge area), has an amoeboid shape and is about 60 km across. The isopach map of the underlying Upper Colorado (Figure 6) in this region shows a complementary erosional thinning of about 80 m. A Lea Park filling of an erosional amphitheatre is indicated, but the extra 10 m thickness of the Lea Park exceeds accommodation afforded by Niobrara relief, and therefore suggests either a negative structural adjustment in the Lea Park depositional floor, or an uncompensated stratigraphic pile. The structure map on the Lea Park Formation does not reflect the morphology of the underlying unconformity, but rather its near complete burial.

h) Belly River and Odanah Formations

The Belly River very fine-grained, quartzose sandy mudstone ranges in thickness from 27 to 70 m. The thicker bodies are township-wide pods aligned in easterly dual belts, one large body located across the southern half of the Weyburn Oil Field area, and another smaller body centred around Township 5 Range 8W2 (Figure 9). A lesser belt of thicks is distributed along Township 2. Broad areas of thins are widespread in the Williston Basin of North

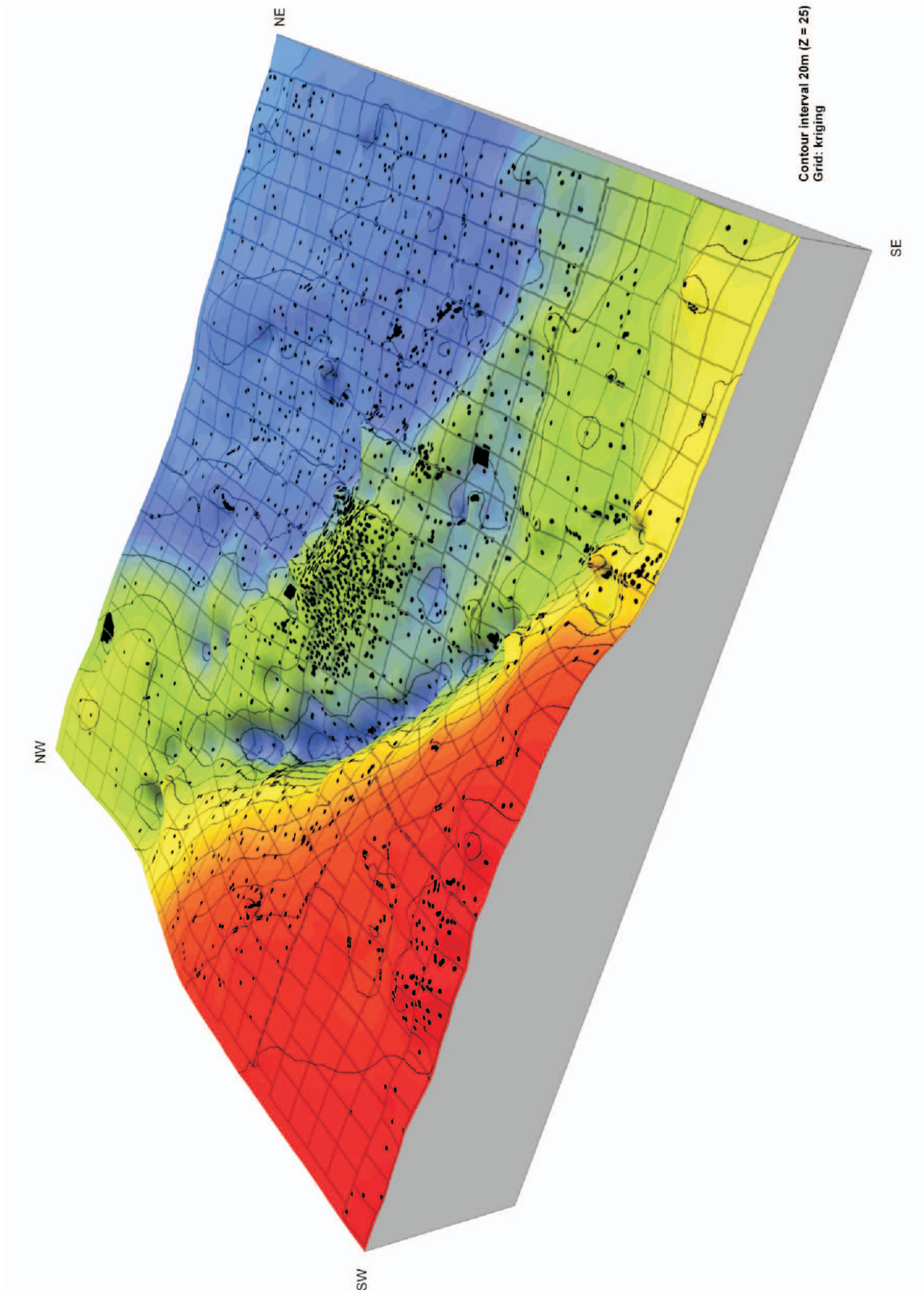


Figure 7 - Isometric block diagram of the sub-Pierre Shale erosion surface.

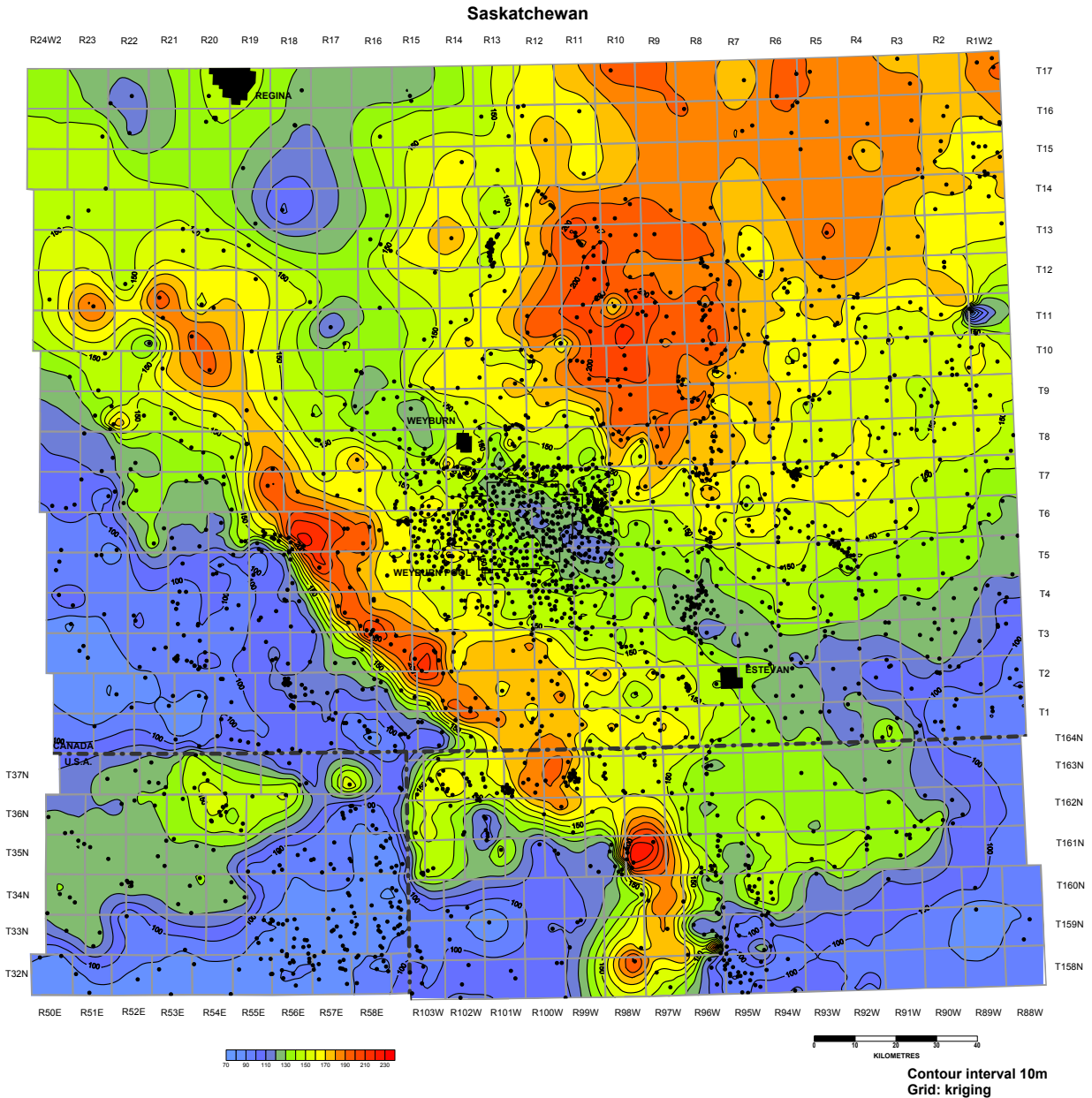


Figure 8 - Isopach map of the Lea Park Formation.

Dakota and Montana. In Saskatchewan, these thins attenuate spatially into north-aligned fingers west and north of the Weyburn Oil Field. Those west of Range 17W2 are associated with the eastern edge of the area affected over time by dissolution of the Devonian salt beds. The Belly River clastics attenuate on the thickened mass of the underlying Lea Park shale north of the Weyburn Oil Field, between ranges 14W2 and 4W2. This relationship is depicted by the 150 m and 180 m contours of the Lea Park superimposed on the Belly River isopach map. The thicks on the southern periphery of the Lea Park 150 m contour are a buildup on the southeastern flank immediately below the crest of the sub-Lea Park topographic high through the Weyburn Oil Field area. The southward embayment of the upper erosional edge of the Bearpaw Formation, around the southern flank of the Weyburn Oil Field area is also a noteworthy coincidence.

The belt of thickening east of Range 6W2 represents the Odanah facies of indurated siliceous shale, here up to 76 m thick. This formation crops out in the Qu'Appelle River Valley in Township 18, east of Round Lake and immediately to the northeast of the study area. Young and Moore (1994) from an exhaustive analysis of the Odanah Formation in the contiguous region of Saskatchewan, Manitoba, and North Dakota, concluded that the siliceous character of the formation is attributable to the presence of biogenic cristobalite. Because the Odanah Formation is

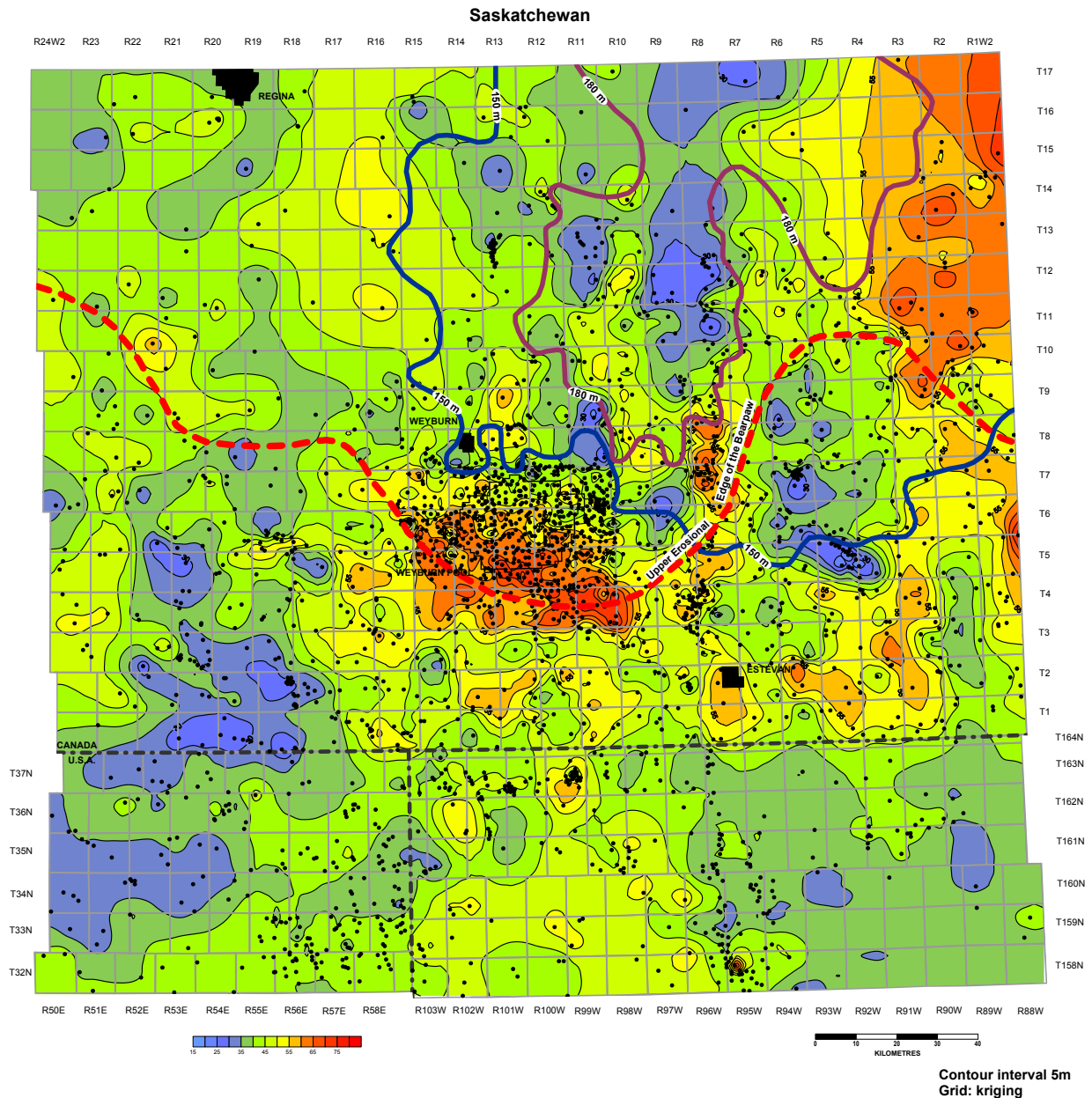


Figure 9 - Isopach map of the Belly River Formation. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation; dashed heavy line delineates the upper erosional edge of the Bearpaw Formation.

light grey and low (1%) in TOC, deposition likely occurred in an open-marine environment. It would appear that the Belly River depositional gradient was extremely low. The Odanah outcrop section is described by Christiansen (1971) and Christiansen *et al.*, 1972, p38) as being made up of noncalcareous, siliceous, hard shale interbedded with grey, noncalcareous clay, commonly brecciated and mylonitic; quartzose silty in part, and 45 m (148 ft) thick. In the cliffs along the Qu'Appelle Valley, the Odanah is decimetre-scale jointed and characterized by rotationally microfaulted blocks. According to Christiansen (1971), water for local use is obtained from fractures in the shale in volumes ranging from small to about 45 500 litres per day (10,000 gpd). Numerous springs discharge water from the Odanah along the Qu'Appelle Valley and its tributaries.

i) The Bearpaw Formation

Ten members of the Bearpaw Formation (Caldwell, 1968) are picked; these are (oldest to youngest): Outlook, Broderick, Matador, Sherrard, Demaine, Beechy, Ardkeneth, Snakebite, Cruikshank, and Aquadell. Because of the post-Paleocene episodes of uplift, erosion, and glaciation, the Bearpaw formation is erosionally truncated from north to south, so that only the oldest member is present as far north as Township 17. The region having full

Bearpaw sections is south of its upper contact with the erosional edge of the overlying Maastrichtian Frenchman (Figure 9). The formation is thickest (420 m) south of the Weyburn Oil Field and in the contiguous region of Saskatchewan, North Dakota, and Montana. It depositionally thins to 350 m west of Range 21W2, but erosional to 260 m east of Estevan. Bentonitic clay and mudstone are dominant components, with subordinate argillaceous sandstone. The Matador, Demaine, Ardkenneth, and Cruikshank members are sandier whereas the other units are thicker and more clay rich. There are no correlatable outcrops in the study area, and few oil-well drill cuttings. Correlations have, therefore, been made using geophysical logs only, with a degree of uncertainty that accompanies picking in a thick formation with only two end members – silty claystone and argillaceous sandstone. Thus the lithological descriptions below are general, as summarized by Caldwell (1968) from outcrops along the Saskatchewan River of south-central and southwestern Saskatchewan.

j) Outlook Member, Broderick-Matador Members

The Outlook Member as mapped in the study includes the underlying Unnamed Member of Caldwell (1968). It consists of dark grey, silty claystone under relatively thin, grey-brown and khaki, poorly indurated sandstone with fossiliferous calcareous concretions. In terms of well-to-well correlation, the Outlook and the Sherrard members are the most variable of the lithological units. The Outlook features marked excursions in conductivity and is variable in thickness relative to the Belly River Formation and the overlying Broderick Member. Most Outlook thicks (up to 129 m) are clustered east of Range 15W2 between Townships 1 and 8 (Figure 10). Northeast of these clusters, the region consists of random thins and general thinning analogous to the Belly River and counterpart to thickening in the Lea Park. The Lea Park 150 m and 180 m isopachs, when overlain on the isopach map of the Outlook Member, confirm this relationship as the Outlook thicks form an annular belt that is well developed between these contours from Township 6, Range 4W2 in the southeast to Township 15, Range 11W2 in the north. To the south and west the annular belt is juxtaposed to regional north-trending thickened Outlook bodies from Range 2W2 (Townships 1 to 4) to Weyburn at Range 15W2 (southward from Township 9). The relationship of the thicks and thins are portrayed in the 3-D isopach map of the Outlook Member (Figure 11), which shows how the outlying thickened bodies overlook the depression to the northeast. The Outlook thicks terminate abruptly at the superimposed 150 m Lea Park contour interval in the area from Range 15W2 Township 8 to Range 9W2 Township 6. For an offshore, marine sedimentary body of silt and mud, the isopach pattern showing scattered highs and lows is unusual. This is also true for the underlying Belly River Formation. Although both have a broadly similar distribution of these irregularities, it should be noted that the east-west belt of Outlook thinning along Township 5 across the southern perimeter of the Weyburn Oil Field is partially complementary to the underlying Belly River body of thicks.

North of the upper erosional edge of the Bearpaw Formation, the Bearpaw surface is sub-glacial. Where the erosional edge sweeps south of the Weyburn Oil Field, it follows in detail the track of individual Outlook thicks across the central region.

The Broderick is lithologically a thinner repetition of the Outlook Member and for purposes of this study can be combined with the thin (3 m) overlying Matador member (Figure 4). Log correlation indicates that these units are locally truncated by the overlying Sherrard Member. This shows up as regional thinning of the Broderick to 15 m east of the north-south 25 m contour along Range 7W2 (Figure 12). As in the Outlook, the thicks are irregular in outline, though commonly north aligned, and are concentrated in a belt extending from Range 18W2 east-southeast to North Dakota south of Estevan and in ranges 14 to 18W2 in the north. They are approximately peripheral to the Lea Park 150 m contour which encloses most of the region of thinning. The region west of Range 18W2 is also one of broad, axial thinning aligned north toward Regina.

k) The Sherrard and Demaine Members

The Sherrard (Caldwell, 1968) outcrops consist of dark grey, silty claystone with much selenite; whereas the overlying Demaine is grey-brown sandstone with ledge-forming, iron-rich, calcareous sandstone and discontinuous ironstone beds, and includes fossils and oyster banks. The Demaine is the most consistently recognizable of the marker beds. It is a 12 m-thick sandstone couplet on Sherrard strata of variable thickness. The isopach map of the Sherrard (Figure 13), like the underlying Bearpaw members, displays a central region of thicks flanked by western and eastern regions of thinning. The member thins to 40 m in both the west and the east, and thickens to more than 95 m in irregular north-south belts centred along Range 3W2 from just south of the Canada-U.S. border to Township 3 and Range 5W2 from Townships 5 to 10 where, within the transposed Lea Park 150 m contour, the area of thickening is widest. To the south, in Township 5, this belt joins the northern rim of an annular body of thicks that occupies the area bounded by Range 8W2 in the west, Range 2W2 in the east, and, in the south, Township 162 of North Dakota. A secondary belt of linear thicks trending northwest from the Williston Basin is cut off south of the Weyburn Oil Field along the edge of the upper erosional edge of the Bearpaw Formation by a track of thins distributed between Ranges 9 and 16W2 and Townships 4 and 8. The northern side of this track lies subparallel to the 150 m contour of the Lea Park. Suggestions of tectonic control are present: 1) the north-northwest oriented linear belt of thickening from the Nesson Anticline in North Dakota (Range 94W, Township 160N) to the southeastern end of the Weyburn Oil Field; and 2) the alignment of the linear thick with the Tabbernor Fault Zone

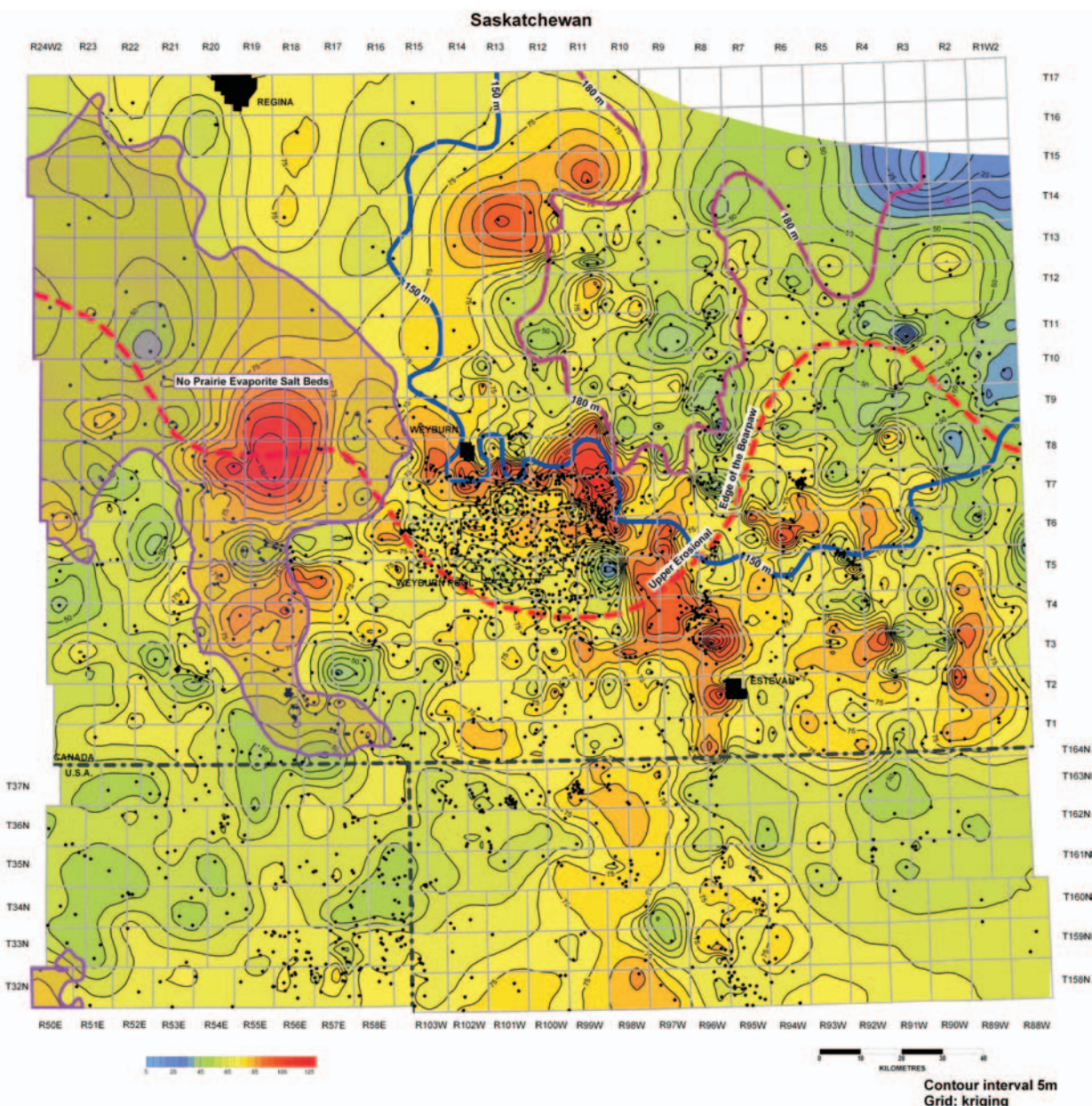


Figure 10 - Isopach map of the Outlook Member. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation; dashed heavy line delineates the upper erosional edge of the Bearpaw Formation.

along Range 5W2. West of the Tabernor Fault Zone, the thicker isopachs of the Sherrard lie, for the most part, on the thin side of the 180 m isopach contour of the Lea Park Formation. In general, thickness variations of the Sherrard essentially reciprocate those of the Outlook Member. The truncational nature of the Sherrard basal contact is observed in log correlation, but it is possible that the Sherrard base is conformable, and that a boudinage distortion of the underlying units has occurred. This deformation would flatten the upper contact of the Sherrard to nearly planar, as indicated by the ubiquitous consistency of the overlying Demaine marker bed. The Demaine is also variably truncated by the overlying Beechy.

The succession of patterns relates to a common post-depositional agent. The base of the distortion appears to be on the sub-Lea Park unconformity as represented by the 150 m and 180 m contours of the Lea Park Formation. This massive body may have been the locus of a differential stress regime created by glacial-ice loading. Thus the “fringing ridges” of Belly River and Outlook strata reflect outward displacement of Lea Park and younger sedimentary deposits by compressional forces directed from the north. Hence the belt of thickened strata in the Broderick Member lies south of that in the stratigraphically lower Outlook Member. This offset probably reflects southward rise of the deformational floor under the southward increasing thickness of overburden due to the presence of the Frenchman and Ravenscrag formations. On the other hand, thickening over the site of Lea Park

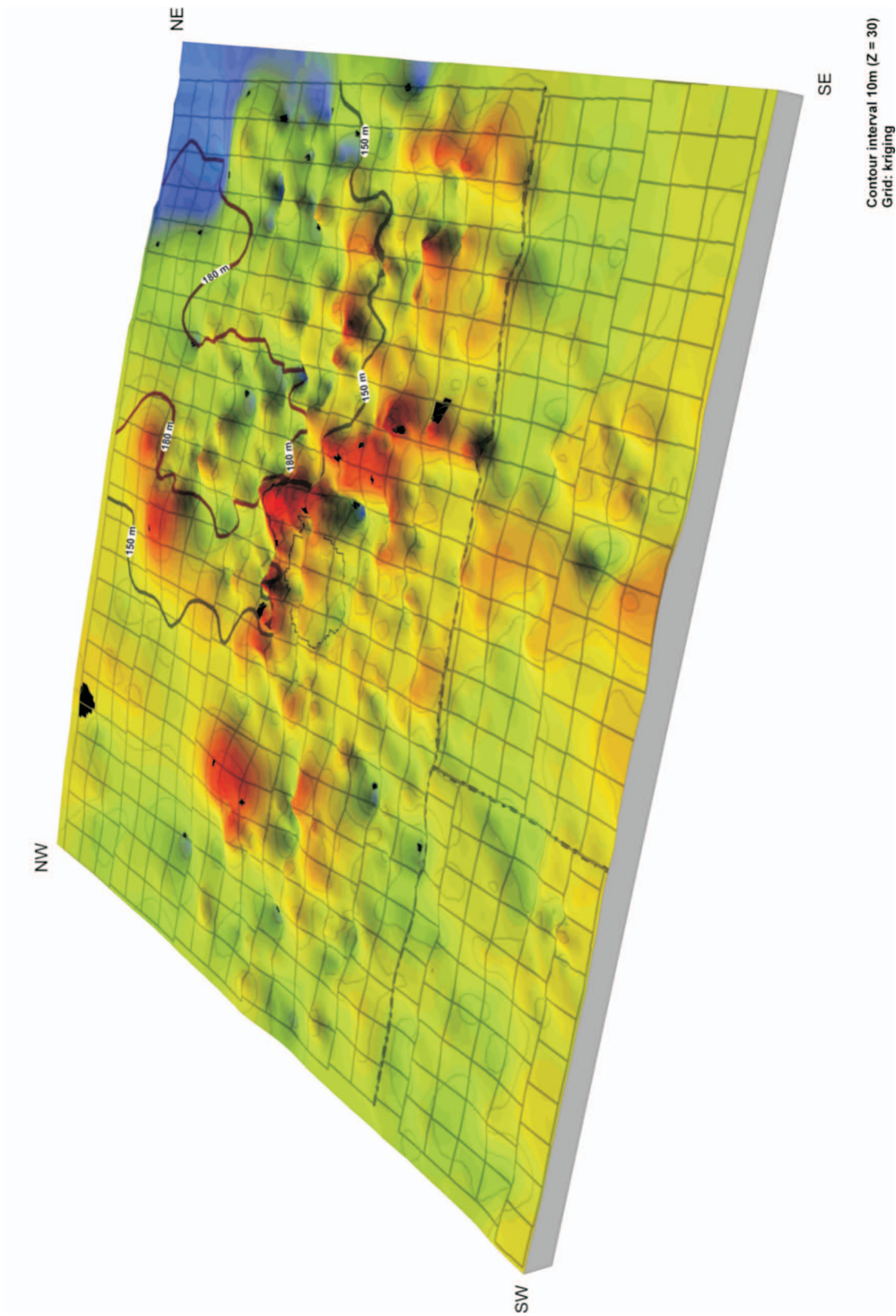


Figure 11 - Three dimensional isopach map of the Outlook Member. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation.

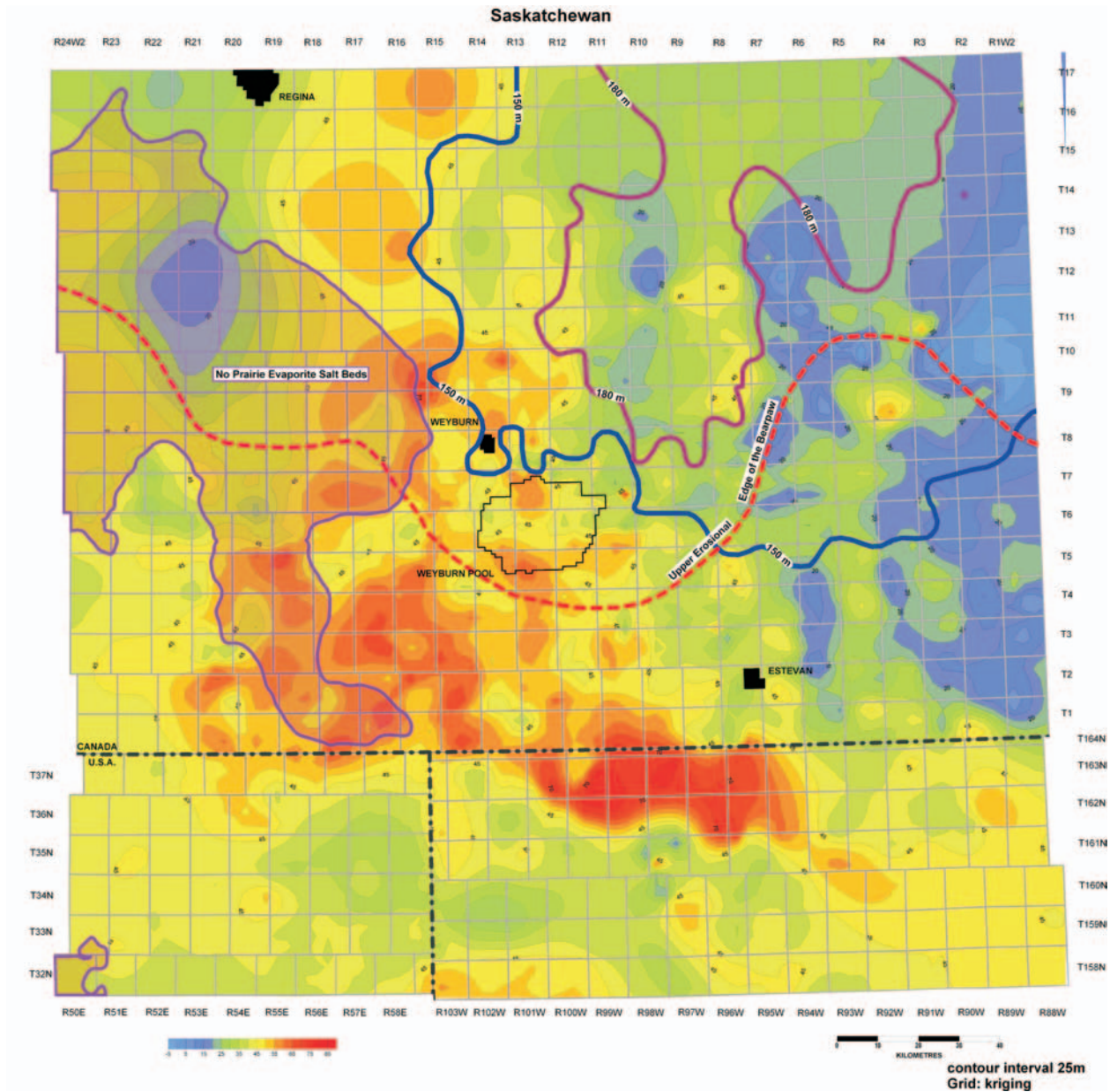


Figure 12 - Isopach map of the Matador and Broderick members. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation; dashed heavy line delineates the upper erosional edge of the Bearpaw Formation.

thickening recurs in the Sherrard and, like that of the Lea Park, suggests an increase in accommodation space created by episodic structural downwarp.

4. Deformation Attributable to Glacial-Ice Loading

Deformation under loading by Pleistocene continental ice sheets apparently has impacted clay-rich and sandy formations in eastern Saskatchewan as deep as 350 m below ground level. Because of Tertiary erosion across the southerly regional dip, the formations affected young toward the south. Thus Colorado Group formations are involved in east-central Saskatchewan, and the Lea Park and Bearpaw formations farther south. It is to be expected that pre-existing landforms exercised some control on glacial-ice flow, erosion and deposition, and that topographic increases in elevation impeded and deflected basal ice motion until sufficient mass developed in the ice to overcome these obstacles. Factors contributing to deformation were: 1) the weight of the ice, about 1.5 km in thick; 2) repetitive glaciation (Barendregt and Irving, 1998), and accompanying meteoric formation-water over-pressures

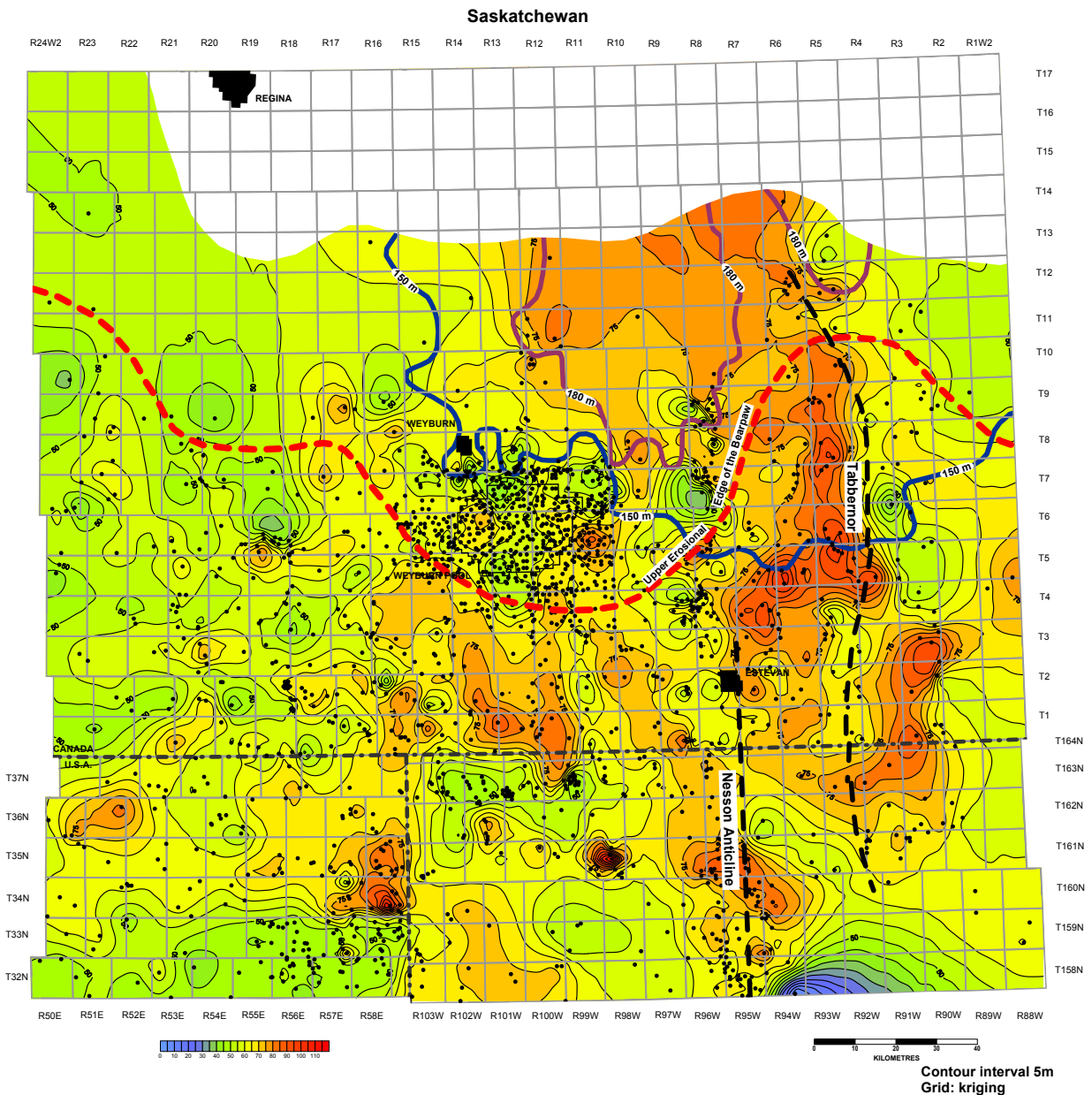


Figure 13 - Isopach map of the Sherrard Member. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation; dashed heavy lines delineate the upper erosional edge of the Bearpaw Formation and the approximate location of the Tabbernor Fault Zone.

(Bluemle and Clayton, 1984; Grasby *et al.*, 2000); and 3) permafrost and thawing. All three factors would have acted on the weakly consolidated formations exposed by Eocene stripping of the landscape. Bentonite was probably an active lubricant in the deformation process under loading. However, for the rocks to have deformed at depth, even by plastic flowage, accommodation space would have been required in that, under the glacial ice, there would have been little free space.

All the formations below the Lea Park are increasingly indurated with depth, and the Jurassic and Paleozoic beds are competent, except for the Middle Devonian salt beds of the Prairie Evaporite Formation at a depth of some 2400 m, which could have yielded to compressional stress, if differentially applied. In their analytical discussion on the relative strengths of salt beds and overburden, Jackson and Vendeville (1994) observed that the creep and frictional strength of dry salt is much weaker than that of any overburden sedimentary rock except shale buried to a depth of less than 100 m. Salt with interstitial water deforms by solution-transfer creep, and is hundreds of times weaker than dry salt, which yields by dislocation creep.

An analogy of such movement has been described from the Paradox Basin in Canyonlands National Park, Utah (Walsh and Schultz-Ela, 2003). There, ductile flow in the 300 m-thick Paradox salt deposits is created by the unloading of overburden in the down-cutting Grand Canyon, against the pressure exercised on the salt bed by the 460 m-thick Pennsylvanian and Permian sandstone and limestone country rock lying beyond the canyon walls. Ductile flow toward the thalweg of the canyon created diapirs under the river and grabens in the country rock, which dilate by flowage of salt toward the river from distances as great as 25 km.

In the Lloydminster area of western Saskatchewan, the presence and absence of the Prairie Evaporite salt beds were attributed by Anderson and Knapp (1993) to mechanisms involving salt dissolution triggered by regional faulting and fracturing, glacial loading and unloading, and salt creep, among others.

In west-central Saskatchewan, caverns created by salt dissolution and their annealing by salt flowage under the weight of the overburden are described by Mackintosh (1995) for the Cominco Fertilizers Limited Mine. He also observed that abandoned galleries in the mine are closed by salt flowage within four years.

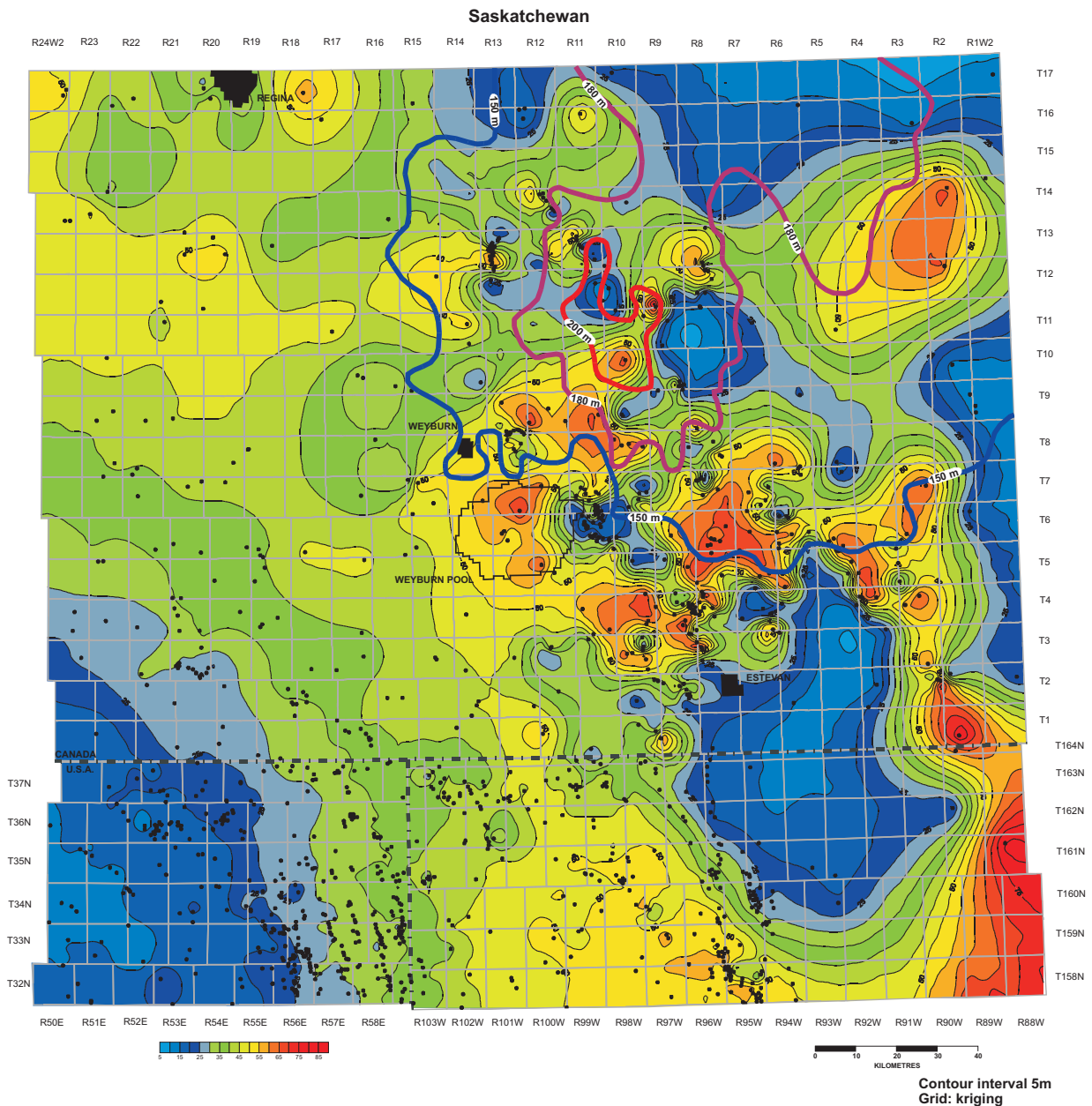


Figure 14 - Isopach map of the Middle Devonian Winnipegosis Formation. Solid heavy lines delineate the superimposed 150 m and 180 m isopachs of the Lea Park Formation.

In the application of the foregoing relationships to the study area, disequilibrium in the stress field of the Prairie Evaporite would have been created by flowage of salt toward sites of salt removal by dissolution. Such flowage would have been constrained in part by the configuration of the underlying salt basin as shaped by the presence of Winnipegosis reefal chains.

A test of the glacial ice-loading hypothesis to deformation in the Upper Cretaceous formations is to apply the isopach analogy of the Lea Park mass distribution as outlined by the 150 m contour to the isopach maps of the Prairie Evaporite and Winnipegosis formations. The map of the Winnipegosis Formation (Figure 14) depicts the 65 m-high reefs as thicks and the up-to-180 m Prairie Evaporite salt thicks mostly as inter-reef lows. The arcuate distribution of the reef trend in Range 3W2 Township 6 east and northeast of the Weyburn Oil Field to Range 13W2 Township 9, approximately coincides with the 150 m contour of the Lea Park, and could indicate a post-Lea Park squeeze against the sub-Lea Park expression of the deeply buried Winnipegosis reef trend. The 180 m contour encompasses two irregular sites of Prairie salt thickening separated by a northeasterly Winnipegosis reefal trend. To the north the Lea Park thick opens up over a corresponding expanse of regional Prairie salt.

The Lea Park is not the only Mesozoic analogue of Devonian stratal morphology. The isopach map of the Sherrard (Figure 13) shows an even closer relationship. Its thicks correspond to sites of thick Prairie salt in the region from within North Dakota into Saskatchewan between Ranges 4W2 and 7W2 to Township 5, and along Range 5W2 north into the area delineated by the 180 m Lea Park isopach. The Sherrard thins are geometrically related to Winnipegosis highs. The writers conclude that compactional effects in the Prairie salt are evident throughout the stratigraphic section, even into the uppermost Cretaceous. These effects were probably tectonically induced, but exaggerated by the shifting weight of glacial ice sheets encountering the cul-de-sac created by the Missouri Coteau and the Ravenscrag escarpment. The overburden load would have been differentially distributed on the salt beds of the Prairie Evaporite by the following factors: 1) the non-uniform salt thickness within the reef complex, and 2) the availability of free space created by meteoric water dissolution along the major front in the west and by local dissolution in the east, especially that related to the Tabbernor Fault Zone between Ranges 3 and 5W2. The salt beds would have yielded by flowage toward dissolution sites through openings in the Winnipegosis reef complex. The stress disequilibrium in the Upper Cretaceous strata was accommodated by plastic deformation toward the depressions created in the Prairie Evaporite, and with a counterpart thrusting against the draped highs of the Winnipegosis reefs. The manner in which the stress field was transmitted through the intervening well indurated Paleozoic carbonates and Jurassic strata is worthy of further study. One would suspect that the medium is a fracture and fault system. That the entire crust in the region has responded by 200 m of isostatic adjustment to glacial loading and unloading (Grasby *et al.*, 2000) also raises the question as to how this was accomplished.

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6. References

- Anderson, N.L. and Knapp, R. (1993): An overview of some of the large scale mechanisms of salt dissolution in western Canada; *Geophys.*, v58 p1375-1387.
- Barendregt, R.W. and Irving, E., (1998): Changes in the extent of North America ice sheets during the Late Cenozoic; *Can. J. Earth Sci.*, v35, p504-509.
- Bluemle, J.P. and Clayton, L. (1984): Large-scale glacial thrusting and related processes in North America; *Boreas*, v13, p279-299.
- Byers, A.R. (1959): Deformation of the Whitemud and Eastend formations near Claybank, Saskatchewan; *Transact. Royal Soc. Can.*, vLIII, series III, p1-11.
- Caldwell, W.G.E. (1968): The Late Cretaceous Bearpaw Formation in the South Saskatchewan River Valley; *Sask. Resear. Counc., Rep. No. 8*, 86p.
- Christiansen, E.A. (1971): *Geology and Groundwater Resources of the Melville Area (62K, L), Saskatchewan*; *Sask. Resear. Counc.*, 1:250 000 scale map.

- Christiansen, E.A., Meneley, W.A., Mickleborough, B.W., and Sauer, C. (1972): Guidebook on geology and its application to engineering practice in the Qu'Appelle Valley area; *in* Christiansen, E.A. (ed.), Regina Geotech. Group/Sask. Geol. Soc., 55p.
- Christopher, J.E. and Yurkowski, M. (2003): A major Late Cretaceous (Campanian) unconformity, southeastern Saskatchewan; *in* Summary of Investigations 2003, Volume 1, Saskatchewan Geological Survey, Sask. Industry Resources, Misc. Rep. 2003-4.1, CD-ROM, Paper A-12, 7p.
- Gilboy, C.F. (1996): Detailed log-based stratigraphic study of Colorado Group and Milk River Formation (Cretaceous), southwestern Saskatchewan; *in* Summary of Investigations 1996, Saskatchewan Geological Survey; Sask. Energy Mines, Misc. Rep. 96-4, p133-135.
- Grasby, S., Osadetz, K., Betcher, R., and Render, F. (2000): Reversal of the regional-scale flow system of the Williston Basin in response to Pleistocene glaciation; *Geol. Soc. Amer., Geol.*, v28, p635-638.
- Jackson, M.P.A. and Vendeville, B.C. (1994): Regional extension as a geologic trigger for diapirism; *Geol. Soc. Amer. Bull.*, v106, p57-73.
- Mackintosh, A.D. (1995): Geological features observed at the Cominco Fertilizers Limited potash operations, Saskatchewan, Canada; *in* Hunter, L.D.V. and Schalla, R.A. (eds.), Seventh International Williston Basin Symposium Guidebook, *Mont. Geol. Soc./N. Dak. Geol. Soc./Sask. Geol. Soc./Fort Peck Tribes*, p383-388.
- McGraw, H.M. (1975): The Pierre Shale-Niobrara unconformity in western Nebraska; *in* Caldwell, W.G.E. (ed.), *The Cretaceous System in the Western Interior of North America*, *Geol. Assoc. Can., Spec. Pap.* 13, p589-606.
- McLean, J.R. (1971): Stratigraphy of the Upper Cretaceous Judith River Formation in the Canadian Great Plains; *Sask. Resear. Counc., Geol. Div. Rep.* 11, 96p.
- McNeil, D.H. and Caldwell, W.G.E. (1981): Cretaceous Rocks and their Foraminifera; *Geol. Assoc. Can., Spec. Pap.* 21, 439p.
- Shurr, G.W. and Reiskind, J. (1984): Stratigraphic framework of the Niobrara Formation (Upper Cretaceous) in North and South Dakota; *in* Stott, D.F., and Glass, D.J. (eds.), *The Mesozoic of Middle North America*, *Can. Soc. Petrol. Geol., Mem.* 9, p205-219.
- Walsh, P. and Shultz-Ela, D.D. (2003): Mechanics of graben evolution in Canyonlands National Park, Utah; *Geol. Soc. Amer. Bull.*, v115, p259-270.
- Wickenden, R.T.D. (1945): Mesozoic Stratigraphy of the Eastern Plains, Manitoba and Saskatchewan; *Geol. Surv. Can., Mem.* 239, 37p.
- Young, H.R. and Moore, P.R. (1994): Composition and depositional environment of the siliciceous Odanah Member (Campanian) of the Pierre Shale in Manitoba; *in* Shurr, G.W., Ludvigson, G.A., and Hammond, R.H. (eds.), *Perspectives on the Eastern Margin of the Cretaceous Western Interior Basin*, *Geol. Soc. Amer., Spec. Pap.* 287, p175-195.