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Formation of Tertiary Coal Basins in Southern Saskatchewan

P.L Broughton

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Abstract

There are seven major Tertiary coal basins in the northern Williston Basin of southern Saskatchewan. Diminished crustal subsidence is not adequate to explain the origin and geometry of thick coal beds in several basins. They are interpreted as an effect of salt solution tectonics, specifically the leaching of up to 130 m of salt from the buried Elk Point (Middle Devonian) evaporite basin. This resulted in sufficient localized collapse subsidence to be structurally reflected in the 2000 to 3000 m of overlying Paleozoic to Cenozoic strata.

Deltaic lobes in the Eastend, Whitemud and Frenchman Formations (uppermost Cretaceous) were vertically accreted where anchored by nearshore structural instability above troughs modified by salt solution activity. Regression of the Bearpaw sea towards the cratonic depocenter resumed with diminished salt solution subsidence. Thick coal seams accumulated above abandoned deltaic sand bodies in successively younger coal basins to the southeast. This was contemporaneous with the transition up-section from subsidence dominated by salt solution to sufficiently diminished cratonic subsidence favourable for accumulation of thick coal beds.

Three types of geometric form characterize the coal basins depending upon the relative interplay of salt solution (local) and cratonic (regional) tectonics. The oldest coal basins, distant from the cratonic depocenter and represented by the Ferris and Anxiety Butte coal zones in the Cypress basin and the Landscape coal zone in the Wood Mountain – Willow Bunch basins, have lenticular coal bodies dominated by local tectonic influences. Up-section, the dominant salt solution influence on coal body geometry persists, but cratonic influences become more pervasive. In the Hart zone coal basin, shape is elongated parallel to and directly above the salt solution axis in the Prairie Evaporite, but isopach thick trends of coal seams cut across this and parallel cratonic lineaments. The youngest coal basins, represented by the Willow Bunch seam coalfield and the Estevan coalfield, are dominated by strong cratonic and distinctly weaker or no salt solution activity. The coal basins and the grain of the seam isopach thicks are elongate parallel to the regional (cratonic) structural grain.

Drainage and the dispersal pattern of sand bodies associated with the coal basins are similarly modified up-section with the shift from salt solution to cratonic influence. Sand bodies dominate the clastic interval between thick coal seams in coal basins strongly modified by salt solution activity, whereas muds are characteristic of cratonic coal basins. The regional drainage pattern was superimposed on southeast- and southwest-trending sets of reticulated basement fractures. The intermittent reactivation of these during the Laramide subsidence of the Williston Basin influenced the pattern of salt solution activity and, in turn, the localization of the drainage pattern and formation of coal basins.

Keywords: *lignite, coal, salt solution, Ravenscrag Formation, Frenchman Formation, Whitemud Formation, coal basin, Saskatchewan, Late Cretaceous, Paleocene, syndeposition, basin analysis*

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Introduction

One of the world's largest lignite deposits was laid down in the Williston Basin during the Late Cretaceous to Early Tertiary. The largest coalfields are distributed throughout an area covering the extreme southern part of Saskatchewan and extending into Montana and North Dakota. These intracratonic coalfields have been attributed to a decline in the rate of cratonic subsidence to almost minimal towards the close of the Laramide Orogeny. However, this does not explain the spatial relationships of thick lignite beds, and entire coalfields, across the northern limb of the Williston Basin (Broughton, 1977). Downwarping of crustal blocks dominated intermittent pre-Laramide subsidence of the Williston Basin since Lower Paleozoic time. Secondary subsidences due to salt removal from the Middle Devonian evaporites occurred and modified the geometry of the coal basins.

Scope of Study

The origin and the preservation from erosion of the Late Cretaceous to Early Tertiary (Paleocene) lignite deposits in the northern Williston Basin across southern Saskatchewan are examined. Tectonic controls on the geometry of coal beds and associated clastic bodies and on the localization of coalfields are analyzed. The Willow Bunch coal basin, which reflects the imbalances between local (salt solution) and regional (cratonic) tectonics, is compared with the Estevan coalfield where only cratonic control is evident. Furthermore, evidence is presented to suggest that some tectonic controls which persisted after burial of the coalfields aided in preservation of the coal beds from major periods of erosion during the Late Tertiary uplift and Pleistocene glaciation. This study complements the work of Irvine, Whitaker and Broughton (1978) which delineated the coal resources of the Ravenscrag Formation. A catalogue of lignite seam picks has been released in microfiche form as Open File Report 82-5 (Broughton, 1982).

Setting

The study area extends 650 km from east to west across southern Saskatchewan and 120 km from the United States border to latitude 50°N (Figure 1).

The Williston Basin is an ellipsoidal depression of the Precambrian basement centred in western North Dakota (Figure 2). It accumulated 4614 m of Cambrian to Pleistocene strata in western North Dakota, but this thins to less than 3200 m in southern Saskatchewan. Significant-Laramide structural deformation occurred during the Late Cretaceous and Early Tertiary, but regional basin subsidence has been intermittent since the Middle Ordovician.

The Williston Basin formed the southeastern portion of the Middle Devonian Elk Point Basin, which extended southeast from the Northwest Territories, across central Alberta and into southern Saskatchewan. The Elk Point Group (Middle Devonian) is dominantly a carbonate succession with thick halite and potash beds. It includes the Prairie Evaporite, up to 200 m thick in southern and central Saskatchewan, which is composed of a lower halite and anhydrite unit overlain by three major potash members with intervening halite beds.

At least 2500 km^2 of these salt beds in southern Saskatchewan have been affected by postdepositional leaching and collapse of the overlying strata. These effects are structurally reflected in the 2000 to 3000 m of overlying Paleozoic and Mesozoic strata.

Acknowledgements

The borehole drilling program on which this study is based was funded jointly by the Province of Saskatchewan (Department of Mineral Resources) and the Government of Canada (Geological Survey of Canada). For a description of this study, see the report by Irvine, Whitaker and Broughton (1978).

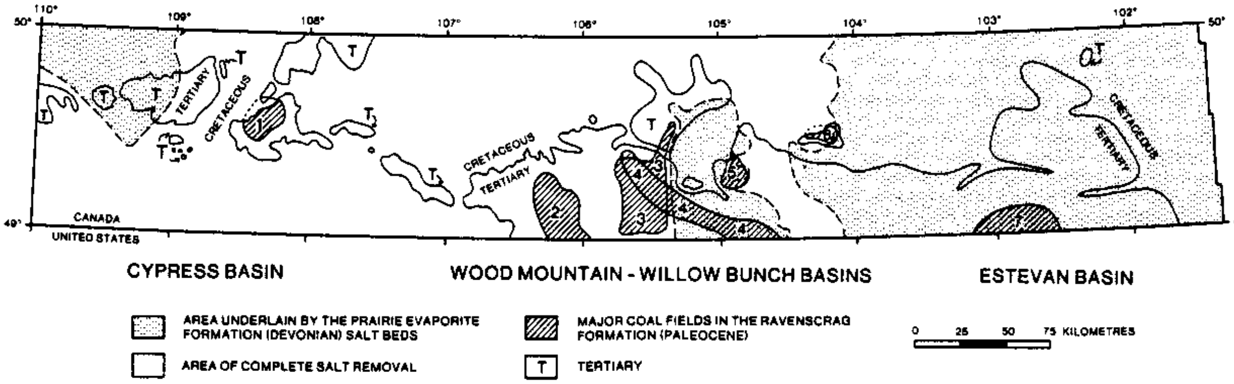

Figure 1 – Coalfields of the Ravenscrag Formation: 1) Cypress, 2) Wood Mountain, 3 to 6) Willow Bunch and 7) Estevan. The Willow Bunch coalfields are: 3) Coronach, 4) Willow Bunch, 5) Bengough; and 6) Radville.

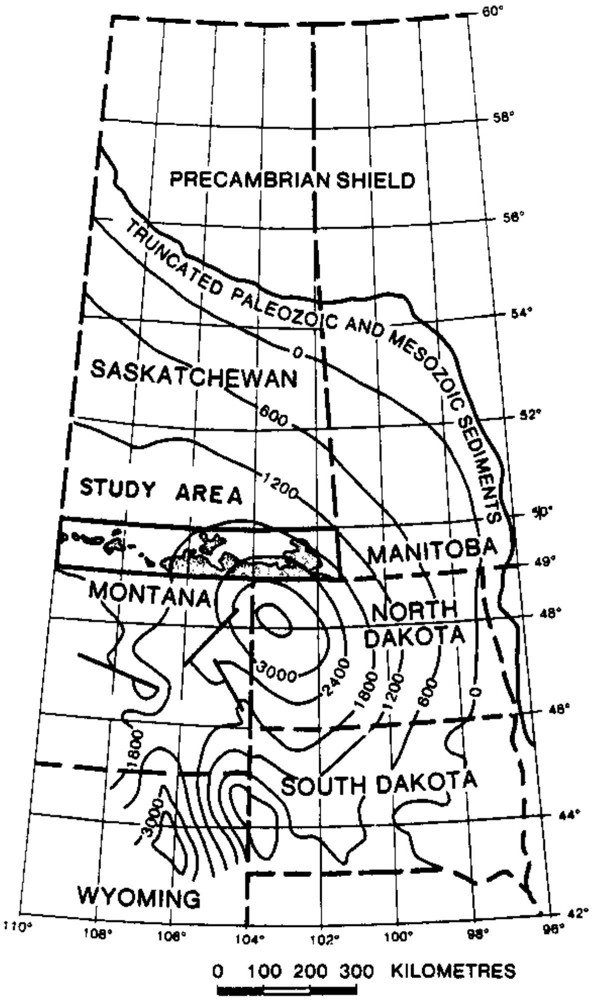

Figure 2 – Location of study area in the Williston Basin and structure contours on the Precambrian basement. Contour interval is 600 m.

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Stratigraphy of the Coal-Bearing Succession

The Upper Cretaceous is dominated by a clastic wedge which thins from 7000 m from the Rocky Mountains to only a hundred metres in the eastern Williston Basin, 2400 km to the east (Weimer, 1960; Williams and Burk, 1964). Sedimentation during the Upper Cretaceous across the Western Interior occurred under conditions of complete inundation of a continental shelf by a Cretaceous sea that transgressed in the Middle Albian, then slowly regressed until the Middle Maastrichtian. The regression was interrupted by sharp subsidences causing major transgressions. The post-Albian portion of these transgressive and regressive sand-shale facies is broadly recognized as the Montana Group (Upper Cretaceous). This includes the widespread Pierre–Belly River and Bearpaw shales in the northern Williston Basin (Figure 3). The withdrawal of the Bearpaw sea from the study area was followed by deposition of continental clastics for the remainder of the Cretaceous and Tertiary, except for thin Paleocene marine beds towards the depocentre in western North Dakota.

Caldwell (1968) points out that the classic concept of markedly diachronous formation contacts characterizing marine regressions and essentially isochronous contacts characterizing transgressions is not valid for southern Saskatchewan. His paleontological evidence suggests that the final regression of the Bearpaw sea took place rapidly, and reinforces the Russell (1939) interpretation that the Whitemud Formation is essentially isochronous from southeastern Alberta across much of southern Saskatchewan. Palynological studies by Sweet (1978) of samples taken across the basal contact of the Ravenscrag Formation in southern Saskatchewan support this view. The foregoing, considered with the relatively uniform thickness of the continental strata between the Bearpaw and Ravenscrag Formations, and the lack of major bodies of intertongued sands in the upper Bearpaw, strongly suggest that these sediments are isochronous.

Stratigraphic Setting

Late Cretaceous to Early Tertiary (Paleocene) strata in the northern Williston Basin are well exposed in the badland-like topography of southwestern Saskatchewan. The eastern Cypress Hills host type sections for the continental formations that overlie marine shales of the Bearpaw Formation. These formations are the Late Cretaceous Eastend, Whitemud, Battle and Frenchman, and the Paleocene Ravenscrag. They are traceable for tens of kilometres between outcrops in the Cypress Hills and eastward into the Frenchman and Big Muddy valleys of south-central Saskatchewan. In the subsurface below the Ravenscrag Formation, the strata (Figure 3) of the continental interval between the Bearpaw and Ravenscrag Formations have rapid lateral lithostratigraphic facies changes.

Cretaceous

Eastend Formation

The type outcrops of the Eastend Formation consist of greenish-yellow to yellowish-brown, fine-grained silty sands between the Bearpaw and Whitemud Formations

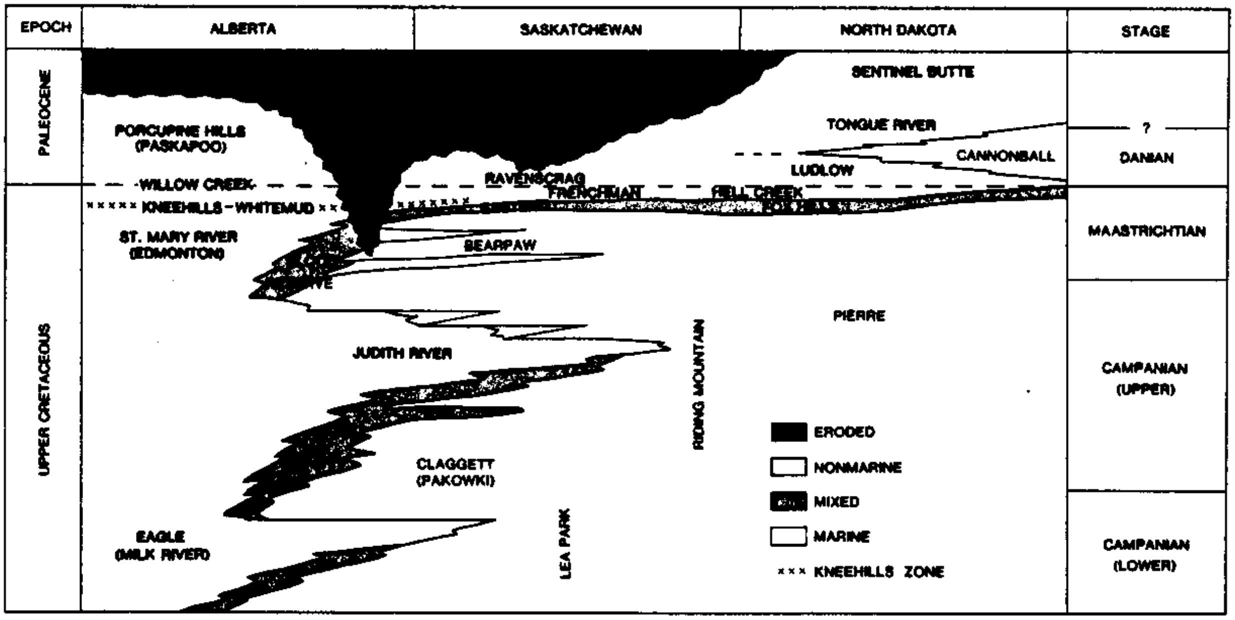


Figure 3 – Schematic cross-section showing intertongued marine and non marine strata characteristic of the uppermost Cretaceous, and their relationship to overlying Paleocene strata (from Irvine, Whitaker and Broughton, 1978).

(Russell, 1932; Kupsch, 1957). It also includes brownish-grey silts and clays in the lower part of the section and very thin carbonaceous beds in the upper. The Eastend Formation is correlative with the Fox Hills Formation in Montana and North Dakota. The rocks are interpreted by Caldwell (1968) and Russell (1943) to represent continental margin accumulations with locally restricted shallow marine or brackish estuarine fauna. The lower contact is gradational and marked by intertonguing of Eastend silts with those of the Bearpaw Formation. The upper contact is identifiable with the distinctive kaolinitic clays of the Whitemud Formation.

Whitemud and Battle Formations

The Whitemud Formation consists of grey to white kaolinitic clays, silts and muddy sands above the Eastend Formation in the eastern Cypress Hills (Davis, 1918; McLearn, 1928, 1929, 1930, 1931; Fraser et al., 1935). An uppermost dark brownish shale above the Whitemud is designated the Battle Formation by Furnival (1946). The Whitemud and Battle Formations are correlated with the Kneehills Tuff Zone in Alberta (Irish and Havard, 1968), which itself is not directly traceable into Saskatchewan because of Tertiary erosion. Correlation is based on the presence of white-weathering clastics under a dark shale. However, the white colour of the Alberta rocks does not originate with kaolinite. This is also true of the equivalent Colgate Member of the Fox Hills Formation in Montana and North Dakota.

Whether or not the kaolinite is detrital or diagenetic in origin has been debated for many decades. Local absences of the distinctive white marker beds indicate an unconformity at the base of the overlying Frenchman Formation, or else diagenetic variation. The depositional setting of the Whitemud Formation is interpreted by McLearn (1928, 1929, 1930) as one of *in situ* kaolinization of feldspathic sediments on an alluvial floodplain. Irish and Havard (1968) provide heavy mineral evidence to support this. In contrast, Byers (1969) favours derivation of the kaolinite by chemical weathering in Montanan source areas prior to transport north and northeast.

Frenchman Formation

This is the uppermost of the Late Cretaceous formations and features light grey to greenish-grey or grey-brown silty sands, silts and silty clays. Coal beds are generally less than 0.3 m thick and restricted (unmappable) laterally and vertically. The sediments of the Frenchman are similar to those of the overlying Ravenscrag Formation, except that the latter has well-developed coal beds and is less kaolinitic. The Frenchman Formation was designated the "Lower Ravenscrag" by McLearn (1929), a unit distinctive from the "Upper Ravenscrag" because of the lack of thick coal beds and the presence of a comprehensive Lance dinosaur assemblage. McLearn's "Lower Ravenscrag" was elevated to formational rank by Furnival (1946). The faunal assemblages are similar to those in the Hell Creek Formation of Montana and North Dakota and the Willow Creek Formation (Upper Edmonton Group) in Alberta. The Hell Creek Formation is a sequence of lagoonal, brackish to fresh water and alluvial flood-plain clastics (Frye, 1969). The Frenchman Formation is generally 30 to 60 m thick west of longitude 104°W, but rapidly thins eastward to between 15 and 30 m (Figure 4a).

Tertiary

Ravenscrag Formation

The Paleocene Ravenscrag Formation consists of up to 300 m of variably interbedded sands, silty sands, silts, clays and lignite beds, and is conformable on the Frenchman Formation. The strata of the Eastend and Frenchman interval thicken westward, whereas the Ravenscrag Formation erosionally thins (Figure 5a).

The contact between the Frenchman and Ravenscrag Formations is described by Fraser et al. (1935) and Furnival (1946) as a time boundary defined by disappearance of *Triceratops*. This boundary was commonly placed in southern Saskatchewan at the base of the first thick coal seam. Palynological studies by various authors (e.g., Sweet, 1978) also reveal a floral change across this boundary. The base of the Ravenscrag Formation is herein placed at the lignitiferous shale or lignite beds above a thick sand unit that is characterized by the lack of laterally continuous lignite seams and by the proximity of the underlying marine shales of the Bearpaw Formation. Sweet (pers. comm., 1976) notes that the basal Ravenscrag boundary is, indeed, essentially isochronous, and coincidental with the onset of a distinctive Paleocene flora.

Coalfields

The structure contours on the Bearpaw and Frenchman Formations are arcuate and parallel to the cratonic basin trend east of longitude 104°W. To the west, however, the structural surfaces of both the Bearpaw and Frenchman Formations are folded into smaller troughs. These are depressions underlying the major coal deposits, herein called coal basins, of which there are four (Figure 1): Estevan, Willow Bunch, Wood Mountain and Shaunavon (Cypress). Total coal thickness in each of the basins is 10 to 15 m. The Willow Bunch basin comprises four coalfields: Coronach, Willow Bunch "seam basin", Bengough and Radville. These are detailed in Irvine, Whitaker and Broughton (1978). See Figure 6 for cross-sections eastward across the areal extent of the Ravenscrag Formation, illustrating coal seam nomenclature and correlations.

Post-Ravenscrag Sediments

The Late Tertiary (Oligocene and Miocene) comprises unconsolidated sands, gravels and conglomerates which are everywhere unconformable with the Ravenscrag. Pleistocene sands without intervening tills are often difficult to distinguish on geophysical logs from the Ravenscrag Formation clastics. Visually, the iron oxide staining that frequently characterizes the basal Pleistocene sands is a useful aid in this differentiation. Failure to distinguish these sands, however, would displace the stratigraphic boundary by no more than 5 to 7 m.

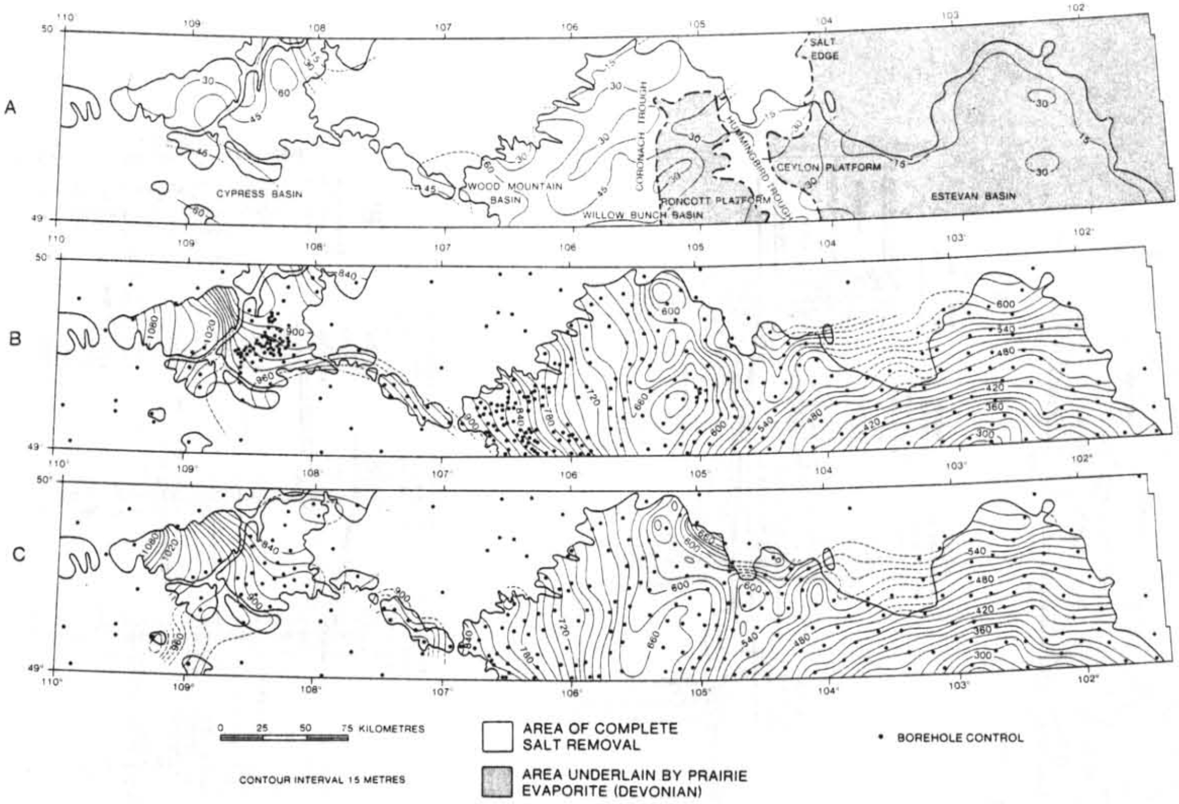


Figure 4 – Maps of the combined upper Cretaceous Eastend, Whitemud and Frenchman Formations: A) isopach, B) structure contour at top, C) structure contour on the Bearpaw Formation.

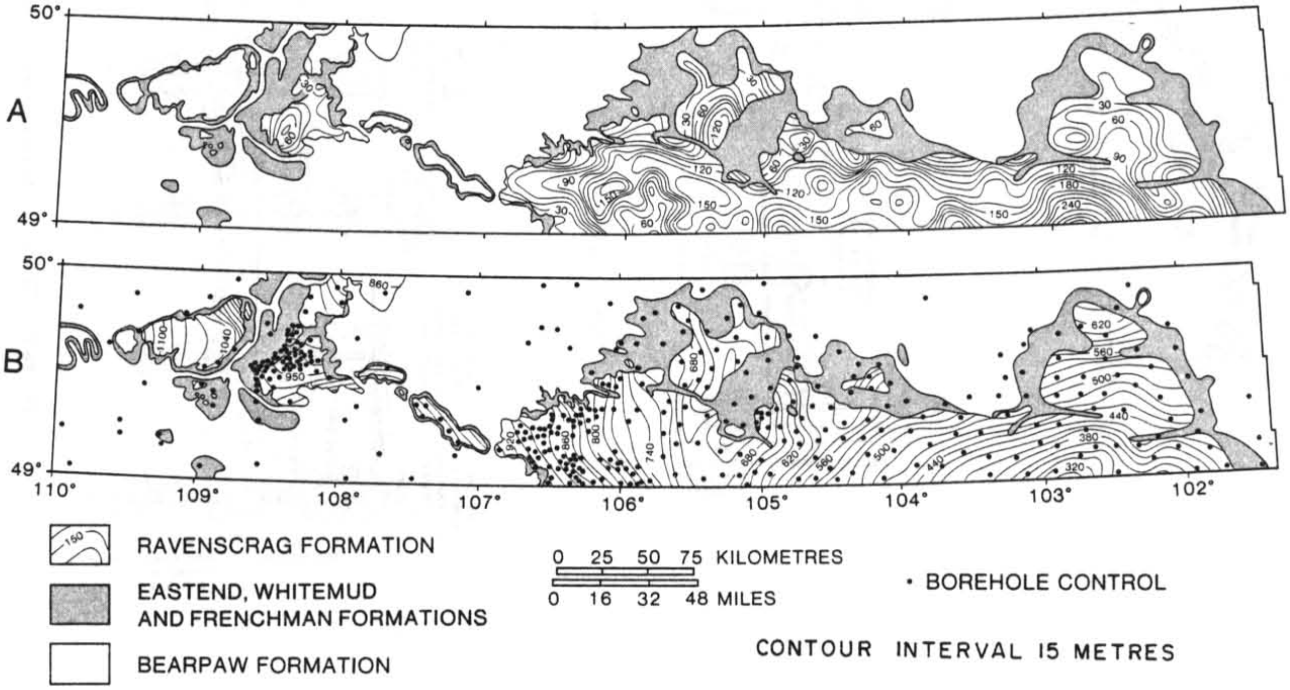


Figure 5 – Maps of the Ravenscrag Formation: A) isopach, and B) structure contour on base.

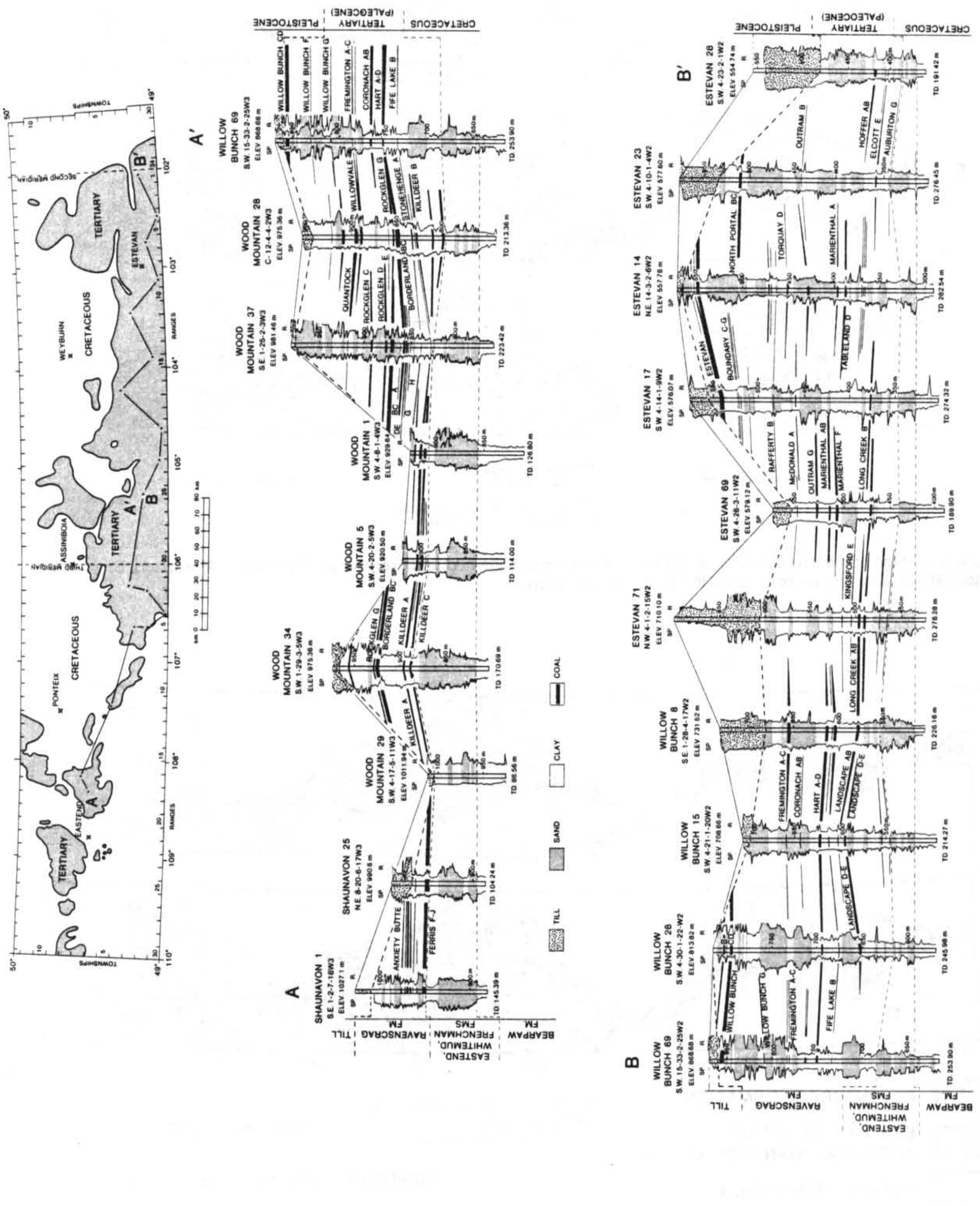


Figure 6 – Cross-sections showing coal seam nomenclature and correlations across southern Saskatchewan.

Interrelationships of the Late Cretaceous Formations

The type stratigraphy of the eastern Cypress Hills is not recognizable in the subsurface, especially east of longitude 106°W. The bulk distribution of sand and shale (see section on "Clastic Distribution Systems") and the juxtaposition of various coloured facies were studied to evaluate the interrelationships of facies and formation boundaries, and the distribution of coal basins.

Recognition of formation boundaries in the Late Cretaceous continental interval has been largely based on distinction of variously coloured facies. The white colour of the kaolinitic beds in the Whitemud Formation separates the Frenchman Formation above from the Eastend Formation below, westward in outcrop at the Cypress Hills. Eastward into the subsurface, however, the kaolinitic clays associated with Whitemud facies are stratigraphically higher and a facies equivalent to portions of the Frenchman interval. In addition, green clays characterize the Frenchman Formation. A series of fence diagrams for this interval was constructed, and simplified versions are illustrated and described here (Figure 7). The Bearpaw Formation is the stratigraphic datum. The coal seam at the base of the Ravenscrag Formation is shown at the top of each section, but in some boreholes this upper contact is absent by erosion.

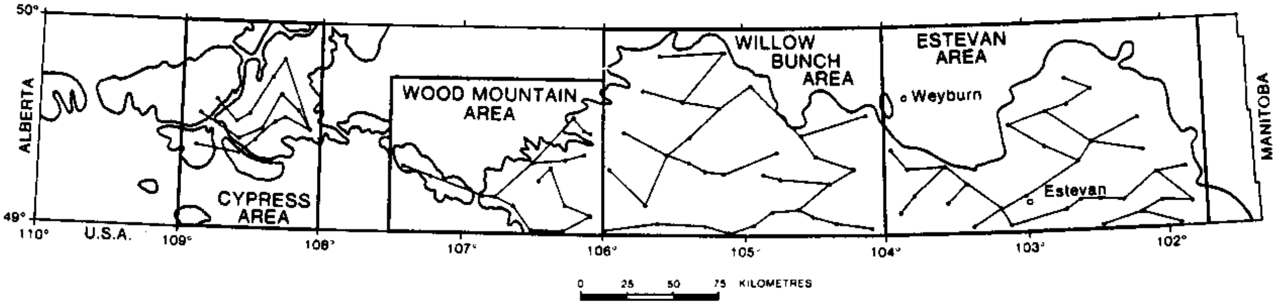


Figure 7 – Location map of fence diagrams for uppermost Cretaceous continental facies in the Cypress (Figure 8), Wood Mountain (Figure 9), Willow Bunch (Figure 10), and Estevan (Figure 11) areas. Datum is on the Bearpaw Formation.

Lithofacies recognized by colour generally bear no relationship to geophysical log signatures or grain-size variation. Transitions from greenish sands and muds to white kaolinitic sands and muds are correlative with bulk sand distribution patterns reflecting development of basins and their associated coalfields. The following observations can be made regarding spatial relationships in the four coal basins:

1) *Cypress Basin (Figure 8)* – Kaolinitic sands are well developed, up to 25 m thick, in the east-central portion of the basin. They pass laterally into grey sands and green shales to the north, east and south. To the west lie thinner, stratigraphically higher kaolinite beds and underlying green beds. The main kaolinite bed is restricted to the central part of the basin, but interfingers with a multitude of green-coloured beds radiating from the basin centre. Both the kaolinite and green beds are voluminous in the Cypress basin when compared with other basins to the east. Some sections with a seemingly complete stratigraphic interval (e.g., Cypress 16) lack both facies.

2) *Wood Mountain Basin (Figure 9)* – This basin area includes one and often two mappable kaolinite beds. Green beds overlie the kaolinite beds. To the east and southeast, both facies yield to widespread grey to yellowish-grey clays and silts; however, no kaolinitic beds were observed.

3) *Willow Bunch Basin (Figure 9)* – A well-developed kaolinite bed, 3 to 6 m thick, in the northwest thins to the southeast. It is stratigraphically higher than the thick kaolinite beds in the basins to the west. The green beds are more restricted in the Willow Bunch basin than elsewhere, but grade laterally into and lie below well-developed kaolinite beds. Frenchman Formation clastics are recognized above and below the Whitemud kaolins. Futhermore, the Whitemud kaolins are laterally discontinuous facies.

4) *Estevan Basin (Figure 11)* – One thick kaolin bed is observed in a locality east of the Hummingbird trough. The section in borehole Estevan 73 is unique because high kaolinite content imparts a white colour to the entire interval. Green beds flank the kaolinitic areas, like in the basins to the west. The Estevan basin, however, includes a brackish water fauna of dinoflagellates near the top of the section. No Whitemud Formation kaolin has been recognized within the Estevan coalfield subsurface.

Petrography of Green And White Beds

Green Beds

Chlorite occurs in all 40 sidewall core specimens examined as clay and silt-sized authigenic and allogenic grains (Plates 1 and 2). The commonest mode of occurrence is as authigenic platelets, arranged in cellular patterns analogous to honeycomb (Plate 2A to C), on most of the detrital grains. This pattern is indicative of pore-fill-

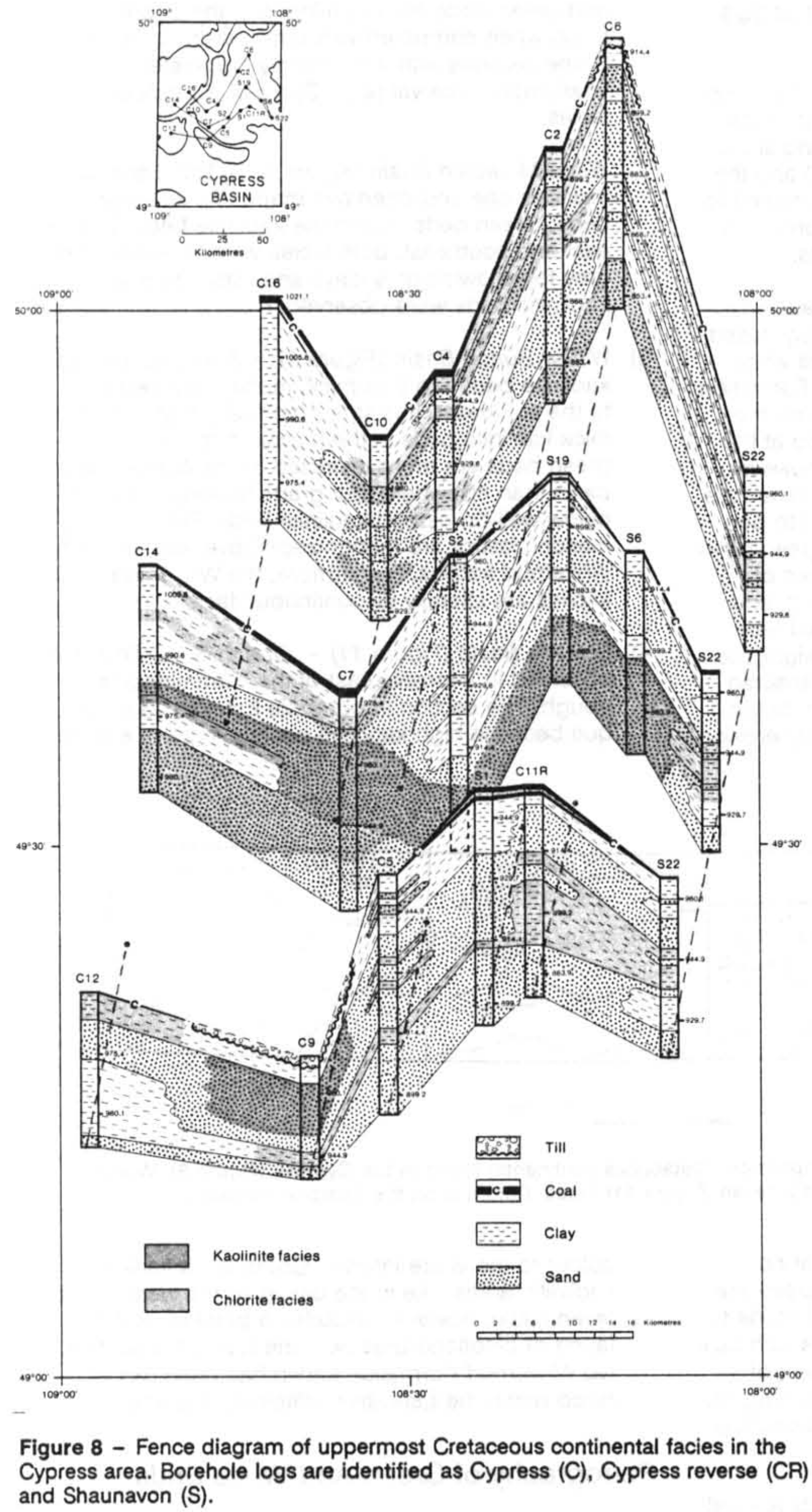


Figure 8 – Fence diagram of uppermost Cretaceous continental facies in the Cypress area. Borehole logs are identified as Cypress (C), Cypress reverse (CR) and Shaunavon (S).

ing chlorite cement (Wilson and Pittman, 1977; Pittman and Lumsden, 1968; Hayes, 1970; Carrigy and Mellon, 1964). The more crinkly and crenulated structure associated with illite/smectite precipitation has not been observed. Chlorite fabrics are composed of individual crystals, whereas smectite crystals cannot be resolved in thin section. The deformed cellular structure of illite curls away from the point of attachment. Chlorite flakes were not observed in radial alignment textures on detrital grain surfaces in the manner illustrated by Wilson and Pittman (1977, Figure 11A) . The cellular microstructural authigenic chlorite lines most pore spaces and imparts a thin but distinct light green pleochroic halo around sand grains. Many of the pores are also filled with interlocked granular cement mosaics (Plate 1D). Most plagioclase feldspar crystal fragments are etched, corroded and partially replaced by chlorite along cleavage traces and fractures (Plate 1F) but there appears to be no preferred mineralogic association between authigenic and detrital chlorite.

Allogenic chlorite is less common than authigenic but readily distinguished because of greater grain size, up to 0.3 mm and larger (Plate 1A and B). The detrital chlorite is a deeper, darker green to greenish-brown and frequently lamellar, in contrast to the more transparent and homogeneous lighter colours of the authigenic crystals. This suggests a difference in composition caused by a narrower range of physico-chemical conditions during chlorite authigenesis (cf. Keller, 1970; Lerbekmo, 1961; Dickinson, 1970). The allogenic chlorite occurs as laminae that deformed and enveloped sand grains during differential compaction (Plate 1E).

White Beds

Kaolinite in the white muds is both allogenic and authigenic (Plates 1G, H and 2G, H). It is observed as mosaics replacing rock clasts, as fine-grained matrix and as vermicular crystal stacks in pores of massive beds to kaolinized, highly mafic (biotite, hornblende) muds. Most of the kaolinite observed with a scanning electron microscope has the appearance of being replacive after very fine grained arkosic rock clasts. Feldspar clasts, in particular, have been almost entirely altered to microcrystalline kaolinite but retain crystallographically continuous zones suggestive of the original clast. The microcrystalline mosaic also passes irregularly into the matrix; this suggests that the rock clasts were partially kaolinized, transported and then diagenetically kaolinized after burial. Compaction aided the disintegration of the friable rock clasts.

Authigenic kaolinite as a pore-filling cement with face-to-face c-axis stacking in vermicular pseudohexagonal plates (Plate 1H) is distinctly less common. It is general-

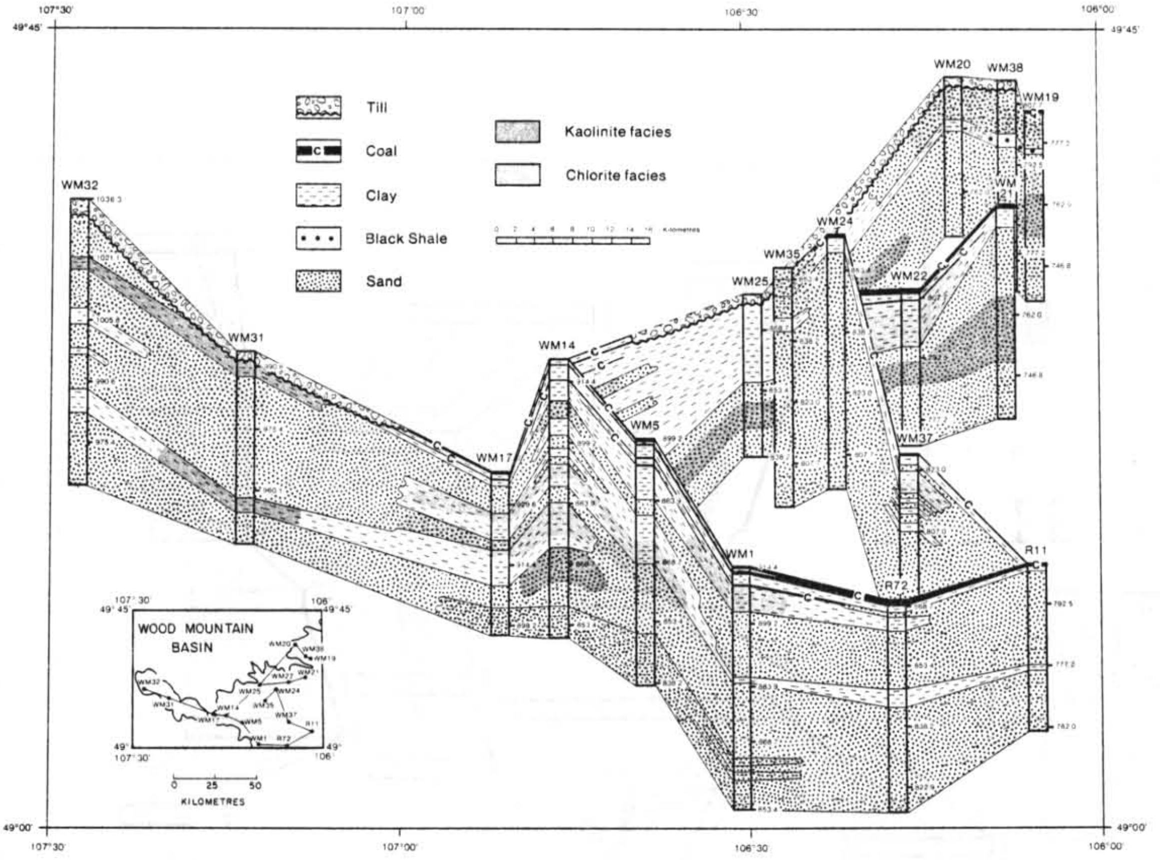


Figure 9 – Fence diagram of uppermost Cretaceous continental facies in the Wood Mountain area. Borehole logs are identified as Wood Mountain (WM) and Rockglen (R).

ly confined to small pore spaces or infrequently extends along contorted paths between several grain boundaries.

Thin section and scanning electron microscopic examination of most kaolinitic mud samples revealed traces of authigenic chlorite.

Depositional History and Tectonic Controls

Tectonic Controls on Paleogeography and Distribution of the Kaolinite Beds

The rapid regression of the Bearpaw sea marks the end of recognizable marine deposits in southern Saskatchewan. Laramide highlands became the source of the clastics that thin eastward into the Williston Basin. These uppermost Cretaceous (Eastend, Whitemud and Frenchman Formations and lower Tertiary (Ravenscrag Formation) sediments were deposited as an advancing fluviodeltaic front followed by an alluvial accumulation.

Vertically stacked delta lobes in bays created by deeply buried salt solution troughs are a distinguishing feature (Broughton, 1977, 1979). The geometry of the prograding coastline was the result of two linked tectonic actions: salt tectonics in the buried Elk Point (Devonian) evaporite basin and cratonic downwarp of the Williston Basin. Salt solution tectonics dominated the western half of the study area but were greatly subordinate to cratonic downwarp in the east.

The high sand percentage trends in the Eastend, Frenchman and Ravenscrag Formations west of longitude 104°W are attributed to vertical stacking of delta lobes along a structurally unstable coast (see section on "Clastic Distribution Systems"). The vertical control exercised by salt tectonics anchored extensive coalfields above the large deltaic deposits west of the Hummingbird trough. The largest of these deltas is a 100 km wide, crescent-shaped complex in the southern Wood Mountain basin and the Coronach trough, that accreted against the western margin of the Roncott platform. Similar high sand percentage contours delineate smaller delta lobes along the east of the Roncott platform and in the Cypress basin.

A minor Paleocene marine transgression in North Dakota is represented by the Cannonball Formation. There is evidence of it having reached the western flank of Turtle Mountain in Manitoba (Broughton, 1972; Irvine, Whitaker and Broughton, 1978).

The shoreline of the Cannonball sea probably extended southwest from south-central Manitoba across west-central North Dakota and into Montana. If the orienta-

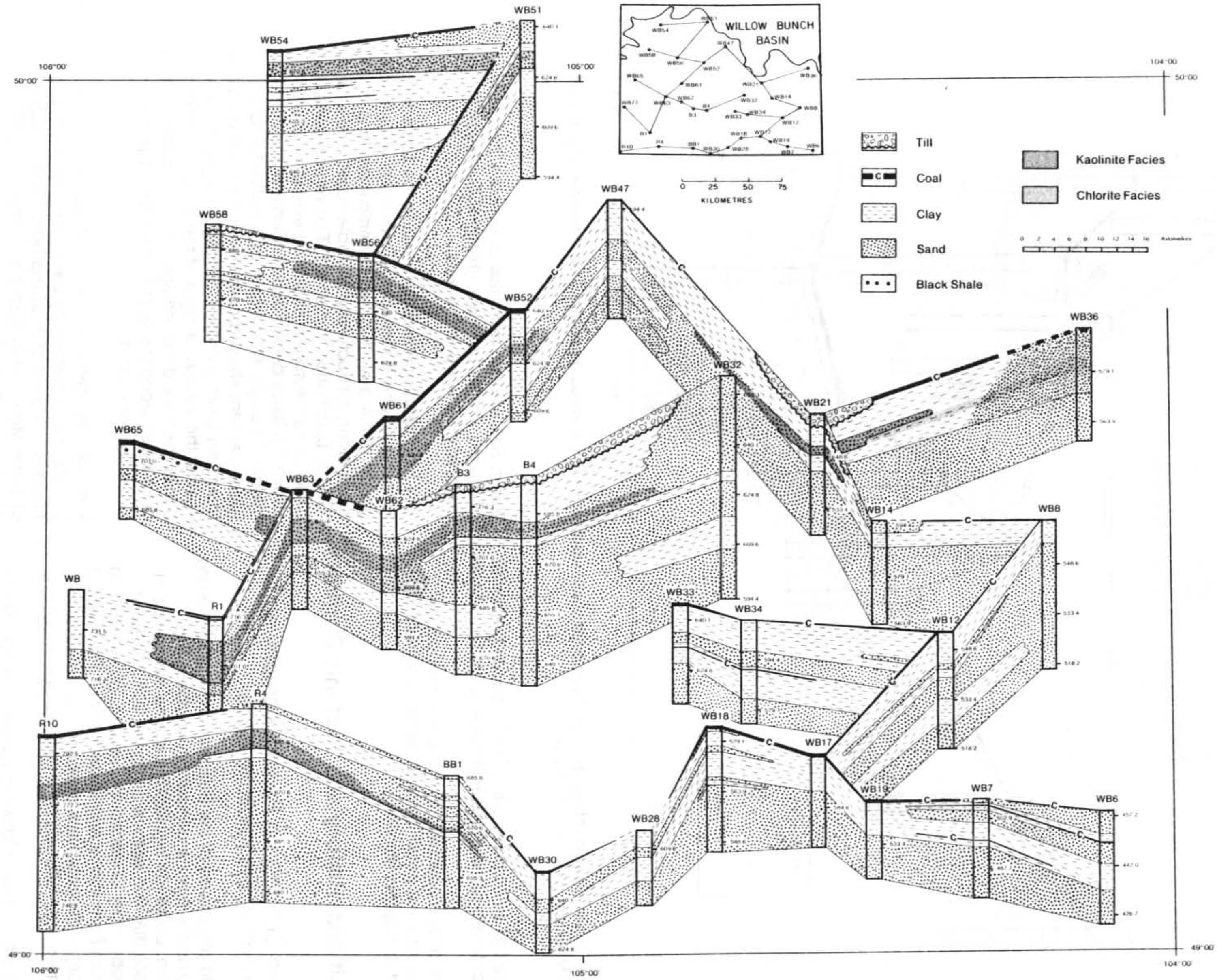


Figure 10 – Fence diagram of uppermost Cretaceous continental facies in the Willow Bunch area. Borehole logs are identified as Willow Bunch (WB), Rockglen (R), Bengough (B) and Big Beaver (BB).

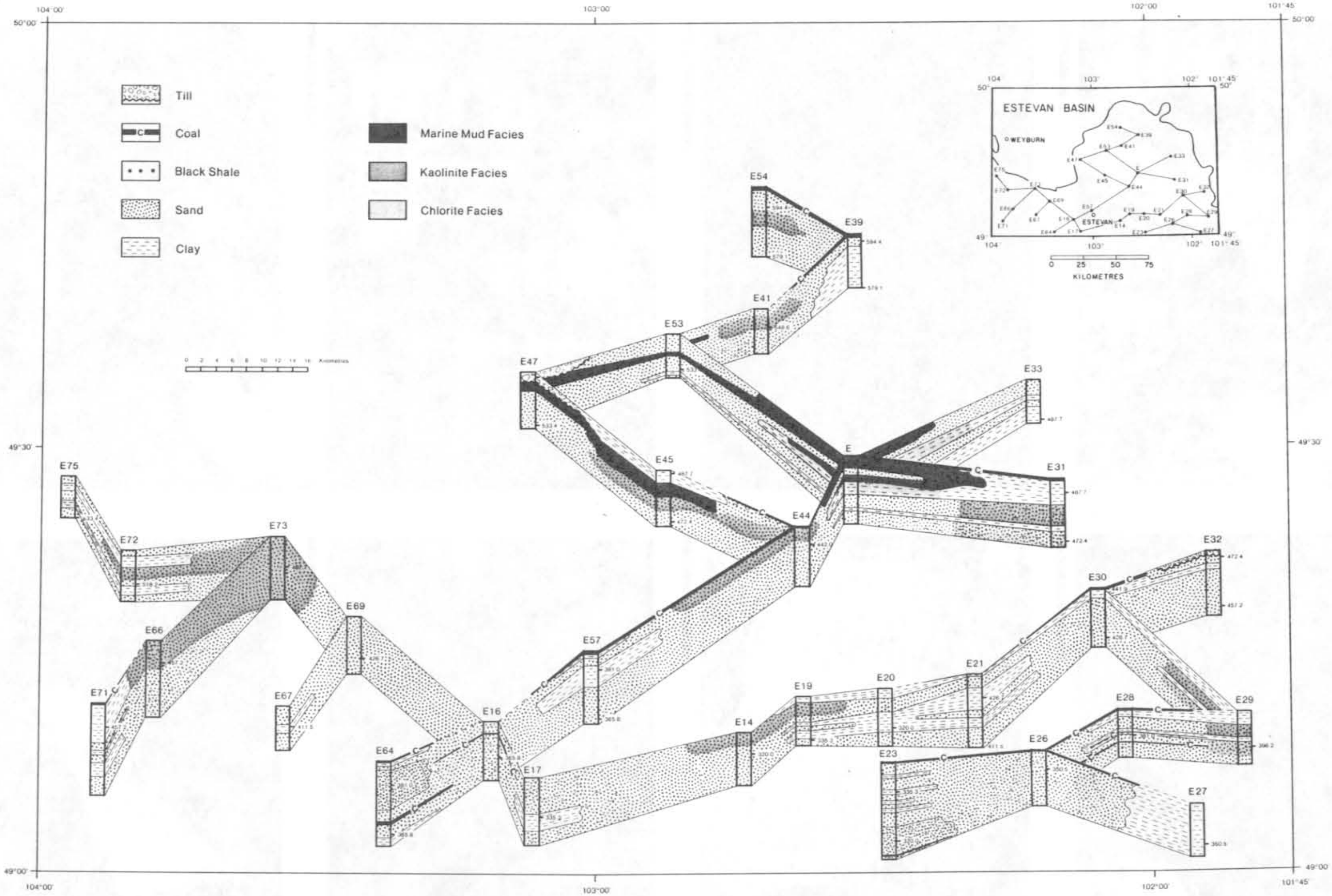


Figure 11 - Fence diagram of uppermost Cretaceous continental facies in the Estevan area. Borehole logs are all Estevan designated.

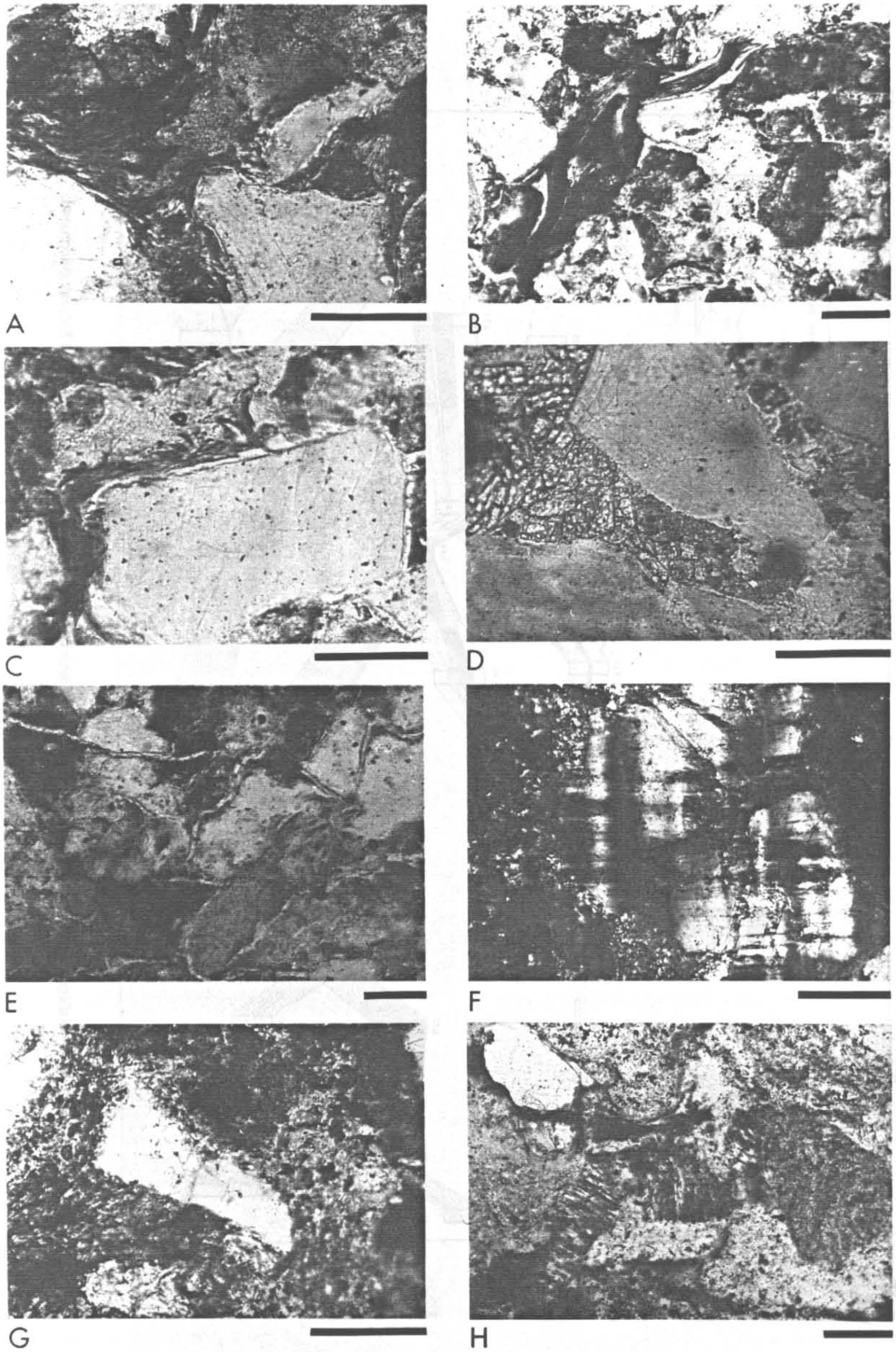

A
B
C
D
E
F
G
H

Plate 1 - Chlorite and kaolinitic cements in clastics of the study interval: A) allogenic chlorite lamellae surrounding sand grains and deformed by compaction; B) bent crystals of allogenic chlorite along several grain contacts; C) authigenic chlorite rims with irregular and relatively diffuse contact, suggesting localized replacement of feldspar clasts; D) pore spaces infilled with interlocked microcrystalline chlorite cement; E) texture induced by compaction orientation of chlorite/biotite detritus; F) chlorite replacing plagioclase; G) kaolinized rock clast irregularly passing into kaolinite matrix; H) authigenic kaolinite with face-to-face c-axis stacking in pseudohexagonal plates. Plane-polarized light, except Figure F which was cross-polarized. All bar scales are 0.1 mm, except Figure F, which is 0.3 mm.

tion of the shoreline during the regression of the Bearpaw sea was similar to that of the Cannonball, it would explain why there is no time transgression associated with the strata of the study interval (Irvine, Whitaker and Broughton, 1978). The broad band of Late Cretaceous to Early Tertiary sediments would have been parallel to such a shoreline and would imply a source area to the north-northwest of the Williston Basin, rather than southwest in accordance with the traditional interpretation. Such a northwestern source is implicit in the distribution of delta lobes suggested by the bulk sand percentile patterns, as well as by the dominant northwesterly orientation of major sand-filled channels in the coalfields across the Wood Mountain and Willow Bunch basins (Broughton, 1978). While the interpretation is not disputed that regional transport of clastics shed from the Rocky Mountains was to the northeast, it appears to have turned to the southeast in central Saskatchewan into channels that skirted the Bow Islan – Sweetgrass arches.

Origin of the Kaolinite Beds

The Whitemud kaolinite beds are interpreted as lacustrine fills because of their restricted distribution in each of the basins across the study area. They form thick beds in outcrop and in the subsurface of the central and eastern Cypress basin, and the northwestern portions of each of the Wood Mountain and Willow Bunch basins. In the latter basins, numerous thin and discontinuous kaolinite beds and kaolinitic bodies are scattered widely at various stratigraphic horizons, but disapppear in the southeastern portions of the Wood Mountain and Willow Bunch areas.

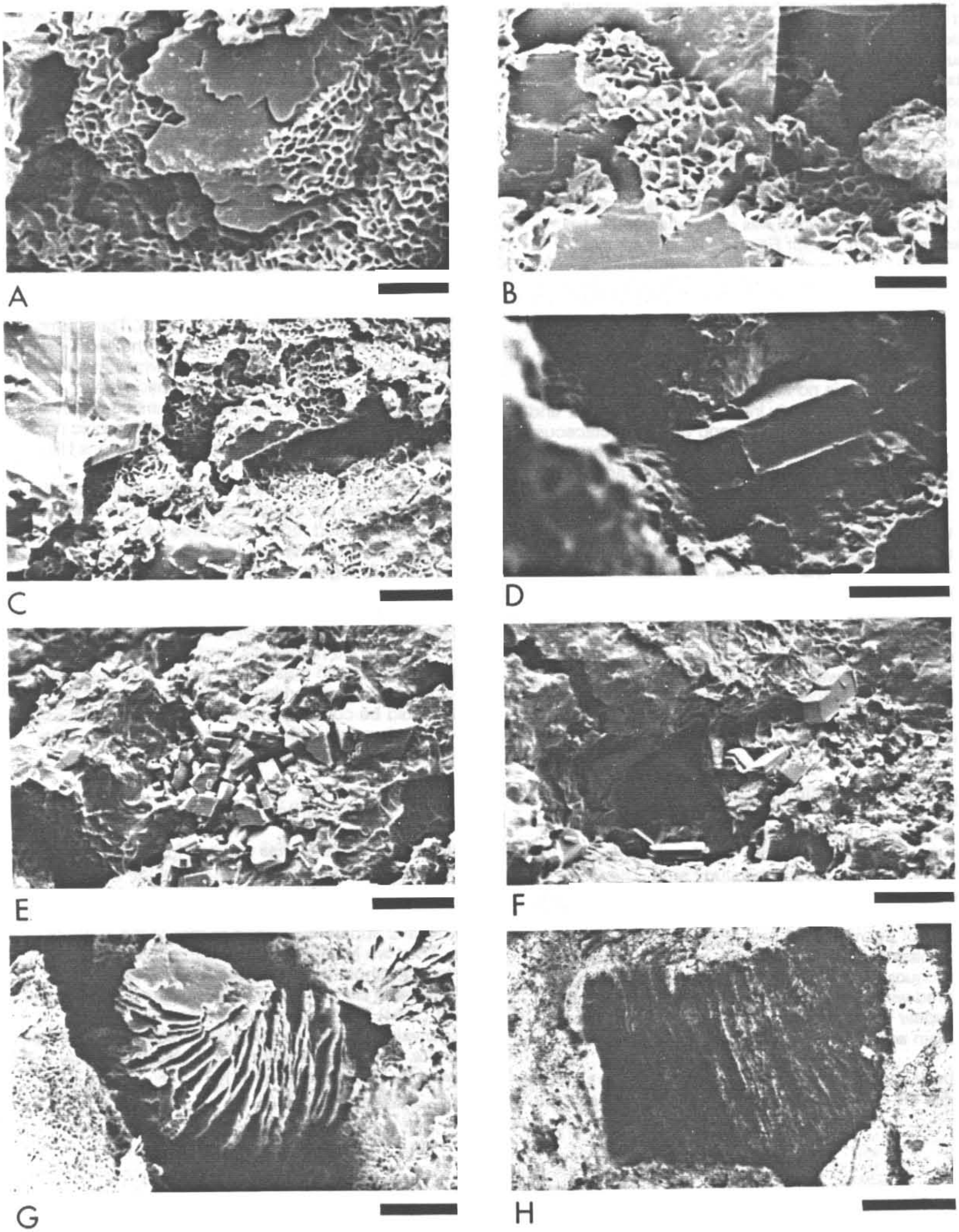
The thick kaolinite beds in the Cypress basin are correlative with the type Whitemud Formation but those of the northwestern Wood Mountain and Willow Bunch areas are stratigraphically higher. The Wood Mountain and Willow Bunch kaolinite beds, ranging from 5 to 15 m thick, are distributed along the northwest front of the delta complex. This suggests influx of clastic detritus into broad lacustrine or backswamp areas behind the delta front. Progradation of the coastline during this time was probably inhibited by tectonically induced downwarp, thereby trapping the kaolinitic sediments in depressions. Waning downwarp led to the resumption of delta progradation and the wide scattering of kaolinitic sediments.

There was no vertical accretion of deltaic facies eastward from the Hummingbird trough and, thus, no thick Whitemud facies. The Whitemud sediments in the Cypress basin are similarly interpreted as detrital fill, but thickening towards the centre of the basin. There is no evidence to indicate a specific source of the sediments. The formal position of the Whitemud Formation above the estuarine-influenced Eastend Formation in the Cypress Hills suggests localizaton of detrital influxes by a drowned valley system. This formal stratigraphic position is not maintained eastward from the Cypress Hills.

The thick kaolinite beds of the Wood Mountain and Willow Bunch basins are interpreted to have been derived from older Whitemud facies deposited within and north of the Cypress Hills. This would explain 1) their stratigraphically higher position east of the Cypress Hills and 2) localized unconformities within and at the top of some Whitemud Formation outcrops in the eastern Cypress Hills. The kaolinitic beds of the Estevan area farther to the east are higher still, and are relatively impure when compared with those to the west. This suggests east-southeasterly reworking of detritus, and that the beds should be considered part of the Frenchman Formation stratigraphic interval rather than separate, mappable Whitemud Formation rocks.

Origin of the Chlorite-rich Beds

Diagenetic modification has resulted in a widespread kaolinite-chlorite association throughout the post-Bearpaw, Late Cretaceous sediments, as well as in the Lower Ravenscrag. The distribution of green to greenish-grey beds is apparently related to that of the kaolinite beds. They are juxtaposed and neither is well developed without the other, especially when the kaolinite beds are thin and widely scattered. Carrigy and Mellon (1964) have recognized widespread chlorite authigenesis in similar rocks of the Cretaceous foothills in Alberta. The geochemistry of this chloritization is reviewed by Hitchon et al. (1971).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Tectonic Controls on the Coalfields

Coal basins west of longitude 104°W have been modified by salt solution tectonics, whereas to the east they conform to arcuate configurations of the Bearpaw and Frenchman Formation structural surfaces, reflective of cratonic downwarp.

The Coronach and Wood Mountain coalfields (basins 2 and 3, Figure 1) are aligned with salt solution axes along the western margin of the Roncott platform. This platform overlies a major salt salient in the area of complete salt removal from the Prairie Evaporite in southern Saskatchewan (Figures 4A and 12). The western edge of the Roncott platform was clearly defined as a north-trending salt solution trough during the Laramide downwarping of the Williston Basin. The eastern margin, flanked by the Hummingbird solution trough, is much older. The latter was largely developed during the post-Mississippian, pre-Middle Jurassic hiatus. The trough was only moderately enlarged during the Laramide, although the eastern edge of the Roncott platform was deeply embayed at the site of the Bengough coalfield (basin 5, Figure 1). No major coalfield developed above the Hummingbird trough. The eastern edge of the Hummingbird trough is also embayed into the salt mass near Ceylon, and small coalfields developed there (e.g., basin 6, Figure 1; Figure 4A).

The Cypress basin (basin 1, Figure 1) may have developed above a salt solution trough, but the then-extant salt beds were probably thin. There are no relict salt platforms underlying or adjacent to the coalfield to evaluate this. The Prairie Evaporite under the Estevan area (basin 7, Figure 1) was not affected by salt solution tectonics.

Pre-Late Cretaceous Solution Subsidences

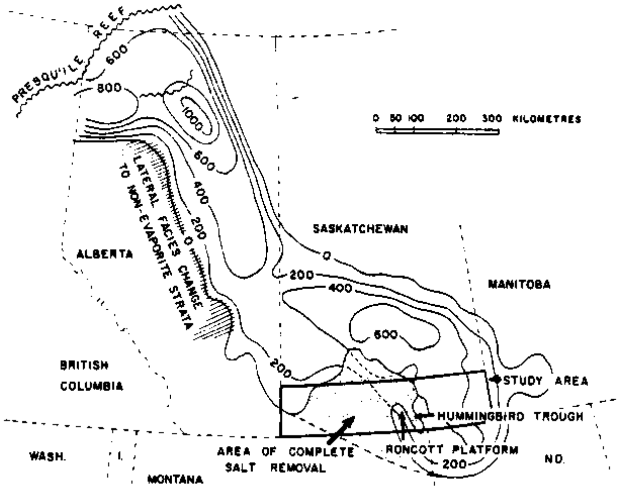


Figure 12 – Distribution of the Prairie Evaporite Formation (Devonian) in the Elk Point Basin. The salt beds to the southeast were completely leached across the western part of the study area. Isopachs in feet.

Salt solution activity across southern Saskatchewan occurred episodically from the Middle Devonian to the Recent. It has led to a variety of collapse features throughout the stratigraphic column in the northwestern Williston Basin. They are described in the regional stratigraphic studies of Bishop (1954), Kupsch (1956), Walker (1957), Sawatzky et al. (1960), Christopher (1961, 1974), Christiansen (1967), Maycock (1967), Kent (1968), Holter (1969) and Broughton (1977, 1978). Significant Paleozoic and Mesozoic subsidences are suggested for the pre-Laramide Williston Basin by correlation of thick isopach trends with enlargement of salt-leached areas. Extension of the Hummingbird trough southward and further definition of the Roncott platform occurred mainly during the post-Mississippian pre-Late Jurassic hiatus (Figure 11). The present western margin of the Roncott salt outlier is Laramide in age.

Plate 2 – Scanning electron micrographs of cements A, B and C illustrate authigenic chlorite platelets arranged in cellular patterns analogous to honeycomb. Photos D, E and F illustrate tabular crystals of an unknown mineral, possibly albite. Photos G and H are kaolinite crystals with vermicular habit. This authigenic fabric was not as widespread as expected and is, in fact, quite rare. It is probable that most of the kaolin is detritus. Photo G is a similar example viewed with cross-polarized light. Bar scales in A, B and D are 10 microns and, in C, E, F and G, 20 microns. Scale in H is 0.1 mm.

The circulation of connate water, which is believed to have caused the salt solution (dissolution), has been attributed to a variety of mechanisms. Sawatzky et al. (1960), Wilson et al. (1963) and DeMille et al. (1964) suggest water flow deflected upward over periodically reactivated basement highs and along compaction-related fractures. Christopher (1961, 1974) deduces that salt solution was accelerated when uplift permitted recharge of hydrostratigraphic units exposed in the central Montana area.

The Prairie Evaporite is overlain by the Dawson Bay and Souris River Formations (Middle Devonian), Duperow and Birdbear Formations of the Saskatchewan Group (Upper Devonian), and Three Forks Group (transitional Devonian-Mississippian), for a total thickness of 460 m. Inspection of isopach and structure contour maps shows anomalies other than tectonic downwarp interpreted as a consequence of salt solution induced syndeposition. For example, the Dawson Bay Formation has a broad thickening of sediments, amounting to approximately 8 m, along the axis of the Hummingbird trough, but lacks ispachous variation at the Coronach trough. Similarly, the Duperow and Birdbear Formations show isopachous anomalies along the Hummingbird trough.

Solution subsidence with overlying penecontemporaneous syndeposition during the transitional Devonian-Mississippian is suggested in the maps of the Torquay, Big Valley and Bakken Formations of the

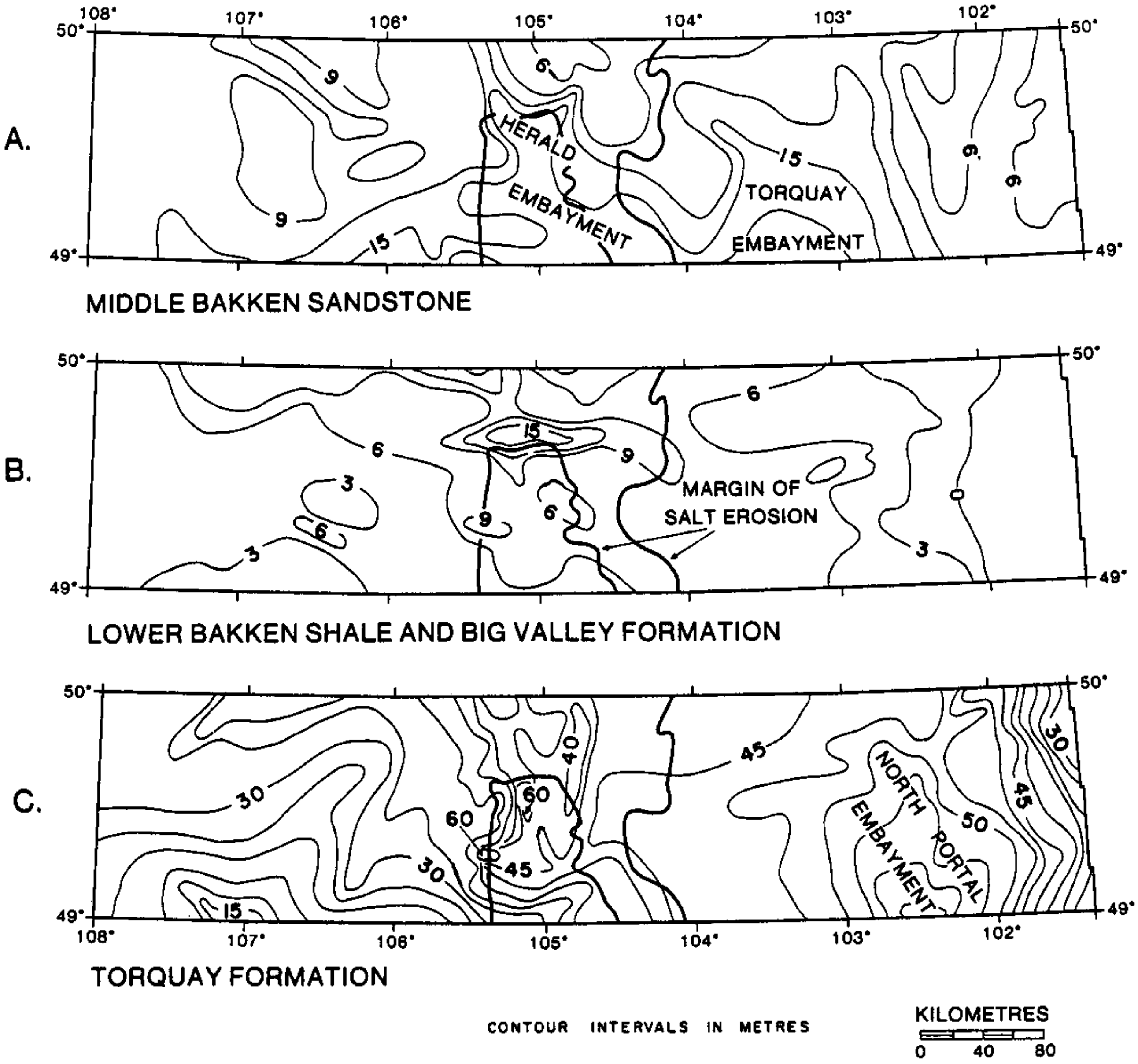


Figure 13 – Isopach maps of the Middle Bakken (A), Lower Bakken and Big Valley (B) and Torquay (C) Formations of the Three Forks Group (after Christopher, 1961).

Three Forks Group (Christopher, 1961). These maps, reproduced in Figure 13, indicate the emergence of the Roncott platform as a salient from the main salt mass by a depositional thickening 1) of more than 60 m coinciding with the Coronach trough, 2) along the northern margin of the platform, and 3) at the ancestral Wood Mountain basin.

The northern shelf of the Williston Basin underwent substantial uplift and erosion at the end of the Mississippian (pre-Triassic). This was associated with deepening of the cratonic depocentre in western North Dakota and its prominent extension into southern Saskatchewan. Paleozoic formations were truncated from the north by stream erosion as deposition continued towards the depocentre. The development of this erosion surface resulted in widespread red beds (Fuzesy, 1960; Christopher, 1961). Triassic red beds of the Lower Watrous Formation, preserved on the Mississippian erosion surface, have isopach trends which coincide with the Hummingbird trough trend. The interpretation is that, at this time, solution subsidence led to emplacement of the red beds in paleogeographic lows, thereby preserving them from further erosion (Figure 14). Solution subsidence was negligible during the subsequent marine inundation of the Lower and Middle Jurassic.

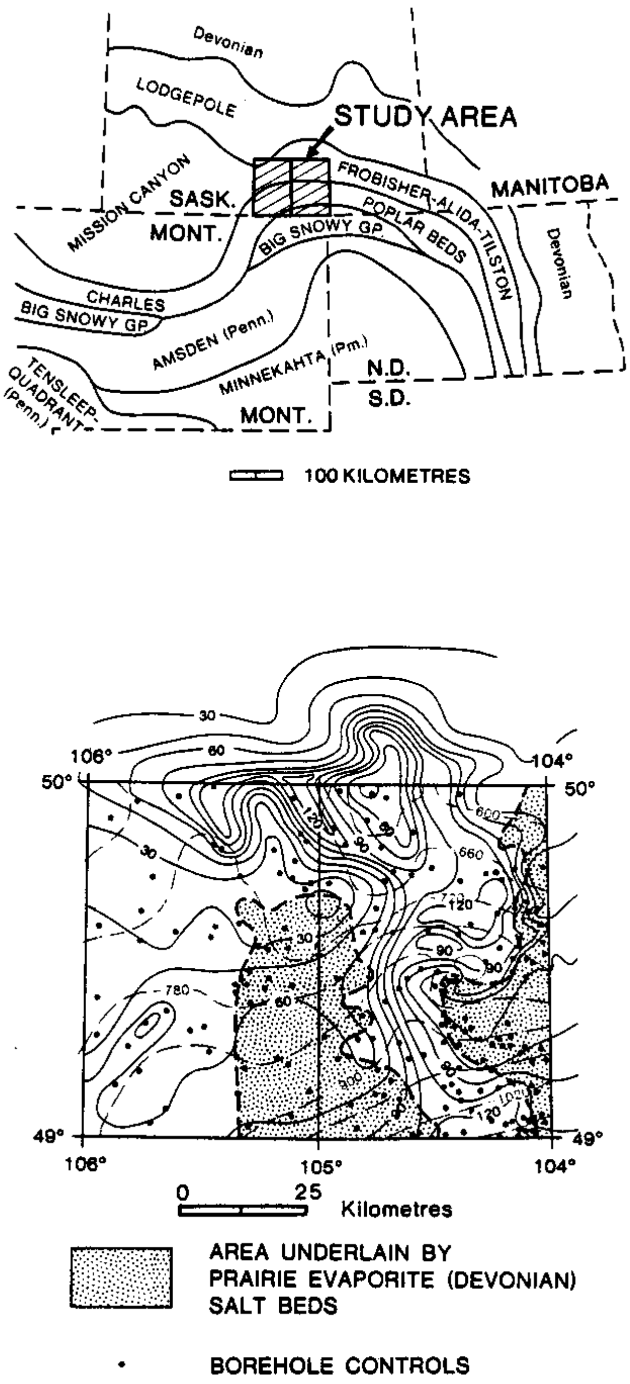


Figure 14 – Isopach map of Watrous red beds superimposed on Prairie Evaporite substrate across the Willow Bunch area, and distribution of Paleozoic formation subcrops. Contours in metres.

Late Cretaceous to Early Tertiary Salt Solution Subsidence

Major isopachous trends attributable to solution subsidence are not recognized in the Colorado marine clastics (Lower to Upper Cretaceous), nor in the overlying Montanan Lea Park and Judith River Formations, nor in the lower part of the Bearpaw Formation. Cratonic and salt solution subsidence trends are interpreted as being dormant during these times. Only in the upper part of the Bearpaw Formation do sand bodies express weak dispersal patterns attributable to reactivation of salt solution troughs marginal to the Roncott platform.

Post-Bearpaw enlargement of the Hummingbird trough by embayment of the Roncott and Ceylon platforms exercised major depositional control on distribution of the Paleocene coal measures. Bearpaw surface structure patterns along the west of the Roncott platform form a linear trough. The Coronach and southern Wood Mountain basins subsided penecontemporaneously, leading to deposition of deltaic sand bodies in the Frenchman Formation and subsequent thick coal seams of the Ravenscrag Formation. Thus, the western flanks of the Roncott platform reached their final form as northerly to northwesterly elements bordering elongated troughs, as compared to the earlier, more local collapse centres dating back to the Upper Devonian.

The Cypress basin was a small depression along the northwest margin of the Bowdoin dome throughout much of the Cenozoic (McLean, 1971; Kamen-Kaye, 1953). The basin was bounded on the west by the Bow Island arch, which was the north-northeastern branch of the bifurcated Sweetgrass arch in southern Alberta. Tovell (1958) and Williams and Burk (1964) suggest that this structure was the divide between the Alberta syncline to the west and the Williston Basin to the east. The Cypress basin became broad and shallow during the period of intense salt solution tectonics in the Wood Mountain and Willow Bunch areas to the east.

Influence of salt solution subsidence on thickening of Late Cretaceous and Tertiary sediments in the Cypress basin is uncertain. Lack of relict salt platforms in or marginal to the basin precludes accurate structural analysis. On the other hand, the Late Cretaceous to Early Tertiary (Paleocene) continental beds have distribution patterns which suggest deposition above salt solution troughs. The Cypress (Shaunavon) coalfield was an isolated Paleocene basin restricted to the area above a series of small deltaic lobes, similar those along the eastern margin of the Roncott platform.

Magnitude of Subsidence Along Roncott Platform Margins

The regional Prairie Evaporite isopachs, based on borehole correlations, can be projected across the Hummingbird trough and other broad zones presently devoid of salt beds (Walker, 1957; Holter, 1969; Broughton, 1977, 1978).

The amount of subsidence in the Coronach trough is estimated to be 60 m consisting of approximately 15 m pre-Laramide and 50 m during the Late Cretaceous to Early Tertiary. It is comparable to the 60 to 75 m of salt removed along the western margin of the Roncott platform by extrapolation of the Prairie Evaporite isopachs.

In contrast, the Hummingbird trough probably had only 15 to 30 m removed since Bearpaw times, whereas upwards of 60 m was leached during the Late Devonian and the post-Mississippian pre-Middle Jurassic. This is based on the 100 m of excess thickening in the Middle to Upper Devonian and Jura-Triassic rocks deposited in the trough and the absence of 90 to 100 m of Prairie Evaporite salt beds.

It is not possible to quantify subsidence in the Wood Mountain basin because of uncertainties as to the original thickness of the salt. Since the basin approximates the Elk Point basin margin, it is unlikely that the area around longitude 107W and the International Boundary had more than 30 m of salt beds. Removal of this salt and resulting subsidence probably occurred during the Late Cretaceous and Tertiary, based on the vertical front accumulation of Frenchman deltaic sand bodies and thickened Ravenscrag coal seams. However, both structural relief of the Wood Mountain basin and syndepositional thickening are less than those of the Coronach trough.

Structure contour maps of the post-Bearpaw formations and coal seams are characterized by small circular depressions up to 2 km in diameter. They are not traceable into the strata below as intermittently rejuvenated subsidence structures characterized by thickened Paleozoic and Mesozoic beds. Nor do they entirely coincide with Frenchman sand bodies or thickened Ravenscrag coal seams. They in part coincide with thinned coal seams that characterize the northern Wood Mountain basin north of the Frenchman deltaic complex. This suggests that the salt beds were removed from below the northern Wood Mountain basin and the broad area extending westward to the Cypress basin after accumulation of the Ravenscrag Formation coal measures. This probably coincided with the moderate regional uplift of the Late Tertiary.

Willow Bunch Coal Basin

The structural configuration of the Willow Bunch basin area (Figure 15) is attributed to subsidence created by solution of Prairie Evaporite halite beds that formed elongate troughs (Coronach, Hummingbird and Radville) proximal to the Roncott and Ceylon platforms. These local structures affected the distribution and geometry of coal seams and modified the regional pattern of reduced cratonic subsidence such that coal basins would accumulate and be preserved.

Stratigraphy of the Coal Seams

There are six thick coal zones in the Willow Bunch basin. They are, in ascending order (with average seam thickness): Landscape (2.3 m), Fife Lake (1.2 m), Hart (3.3 m), Fremington (1.3 m) and Willow Bunch (2.7 m). The coal-bearing clastic interval is about 100 m thick.

Landscape Zone

Stratigraphically lowest lignite seams in the Ravenscrag Formation of the Willow Bunch area constitute the Landscape zone. There are two main coal beds: AB (Upper) and DE (Lower). The Landscape zone (beds A to E) varies in thickness from 6 to 15 m in the Coronach and Hummingbird troughs, but is thickest in the Bengough coalfield on the eastern edge of the Roncott platform and in the Coronach trough. Areas which accumulated the thickest Upper Landscape seams approximately coincide with areas with the thickest Lower Landscape seams. In contrast to the distribution pattern of the younger zones, these seams do not drape the western edge of the Roncott platform.

Fife Lake Zone

The Fife Lake zone has several thin but widespread seams in both the Coronach and Hummingbird troughs. The zone consists of at least four beds, generally not locally combined, within 10 m of stratigraphic section. These seams are thickest subjacent to areas of thickened overlying Hart seam. Bed A is 0.3 to 1 m thick and occurs 3 m below the overlying Hart zone. It is lenticular and restricted in distribution. Bed B underlies bed A by 1.2 to 2.4 m and is the only widespread seam in the zone. Beds C and D are 3 to 10 m lower, but generally less than 1 m thick. They are not stratigraphically important and appear to be restricted to the same general areas as bed B.

Hart Zone

The Hart zone contains the thickest and most widespread lignite seams in the Ravenscrag Formation. The main seam is locally split into four beds, designated from top to bottom by the letters A to D. Distribution of the Hart (A-D) beds across the Willow Bunch basin is shown in Figure 15.

The Hart (A-D) beds are thickest (11 m) in the central portion of the Coronach trough, from the town of Coronach and the East Poplar River north to the town of Willow Bunch (Townships 2 to 4, Ranges 27 and 28). The zone thins eastward into Range 26 above the western edge of the Roncott platform. It is poorly developed above the platform in Ranges 24 and 25, except to the southeast in Township 1, Range 24, where locally it is 1.2 to 1.8 m thick.

The Hart zone is less developed above the Hummingbird trough and along the eastern margin of the Roncott platform. The main seam is generally less than 1.2 m thick and locally absent across the western and southern parts of the Roncott platform. It is, however, thicker above the Roncott platform than stratigraphically lower coal seams. In the Bengough coalfield, the seam is usually 1.2 to 2.4 m thick (Ranges 22 and 23, Townships 3 and 4) with localized thickening to 3 m.

Coal seams of the Hart zone were not deposited to any significant extent in the Hummingbird trough. Several small and isolated occurrences are recognized. The largest of these is above a major reentrant to the Ceylon platform called the Radville trough.

Underlying seams (E-F) of the Hart zone are thin (0.3 to 1.0 m in thickness), discontinuous and interfinger with

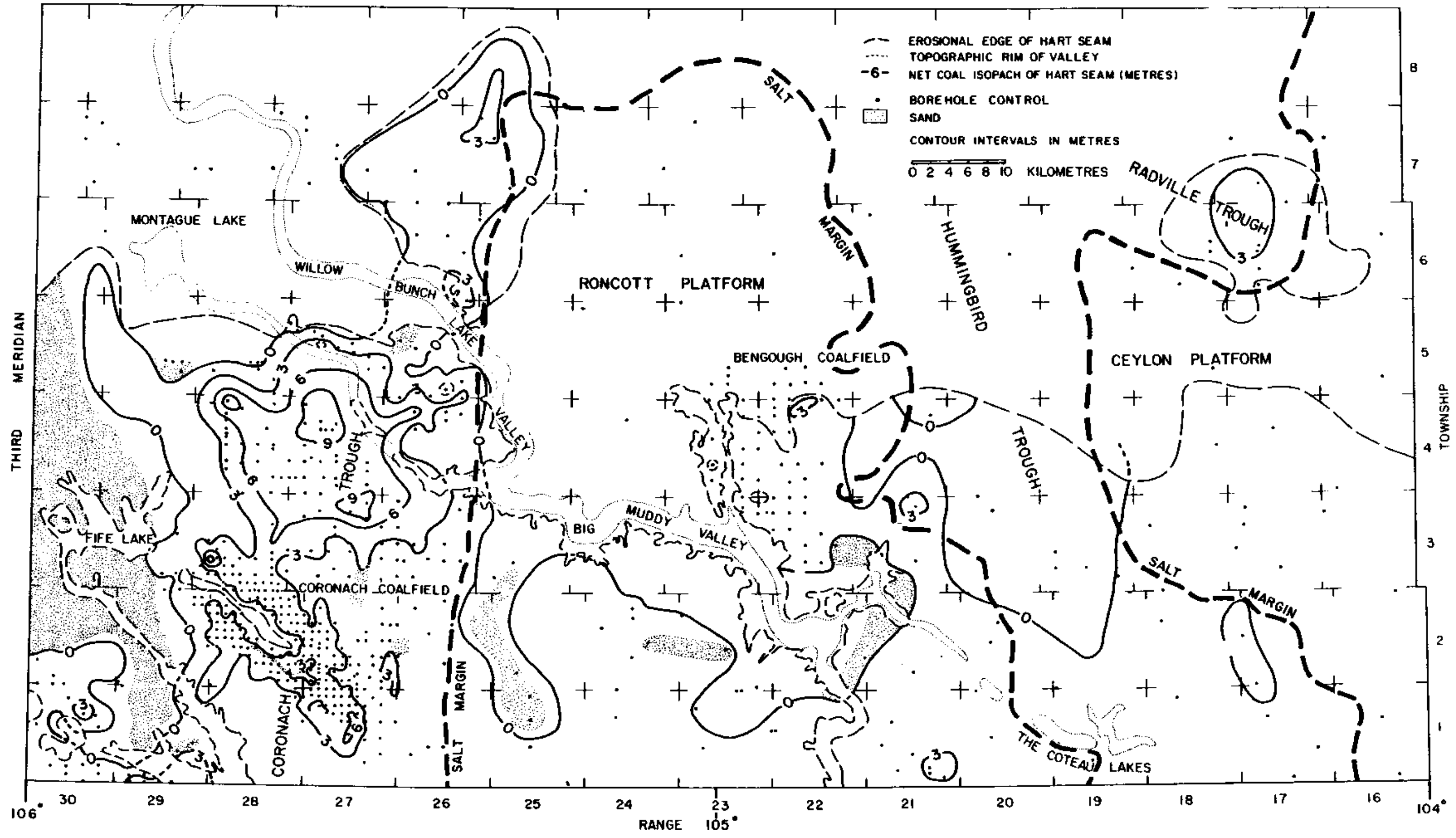


Figure 15 – Distribution of the Hart (A-D) seam across the Willow Bunch basin.

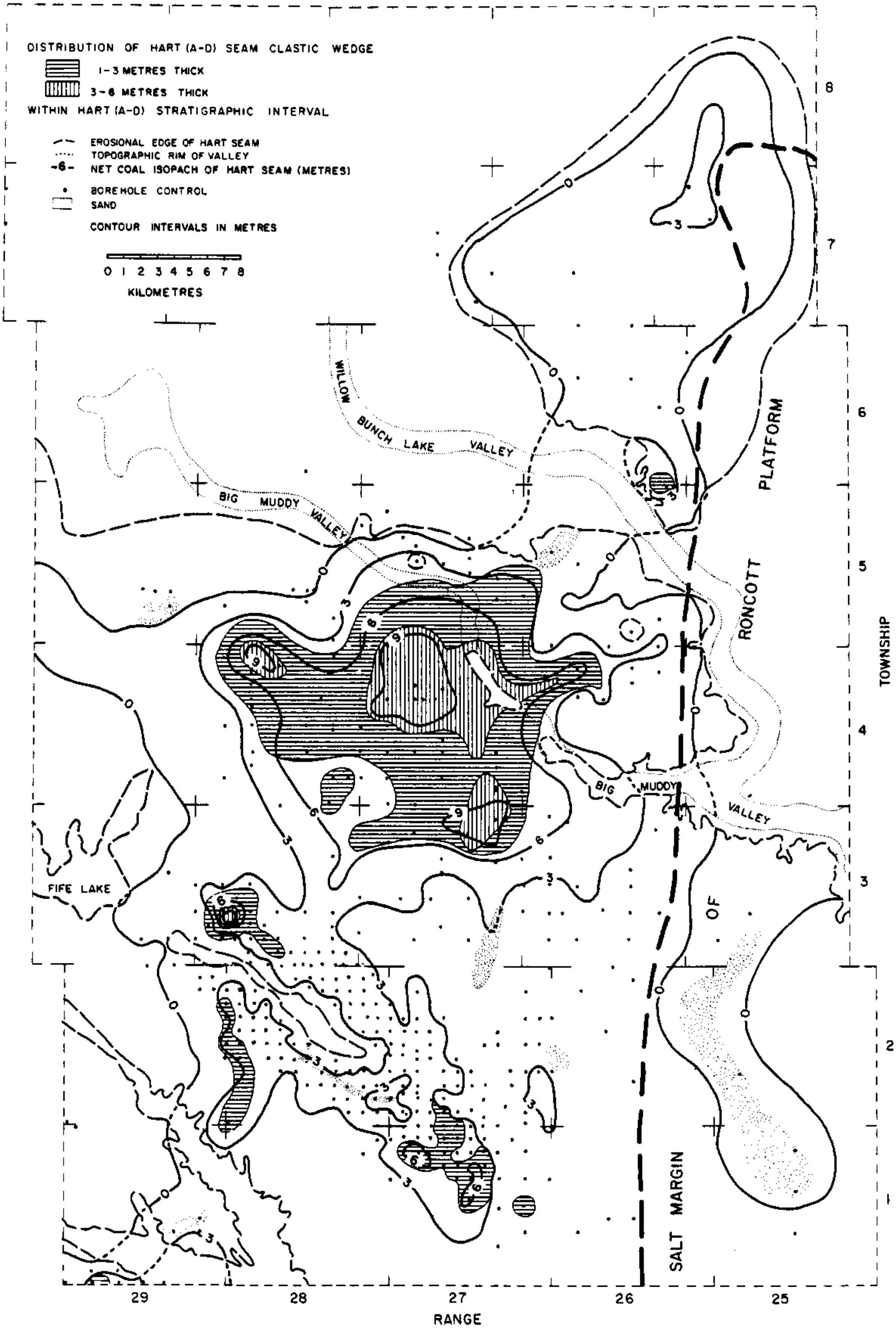


Figure 16 – The clastic body within the Hart (A-D) seam in the Coronach trough.

the coal seams of the upper Fife Lake zone. They, and the Fife Lake beds, are present where the overlying main Hart (A-D) seams are very thick.

The extensive clastic body that characterizes the middle of the Hart (A-D) seam (Figure 16) in the Coronach trough was not deposited in the Hummingbird trough. Equivalent seams in the Bengough coalfield contain less than 0.5 m of intercalated shale. Correlation of the upper (AB) and lower (CD) beds eastward is therefore difficult and the Hart (A-D) seam of the Coronach trough may not be entirely represented to the east. The Hart seam is very thin, generally less than 1 m thick, across the Ceylon platform. Correlation eastward towards the Estevan coalfield is tenuous because it is often absent.

Coronach Zone

Seams of the Coronach zone were deposited 12 to 20 m above the Hart seams. The zone is composed of a relatively thick AB bed as well as several thinner unmappable subjacent seams. Deposition trends suggest that accumulation was greatest in several subbasins linked by areas of continuous but thinned seams. The AB bed is thickest (2 to 4 m) above the thick Hart (A-D) seam of Township 3, Range 26, southern Township 4, Range 27 and northern Township 2, Range 26 (Figure 17). The seam is thin but persistent across the Roncott platform (Townships 1 and 2, Range 23). The only significant deposit of the AB bed in the eastern Willow Bunch area is a 2 to 2.5 m outlier in the Bengough coalfield.

There are at least two minor, 0.3 to 1 m thick beds (C and D) about 6 m below the main seam.

Fremington Zone

The Fremington zone is dominated by a single, regionally persistent, thick seam that locally splits into three component beds (A, B and C). They are mapped as a unit within the Coronach trough where maximum thickness ranges from 4 to 8 m. This, however, often includes a substantial interval of clay partings. Average thickness for unparted beds (A-C) is 1.5 m. Underlying D and E beds are thin, generally 0.3 to 0.6 m each.

Thick Fremington (A-C) seam areas coincide with distribution of thick Hart (A-D) seams in the central Coronach trough (Figure 17).

Fremington (A-C) beds are thin to absent across the west of the Roncott platform (Townships 1 to 3, Ranges 24 to 26), but thicken to 1.5 m eastward into the Hummingbird trough (Township 2, Range 23 and eastern Townships 1 and 2, Range 24). The zone was eroded from the Bengough coalfield and cannot be correlated with certainty onto the Ceylon platform east of Range 19. Nevertheless, thin discontinuous seams are recognized at this horizon eastward towards the Estevan area.

There is only one important bed (D) in the Fremington zone below the thick A-C seam. It is 0.6 to 1.5 m thick and has distribution restricted to the Coronach trough.

Willow Bunch Zone

The Willow Bunch is the youngest of the Ravenscrag coal zones, and preserved as outliers extending from Township 5, Range 29 southeast to Township 1, Range 21 and Township 3, Range 19. There are nine seams (A to I) but only the CD seam, 3 to 4.5 m thick, can be mapped with reliability across the Willow Bunch basin (Figure 17). Lower seams are preserved only in the central Coronach trough. Willow Bunch E, less than 0.6 m thick, lies approximately 1.5 to 5 m below the CD beds. Willow Bunch F is between 1 and 2 m thick and 6 to 10 m below the CD beds. The most important of the lower zone beds is G. This 1 to 2.5 m bed has been mapped across Townships 2 and 4, Ranges 25 and 28. Bed H, approximately 1 m thick, is also restricted to the same area. Beds I and J are less than 0.6 m thick and not important. The thickness trends in these beds are to the southeast across the Roncott platform and oblique to the coalfield deposition axes of stratigraphically lower seam zones. The Willow Bunch zone coalfield is elongated towards the cratonic depocenter to the southeast.

Structural History of the Willow Bunch Basin

There were four events in the growth of the Willow Bunch coal basin in general and the Coronach trough area in particular:

1) *Strong cratonic and strong salt solution subsidences* – This combination resulted in the deposition of thick Frenchman and lower Ravenscrag sandstones. The subsidence rate was too great for the formation and preservation of more than thin, discontinuous lignite beds.

2) *Weak local cratonic and strong salt solution subsidences within strong regional cratonic subsidence* – Basal coal seams (Landscape zone) accumulated along the margin but did not onlap the Roncott platform. This is interpreted as dominance of salt solution-induced subsidence over cratonic subsidence. Trends of the younger beds are southeastward (i.e., parallel to cratonic lineaments). Strong regional cratonic subsidence is suggested as the cause of this shift, while subsidence attributable to salt solution below the Coronach trough slowed sufficiently to permit accumulation of the coal beds.

3) *Weak cratonic and strong salt solution effects* – Coal beds between the Fife Lake and Fremington zones were deposited above salt solution troughs along the margins of the Roncott platform. Thick seams are restricted to the troughs, but, unlike the Landscape beds, thinned edges of the coal seams drape onto the buried salt platform. The axes of thick seams trend northward (i.e., along the salt solution axis), but the thickened trends of individual beds are aligned northwesterly, parallel to the cratonic lineaments.

   Cratonic subsidence was weaker than that induced from salt solution since there was no progradation of the coal beds across areas not affected by salt tectonics.

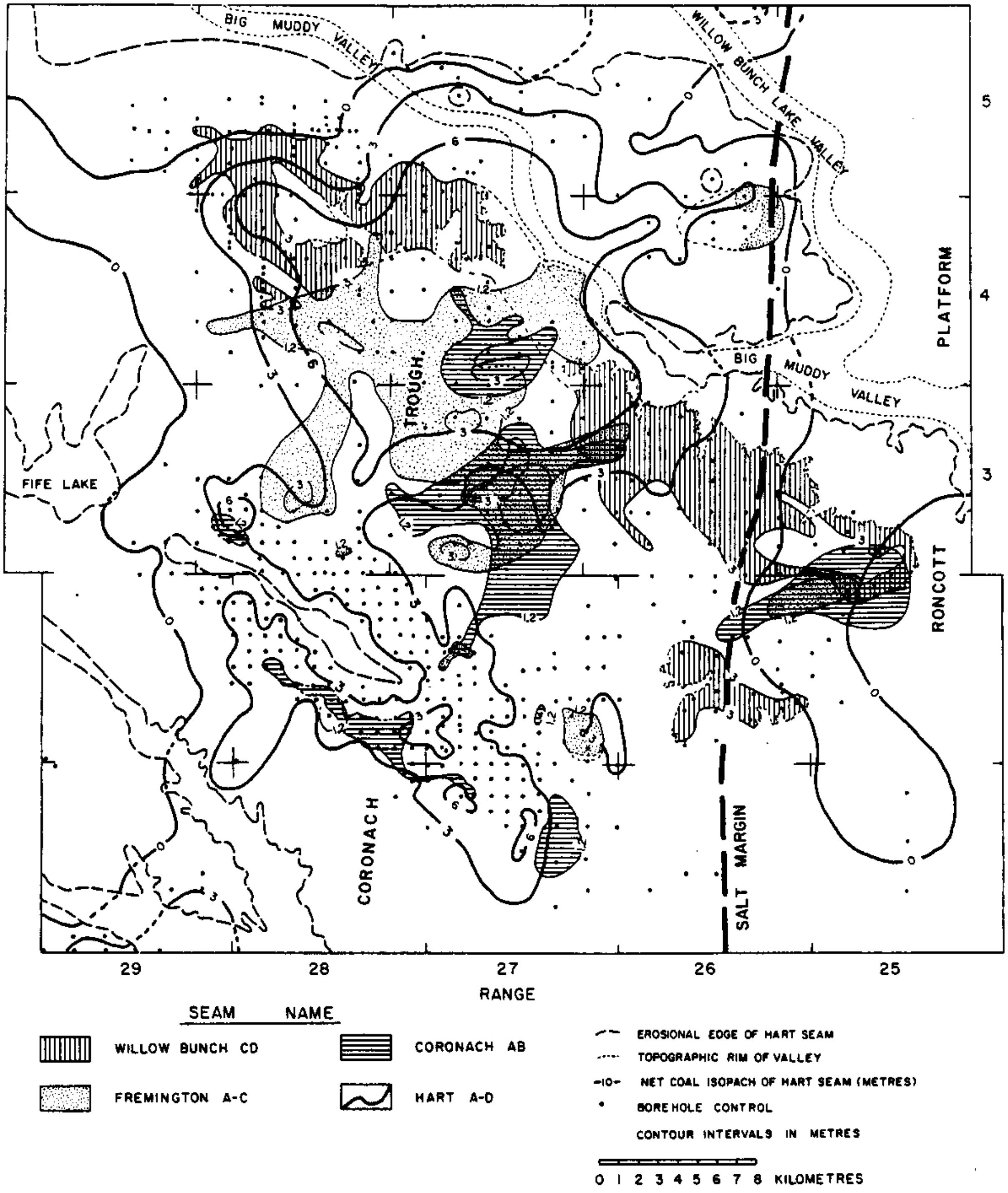


Figure 17 – Composite map of thick seam areas in the Coronach trough.

4) *Weak cratonic but weaker salt solution influences* – The uppermost zone of the Willow Bunch basin (basin 4 on Figure 1) is called the Willow Bunch seam basin. The depositional axes of these beds trend obliquely across the Roncott platform and the Coronach trough. This indicates the onset of markedly diminished influence of subsidence by salt solution and the assertion of the regional southeasterly cratonic tilt. The cratonic subsidence was nevertheless weak enough to permit the accumulation of thick seams across the northern Williston Basin. The seam geometries reflect structures of both north-trending salt solution troughs and southeasterly-directed cratonic trends.

Estevan Coalfield

The Estevan coal basin is cratonic in origin and not modified by salt solution tectonics.

Stratigraphy of the Coal Seams

The Estevan coalfield is a northerly salient of the uppermost section of the Ravenscrag Formation. The area preserved is approximately 40 km long and 16 to 25 km wide, and is terminated on all sides except the south, by Late Tertiary and Pleistocene erosion surfaces. The coal-bearing interval continues southward into North Dakota. There are five major seam zones within 50 to 75 m of the surface. This coal-bearing section is approximately 200 to 250 m above the Bearpaw Formation (Figure 18). Lower beds are poorly developed and limited in areal extent.

The five zones mapped in the Estevan coalfield by Irvine, Whitaker and Broughton (1978) are, in ascending order: Boundary, Estevan, Souris, Roche Percée and Short Creek (Figure 19). The stratigraphic position of the Boundary zone is equivalent, on the basis of palynology, to the Willow Bunch CD beds in the Willow Bunch basin, and the succeeding Estevan zone to the Willow Bunch AB beds.

Boundary Zone

Thick net coal of 2 to 3 m distributed along the northern edge of the coalfield forms the Boundary zone (Figure 19). Maximum thickness of 4 m has been recorded in the west-central region of Township 1, Range 9. The trend of the areas enclosing thicknesses greater than 2 m conforms to the erosion front. The net coal thins southeastward to less than 1 m in Township 1, Ranges 7 and 8. Likewise, it thins locally, and toward the northeastern erosional margin passes laterally into fluviatile clastics.

Estevan Zone

Thicker net coals occur about 15 m above the coal beds of the Boundary zone. The net coal thickens to a maximum of 4.8 m in the south-central part of Township 2, Range 6. The Estevan and Boundary zone coal seams are the thickest and most widespread in the Estevan coalfield.

Souris Zone

These beds are approximately 20 m above the Estevan zone. The main seam is relatively unsplit and thickest across Township 1 of Ranges 6 and 7 and the greater part of Range 8. There are five main deposits, four of which are approximately 5 km^2 in area, while the one in the south of Township 2, Range 6 is 15 km^2 (5 by 3 km). The thickest net coal is 3 m and is in Township 1, Range 6.

Roche Percée Zone

These beds are 10 m above the Souris zone, but are preserved only in the eastern part of Ranges 7 and 8. The 2 to 2.5 m of net coal has several splits.

Short Creek Zone

This zone, which occurs as an outlier of less than 50 km^2 (Figure 19B) has many splits with rapid variations. The better developed areas with 2 to 2.5 m of net coal are in Township 1, Range 6. Maximum thickness is 3.4 m. The structural geometry of the seams does not appear to conform to the cratonic curved pattern of stratigraphically lower seams, but this is difficult to delineate with certainty because of proximity to the erosion front.

Regression Analysis of the Coal Zones

Regression surfaces applied to structural data on the base of a thick seam in each zone suggest a model of cratonic subidence. A simple concave basin form was considered sufficient to model the Williston Basin downwarp. This fitted a second-order surface, but, since the input data was only half a concave form (northern Williston Basin), a higher order fit was required. The order was raised with improved least-squares goodness of fit until the geometric form approximated, by inspection, a model of the craton that compared to known Precambrian basement structure. The fourth order was considered satisfactory. Residuals derived from application of this surface to the coal seams are suggested to represent elements created by subsidence above the Precambrian basement and induced by differential subsidence between basement blocks.

Graphic fourth-order polynomial equations of 15 terms for the seams are illustrated in Figure 20. The contours approximate the geometry of the northern flank of the Williston Basin with a slope towards Range 9. This form is clearly expressed on structural surfaces of the Boundary and Estevan zones, but distorted on higher beds because of looser borehole control. Positive and negative residual areas for each of the seam surfaces are shown in Figure 21.

Comparison of the thick seam distributions suggests depocentre displacements between the Boundary and Estevan beds, on the one hand, and the younger Souris, Roche Percée and Short Creek beds on the other. Thick seams of the Boundary and Estevan zones are vertically positioned above the other, whereas thick beds of the younger seams are situated above thin seams of these two lower coal zones (Figure 21).

Over 50 residuals common to all seams have been identified (Figure 22). Most of these linears are oriented northeast and northwest. Negative trends generally correspond to thick seam deposits for each horizon. However, negative structural trends in thin seam areas are also observed below thickening in overlying seams. Major anticlinal trends are observed only where all seams are thin or absent.

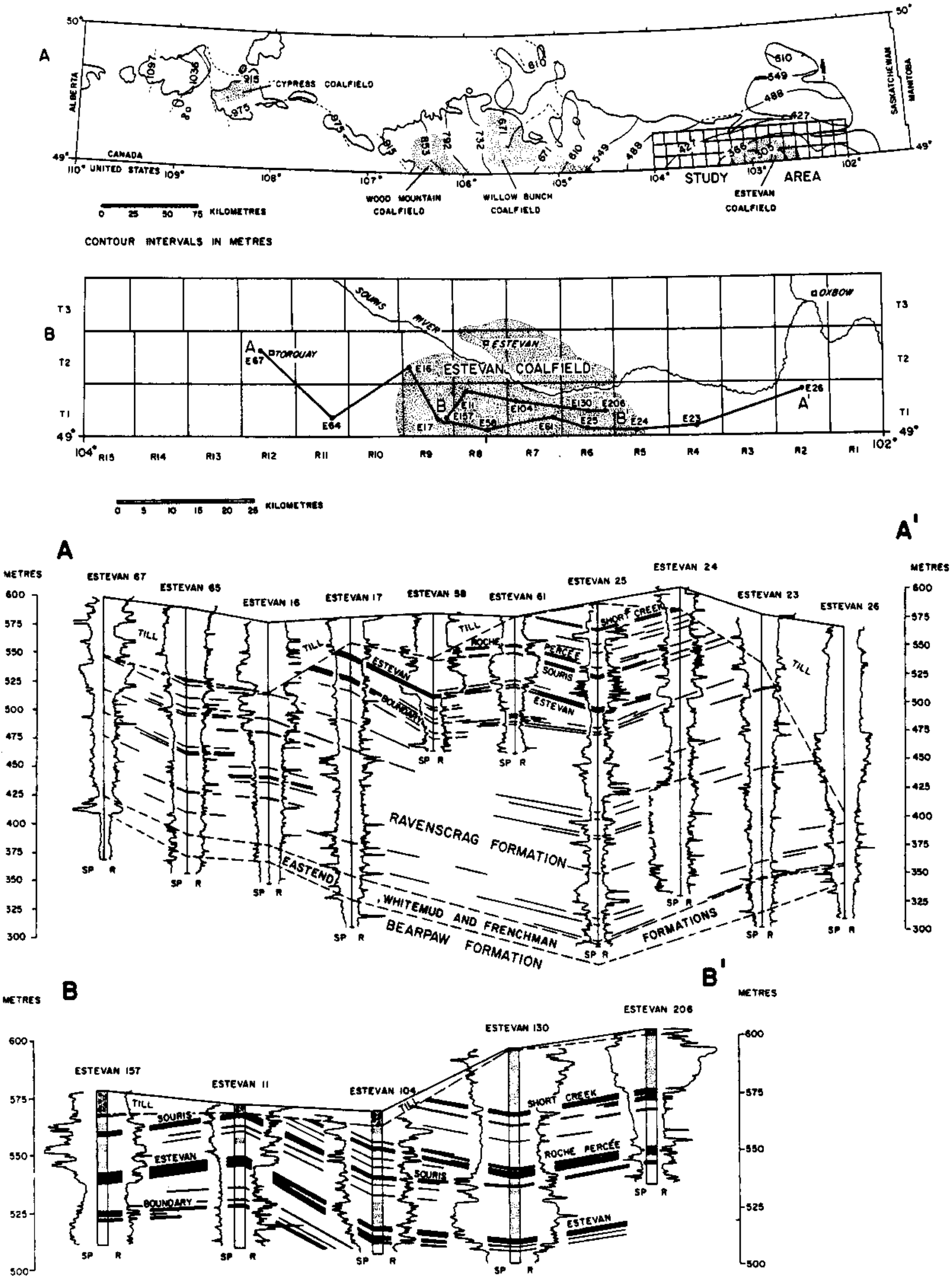


Figure 18 – Structure map and cross-sections of the Estevan coalfield.

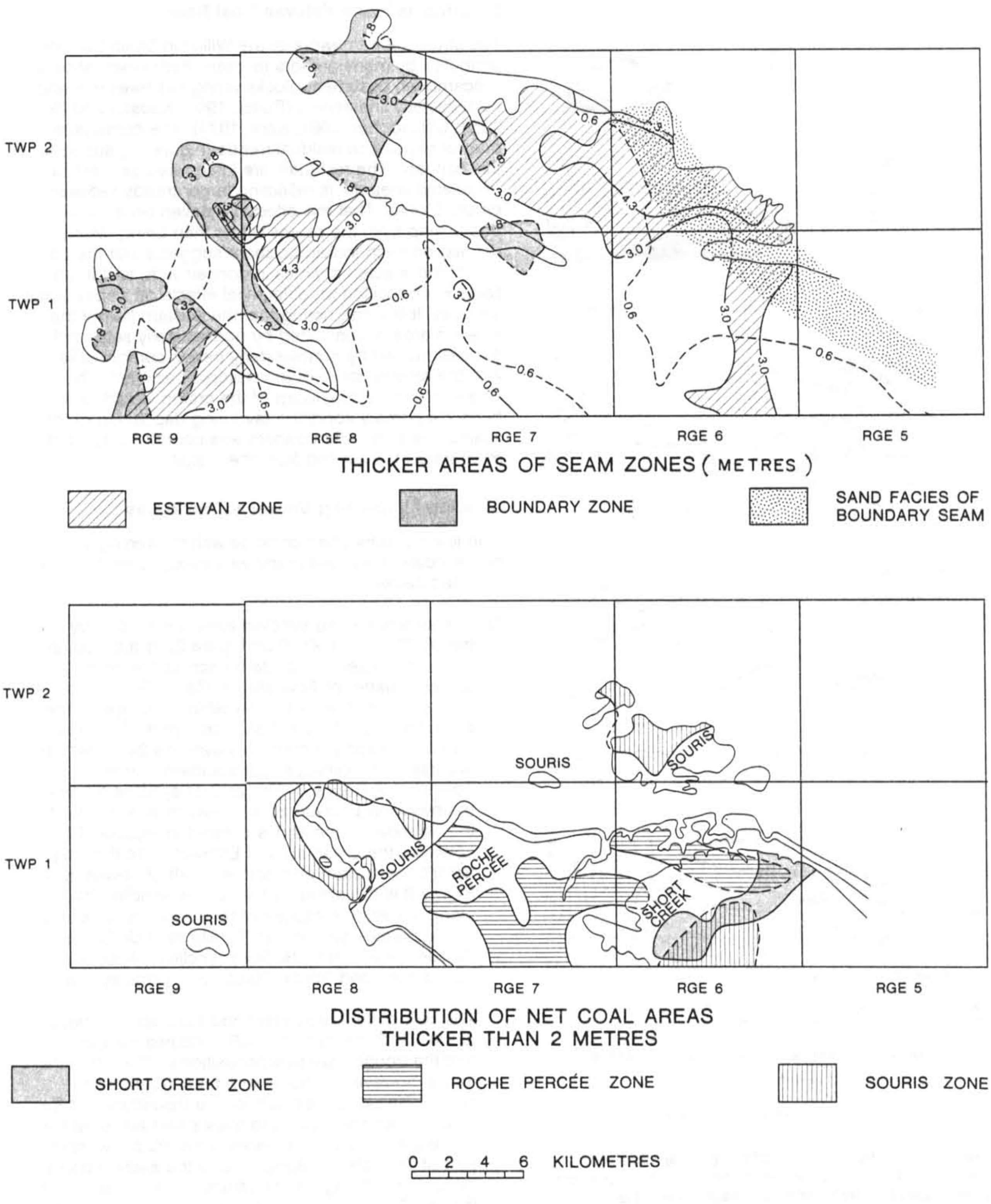


Figure 19 – Generalized net coal isopach maps for the Estevan coalfield: a) Boundary and Estevan zones, b) Souris, Roche Percée and Short Creek zones. Contours in metres.

These regression surface residuals are interpreted to reflect positive and negative warping that accompanied growth of the coalfield, but were distinct from regional cratonic subsidence. Two types are apparent: local trends along sets of lineaments and negative trends overprinted from an overlying bed.

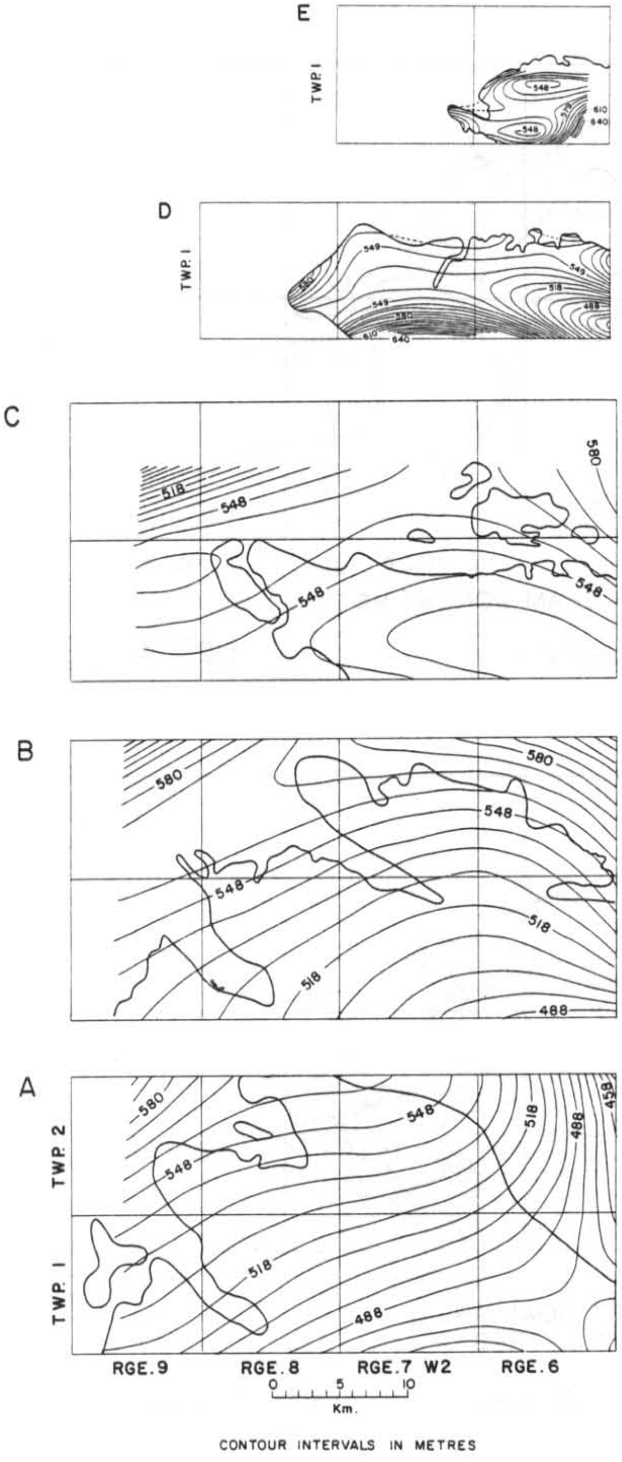


Figure 20 – Structural analysis of the Estevan coalfield. Regression surface (fourth-order) maps on bases of thickest and most laterally persistent bed in each zone: A) Boundary C-H, goodness of fit 89.8 percent; B) Estevan C-G, goodness of fit 79.5 percent; C) Souris C-E, goodness of fit 77.5 percent; D) Roche Percée C-E, goodness of fit 81.1 percent; E) Short Creek, goodness of fit 98.4 percent.

Lineaments in the Estevan Coal Basin

The structural framework of the Williston Basin has been attributed by many authors to intermittent reactivation of Precambrian basement blocks along northwesterly and northeasterly lineaments (Buller, 1958; Kupsch and Wild, 1958; Christopher, 1961; Kent, 1974). The composite map of regression residual trends (Figure 22) supports this concept. The residuals are interpreted as a set of reticulated lineaments reflecting larger trends between crustal blocks. That this effect is detailed on a composite map from the seams rather than being clearly defined on each individual seam suggests that the basement blocks acted at times in concert with, and at other times in opposition to, differential effects on depositional surfaces. It is worth noting that the western half of the Estevan area is dominated by northeasterly sets, and the eastern half by northwesterly trends conformable with the arcuate strike of the cratonic basin rim. Thus, whereas waning downwarp of the craton would have been the primary condition favouring deposition of thick seams, the distribution pattern was controlled by lineament traces transmitted from the craton.

Structural Imprinting Between Coal Zones

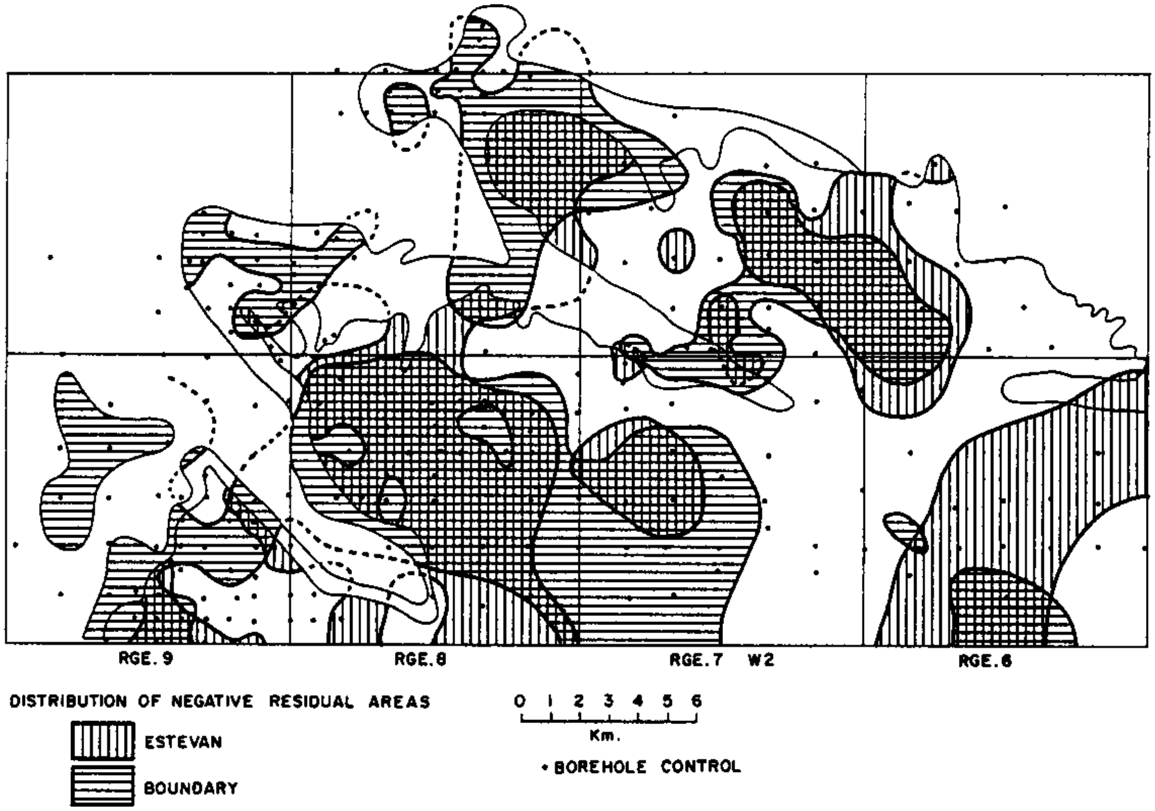
Thin lower seams often coincide with thickening in higher coals. There are many examples, some of which are cited below:

1) The superimposed syncline axes designated by the trends 17-18 and 19-20 on Figure 22 is a broad, shallow northwesterly, depression across the northeastern quarter of Township 1, Range 8 and the southwestern quarter of Township 1, Range 7. The Boundary zone here is less than 1 m thick. It also forms the southern margin of syncline 24-25, which is a site of thickening in the southern part of Township 2, Range 7. The area of syncline 17-18 in the overlying Estevan zone is less than half that of the Boundary zone and is centred at location 17. Likewise, the broad area of Estevan zone thinning across the eastern and northern half of Township 1, Range 8 is bissected by the narrow anticline 31-33 along the eastern margin of the township. This structure separates syncline 34-35, site of thick Roche Percée zone coal beds, from syncline 19-20, site of thick Souris and Roche Percée zone coal seams.

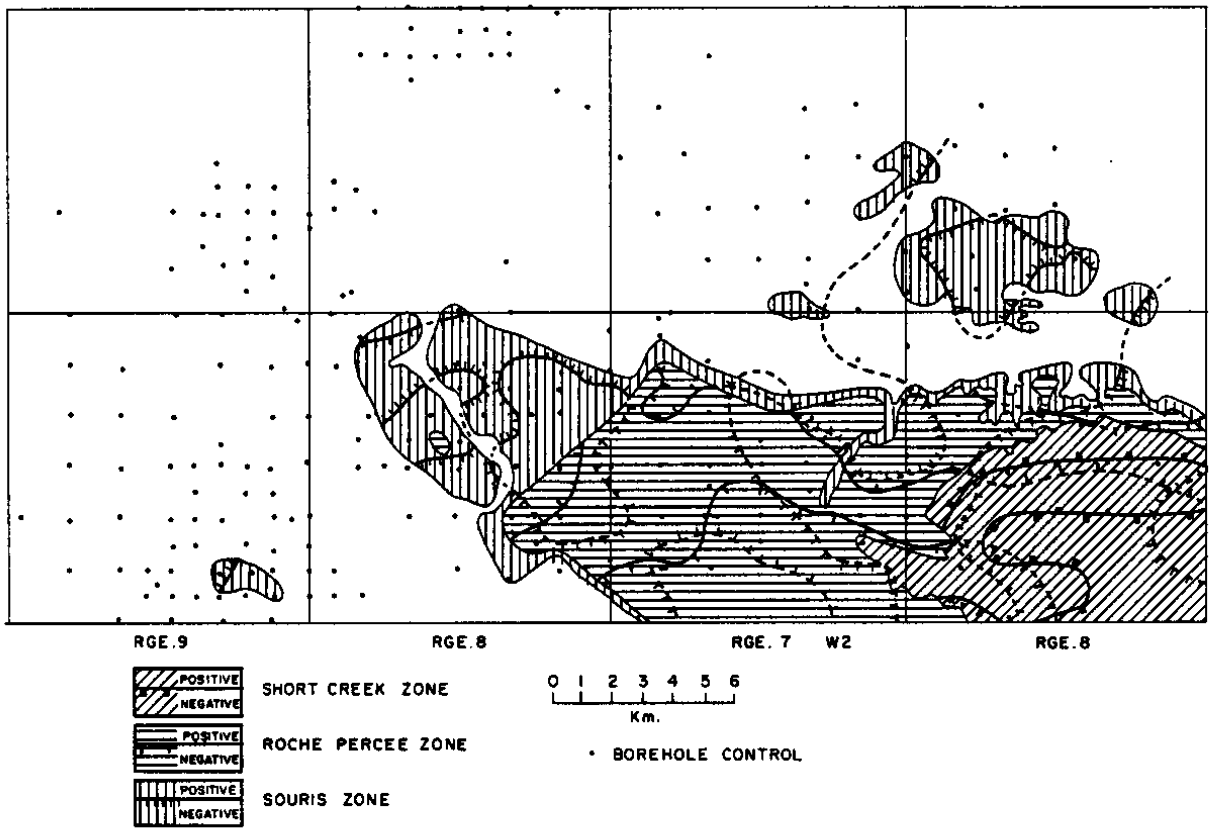
   The lack of thick Boundary and Estevan coal beds at the 17-18, 19-20 and 34-35 synclines suggests that the troughs are postdepositional. The structural forms, however, coincide with thick Souris zone seams. Negative residuals for the Boundary and Estevan zones correspond to thick seam areas parallel to the erosion edge. However, towards the western part of Township 1, Range 7 and the eastern part of Township 1, Range 8, the structural depressions on thinned Boundary and Estevan zone seams contain thickened, overlying seams. These are interpreted as

Figure 21 – Composite maps showing distribution of positive and negative residual areas in the Estevan coalfield: A) Estevan and Boundary zones; B) Short Creek, Roche Percée and Souris zones.

A


TWP. 2
TWP. 1
RGE. 9
RGE. 8
RGE. 7 W2
RGE. 6
DISTRIBUTION OF NEGATIVE RESIDUAL AREAS
ESTEVAN
BOUNDARY
0 1 2 3 4 5 6
Km.
• BOREHOLE CONTROL

B


TWP. 2
TWP. 1
RGE. 9
RGE. 8
RGE. 7 W2
RGE. 8
POSITIVE
NEGATIVE
SHORT CREEK ZONE
POSITIVE
NEGATIVE
ROCHE PERCEE ZONE
POSITIVE
NEGATIVE
SOURIS ZONE
0 1 2 3 4 5 6
Km.
• BOREHOLE CONTROL

an overprint on the Boundary and Estevan zone beds by subsidence associated with deposition of the Souris and Roche Percée seams.

2) In the superimposed syncline trends 24-25-26-27 (Figure 22), the Boundary and Estevan zone seams are approximately delineated by the area of this axis. Thick seams (greater than 2 m net coal) in the Boundary zone are restricted to a small basin 5 km long and 3 km wide around synclines 24 and 25. In the remainder of the depressions, along 26-27, 28 and 8, only 1 m of net coal is present. The Estevan zone centre of deposition lies to the northeast at site 26-27, where more than 4 m of net coal accumulated. Subsidence of the Estevan zone beds was accompanied by deformation of the Boundary zone beds. The Souris zone and younger seams are eroded from the section, except for 2 m of Souris net coal in outliers at synclines 8 and 10, and less than a metre along anticline 9. These are above the thickest net coals of the Estevan zone and, as such, are attributed to continued basin subsidence.

3) Boundary, Estevan and Souris beds in syncline 37-38 form a structural basin across the northwest quarter of Township 1, Range 8. It is a broad extension of syncline 20 in the east-central part of the township. The structural surface of the thinned Boundary seam reflects the 5 km diameter, roughly circular depression in the overlying Estevan zone, containing 3 to 4 m of coal. The structure is present in the Souris zone and forms an arcuate coal deposit 2 m thick oriented along the erosion margin. Small (2 km diameter) minor anomalies on the Souris zone surface may also reflect eroded Roche Percée or younger deposits.

Conclusions

Development of the Ravenscrag coal basins is ascribed to a *regional* retardation in the rate of cratonic subsidence that enabled thick coal beds to accumulate. Contemporaneous subsidences above sites of salt solution modified this and regulated the distribution and geometry of some of the coalfields and clastic syndeposition depocenters.

All seams in the Coronach trough coal measures that are of sufficient thickness to be correlative between boreholes have their maximum thicknesses stacked vertically along the edge of the Roncott platform and, with the exception of the lower seams, similarly thin as they encroach and onlap it. Salt solution induced subsidence

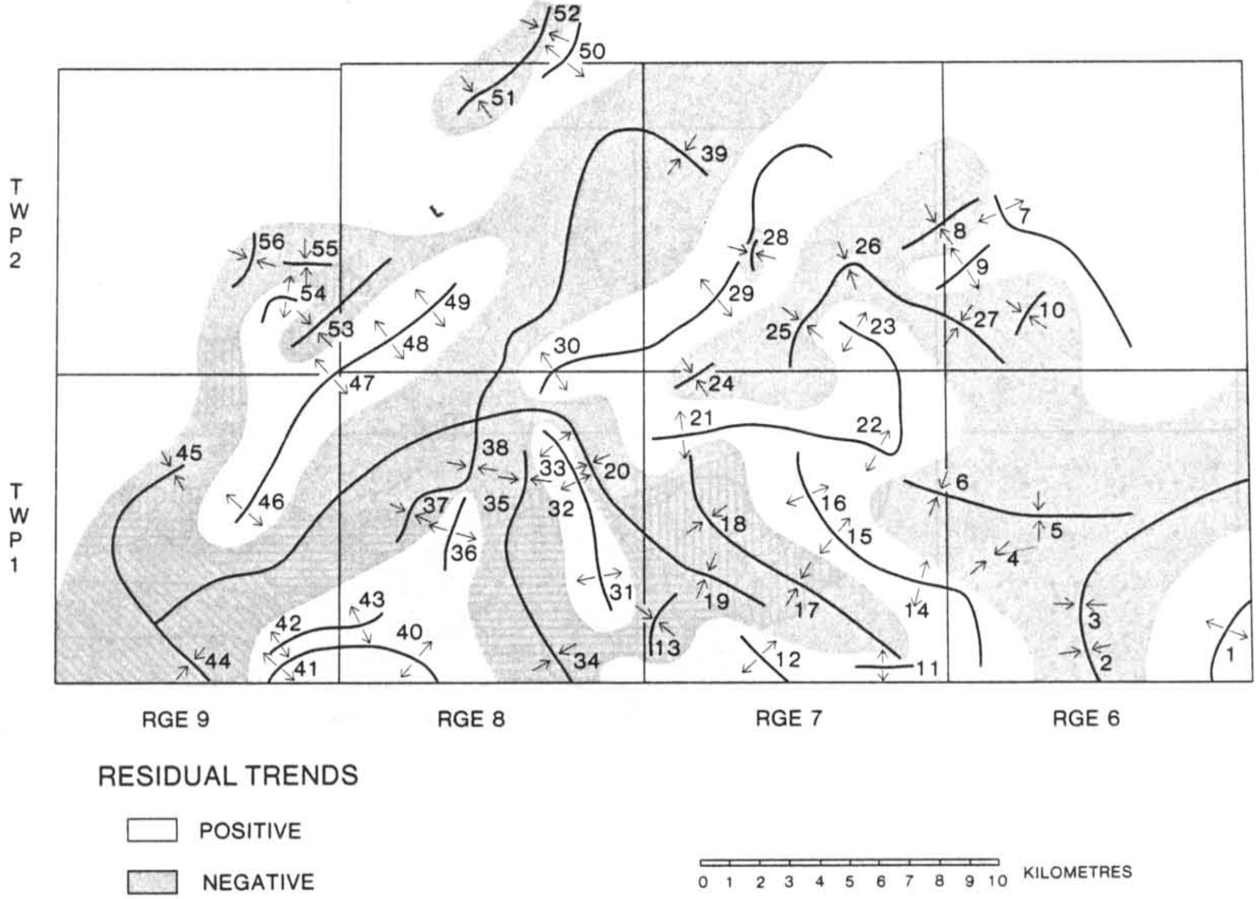


Figure 22 – Diagram of structural trends in the Estevan coalfield compiled from residual maps of the Boundary to Short Creek zone interval.

effects diminish up-section as the seam encroachment of the platform becomes greater. Finally, the Willow Bunch seam basin trend forms oblique to the axis of the Coronach trough and crosses the Roncott platform with markedly diminished influence of salt solution subsidence and assertion of dominant cratonic influence.

Likewise, the Bengough coalfield on the western margin of the Hummingbird trough is situated above two embayments in the east-central margin of the Roncott platform. Elsewhere along this front, solution subsidence was minimal and the coal seam subbasins are small and patchy, yet nonetheless more developed than those above the stable western margin of the buried platform.

Succeeding trends of thick coal seams accumulated in the Estevan coalfield regress towards the Williston Basin depocentre in western North Dakota and reflect waning rate of subsidence of the intracratonic coal basin. This contrasts with the superposition in vertical profile of coal beds in the Willow Bunch basin. The coal seams follow an arcuate growth front conforming to the strike of the Estevan basin rim. Localized coal bed geometries are also aligned parallel with buried reticulate Precambrian lineaments, indicating a remarkable sensitivity of the evolving coal basin geometry to subtle differential movements within the regional craton downwarp.

The coal seams feature postdepositional warping. This phenomenon is widespread in the Estevan basin but rare in the salt solution-dominated basins to the west. It suggests that load compaction may have been considerably different for the two types of subsiding basins.

The alignment of coalfields developed above salt solution troughs partially to largely marks the influence of northwest-trending axes developed as a consequence of cratonic lineaments. Nevertheless, coalfields elongated above salt solution axes have subordinate geometries parallel to cratonic lineaments. Thus, the general coalfield geometry may be controlled by salt solution, while individual thick bed trends parallel cratonic influences, often at oblique trends to each other.

Initiation of thick seams in the coal basins of the northern Williston Basin was progradational southeastward towards the depocentre in northwestern North Dakota (Figure 23). Thus, well-developed seams of the Cypress basin (Ferris and overlying Anxiety Butte seams) are between 3.6 and 7.3 m thick at the base of the Ravenscrag Formation. They are approximately contemporaneous with the relatively thin Landscape seams, but a few metres higher, in the equivalent stratigraphic section of the Willow Bunch basin, 250 km to the east. The thick Hart seam of the Willow Bunch basin occurs 100 m higher in the section. Similarly, in the Estevan coalfield, another 250 km to the east, an additional 100 m of section above thin and discontinuous equivalents of the Hart zone is the stratigraphic position for the onset of thick seams of the Boundary zone. They are isochronous with the stratigraphically high Willow Bunch CD seam across the Willow Bunch basin.

This eastward and upward shift in coal-accumulating retarded cratonic subsidence was contemporaneous with the more local subsidence dominated by salt solution. Cratonic subsidence was reasserted as the dominant basin structural control in all the uppermost coal measures. In the case of the Willow Bunch basin, the Hart zone beds are an example of salt solution control and the Willow Bunch zone beds an example of cratonic control.

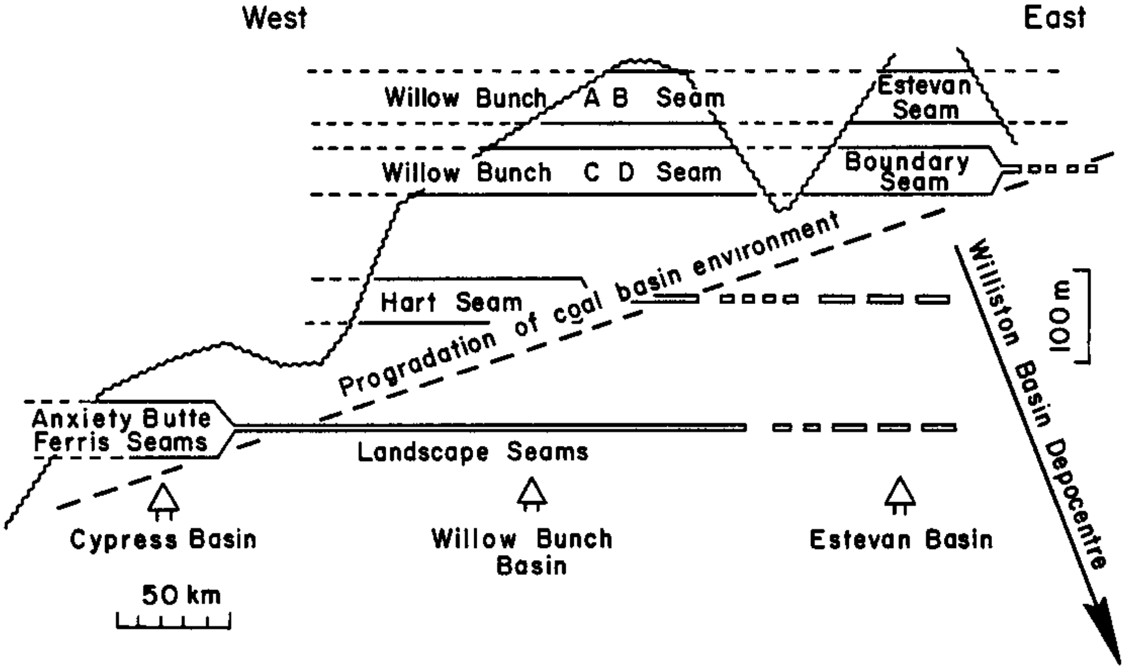


Figure 23 – Diagram of the up-section accumulation of thick coal seams as a linear progradation of younger coal basins across the northern Williston Basin towards the cratonic depocentre.

Clastic Distribution Systems

Marine to Continental Transition

On the basis of borehole cuttings and sidewall cores, the transition from marine to nonmarine clastics was approximated by the change from greyish-brown clay, with minimal silt but locally glauconitic, to yellow-grey silty sands and muds.

Geophysical Logs and Grain size

Electric logs were used to delineate clastic textural patterns in the relatively unconsolidated strata, and for correlation between sand bodies. Radiation logs were used to map coal beds. Depositional environment information based on geophysical log signatures is imprecise at best, but this approach has been recognized by many authors (e.g., Fisher and McGowen, 1969; Fisk, 1955; Fisk et al., 1954; Gagliano and McIntire, 1968; Edwards, 1981).

Electric log signatures (Figures 24 and 25) were grouped into five types, on the basis of upward textural changes within a clastic section or sand body, for the interval above the marine-continental boundary (basal 15 to 30 m):

1) indistinct basal contact, coarsening upward grain size;
2) moderately distinct basal sand, coarsening upward grain size;
3) indistinct basal contact, no basal sand;
4) poorly developed basal sands;
5) distinct basal sand, fining upward grain size.

The mapped textural patterns for the transition from top of the Bearpaw Formation into the Eastend and Frenchman Formations across southern Saskatchewan are shown in Figure 24. The distribution of these textural facies suggests a relationship to the pattern of salt solution tectonics.

Deltaic Lobes Above Salt Solution Trough Axes (Type 1)

The type 1 facies is recognized on electric logs as coarsening upward sand signatures above an indistinct basal contact, and is interpreted as representing vertically stacked deltaic sand bodies. This facies is situated above salt solution troughs, especially as large crescent-shaped forms across the southern regions of the Wood Mountain basin and southern Coronach trough. It is bounded to the east by the Roncott platform. Smaller and narrower bodies are above the western edge of the Hummingbird trough, the embayments of the Ceylon platform and the central Cypress basin.

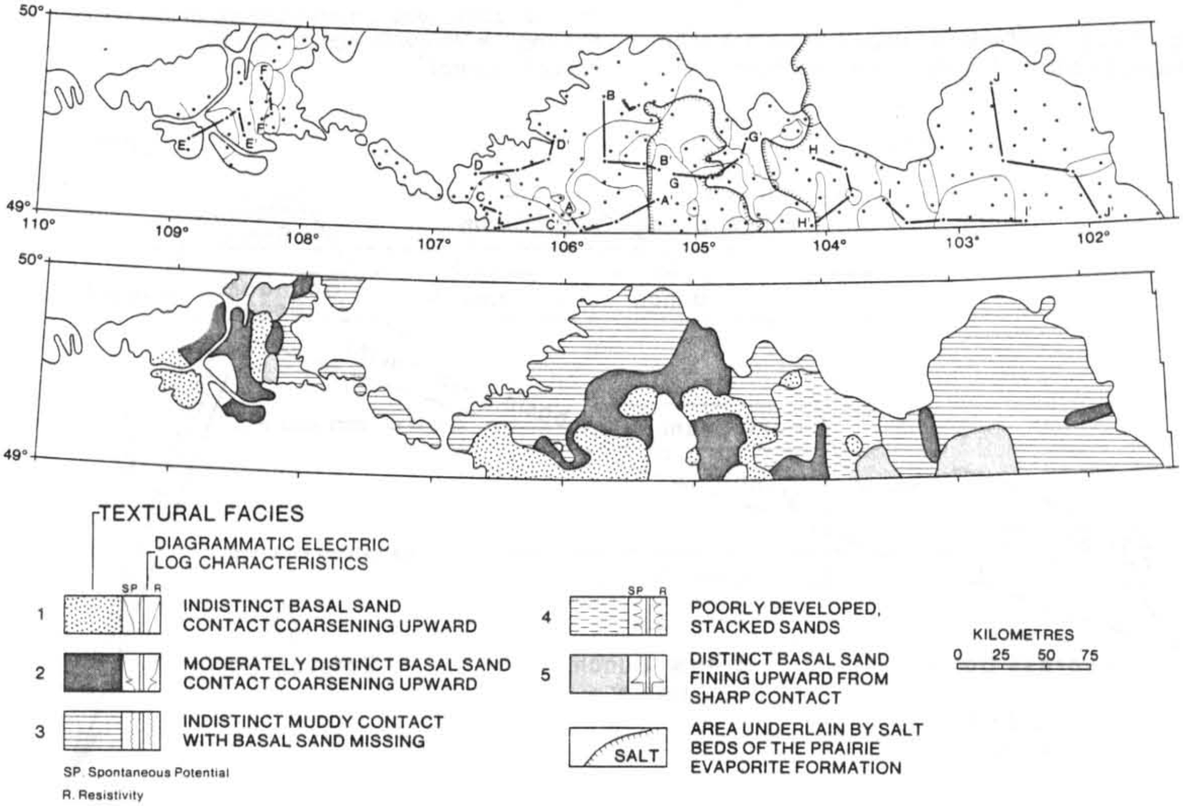


Figure 24 – Distribution map of textural facies at the Bearpaw Formation marine shales transition to the succeeding continental clastics. Cross-sections referred to are in Figure 25.

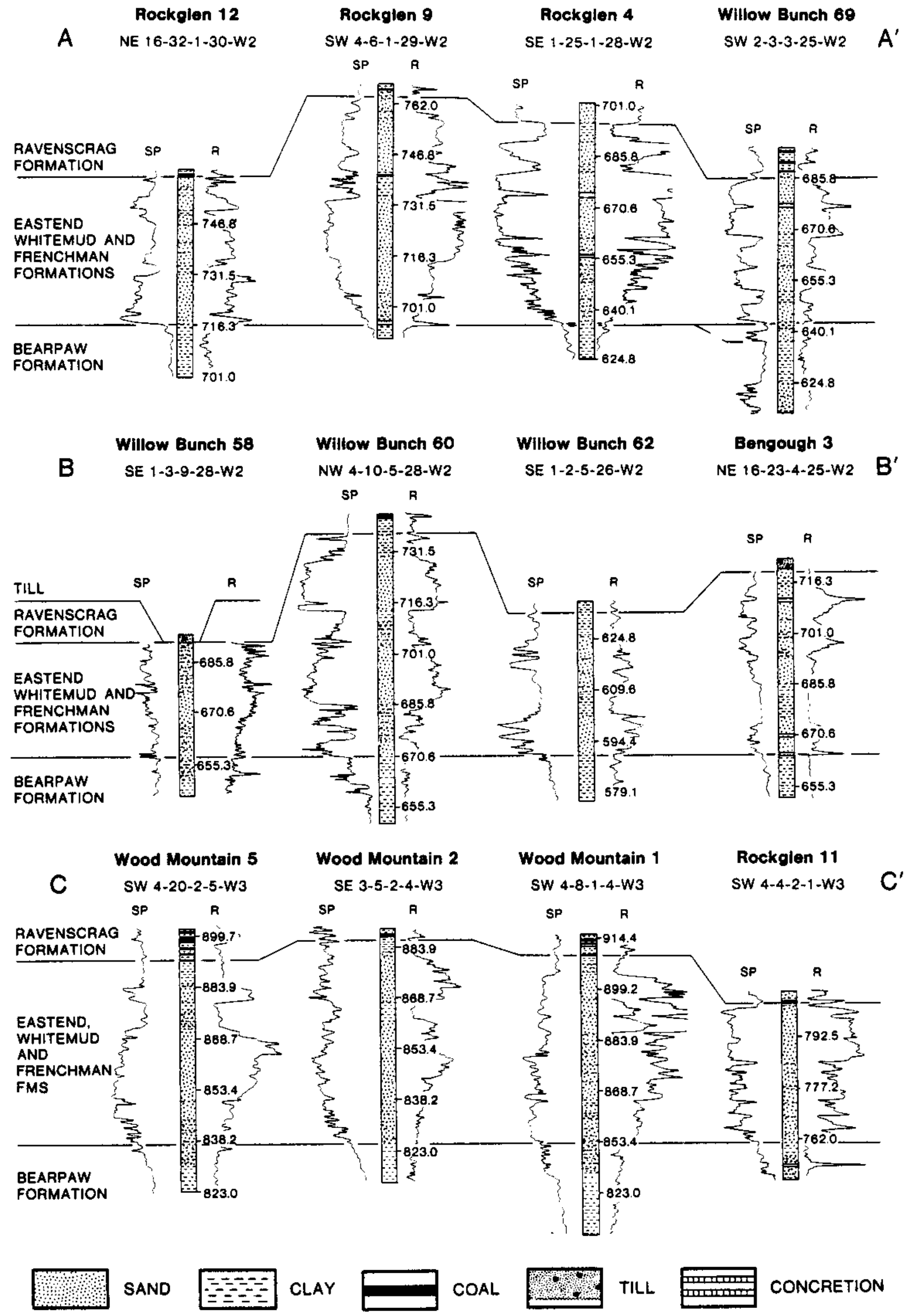


Figure 25 – Cross-sections of the uppermost Cretaceous continental interval. Refer to Figure 24 for location of sections.

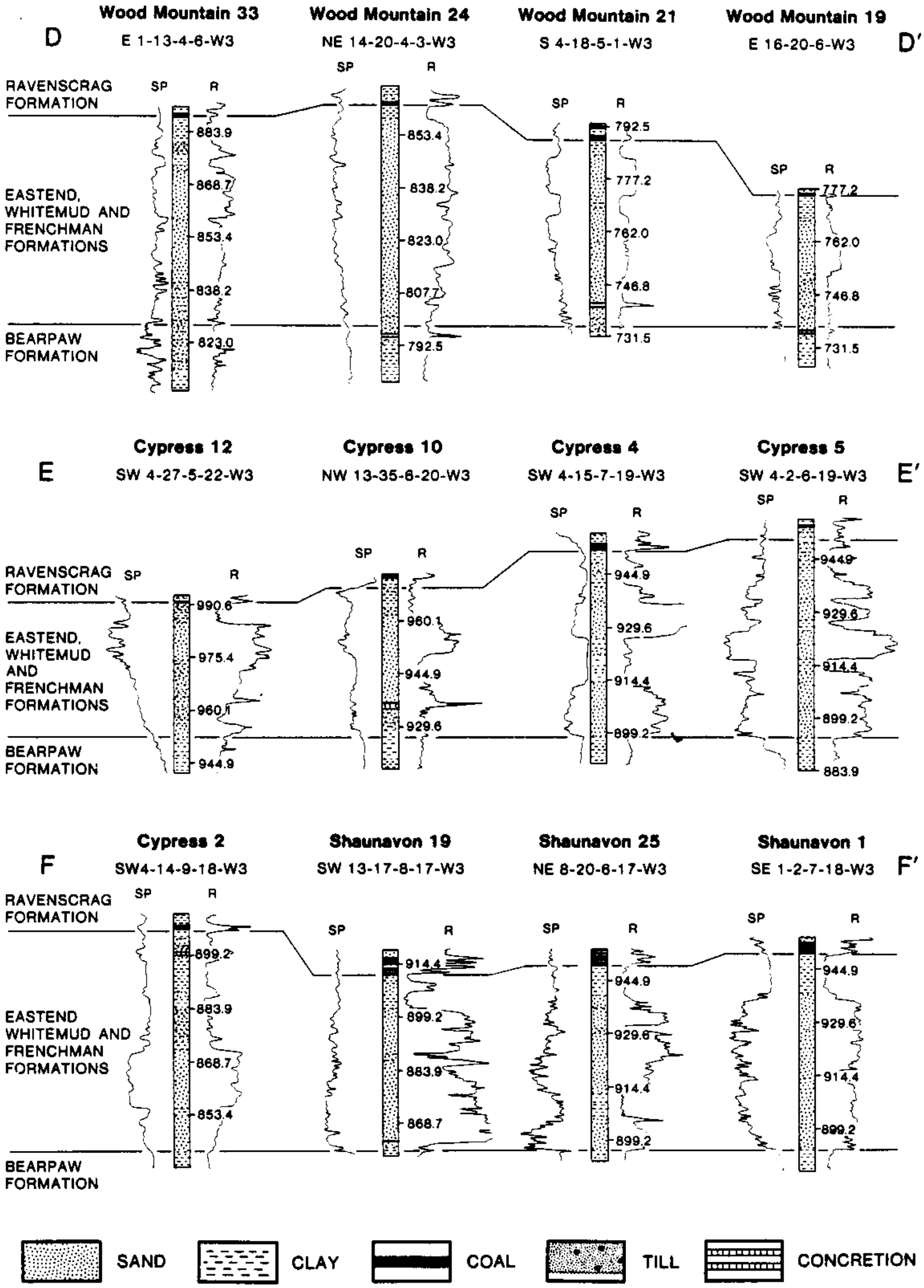


Figure 25 (cont.) – Cross-sections of the uppermost Cretaceous continental interval. Refer to Figure 24 for location of sections.

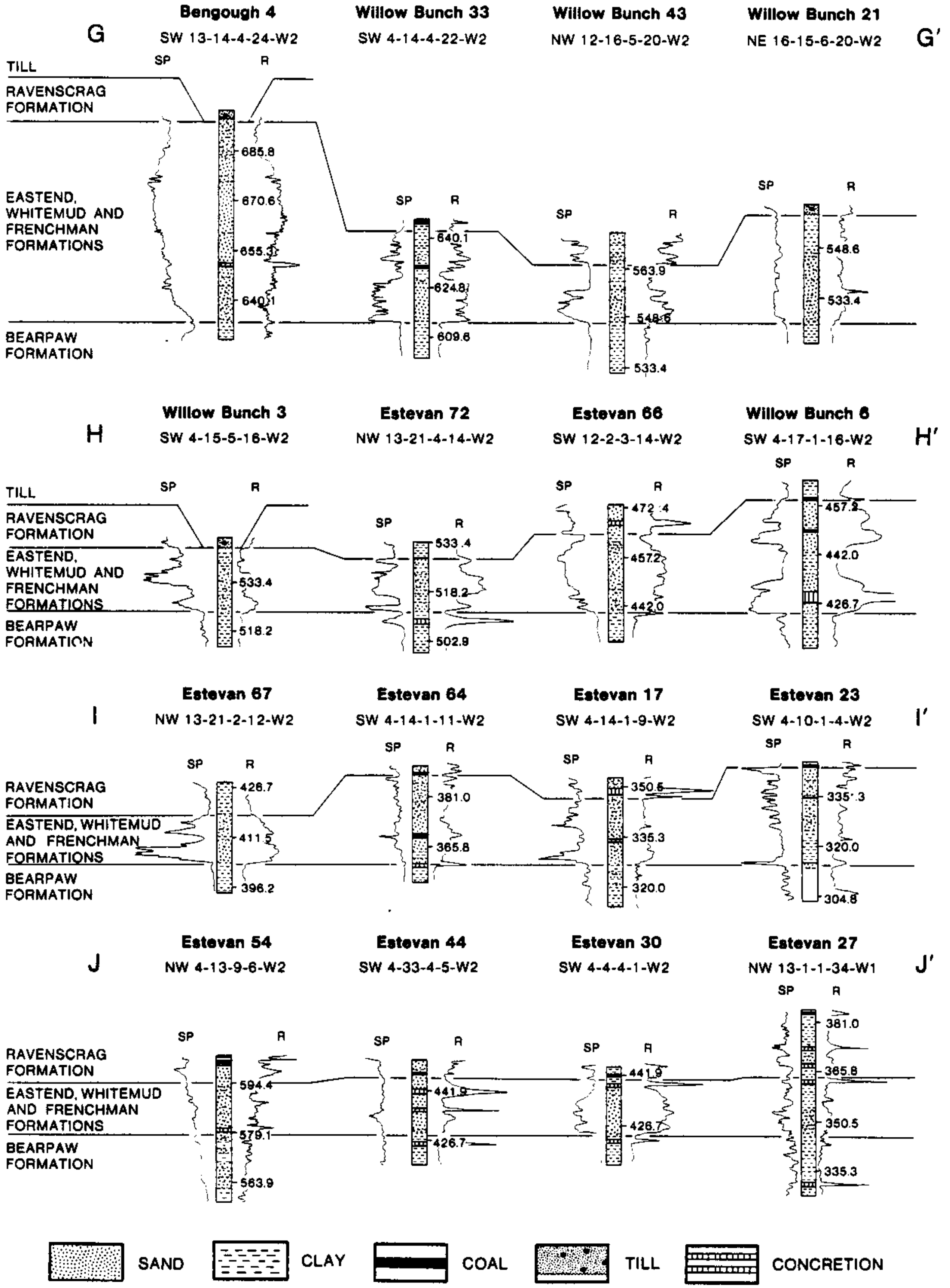


Figure 25 (cont.) – Cross-sections of the Uppermost Cretaceous continental interval. Refer to Figure 24 for location of sections.

The deltaic body west of the Roncott platform is approximately 100 km across and extends south beyond the International Boundary (Figure 26). Two large lobes coincide with salt solution subsidence axes in the Coronach trough and the Killdeer-Rockglen trough of the Wood Mountain basin (Figure 26). The sand body is thickest (60 to 90 m) in the southern part of the Coronach trough.

Clastics of type 1 textural pattern dominate the lower Frenchman section above the western part of the Hummingbird trough and embayments into the Roncott platform. The linear trace of these deltaic lobes along the western margin of the Hummingbird trough is suggestive of coalescing delta fans extending from the central portion of the Roncott platform onto the semistable eastern platform region of partial salt solution subsidence.

Coarsening Upward Small Sand Bodies on Semistable Areas (Type 2)

This facies is recognized as moderately distinct sand bodies (often only one), coarsening upward from the contact with Bearpaw marine shales. The basal sand section is transitional between types 1 and 3. Type 2 facies is well developed in the northern Coronach trough, across the northern and eastern regions of the Roncott platform. It is also associated with type 1 facies in the central trough area of the Cypress basin. This facies lies adjacent to type 1 and occurs on the flanks of salt solution troughs. It characterizes the interval above the eastern Roncott platform, which has been subjected to incomplete removal of the salt. Where this salt has been completely removed, only type 1 facies has accumulated above. Likewise, type 1 and 2 facies are approximately situated at major embayments into the Ceylon platform. Similar in distribution to type 1, type 2 does not occur east of longitude 104W, where salt solution tectonics are not recognized, except for two very small anomalous areas.

Muddy Facies Above Stable Platforms (Type 3)

Log signatures of this facies at the continental contact with Bearpaw marine shales indicate a predominance of mud. The basal sand needed for more precise stratigraphic control is missing in the subsurface east of the Cypress Hills. Stratigraphic position is approximated by extrapolation from structural calculations in nearby boreholes. Type 3 facies is extensive, especially where penecontemporaneous Cretaceous salt solution phenomena at the close of Bearpaw time are absent in the region between the overlying coalfields. Boreholes with type 3 facies at the calculated stratigraphic position of the Bearpaw-Eastend (and Frenchman) Formation contact, near extensive areas of type 1 and type 2 facies, penetrate shallow marine sand bodies near the top of the Bearpaw Formation. The best examples are on the stable western portion of the Roncott platform, overlooking the Coronach trough. The deposits are series of 3 to 10 m thick silty sands and sandy muds with deposition trends oriented north-south 15 to 30 m below the calculated stratigraphic top of the Bearpaw shales. These muddy sands are included within the Bearpaw because of their glauconitic pellets, but the author considers them to be offshore lithofacies

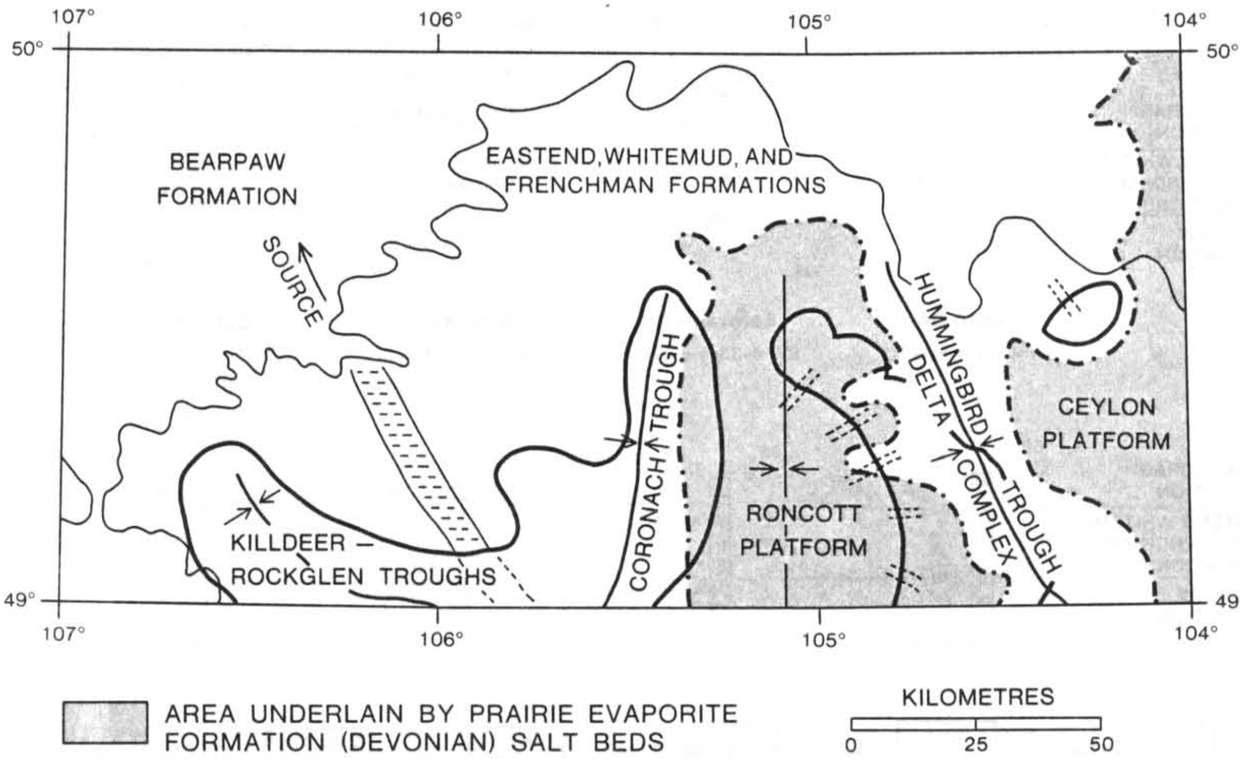


Figure 26 – Deltaic depositional basin elements of the Eastend, Whitemud and Frenchman Formations.

equivalents of Frenchman delta lobes, anchored by the salt solution-controlled subsidence and flanked by muddy tidal flat shores. They are probably sandy muds winnowed by longshore currents from the deltaic lobes. Their muddy matrix indicates that they lay free of wave action and thus should not be considered barrier island deposits. On the other hand, lateral migrations of tidal inlets in a barrier system would have removed the upper level of barrier sediments, leaving modified channel sediments (Brenner and Davies, 1974). Preservation of low barrier islands would have been unlikely (Hoyt, 1967; Hoyt and Henry, 1965). Unfortunately, a lack of recoverable samples with primary sedimentary structures precludes further insight on the origin and preservation of these indistinct sandy mud facies.

Muddy Sand Bodies (Type 4)

This facies is a variation of type 3 because of the dominant muddy clastics, but also includes many *small* silty and muddy sand bodies. Such bodies may be a less well-developed example of the interval below the type 3 deposit above the Roncott platform because of their lateral proximity to well-developed type 1 and type 2 sands. This facies dominates the interval above the eastern side of the Hummingbird trough deltaic complex, an area transitional between the salt solution-modified cratonic region to the west and the unaltered cratonic area to the east.

Fining-Upward Sand Bodies on Stable Platforms (Type 5)

This facies is recognized only in the Estevan area, centred about longitude 103°W and at small scattered localities in the Cypress basin. A distinct basal sand fines upward from a sharp contact with Bearpaw shales. It is unknown, or not very distinctive, in most of the area known to have been affected by salt solution subsidence. Fining upward sequences on electric logs generally suggest point-bar or fluvial deposition. These sand bodies are in sharp contact with underlying marine shales and may represent offshore marine bars with strong fluviatile influences that perhaps accumulated at river mouths. Type 5 facies distribution in the Estevan basin area is on either side of a saddle in the Bearpaw structural surface and suggests a depositional response to contemporaneous cratonic subsidence.

Bulk Sand Distribution

Eastend and Frenchman Formations (Late Cretaceous)

Thickness of sand bodies and percentage of total sand in the Eastend and Frenchman stratigraphic interval above the salt solution troughs and relict salt platforms west of the Hummingbird trough are different from the cratonic area to the east. The strata to the west are 30 to 60 m thick, whereas they are 15 to 30 m thick (Figure 4A) eastward towards the Williston Basin depocentre. The western study area is characterized by two or three prograded sheet sands, whereas eastward towards the cratonic depocentres, a single siltier sand body is generally traceable. Bulk sand distribution in the interval of the Eastend and Frenchman Formations is illustrated in Figure 27. Sand percentage trends approximate the configuration of the Bearpaw structural surface as shown:

1) *Cypress Basin* – Sand percentage increases basinward from less than 60 percent to over 90 percent. The higher percentages occur in a 30 km diameter, north-south elongated area separated from the Wood Mountain and Coronach basins to the east by an extensive region of muds (sand percentages less than 40).

2) *Coronach and Wood Mountain Troughs* – The largest sand body is west of the Roncott platform. A crescent-shaped delta complex 100 km in diameter is delineated by the 70th percentile isopach following the axes of the Coronach and Rockglen–Killdeer troughs of the southern Wood Mountain basin (cf. Figures 26 and 27).

3) *Hummingbird Trough* – Sand values of up to 90 percent front the eastern Roncott platform. The

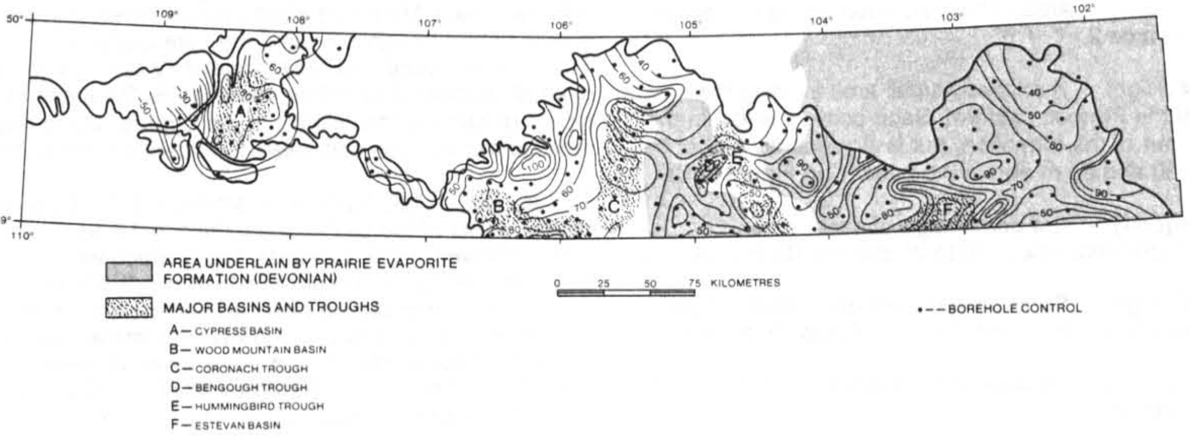


Figure 27 – Sand percentage map of the uppermost Cretaceous continental interval (Eastend, Whitemud and Frenchman Formations).

southern part of the Hummingbird trough, however, has relatively low values of between 40 and 50 percent.

4) *Estevan Basin* – Two high-percentile arcuate sand trends alternate with two high-mud (low-sand) trends in the region roughly bounded by longitudes 101°W and 104°W. They conform to the arcuate configuration of the Bearpaw structural surface contiguous with the cratonic basin rim.

Ravenscrag Formation (Paleocene)

Distribution of sand-sized clastics in the Ravenscrag Formation was mapped for the basal 30, 60 and 90 m of the formation because of erosional dissection of the upper part. A fourth map illustrates the sand distribution as a percentage of the total preserved section. These four maps (Figure 28) exclude the Cypress Hills region between longitudes 108°W and 110°W because most boreholes that penetrate the base of the formation in this area are less than 50 m in length. Only the total sand percentage in the section was mapped only for this area (Figure 29).

Comparison of the sand distribution maps delineates ten regions of successive sand concentration, of which six are highs and four are lows (Figure 30). Greater sand percentile areas have sand and silty sand bodies recorded over 30 to 50 percent of the stratigraphic interval, and locally as much as 80 percent. Lower sand percentile regions generally have 10 to 30 percent sand and silty sand.

Area 1 (High) – This area, trending to the northwest, is approximately 50 km long and 8 km wide. The continuity of the sand body is discernible throughout the section, but is siltier upward and less well defined on the 90 m interval map.

Area 2 (High) – This area, bounded by longitudes 105°30'W and 106°00'W, is separated from area 1 on the west by a narrow trend of low sand percentage. Area 2 is itself composed of two distinct sand trends (A and B on Figure 28B) on the basal 60 m interval map.

Area 3 (Low) – Area of thinned Ravenscrag Formation north of area 2.

Area 4 (High) – A relatively small area fronting the east side of the Roncott platform. Sand content is low in the lower part of the formation, but is significantly higher between 30 and 60 m above the base (C in Figure 28B).

Area 5 (Low) – The percentage of sand in all stratigraphic intervals is 10 to 20 percent (D, Figure 28B).

Area 6 (High) – Sand contents are consistently greater than 40 percent throughout the stratigraphic interval.

Area 7 (High) – An area with up-section diminishing of sand content.

Area 8 (Low) – Sand content is 10 to 20 percent, between arcuate high-percentage sand areas 7 and 9.

Area 9 (High) – Highest sand percentage after area 7, although sand content decreases up-section from 50 percent. This arcuate area narrows and becomes discontinuous toward area 7 in the west.

Area 10 (Low) – An arcuate trend northeast of area 9 with 20 to 40 percent sand content in the basal 30 m (Figure 28C).

Cypress Basin – Sand content of the Ravenscrag Formation in the eastern Cypress Hills ranges between 20 and 35 percent (Figure 29), but is representative of only the preserved lower 30 to 45 m of the formation.

Paleogeography of Continental Progradation

Vertically stacked deltas in structural sediment traps created above salt solution axes are the distinguishing sedimentary feature of the study area. The distribution of textural patterns in the basal continental clastics can be correlated with the presence or absence of active salt solution induced syndeposition troughs marginal to the Roncott and other buried salt platforms.

Type 1 facies is interpreted as sand bodies that accreted along tectonically active coastal margins above salt solution troughs. Clastics from the west and northwest were transported along low paleoslopes, associated with only moderate subsidence, towards offshore salt solution troughs. The largest delta is a crescent-shaped body infilling the southern Wood Mountain basin (Killdeer – Rockglen troughs) and Coronach trough. These deltas were initially inhibited from extensive progradation beyond the areas above the salt solution axes by relatively rapid subsidence impinged against the structural barrier created by stable salt platforms offshore. Progradation in the Bearpaw sea was not restored until infilling of the troughs exceeded subsidence, thereby permitting onlap of the Roncott structure. This is an example of vertical accumulation of deltaic facies in balance with a subsiding coastal margin.

These large delta lobes were associated with areas of contemporaneous (and complete) salt removal during the Late Cretaceous – Early Tertiary downwarp of the Williston Basin. Most of the salt section removal in the Hummingbird trough predated the Late Cretaceous. Thus, this structure was only moderately enlarged by additional removal of salt along its margins. Presence of type 1 deltaic lobe transitions in the Cypress basin may indicate salt solution-controlled subsidence there as well.

The stacked deltaic framework is similar to the Eocene Wilcox deltas of the Gulf Coastal Plain in Texas (Fisher and McGowen, 1969; Edwards, 1981) which were deposited along the margin of a tectonically active coast. There, subsidence matched sediment load by means of growth faults which prevented lateral coalescence for a substantial period. Another modification of this coastal process is reported by Miall (1976) in the Banks basin of Arctic Canada.

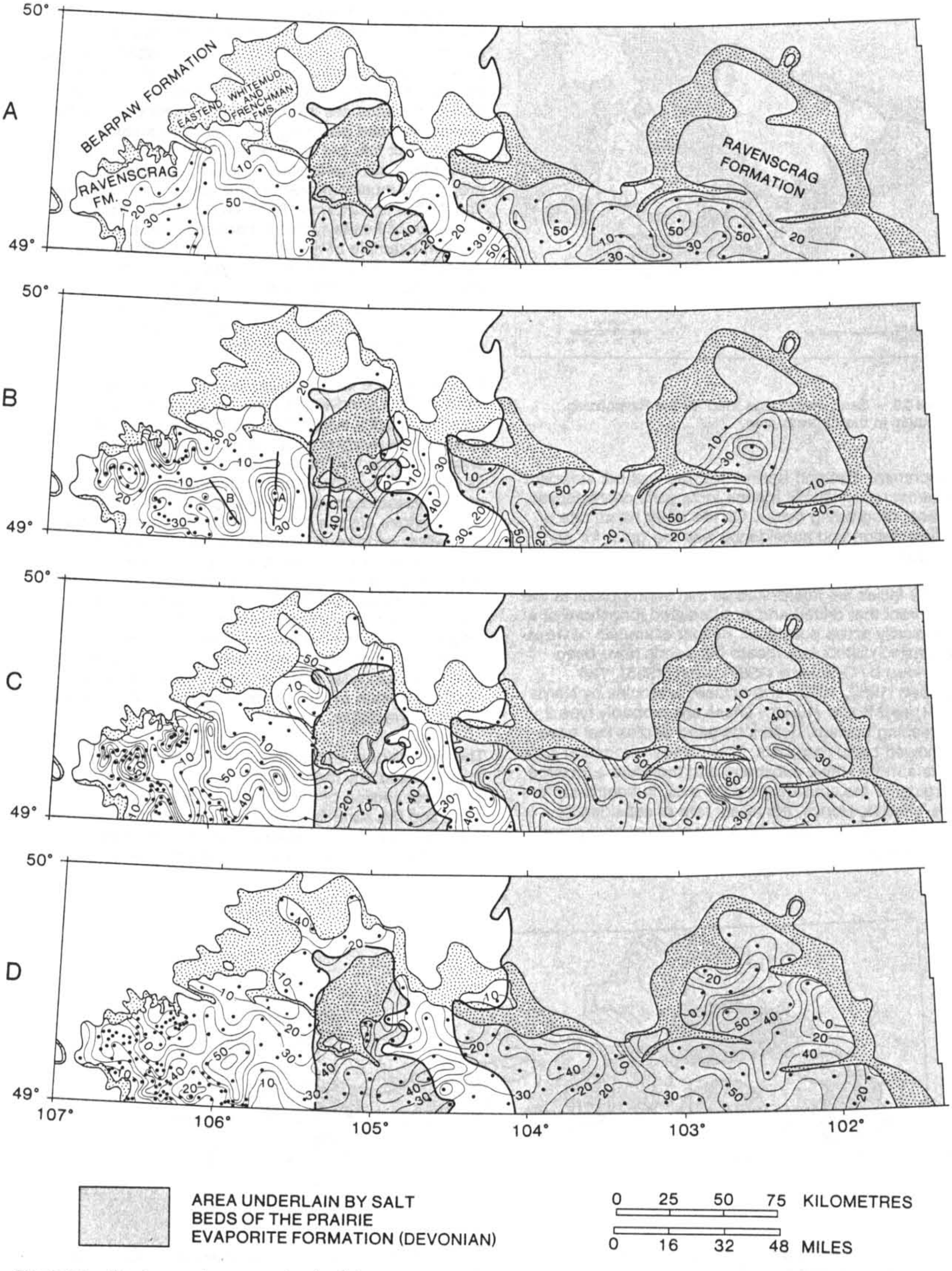


Figure 28 – Sand percentage maps for the A) lowest 100 m, B) lowest 60 m, C) lowest 30 m, D) entire preserved thickness of the Ravenscrag Formation (excluding the Cypress area).

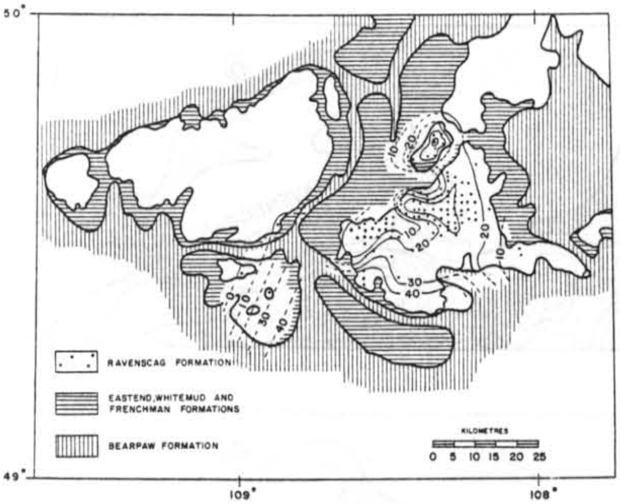


Figure 29 – Sand percentage map for the Ravenscrag Formation in the Cypress area.

Frenchman–Eastend basin instability was not sufficient to permit recognizable marine incursions characteristic of most prograding deltas. On the other hand, rate of sedimentation and subsidence was too great for accumulations of thick coals.

Type 2 facies are interpreted as thin sand bodies at the delta front that drifted and accumulated longshore of a tectonically active coastline. Recent examples of wave-dominated distributary mouth bar sands have been described by Oomkens (1967), Kruit (1955), Van Straaten (1959, 1960), and ancient examples by Nanz (1954) and Potter (1963). These are probably type 2, coarsening upward, delta lobe sand bodies that have winnowed basal members. This paleoenvironment suggests a more stable substrate, and therefore a location marginal to the subsiding trough axis, in contrast to the type 1 facies. Hence, the lesser rate of subsidence favours longer exposure for longshore reworking and moderate progradation.

Large portions of the study area are interpreted as sand-starved, prograded tidal flats that enveloped deltaic sands trapped in salt solution troughs. Stability (i.e., the absence of contemporaneous salt removal below the muddy shoreline as indicated by the spread of type 3 facies) characterizes the Frenchman interval above the western Roncott platform, and interbasin areas which are now salt free but were probably underlain by salt during the Late Cretaceous. Ancient examples of prograded muddy shorelines are rare in the literature. The Walker and Harms (1971) study of the Upper Devonian of Pennsylvania is frequently cited. The modern example of the Mississippi River delta area, on the other hand, illustrates progradation as a sequence of tidal mud flats. The Louisiana coast receives longshore muds from the Mississippi River delta, which results in progradation of tidal flats and marshes (Byrne et al., 1959; Gould and McFarlane, 1959).

Type 4 facies is interpreted to represent a more sandy variant of the sand-starved muddy coastline. The paleogeography suggests a band of beaches characteristic of low-lying coastal plains, comparable to cheniers of the Louisiana coast. These are interpreted as chenier-like, rather than sandy beach ridges, because of their association with the type 3 tidal flat sediments. Beach ridges are the product of storm waves or other high-water conditions beyond the mean high-water line, but a chenier is separated from the shoreline by deposition of fine-grained clastics on its seaward side, which are generally represented by marsh conditions (Russell, 1968). Type 4 sands occur where there is significant thinning of the formation eastward from the Hummingbird trough deltaic complex. Stratigraphic thickness of less than 30 m suggests that this area underwent relatively rapid regression of the Bearpaw sea beyond the eastern extent of the deltas.

The depositional environment of type 5 facies is difficult to interpret in any manner other than by a gross model. The lower section of the basal sand is relatively clean of mud, and the sand fines upward. An estuarine environment is suggested because of the difficulty of having fining upward sequences in a coastal sequence other

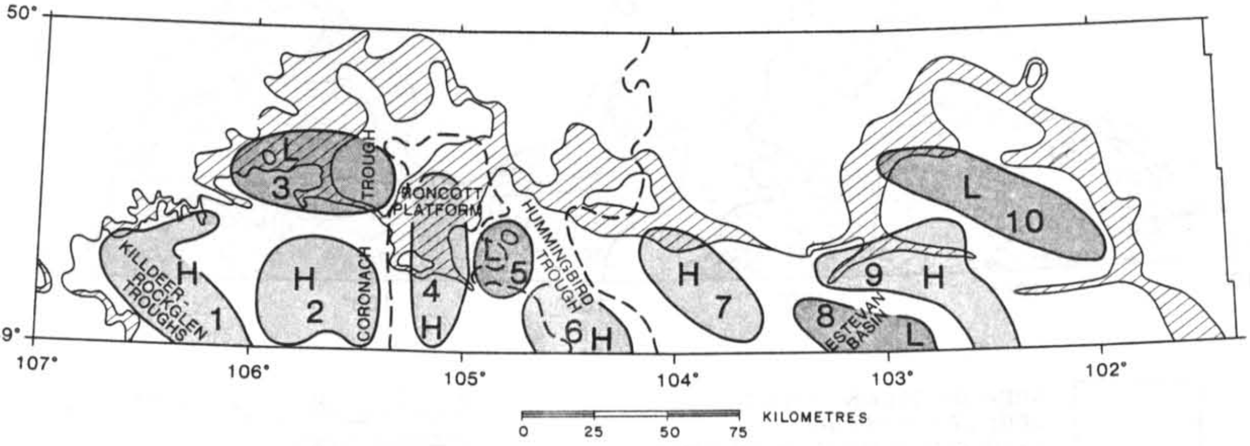


Figure 30 – Generalized high (H) and low (L) sand percentage areas for the Ravenscrag Formation. Frenchman Formation subcrop area indicated by hachuring.

than as point bar tidal creek deposits. Deposition as sand bars in an estuarine environment or at river mouths offshore would provide an effective mechanism for such size segregation. Suspension load would be removed by both the flood and ebb flows. During periods of low flow, the dominance of flood tidal processes are reflected in sand waves created by both suspended and bedload sediment transport. The channel is dominated by scour of its base during ebb flow (Visher and Howard, 1974). Klein (1970) documents sharp erosional contacts of intertidal sand bodies reflecting such turbulent flow in open channels. Campbell and Oaks (1973) discuss an occurrence of coarse sand infilling scours, cut at the mouths of numerous small streams along a coast in the Cretaceous of Wyoming. This, and those of the study area, are comparable in size and sorting to the large estuaries of Holland (Boersma, 1967; Oomkens and Terwindt, 1960; Terwindt et al., 1963; Terwindt, 1971). Likewise, sediments of the lower Rhine estuary are similar to type 5 facies of the Estevan area, as clayey to fine-grained sands are the dominant mode. They note inconsistencies in grain-size vertical distribution, in that correlative sequences coarsen on one hand and fine upward on the other. Beds of an upper estuary are more characteristic of fluvial processes and tend to fine upward (Estevan area), whereas those of the lower estuary irregularly give way to downward fining into marine muds (Cypress basin). The Estevan basin is largely a type 3 facies area, with type 5 occurring seaward and confined to a structural depression that can be speculated to approximate the geometry of an estuary. This interpretation is also applicable to the Cypress basin as an area of low-lying coast entered by numerous streams. The patchwork distribution of facies types in the Cypress area also seems compatible with an estuarine origin.

The rate of sedimentation and subsidence during the Late Cretaceous was too great for thick accumulations of coal. However, during the Paleocene, subsidences associated with salt solution troughs and the regional cratonic downwarp slowed sufficiently for extensive and thick lignite seams to develop above the delta lobes.

Ravenscrag Formation (Paleocene)

Delineation of sand and silty sand bodies in the Ravenscrag Formation section is more diffuse but recognizable as a repetition of the uppermost Cretaceous pattern. Ravenscrag sand basins (and coal) overlie the large deltaic sand complexes of the Frenchman Formation. The Ravenscrag sedimentary subbasins west of the Roncott platform were enlarged by salt solution subsidence, whereas, to the east, cratonic subsidence dominated. The troughs west of the Roncott structure, because of their relatively great rate of subsidence favoured vertical accretion of deltaic sedimentation and accumulated a high proportion of sand. In contrast, the cratonic coal basins are associated with low sand percentages in the section. The smaller coal basins above the margins of the Hummingbird trough share characteristics of both cratonic and salt solution troughs and have moderate sand concentrations.

For example, high sand percentage area 1 is associated with the Killdeer–Rockglen troughs (Figure 30), and high sand area 2 is in the southern part of the Coronach trough. These are contiguous with the Frenchman deltaic lobes above the salt solution troughs west of the Roncott platform. The western region of the Roncott platform is a high sand percentage area but separate from the adjacent high sand area of the southern Coronach trough. Low sand percentage area 5 is situated above the east-central Roncott platform where it is deeply embayed by the Hummingbird trough. High sand percentage area 6 is situated across the southeastern margin of the Roncott platform and along the axis of the southern part of the Hummingbird trough. Basinward increase of sand percentages also appears in the Cypress basin, which may have been a partial salt solution subsidence structure. Small coalfields along the margins of the Hummingbird trough are also situated above deltaic sand bodies. These areas are interpreted as transitional between coal and high sand percentage association of salt solution modified subbasins to the west and coal association within low sand percentage cratonic areas to the east. The Estevan coalfield coincides with a very low sand percentage area as an example of the latter.

Clastic distribution systems associated with the salt solution basins are in marked contrast to cratonic dominated sites. This relationship is observed between the eastern and western portions of the study area as well as up-section. Sand bodies between coal beds in salt solution troughs tend to be nonlinear, somewhat rounded, due to their accumulation in lacustrine basins and as coalesced distributary sheet sands. In contrast, the sand bodies in cratonic areas are more linear and less muddy. The geometry of the coal beds in the salt solution troughs is generally similar to the associated sand bodies, as the coals filled lacustrine areas. On the other hand, cratonic subbasin coal beds are elongated parallel to major river channels and their sand fills. With respect to the salt solution trough, such fluvial sand bodies lie *outside* the coal basins. Thus a major fluvial deposit separates the Wood Mountain and Coronach basins into two basins rather than dissects a single "superbasin". This interpretation is supported by the isopach trends within each coal seam, in that they are independent of the position of the sands. This contrasts with the cratonic Willow Bunch seam basin and the Estevan basin where coal bed isopachs elongate parallel to the river channel complex. During intermittent subsidence of the salt solution troughs, the large river channels outside the basin may have been sources of clastics for coalescing sheet sands during flooding of the coal basin by channel diversion. Consequently, western basins have high sand percentages. In a cratonic basin, higher rates of subsidence would lead to buildup behind a levee, as indicated by the high mud content (low sand percentage) of the section between the coal seams.

The coalfields on the eastern and western margins of the Coronach trough are illustrative of main channel sand diversion from the high sand percentage (salt solution trough) area during the time of the thick peat accumulation. The coal beds in the solution subsidence axis are contemporaneous with a 10 to 15 km wide body of fluvial clastics along the western margin. This channel sand body, oriented to the southeast, is situated between the southern Wood Mountain coalfield (high sand area 1) to the west and the Coronach trough coalfield (high sand area 2) to the east. It is interpreted as a Paleocene appearance of the main channel that supplied sands forming the Eastend–Frenchman delta lobes.

Broad sand bodies also occur on the western edge of the Roncott platform at stratigraphic horizons equivalent to thick coal seams. These sands were also spread across the coal basins when subsidence rates were increased, resulting in high sand percentages in the section wherever there are coal basins. This is in contrast to the clastic distribution system of cratonic coal basins. Sediment dispersals associated with cratonic (and subordinate salt solution subsidence modified) basins were by rivers that alluviated their floodplains. These coalfields are integrated with elongated overbank deposits. The Estevan coalfield has 15 to 30 km wide fluvial sand complexes. The channels were relatively stationary, and peats accreted laterally to them; thus, coalfields are found above the low sand areas. The Estevan coalfield, for example, is situated within low sand percentage area 8.

The upsection domination of cratonic subsidence over salt solution tectonics in the Ravenscrag also culminated in deposition of the Willow Bunch zone coals (basin 4, Figure 1) and clastics across the Roncott platform. Eastward, the sand and mud trends conform to the strike of the arcuate cratonic basin rim surface. Waning of cratonic downwarp culminated in the Estevan coalfield (basin 7, Figure 1) and the Willow Bunch coals of basin 4 (Figure 1). Ravenscrag sands of the Willow Bunch area coalfields change orientation upsection from south to southeast. This reflects initial dominance of north-south salt solution axes but the subsequent expansion of cratonic subsidence. This gradual change is also apparent in the eastward migration upsection of the major sand bodies between the Killdeer–Rockglen troughs (Wood Mountain coalfield) and the Coronach trough (Coronach coalfield).

Morphological History of the Coalfields in Relationship to Ancestral Valleys

Late Cretaceous to Early Tertiary coalfields in the northern Williston Basin were preserved as topographic features during Late Tertiary to Pleistocene periods of widespread erosion. The thickest coal seams, up to 5 and 10 m thick, are within 10 to 50 m of the surface. The margins of the coalfields tend to be determined by the original basin geometries rather than by erosion fronts. The author proposes that such coalfield preservation is related to repeated and superimposed drainage patterns and structural inversion persistent from the Late Cretaceous into the Holocene. Drainage patterns and paleogeographic relationships were reinforced because of control by regional and local lineaments, originating in the Precambrian crust, that were intermittently active during and after the Laramide Orogeny.

The region of the Williston Basin underwent major Tertiary uplifts. Tertiary coarse conglomeratic clastics, gravels and sands now cap uplands as erosional remnants and rest unconformably on and within the area of the Ravenscrag Formation. The most important of these are the Cypress Hills (Miocene-Eocene) and Wood Mountain (Miocene) Formations. The Wood Mountain gravels are traceable eastward as scattered outliers into the Willow Bunch coalfield (Figure 31).

Quaternary modification of the Willow Bunch and Wood Mountain areas was characterized by southeasterly trending meltwater valleys cut into bedrock during glaciation. The larger of these valleys are the Big Muddy, Rockglen, Poplar River, Twelve Mile Lake, Lake of the Rivers and Long Creek (Figure 31). Their history during the several glacial advances and retreats is described by Parizek (1964), Witkind (1959) and Howard (1960).

Many topographic features of the bedrock are preglacial (Figure 32A). There are major southeasterly trends across the central area (longitudes 104° to 107°W). The Wood Mountains flank the Big Muddy valley area of the Willow Bunch basin to the east. The area west of longitude 108°W is dominated by the Cypress Hills. This general relationship is similar to the paleogeographic elements delineated by Late Tertiary and Early Pleistocene buried valley patterns (Howard, 1958, 1960; Meneley et al., 1957; Stalker, 1961; Kupsch, 1964). The largest of these valleys, the Big Muddy, is recognized by Howard (1958, 1960) as a southeasterly draining tributary of an ancestral Missouri River (inset, Figure 31). Others are the Poplar and East Poplar, which border the Wood Mountain coal basin on the west and east respectively.

The bedrock east of longitude 104°W (Figure 32A) is entrenched by the arc of the partially exhumed Estevan buried valley between longitude 102°W and a point just west of 103°W (Figure 33).

The Estevan Valley enters Saskatchewan at the International Boundary southwest of the Estevan coalfield and trends eastward into Manitoba (Figure 33) and is interpreted to be an ancestral valley of the Missouri River (op. cit.). The ancestral Yellowstone River also is postulated to cross the International Boundary and, about 20 km to the north, joins the Missouri River. The valleys are buried under 15 to 100 m of Late Tertiary fill and Pleistocene drift.

North of the Ravenscrag Formation erosion front, similar valleys are carved into the Bearpaw Formation shales. These Quaternary drainage courses, however, flowed to the northeast and are apparently ancestral tributaries of the Qu'Appelle River (Figure 31).

Late Tertiary-Early Pleistocene valleys are generally steep walled and less than a mile in width. In contrast, Early Tertiary valleys are wider, gentler walled and flanked by Paleocene sediments. There are two lines of evidence for establishing a spatial relationship between Late Tertiary-Pleistocene geomorphic features and preservation of Paleocene coal basins: 1) the distribution of Paleocene sand-filled valleys and offset lignite seam geometries. Eroded to partially eroded Paleocene fluvial channels were traced by the geometry of adjacent lignite beds. Coal beds that are elongated along a Holocene valley suggest it as a successor to a Paleocene channel, so long as the seam front thins because of nondeposition rather than by subsequent erosion. Thick seam trends across a coalfield are interpreted to follow a major fluvial channel, whether or not the clastic equivalents are preserved, although they are in many cases.

Thus, a fluvial sand body, 15 to 30 m thick and approximately 60 m below the thickest of the Estevan coalfield seams, parallels the periphery of the coalfield and offsets the Estevan valley (Figure 33). The trends of thick lignite beds in the Wood Mountain and Willow Bunch coalfields are also parallel to 1) sand-filled channels within each seam basin and 2) channel fill of major rivers marginal to the coalfields. The general trend is to the southeast. One such Paleocene sand-filled channel, 8 to 16 km wide, is traceable in the coal-bearing section between the Wood Mountain and Coronach coalfields and lies parallel to the Holocene Poplar River valley. The adjacent beds of these coalfields thin laterally into fluvial clastic fills in the Ravenscrag Formation, towards the East Poplar River valley.

The Landscape to Fremington seams in the northern Coronach coalfield and Bengough coalfield similarly attenuate along the Big Muddy valley, as well as along a Ravenscrag fluvial sand trend between the coal beds and the present valley walls. Likewise, the Willow Bunch zone seams, the youngest in the coal measures (basin 4, Figure 1) front the southwestern flank of the Big Muddy valley. Projections of seam isopach trends support this relationship where minor erosion has cut back the face of the coal basins. Other examples are the Wood Mountain coalfield overlooking the Poplar River and the major southeasterly salient of the Coronach coalfield along the trend of Fife Lake-Long

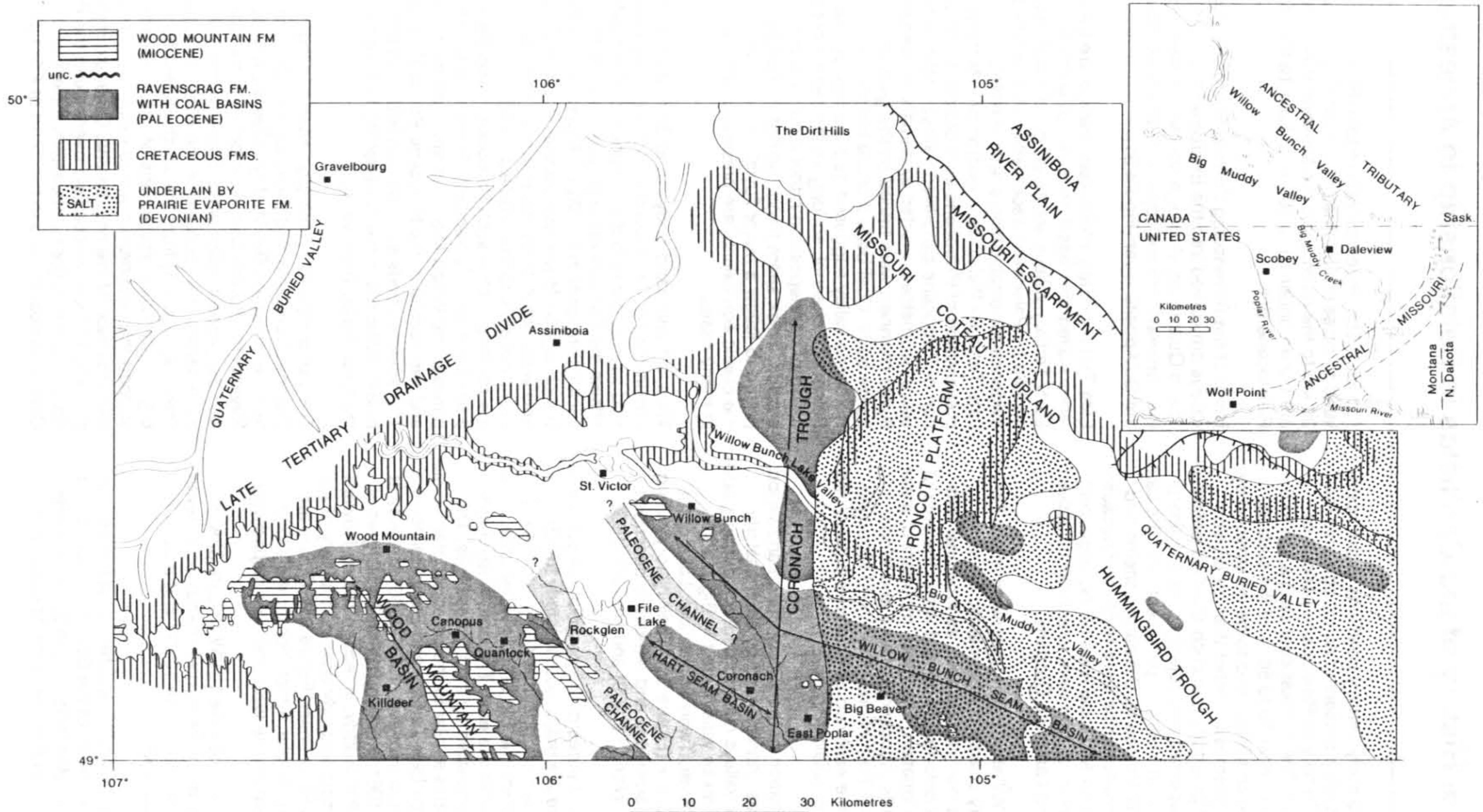


Figure 31 – Cenozoic paleogeography composite map for the Wood Mountain and Willow Bunch areas. Inset (upper right) is the trace of the ancestral Missouri River and its tributaries.

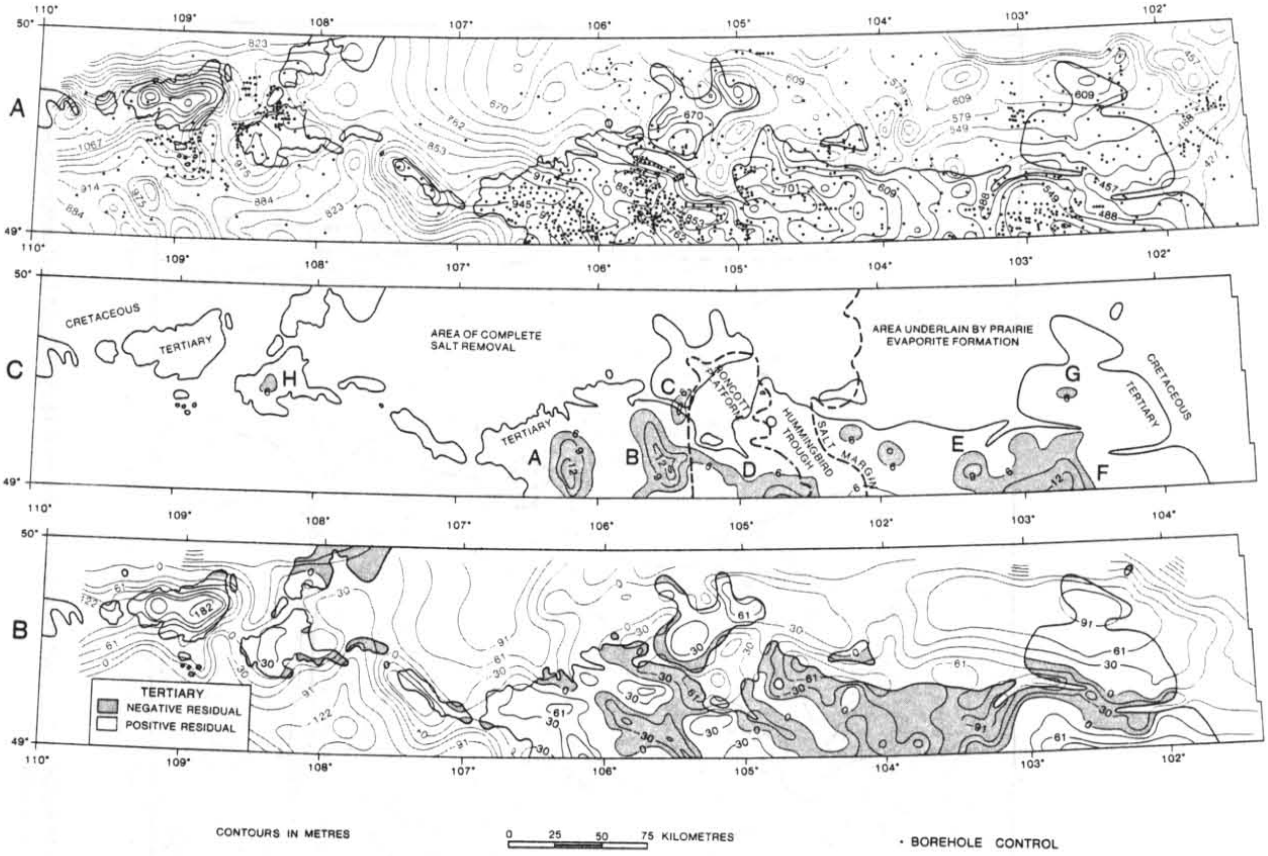


Figure 32 – A) Late Tertiary to Early Pleistocene bedrock topography across southern Saskatchewan. Contours in metres below surface. B) Simplified coal thickness map for the Ravenscrag Formation. Contours in metres. Major coal basins: A, Wood Mountain; B, southern Coronach Trough; C, northern Coronach Trough; D, Willow Bunch; E and F, Estevan. C) Residuals of the third-order regression surface.

Creek. The Estevan coalfield is restricted by the inner bow (southward) of the Estevan valley. An isopach map of the total coal thickness east of longitude 104°W delineates major areas of coal accumulation conforming to both sides of the Estevan valley (Figure 33). These beds, as typified by the Boundary and Estevan seams, thin depositionally towards the centre of this arc as well as towards the Estevan valley. Below the Estevan valley, however, there are no thick seams and total coal measurements reflect the cumulative effect of numerous very thin lignites.

Tectonic Controls, Glacial Ice Movements and Coalfield Preservation

The regional joint system overprinting cratonic lineaments controlled the drainage pattern of the ancestral Missouri River system. Thick seams in the Estevan coalfield are directed both along the reticulate fracture system and along the arcuate strike-front of the structural Williston Basin. This resulted in the course of the ancestral Missouri River along a bend conformable with a composite of underlying tectonic lineaments. This suggests that the Estevan valley was positioned above the break in the paleoslope between the limb of deeper basin area and the younger shelf.

In general, both the Estevan coalfield and the Estevan valley conform to structural embayments of the Williston Basin (i.e., the North Portal embayment of the Upper Devonian Torquay Formation and the Torquay embayment of the Early Mississippian Middle Bakken Formation. The arch between the two cratonic salients is thus interpreted to coincide with the confluence of the ancestral Yellowstone River and the ancestral Missouri River.

The catchment of the Late Tertiary Missouri River in southern Saskatchewan is approximately indicated by the preserved remnant of the Ravenscrag Formation east of the Cypress Hills. North of the Ravenscrag Formation erosional front, the Tertiary drainage was in the opposite direction and to the northeast.

The coalfields were largely protected from glacial advances by their alignment with tectonic features and the subsequent drainage patterns. Coarse clastics of the Wood Mountain Formation (Miocene) infilled troughs positioned above the Wood Mountain coalfield and, to a lesser extent, above the Willow Bunch coalfield. Structural subsidence in the northwestern Wood Mountain basin suggests salt solution collapse had continued intermittently from the end of the Paleocene until the Late

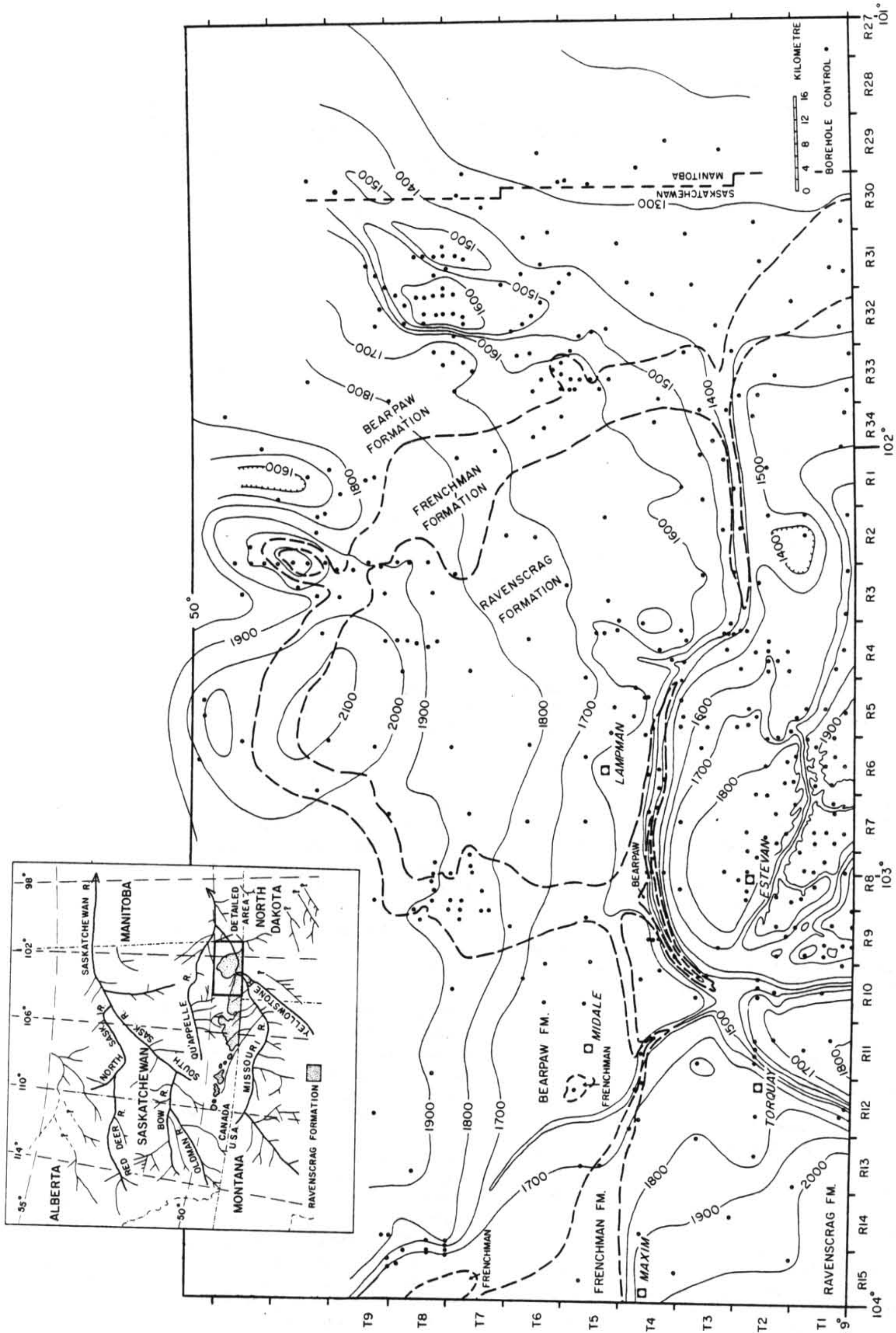


Figure 33 – Late Tertiary bedrock surface in the Estevan basin area. Contours in feet. Inset (upper left) shows drainage of ancestral Missouri and Saskatchewan Rivers across southern Saskatchewan.

Tertiary. Miocene gravels capping the coalfields helped to ensure preservation of the basins as positive physiographic features, protected from encroachment by the Late Tertiary entrenched drainage and the succeeding glacial advances. Each successive ice sheet advancing onto the Missouri upland was deflected by the Wood Mountain outliers along their less protected margins. Parizek (1964) notes that the margin of the initial and major glacial advance in the southwest of the Willow Bunch area was approximated by the line of the present Poplar River. The Coronach and Willow Bunch coalfields, although overrun by the first glacial advance, were nevertheless protected by remnants of Miocene gravels. The Wood Mountain uplands, on the other hand, were dominated by thicker gravels, and remained largely unglaciated across the centre of the coalfield. The Coronach trough may have survived by continued solution subsidence which carried it below the level of glacial scour. Parizek (1964) describes several end moraines that are apparently confined to the Coronach trough.

The Estevan coalfield is an outlier preserved from the effects of glacial advance by its alignment along the Estevan valley. There are 75 to 125 m of post-Ravenscrag sediments deposited peripheral to the coalfield, and upwards of 125 m of surficial sediment on the southern slope of Moose Mountain, compared to less than 6 m covering the Estevan coalfield. During glacial advances, the positive relief of the ancestral Moose Mountain deflected the ice sheets southeastward along the Estevan valley. The southern wall of the valley, 120 m high, acted as a barrier to southward ice advance, even though the northern bank was heavily gouged. Ice removed 30 to 60 m of Ravenscrag strata from the southern slope of Moose Mountain and all of the thick lignite seams north of the Estevan valley, and took 30 to 60 m off the height of the northern wall.

Conclusions

Subsidences in the Williston Basin throughout the Paleozoic and Mesozoic were marked by reactivation of Precambrian basement blocks along linears. Many of these northwesterly and northeasterly oriented fracture sets have been described for the northern Great Plains (Buller, 1958; Christopher, 1961; Kupsch and Wild, 1958; Kent 1974; Mollard, 1957a, 1957b, 1958; Robinson et al., 1969; Thomas, 1974).

The North American midcontinent crust behavior has been described as a series of block-like structures, bounded by deep-seated fractures and zones of weakness, with oscillatory movements of only a few metres for deformation (Adams, 1980). Other tilting block models with orthogonal fracture sets in the crust are discussed by Gay (1973) and Sbar and Sykes (1973).

Partial solution (dissolution) of the Middle Devonian Prairie Evaporite salt beds occurred along broad lineaments contiguous with the Hummingbird, Coronach, southern Wood Mountain basin (Rockglen - Killdeer troughs) and Shaunavon (Cypress) coalfields. These solution trends overprint or offset gravity anomalies of the craton.

Enhanced periods of salt solution subsidence and, by inference, movements of cratonic blocks were episodic events across the northern Williston Basin. Solution troughs were variously enlarged during hiatuses in the Paleozoic and Mesozoic, with resultant subsidence and syndepositional thickening at the surface. Major cycles of uplift, salt solution and syndeposition were associated with the Middle and Late Devonian, Late Mississippian, Late Cretaceous to Early Tertiary, and Late Tertiary.

Sloss and Speed (1974) modelled various cratonic movements relative to plate boundaries. Phases of salt solution subsidence may be related to cratonic emergence within both oscillatory tectonics and the dominantly submergent modes immediately preceding them. Late Mississippian to Early Jurassic and Late Cretaceous to Tertiary salt solution occurred in response to oscillatory uplifts in the craton (relative to sea level). Late Devonian and Late Jurassic to Early Cretaceous movements were of the more moderate submergent type. Various cratonic movements modelled by Sloss and Speed (1974) may have accompanied convergence of crustal plates. Subsidence in basins by progressive spread of block faulting across the craton from the margin would have resulted.

Near-correlative seams in all four of the major coal basins herein described in the northern Williston Basin indicate regional deceleration of cratonic subsidence. This would indicate some degree of linkage with salt solution activity, since coal basin geometry was defined by the former and individual coal bed geometry by the latter.

Salt solution subsidence prevailed in the western half of the study area, and has not been observed east of the Hummingbird trough despite the increased salt thickness. The reason for this is by no means certain, but proximity to the cratonic depocentre may be important. Coincidence of the Hummingbird Trough with the Nemo-Estes gravity trend suggests its importance as a hinge line between uplifted salt solution modified zones to the west and unaffected stable salt platform to the southeast.

Significance Of This Study

Coal swamp deposits have been traditionally associated with surficial processes, and often only indirectly related to regional tectonic framework. Study of coal accumulation has been generally considered in the context of fluvial processes, with only brief reference to paleogeography. Controls on sedimentation are typically envisioned as local, and are generally related to such events as distributary channel abandonment or flooding of inactive depositional lobes. Sediment distribution systems are generally viewed as a network of comparatively restricted channels with localized accumulation of mud, sand and peat.

Regional basin analysis with adequate subsurface control is comparatively less common. Such studies in Carboniferous and Permian coal basins have illustrated the importance of understanding the regional tectonic framework on stabilizing coal swamps. Distribution patterns of facies are useful in evaluating the influence of broader tectonic controls on basin subsidence. Studies of facies in coal basins, such as those associated with the Mississippian-Pennsylvanian interval of North America, have related the local accumulation and preservation of coal beds to underlying intracratonic subsidence. Accumulation of thick coal beds has usually been related to a single tectonic influence, such as, diminished subsidence of a fault-block basin along a coastal margin or a cratonic depocentre that has yielded to the weight of the sedimentary column.

The Williston Basin, in contrast, has a dynamic tectonic framework consisting of two variables related by an underlying larger scale influence. The local variables were downwarping of the craton and the effects of the salt solution activity. These two modes of subsidence had effects on coal accumulation both independently and in concert, but their interplay was related to the ubiquitous control of movements between Precambrian blocks. This underlying crustal control ultimately affected the geometry and distribution of coal beds in conjunction with one or both of the other more localized forces. Net subsidence of the northern Williston Basin was diminishing at a constant rate, but the relationship between crustal lineaments and the two subsidiary components of the tectonic framework varied with time. Their interplay provides an opportunity to resolve the effects of three components on evolving coal basin geometries and between subbasins and regional basin evolution. The shape of a subbasin with thick coal beds corresponds to the underlying zone of salt solution collapse activity, whereas geometries of the coal (and sand) bodies within such basins are more sensitive to the pattern of crustal lineaments.

Salt solution troughs were essentially closed basins that favoured vertical stacking of facies. Vertical variation of lithofacies can be used as a measure of changes in basin subsidence, for comparisons from one subbasin to another (or interbasin areas), and to understand the interplay of tectonic parameters. This research suggests that intermittent periods of excess sediment influx were coordinated with pulses of salt solution activity that resulted in sand concentration above solution-collapse zones. This implies a relatively rapid rate of subsidence that was punctuated by periods of sufficiently diminished net subsidence for the accumulation and preservation of thick coal beds. Paucity of thin coal beds in coal basins above salt collapse zones, compared to interbasinal areas and the cratonic coal basins (unaffected by salt solution), suggests that rapid alternations of coal-forming conditions with brief periods of moderate subsidence were more commonly associated with the basin margins. Fewer cycles of longer duration (thick coal–sand–thick coal) were favoured towards centres of subsidence.

Larger scale, regional processes such as oscillatory intracratonic movements, associated with eustatic changes of sea level, would tend to favour an equal number of coal/noncoal transitions, regardless of thickness, across the entire Williston Basin, in addition to an increase in the average thickness of each cycle towards centres of greater net subsidence. However, in the Williston Basin, the thickness of each cycle increases while the total number decreases at subsidence centres without an appreciable change in the total thickness of the strata. This suggests that the infilling of coal basins with clastics was regulated by the movements of the underlying tectonic lineaments in such a way as to maintain equilibrium between loading and subsidence in areas of active salt solution.

Because there was a persistent progradation of younger coal basins towards the cratonic depocentre (and thus constant deceleration of cratonic subsidence), excess sediment influxes were balanced by rejuvenation of the down-faulted salt solution troughs. If salt solution activity was independent of sediment supply, significant marine transgressions would have been expected.

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