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Sequence Stratigraphy of the Lower Cretaceous Mannville Group of East-Central Alberta

BY

Don A McPhee ©

A THESIS SUBMITTED TO THE FACULTY OF
GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

FALL, 1994

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42 Edgedale Crt.,
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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **SEQUENCE STRATIGRAPHY OF THE LOWER CRETACEOUS MANNVILLE GROUP OF EAST-CENTRAL ALBERTA**, SUBMITTED BY DON A MCPHEE IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Dr. S. George Pemberton - Supervisor

Dr. B. Jones

CR Stelck
Dr. C.R. Stelck

G E Ball
Dr. G.E. Ball

Date: July 4, 1994.

Abstract

The Mannville Group is subdivided into a lower "Transgressive Systems Tract" and an upper "Highstand Systems Tract" at the transition from dominantly retrogradational to progradational stratal geometry. On both of these systems, transgressive/regressive cycles are superimposed.

The "Transgressive Systems Tract" is subdivided by three major flooding events. The initial flooding event is associated with the transgression of the Boreal Sea during which time paleo-valleys on the sub-Cretaceous unconformity were filled with fluvial deposits. The flooding of broad fluvial plains formed broad embayments separated by a chain of north-northwest trending Paleozoic highlands. Embayments on the western side of the Paleozoic Highs and closer to the foredeep of the foreland basin were more sediment-starved compared to those on the east. The flooding event was followed by a major drop in sea-level contributing to deep incision. The second flooding event transformed incised valleys into long estuaries which later formed broad estuaries as sea-level continued to rise. During the relative still-stand of the sea, the progradation of the shoreline results in the deposition of a widespread, 10 to 15m thick, sandstone sheet. The third flooding event marks the time of maximum transgression, during which an open marine environment covered the northern half of the Alberta Foreland Basin.

The "Highstand Systems Tract" is subdivided by at least six major flooding events. Between each flooding event, three distinct lateral components are generally recognized. In the south, each succession generally consists of a 15 to 25 m thick, upward-shoaling, muddy to sandy facies often capped by a thin 0.5 to 2 m thick coal. This part of the succession may extend over a distance of 300 km before rapidly translating to the northwest into a 20 to 40 m thick, clean, blocky sandstone forming linear, 20 to 100 kilometre wide bands, trending northeast -southwest. The blocky sandstone bands gradually translate to the northwest, over 20 to 30 kilometres, into a laterally extensive mud dominated successions containing laterally extensive thin sandstone stringers.

The thicker, blocky sandstone bands occur along and to the northwest of the Snowbird Tectonic Zone (STZ). Relative to the STZ, lowstand incision is prevalent to the south but difficult to recognize to the northwest. The STZ marks the southeastern limit of Precambrian basement subsidence associated with the collapse of the Peace River Arch during the Lower to Upper Cretaceous. Accommodation space, formed during each flooding event, was a function of both relative sea-level rise and basement subsidence. Southeast of the STZ, accommodation space was primarily a function of relative sea-level rise whereas to the northeast, accommodation space was a function of both relative sea-level rise and basement subsidence.

During the stillstand, following each transgressive phase, the rate of shoreline progradation slowed or stoped as it advanced towards the STZ, a region of greater subsidence. A stacked shoreline sandstone evolved while the coastal plain was incised by shallow fluvial systems. If sea-level dropped or sediment input increased, the shoreline moved seaward with an increase in the depth of regional incision. If sea-level rose, a stranded barrier system may have been localized along the former shoreline position with an extensive brackish /marine lagoon formed behind it. Analysis of the cross-section data, supports a cycle of sea-level rise, standstill and sea-level fall. The area to the south of the STZ was dominated by shallow, marine to brackish, lagoonal environments while the area to the north was dominated by deeper marine environments.

Acknowledgements

To George Pemberton, my aunt Sister Catherine McPhee, Mike Ranger, Tim Berezniuk, Marion Sinclair, Irena Shetson, Grant Mossop, Dave Lawson, Joclyne Legault, Jan Boon, Brian Zaitlin, Ian McInraeth, Mike Watson and my family, I owe a staggering debt of gratitude. Thanks George, Dave and Sister Catherine for your trust in my ability to return when I would wander down dark forbidding allies.

To my Grandmother, Mary Ann MacIssac, a Celtic Lady from a culture rapidly fading from Cape Breton, Nova Scotia, I thank for the push as a small boy.

Beyond moral support, this study was made possible by financial support from: the Alberta Oil Sands Technology and Research Authority through George Pemberton; the Alberta Research Council through Irena Shetson and Grant Mossop; and PanCananadian Petroleum Limited through Ian Mcinrath and Brian Zaitlin.

As a kid, I would occasionally accompany my father to the Port Hood Co-op. Usually, we would drop in on the Manager, Alex Rory MacKillop. The Manager's desk covered with notes, bills and pencils reflected his load in servicing a widespread rual district. Yet the stern eyes of this man never reflected impatience but rather calm and welcome. Many years later I was honored to meet a similar gentleman in the name of Dr. George Pemberton, my supervisor.

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CS 1 part A	Stratigraphic cross-section along east side of Wainwright Ridge from Township 94, Range 21W4 to Township 40, Range 1W4; facies distribution shown in relation to the Gamma Ray log.
CS 1 part A	Stratigraphic cross-section along southwest side of Wainwright Ridge from Township 40, Range 1W4 to Township 63, Range 21W4, then progressing across the Wainwright Ridge to Township 72, Range 6W4; facies distribution shown in relation to the Gamma Ray log.
CS 2	Schematic stratigraphic cross-section condensed directly from cross-sections CS1 part A and part B.

1 Introduction

1.1 Purpose, scope and study area

This study is a re-interpretation of stratal elements that reflect fourth to fifth order phases of regional deposition, which comprise the Lower Cretaceous Mannville Group in the study area extending from Township 40 to 100 between the fourth and fifth meridians in Alberta (Figure 1). The aim of this study was to provide a grid of stratigraphic cross-sections to be a reference framework and context for understanding the lateral and vertical distribution of facies comprising the Lower Cretaceous Mannville Group. In addition to the grid, the regional distribution of each fourth order phase of deposition and the associated flooding event is mapped. A database of geophysical well logs from more than 3000 wells forms the foundation of this study. Core was examined to confirm the interpretion of measured geophysical properties including radiation, electric and sonic.

1.2 Previous work on the stratigraphy of northeast and east-central Alberta

Within the study area many authors have attempted to resolve the riddle of the siliciclastic Lower Cretaceous Mannville Group of northeastern and east-central Alberta (McConnell, 1893a and 1893b; McLearn, 1917; Nauss, 1945 and 1947; Wickenden, 1948, 1949 and 1951; Hume and Hage, 1949; Layer *et al.*, 1949; Hunt, 1950; Loranger, 1951; Stelck *et al.*, 1956; Glaister, 1959; Williams, 1960 and 1963; Carrigy, 1959, 1963 and 1966; Clack, 1967; Mellon, 1967; ERCB, 1973; Jardin, 1974; Kramers, 1974; Williams and Stelck, 1975; ERCB, 1976; Cartier, 1976; Flach, 1977; James, 1977; Vigrass, 1977; Orr *et al.*, 1977; Keeler, 1978; Nelson and Glaister, 1978; Gross, 1980; MacCallum, 1981; Haidl, 1984; Smith *et al.*, 1984; Wightman and Bereznuik, 1985; Kramers, 1986; McPhee, 1986; Keith *et al.*, 1987; MacGillivray *et al.*, 1989; Fox, 1988; Mattison, 1988). Most of these authors have subdivided the succession on the basis of lithologic variation and microfossil data rather than on the recognition of surfaces reflecting relative sea-level change. Their interpretations, based on both outcrop and borehole data from five widely separated areas (Figure 1) (Fort McMurray, Wabasca, Cold Lake, Lloydminster and Edmonton), has resulted in three distinct lithostratigraphic subdivisions (figure 2).

In the Fort McMurray region (T 89, R 9W4M), three formations have been defined and include, in ascending order, the McMurray, Clearwater, and Grand Rapids formations. In the Lloydminster area (T 50, R1W4M), nine members are recognized and include in ascending order: the Dina, Cummings, Lloydminster,

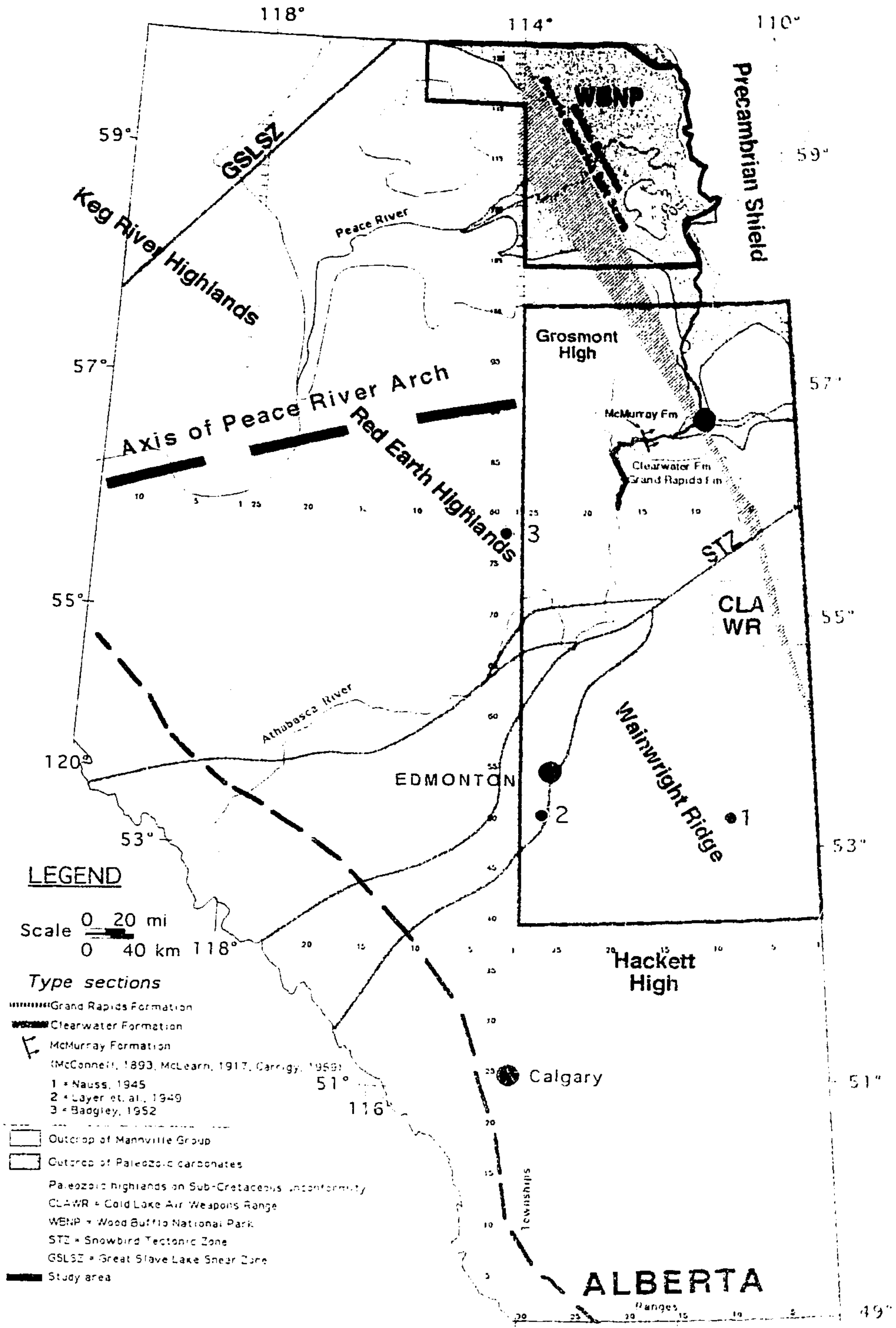

FIGURE 1 Study area shown in relation to sub-Cretaceous Highs, Precambrian basement faults, and outcrops of the Mannville Group, Paleozoic strata and the Precambrian Shield (modified from: Rudkin, 1964; Green, 1972, Ross and Stephenson, 1989; Leckie and Smith, 1992; Ranger, 1994).

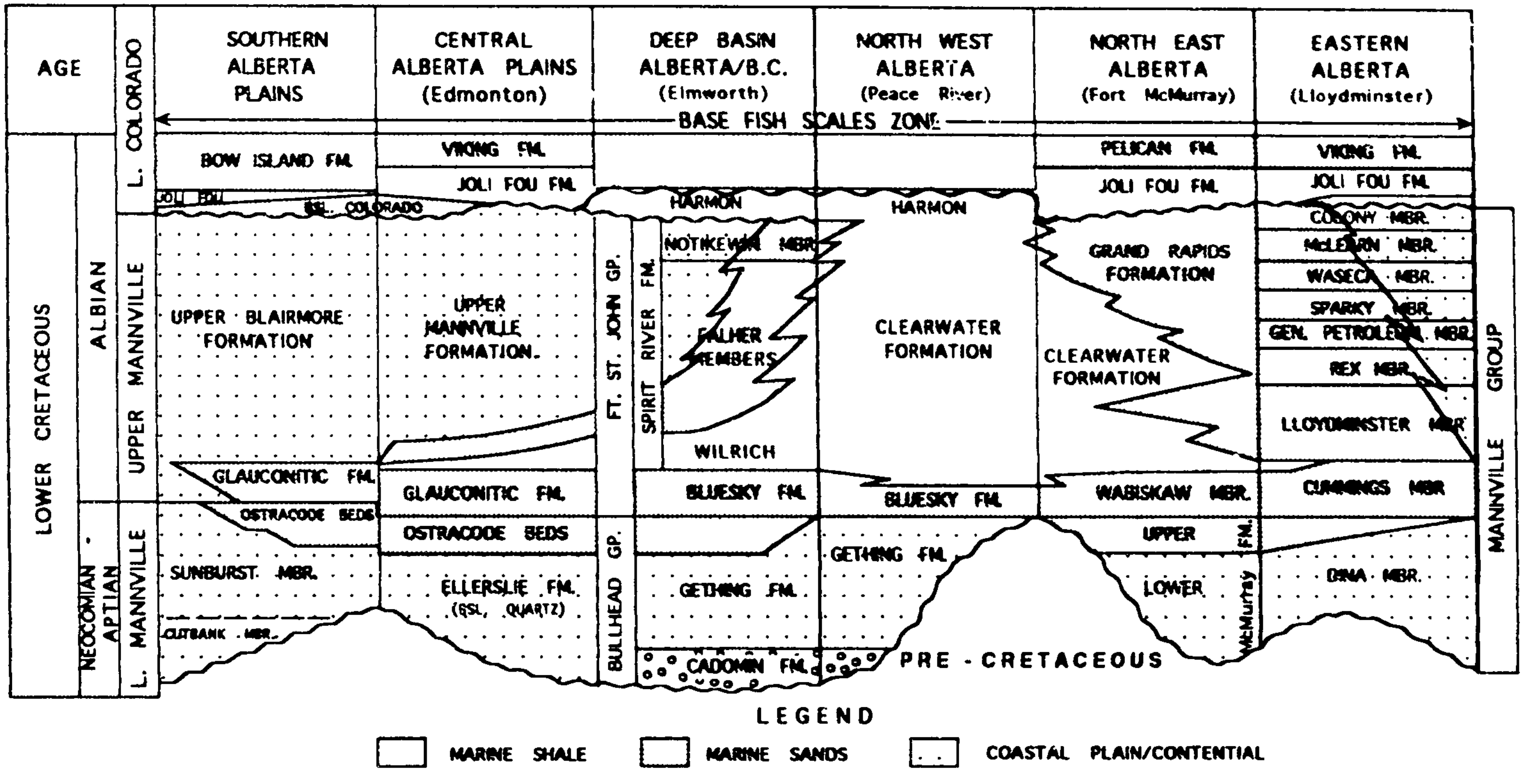

Figure 2 Regional stratigraphy of the Lower Cretaceous in Alberta (modified from Jackson, 1984).

Rex, General Petroleum, Sparky, Waseca, McLaren, and Colony. In the Edmonton area (T 52, R 24W4M) five units are recognized and include in ascending order: Deville Formation, Ellerslie Formation, Ostracode Member, Glauconite Formation and the Upper Mannville Formation.

The stratigraphic nomenclature applied to northeastern Alberta has evolved from outcrops along the banks of the Athabasca River between Townships 83-87 (Figure 1). McConnell (1893), on the basis of lithology, subdivided the succession into three formations and assigned the names in ascending order; 'Tar Sands', 'Clearwater Shale' and 'Grand Rapids Sandstone'. At the head of Grand Rapids, McConnell (1893) described the Grand Rapids Sandstone as consisting of fifty feet (15.2m) of soft yellowish almost homogeneous sandstone, packed thickly with nodules, and weathering into almost vertical cliffs. Resting on this is about 100 feet (30.5m) of alternating sandstone and shales, then fifty feet (15.2m) of greyish and yellowish sandstone overlain by a seam of lignite four to five feet (1.2 to 1.5m) thick, above which comes the flaky Pelican shale. Note was made of beds of fine-grained conglomerate, of which a small bed of ferruginous conglomerate lies between the Grand Rapids sandstone and the overlying Pelican shale. The "Clearwater Shale" estimated to be 83.8m (275 ft.) thick, (at the outcrop 4.8 km (8 miles) downstream from Grand Rapids at Pointe La Biche [Tp. 86, R. 18, W. 4th Mer.]) consists of dark and lead grey shales and clays, a considerable proportion of greyish sandstone, greenish glauconitic sandstone and ironstone. In 1917, McLearn raised both the 'Grand Rapids Sandstone' and the 'Clearwater Shale' to formation status. McLearn (1917) proposed the name "McMurray" Formation for the bituminous sands underlying the Clearwater Formation and overlying the sub-Cretaceous unconformity, and defined the upper limit at the base of a green sandstone, the basal unit of the Clearwater Formation. In 1952, Badgley introduced the term "Wabiskaw" Member for the the 'green sandstone' occurring at the base of the Clearwater Formation.

The stratigraphic nomenclature applied to the Mannville Group of the Lloydminster region has evolved through a complex history of terms introduced by drillers and through scientific papers. Terms for the members above the Cummings Member are drillers words accepted by the oil industry. The Mannville Group as noted above is informally subdivided into nine units based on lithological variations defined by petrophysical log characteristics (Vigrass, 1977; Orr *et al.*, 1977). Both Vigrass and Orr *et al.*, (1977) use the same nine informal stratigraphic subdivisions except that Vigrass called them members whereas Orr *et al.*, (1977) refer to them as formations. Only the Dina and Cummings have been formally described (Nauss, 1945, 1947). The terms Colony, Sparky, Rex and Lloydminster were referred to prior to Nauss's published account of nomenclature (Edmunds, 1948). Later, oil field workers separated the General

Petroleums from the Sparky sandstone (Kent, 1959). Still later, industry began to restrict usage of "Colony" to only the uppermost sandy cycle of the Mannville rather than applying it to all the Mannville strata above the Sparky. Industry adopted the term "McLaren" and "Waseca", where applicable only in field areas east of Lloydminster, for the sandy cycle below the restricted Colony sandstone (Fuglem, 1970).

In 1945, Nauss, on the basis of drill core, established a lithostratigraphic subdivision for the Lower Cretaceous succession at Vermilion (1-18-50-8W4) based on the presence or absence of dark minerals in the sands, the rounded, frosted, and well sorted character of the quartz sands, and on microfauna. He subdivided the succession in ascending order into the Dina, Cummings, Islay, Tovell, Borradaile, and O'Sullivan Members.

With regard to the Lower Cretaceous strata exposed along the Athabasca River, Nauss (1945), on the basis of stratigraphic position and lithology, suggested that the Dina member was an equivalent of the McMurray Formation and that the Cummings member was a wedge edge of the Clearwater shale. Wickenden (1949) suggested that the Islay Member and all those above it were equivalent to the Grand Rapids Formation along the Athabasca River.

Nauss (1945, 1947) applied the name "Mannville" Formation to the subsurface Lower Cretaceous sandstone-shale succession resting unconformably on Devonian dolomites and conformably underlying the Joli Fou shale (Lloydminster shale, Nauss, 1945). He regarded the contact between the Mannville Formation and the overlying Joli Fou shale to be conformable. Later this contact was regarded as disconformable by: Badgley (1952), Stelck (1958) Mellon (1967), Christopher (1974), and Vigras (1977). Wickenden (1948) extended the Mannville Formation to the Lloydminster area. His attempt to apply the subdivision proposed by Nauss met with indifferent success and instead he proposed dividing the Mannville into a basal or lower division of continental origin, a middle division with marine attributes, and an upper division which is largely continental. In 1952, Badgley published the first comprehensive regional correlations of the Lower Cretaceous section of Central Alberta and raised the Mannville to group status to include the McMurray, Clearwater, and Grand Rapids Formations.

The Mannville Group in the Cold Lake area, in addition to being referred to by the stratigraphic subdivisions of the Fort McMurray and Lloydminster regions, is informally referred to in descending order as the A, B, C, and D units (Vigrass, 1966). Clack (1967) correlated the 'A' and 'B' units with the Grand Rapids Formation and the 'C' and 'D' units respectively with the Clearwater and McMurray formations as defined by Williams (1960, 1963) in the Edmonton area.

In central Alberta, the Mannville Group is subdivided in ascending order into the Deville (Detrital) Formation (Badgley, 1952), Ellerslie (Basal Quartz) Formation (Hunt, 1950), Calcareous Member (Glaister, 1959), Glauconite Formation (Layer *et al.*, 1949; Glaister, 1959), Clearwater Formation, and the undifferentiated Upper Mannville Formation (Glaister, 1959). The Calcareous Member, defined for a lithostratigraphic interval, is more commonly referred to in industry as the Ostracode Zone (Hunt, 1950; Loranger, 1951), a term originally designated as a biostratigraphic zone. Farshori (1983) redefined the Calcareous Member of Glaister (1959), renaming it the Ostracode Beds to include the Bantry Shale and the Ostracode Limestone of the Ostracode Zone and Calcareous Members. The Upper Mannville Formation of Glaister (1959) includes the succession between the top of the Calcareous Member and the base of the Colorado Group. The Clearwater Formation (McConnell, 1893; McLearn, 1917) wedges-out south of Township 50, Range 1 west of the 5th Meridian.

1.3 Stratigraphic setting

The Mannville Group of eastern Alberta forms the distal part of a northeastward tapering wedge of Aptian to Middle Albian strata deposited in a foreland basin (Figure 3 and 4) formed by tectonic activity along the Columbian orogenic belt. Deposition of detritus was influenced by the topography of a deeply eroded surface of Early Cretaceous to Paleozoic beds, the southward transgression of the Boreal Sea, local basement subsidence of the Peace River Arch, and salt solution of Middle Devonian evaporites.

The Mannville Group and stratigraphic equivalents form the second of four clastic wedges deposited in the Alberta Foreland Basin (Cant, 1989). The development of the foreland basin is linked to the accretion of displaced terranes onto the Pacific margin of the North American continent between the Middle Jurassic and Early Tertiary. Tectonic shortening and thickening of the crust, by imbrication and tectonic progradation of the thrusted slices of the older miogeocline over the craton margin, resulted in flexural depression of the lithosphere in the foreland adjacent to the deformed belt (Price, 1973; Beaumont, 1981) (Figure 3). The topographic relief of the thrust sheets and concomitant erosion also generated great volumes of sediment, which were shed into the foreland basin. The tectonics of terrane accretion therefore controlled not only basin subsidence, but also the supply of sediment.

The form of the foreland basin was also influenced by the tectonics of deep seated basement structures and evaporite dissolution. The crystalline basement in Alberta is segmented by two major northeast trending crustal discontinuities: the Snowbird Tectonic Zone in central Alberta and the Great Slave

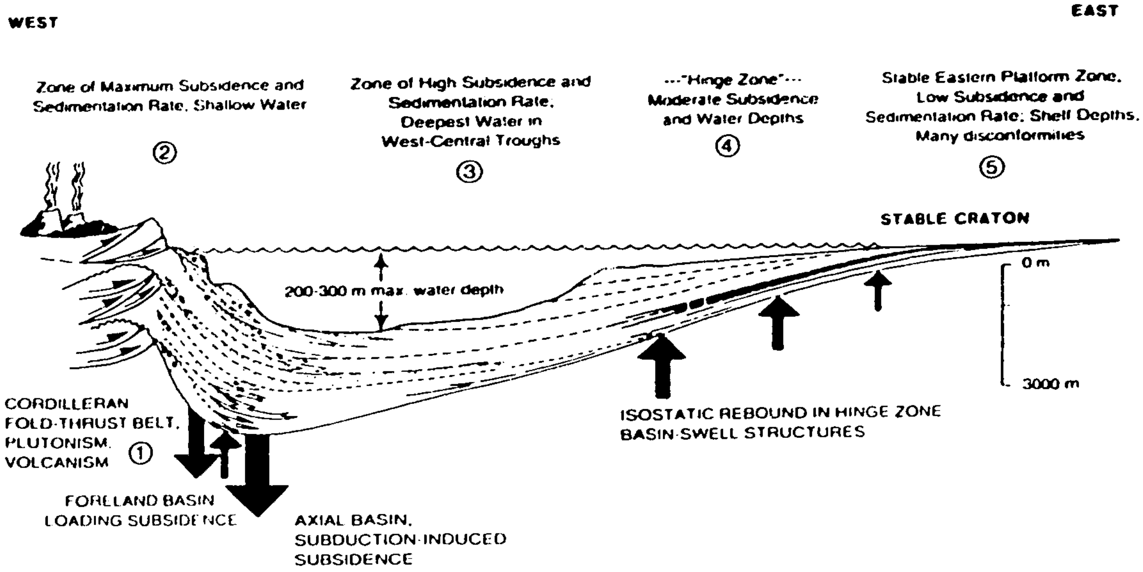

Figure 3 Idealized structural and stratigraphic cross-section across the Western Canada foreland basin at a time of maximum transgression. The positions, directions, and sizes of arrows indicate relative thrusting, subsidence, and uplift (rebound). The numbers in circles refer to the major components described in the text (modified from Kauffman, 1984).

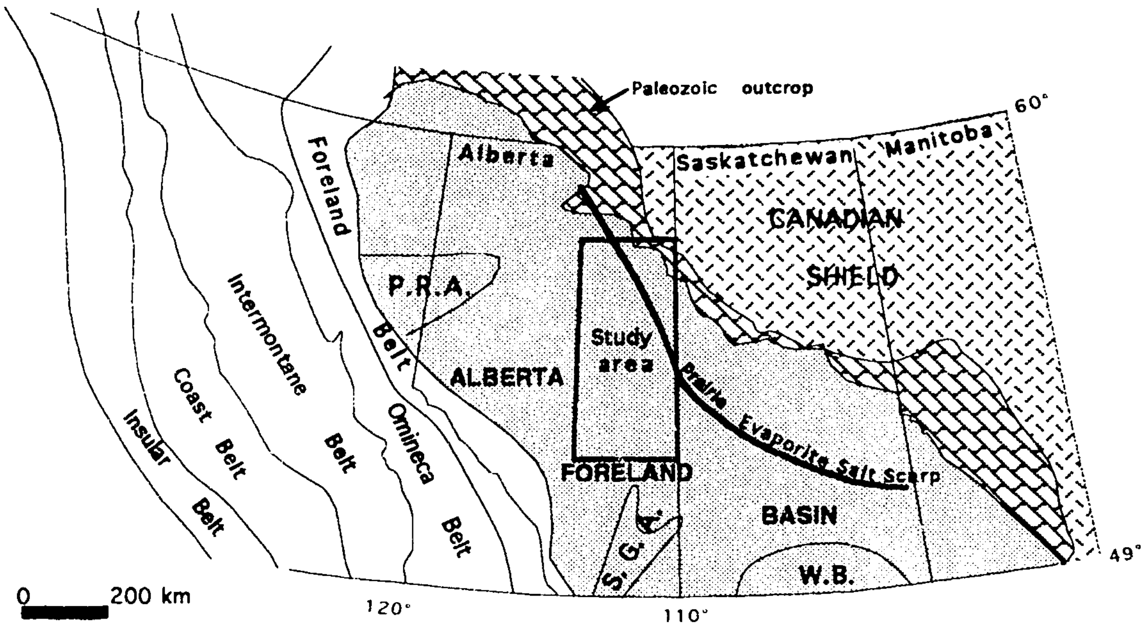

Figure 4 Tectonic setting of the study area (modified from Cant, 1989) (S.G.A. = Sweet Grass Arch; W.B. = Williston Basin; P.R.A. = Peace River Arch)

Lake Shear Zone in northern Alberta, both of which can be traced into the Canadian Shield (Figure 5) (Ross & Stephenson, 1989). The foreland basin is divided internally by two large basement structures which originated in the Paleozoic, but still affected sedimentation in the Cretaceous. These structures, the Peace River and Sweetgrass arches (Figure 4) moved upward and downward, perhaps in response to thrust loading in the Cordillera. Maximum thickening of the Upper Mannville Group occurs between the Snowbird Tectonic Zone and the Great Slave Lake Shear Zone with maximum thickening occurring over the axis of the subsiding Peace River Arch (Figure 6). Both shear zones may have controlled the extent of the subsidence of the crystalline basement resulting from tectonic compression during the Columbian Orogeny.

Subsidence of the passive margin due to thermal contraction during Middle Cambrian to Middle Jurassic time (McKenzie, 1978; Bond & Kominz, 1984) led to the westward tilting of the overlying Paleozoic succession. Westward tilting was associated with the westward migration of the eastern limit of Paleozoic seas from late Devonian to Triassic time. Erosion of Devonian strata adjacent to the Canadian Shield initially led to the exposure and dissolution of Middle Devonian evaporites (Figure 7). Continuing dissolution by the downdip migration of groundwater led to extensive subsurface evaporite removal. Within the study area, the collapse of strata overlying the site of salt removal has contributed to the development of a monoclinal structure (Figure 8). The reversal of regional dip of the monoclinal limb corresponds to the dissolution scarp of the Middle Devonian Prairie Evaporite Formation. Dissolution scarps of the thinner, Middle Devonian Cold Lake and Upper Lotsberg salts are offset further to the east in Saskatchewan. From Late Devonian to the present, the maximum thickness of salt removed from the three evaporite units is 400 metres. A maximum thickness of 175 metres was removed from along the Prairie Evaporite Salt Scarp (Figure 9). During the Laramide Orogeny, a maximum thickness of 75 metres was removed form along the Prairie Evaporite Salt Scarp (Figure 10).

The Mannville succession was deposited on an erosional surface resulting from flexurally generated erosional episodes related to the interplay of passive margin subsidence, thrust loading, and evaporite dissolution. Differential erosion of various shelf lithologies (Paleozoic to Jurassic subcrops) resulted in a north-northwest trending ridge and valley system roughly parallel to the axis of the foreland basin (Figure 11). To the west of the Prairie Evaporite Salt Scarp, resistant carbonate units between less resistant units formed ridges with relief up to 100m (Rudkin, 1964; Christopher, 1980). During deposition of the Lower Mannville succession, these ridges remained exposed, supplied sediment and localized shoreline sand bodies. Along the northeast and southeastern part of the foreland basin, the increased thickness of the Lower

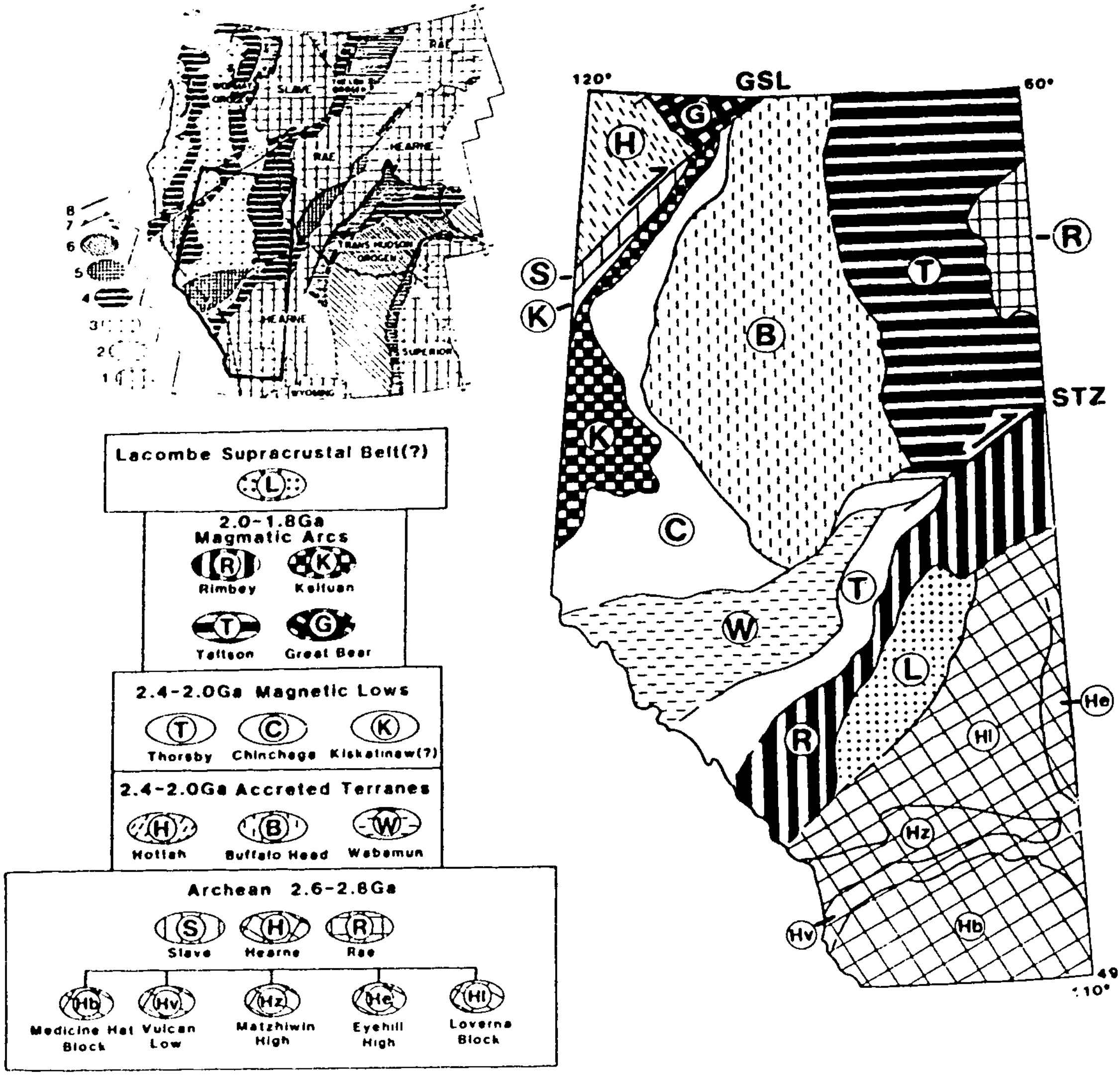

Figure 5 Map of tectonic domains postulated in the basement of Alberta. The outline of the domains corresponds to aeromagnetic boundaries. Ages for each domain are based on U/Pb zircon and monazite geochronology. Key for inset: 1. Archean (>2.6 Ga); 2. reactivated Archean crust; 3. Early Proterozoic (2.4-2.1 Ga) crust; 4. 1.97-1.81 Ga magmatic arcs; 5. crustal blocks of uncertain age along Snowbird tectonic zone; 6. juvenile Proterozoic (1.91-1.85 Ga) crust; 7. edge of Cordilleran deformation; 8, edge of Phanerozoic cover (modified from Ross and Stephenson, 1989).

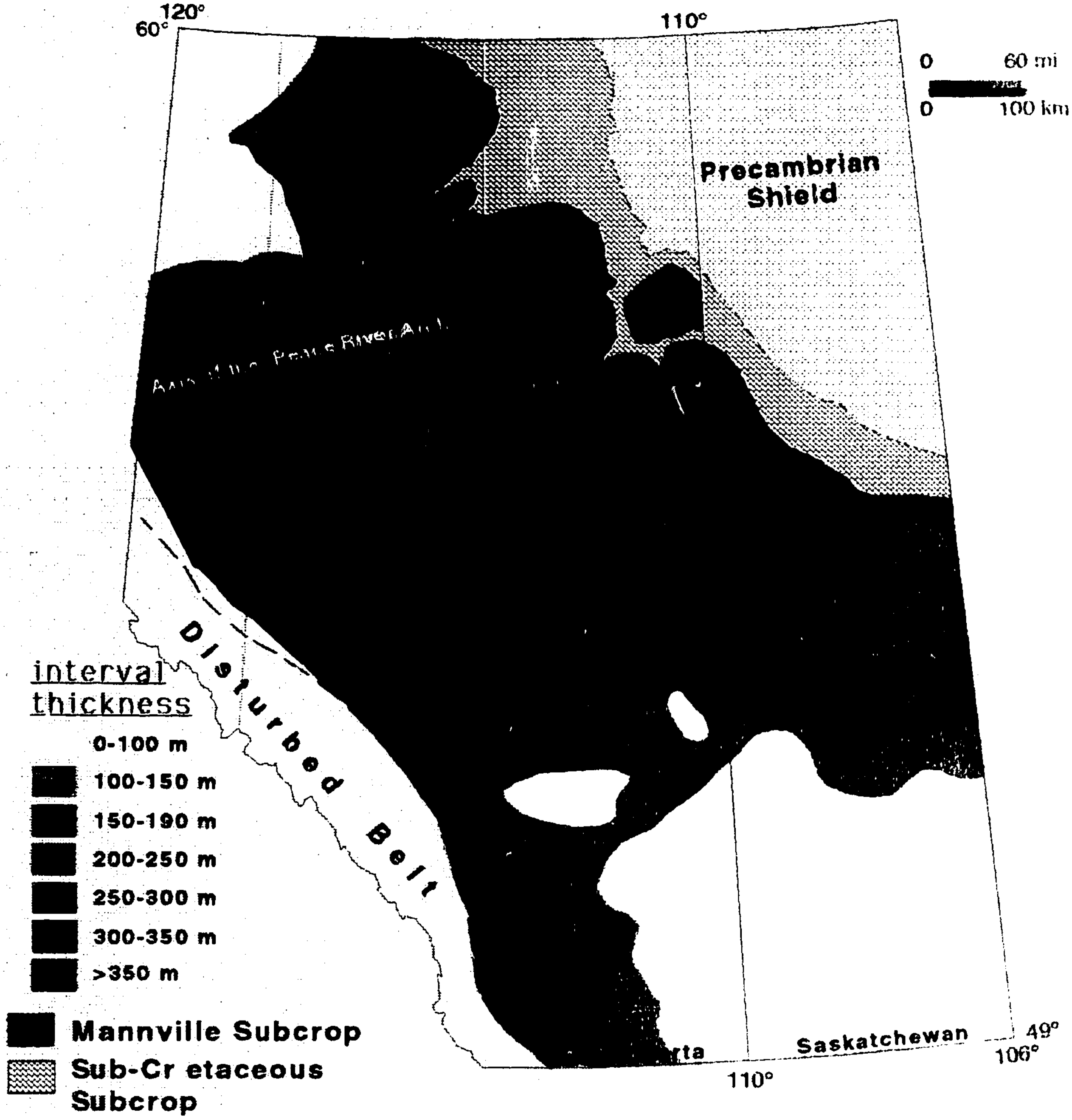

Figure 6 Isopach of the Lower Cretaceous Upper Mannville sub-group showing subsidence along the axis of the Peace River Arch

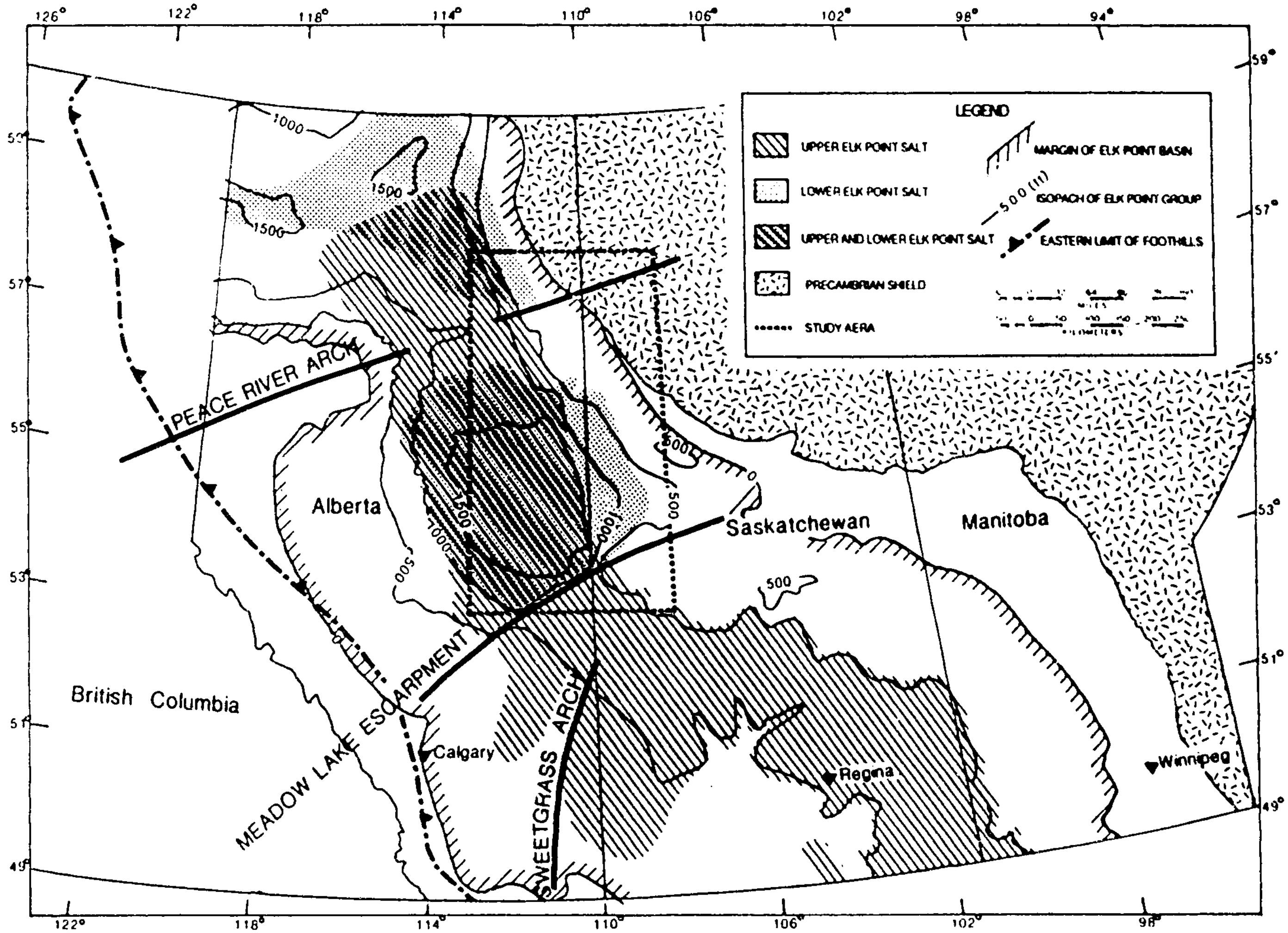

Figure 7 Isopach of the Elk Point Group in the Prairie Provinces, with distribution of salt in the lower and upper Elk Point Subgroups (modified from Hamilton, 1971).

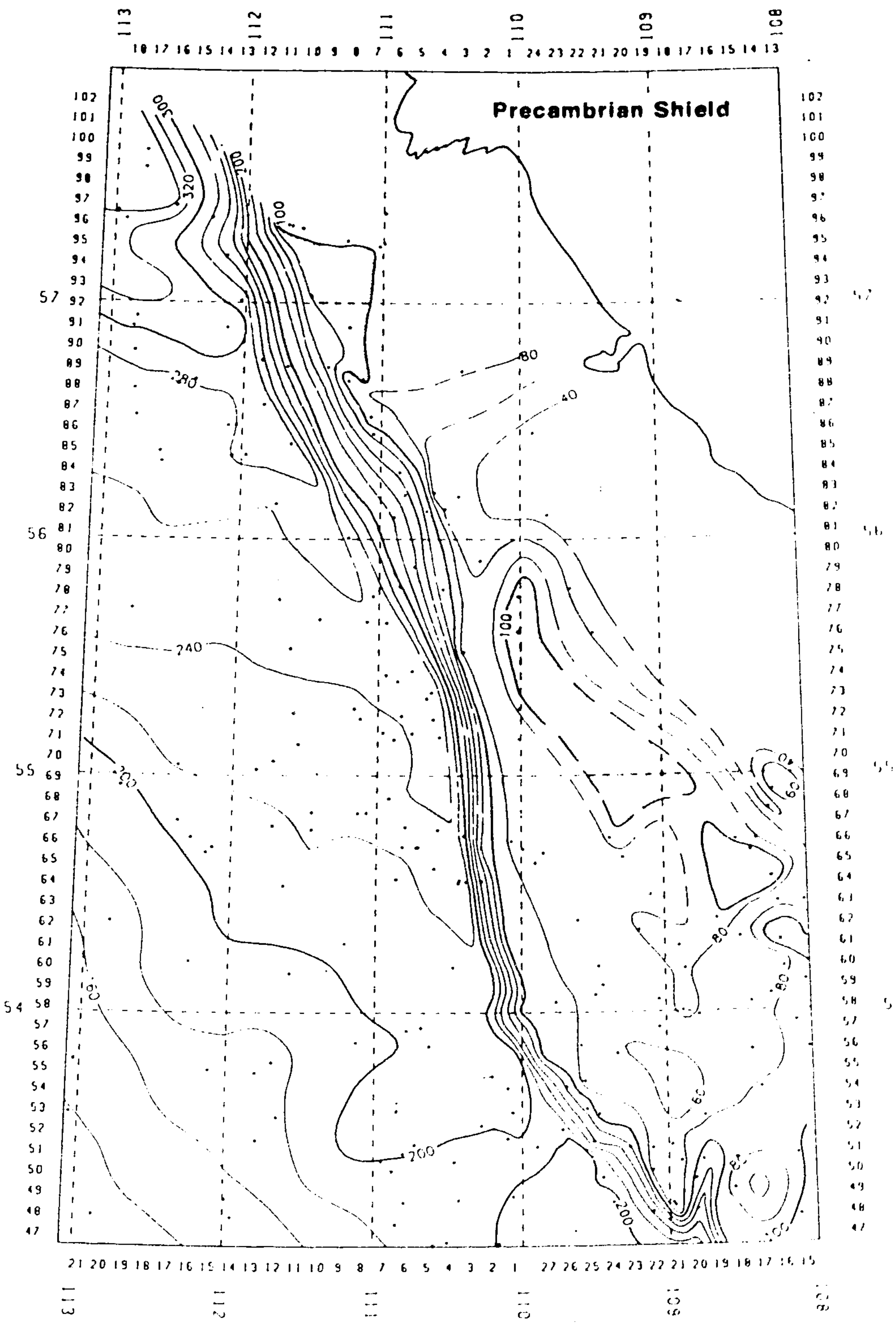

Figure 8 Structure on the Middle Devonian Elk Point Group with the closely spaced contours outlining the dissolution scarp of the Prairie Evaporite Formation. (contours in metres)

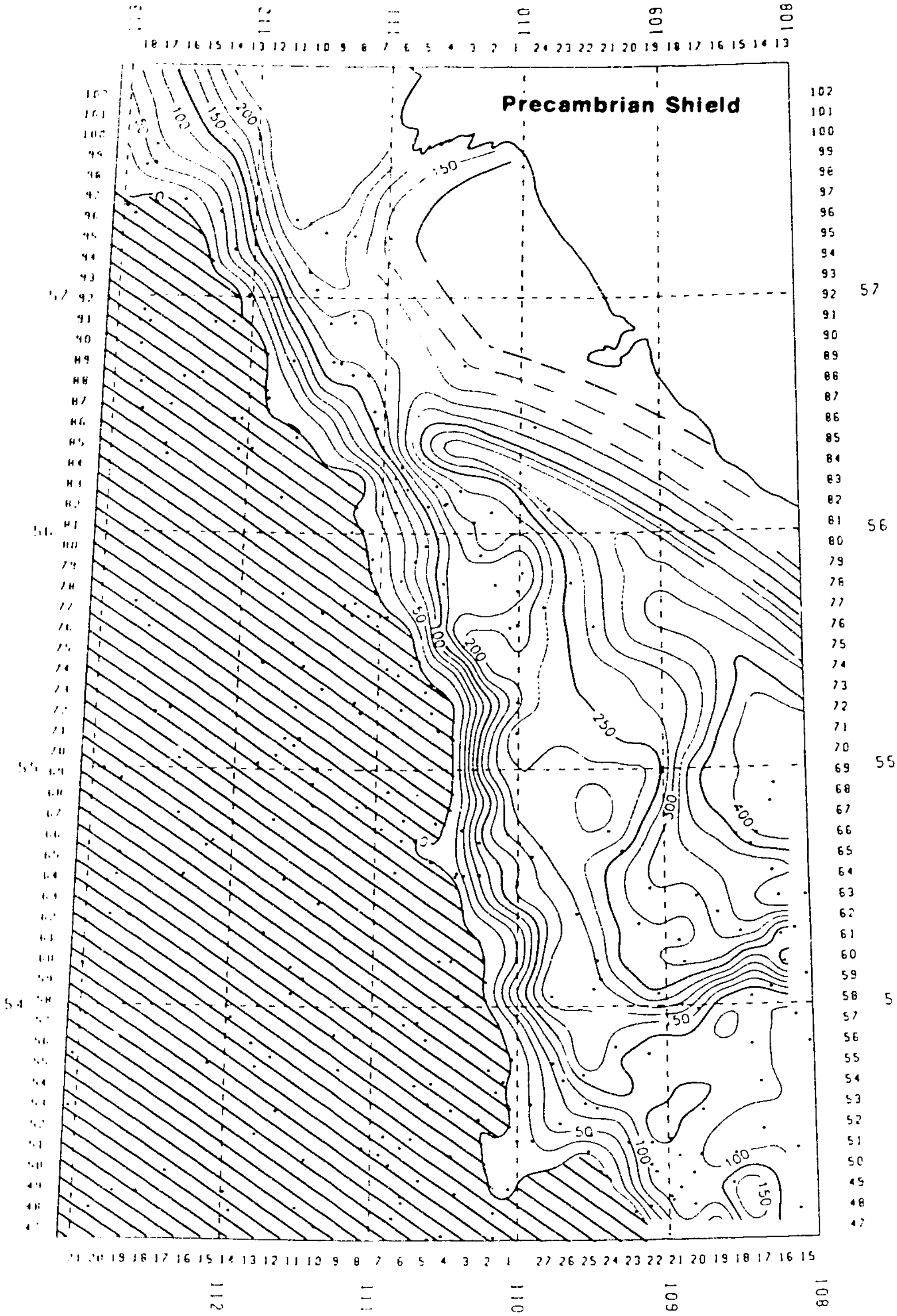

Figure 9 Estimate of total salt removal from all evaporite units in the Middle Devonian Elk Point Group. (contours in metres)

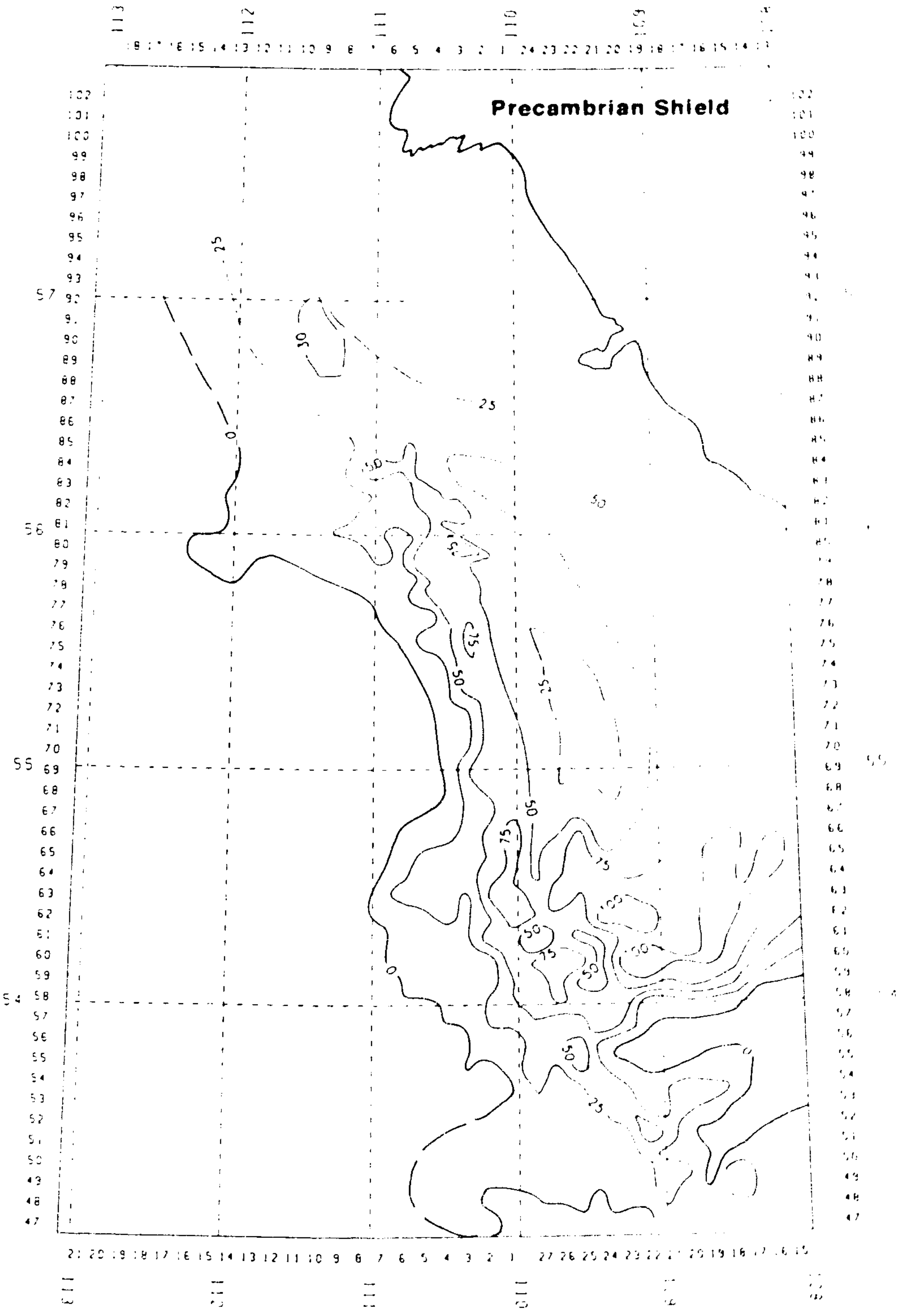

Figure 10 Estimate of total salt removal from all evaporite units in the Middle Devonian Elk Point Group following the Larmide Orogeny. (contours in metres)

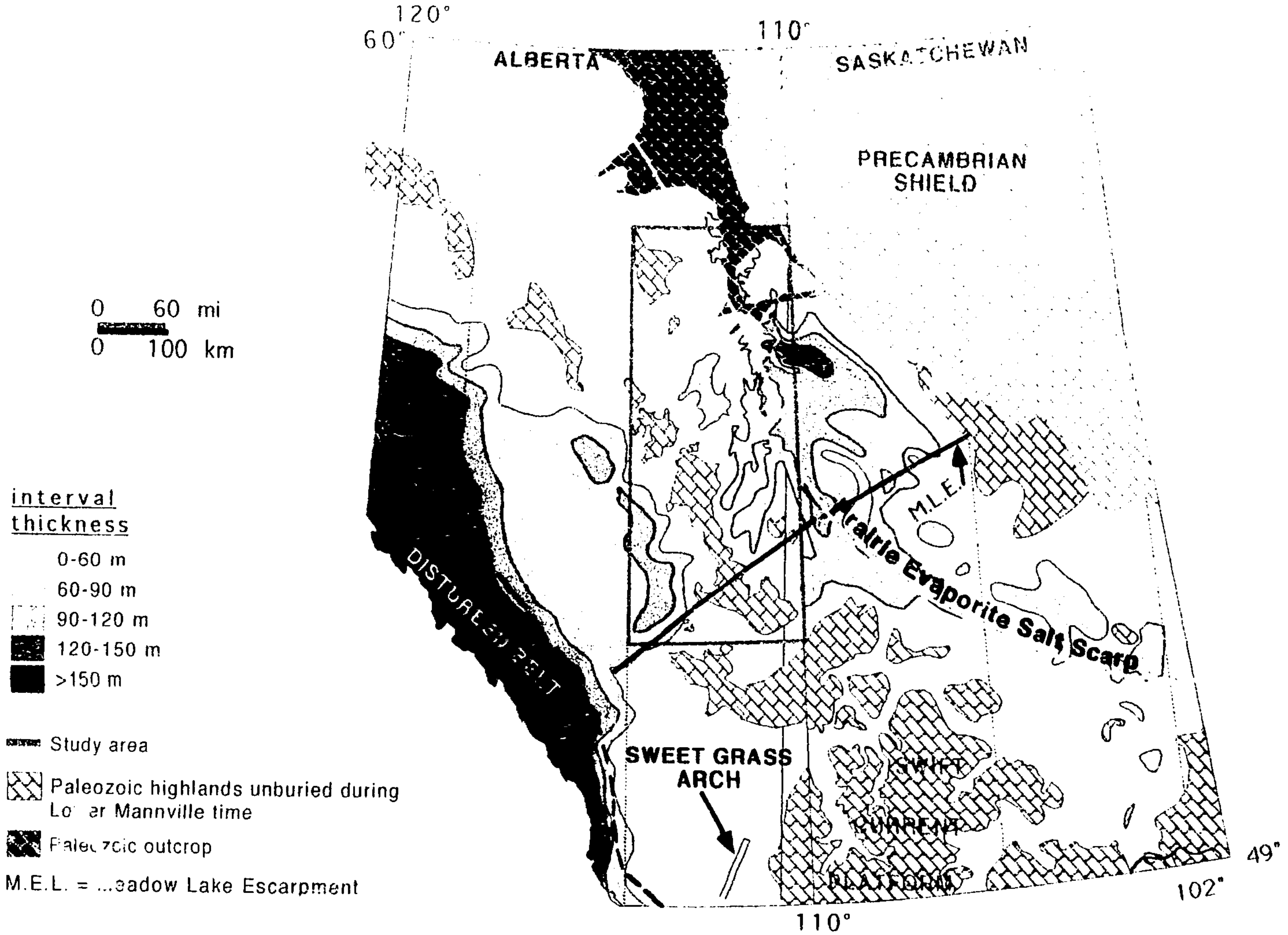

Figure 11 Isopach of the Lower Cretaceous Lower Mannville succession shown in relation to the dissolution scarp of the Middle Devonian Prairie Evaporite Formation (modified from Grayston et. al., 1964; Green, 1972; Hamilton, 1971; McPhee and Wightman, 1991).

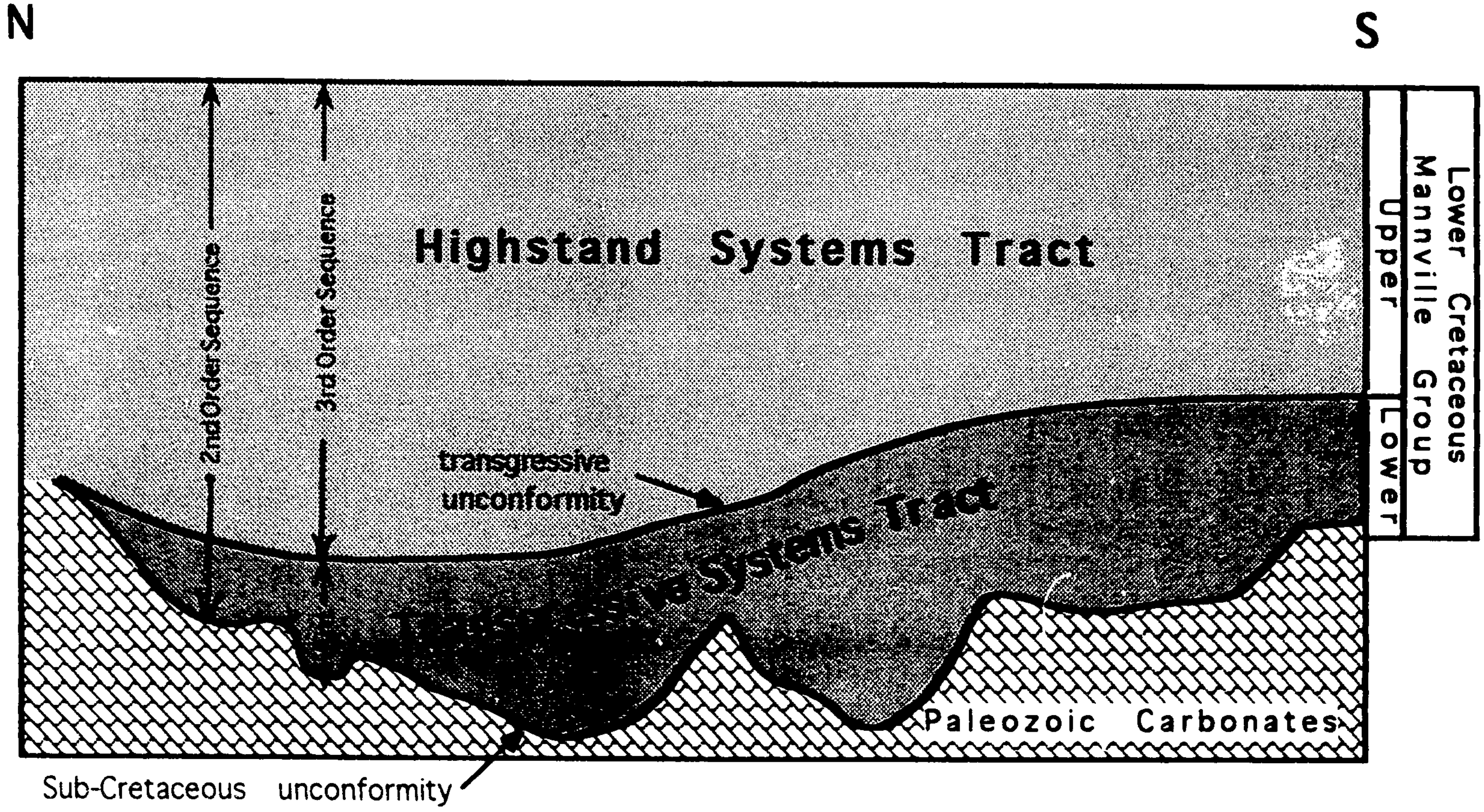

Figure 12 Interpretation of the ranking of unconformity bound sequences of the Lower Cretaceous Mannville Group relative to the First order Zuni Sequence (Sloss, 1963; Cant, 1989).

Mannville sub-group reflects topographic lows resulting from salt dissolution.

Within the Alberta Foreland Basin, the Mannville Group and equivalents form a second order sequence within the first order Zuni Sequence (Sloss, 1963; Cant, 1989). The timing of sea-level rise together with tectonic uplift and subsequent mass wasting resulted in the generation of two, third order sequences consisting of a lower "Transgressive Systems Tract" and an upper "Highstand Systems Tract" (Figure 12). Within each systems tract, higher order cycles reflect the interplay of eustasy, sediment supply and tectonic activity. This interplay is reflected in transgressive-regressive shoreline sequences and the incision of valleys into nonmarine and marginal marine sediments.

The Mannville Group is unconformably overlain by the Joli Fou Formation, the basal unit of the overlying Lower Cretaceous Colorado Group. The entire stratigraphic section above the Mannville Group in the study area is composed of the Lower to Upper Cretaceous marine shales of the Colorado Group, unconformably overlain by a thin layer of Pleistocene glacial deposits. The Mannville Group outcrops in the northern part of the study area (Figure 1) and depth of burial progressively increases to 1200 m in the southwest.

1.4 Method

The investigation was initiated by a review of all type sections both formally and informally described. Having gained an understanding of the existing local lithostratigraphic subdivision and nomenclature, the next step was to establish regional equivalency. To avoid being strongly biased by the existing stratigraphic systems, the mode of regional correlation was focused on the identification of regional flooding events and lowstand surfaces of erosion. Initially, the mode of correlation was focused on the correlation of flooding surfaces for the purpose of identifying genetic stratigraphic sequences as defined by Galloway (1989). Later, the principles of Sequence Stratigraphy defined by Van Wagner *et al.* (1988) were applied. The identification of regional unconformities requires far more respect to detail than the correlation of regional flooding surfaces. For this reason, the correlation of regional flooding surfaces was given first priority, establishing a framework for the further unravelling of the depositional history. The truncation of flooding surfaces, marker beds between major flooding surfaces, downward shifts of facies and obvious incised valley fill were later mapped to verify regional unconformities, providing another reference point for the definition of genetic successions. Due to nature of the data, the size of the region covered, and the wide spacing of the cross-section grid, the existence of regional unconformities is more implied than defined. Verification of regional unconformities would require the examination of core as well as a closer grid spacing.

Well log cross-sections were oriented in a north-northwest and a southwest trend on the basis of several factors. The relief on the sub-Cretaceous unconformity (Rudkin, 1964; McPhee, 1986; Hayes *et al.*, 1994; Ranger, 1994), the orientation of the dissolution scarps of the Middle Devonian evaporite successions (Hamilton, 1971; McPhee and Wightman, 1991), and the axis of terrane accretion and tectonic thrusting (Grayston *et al.*, 1964; Porter *et al.*, 1982) along the western margin of the North American plate during the Lower Cretaceous provide the Alberta Foreland basin with a strong north-northwest grain. From the southerly advance of the Boreal Sea, the axis of the Peace River Arch and the Snowbird Tectonic Zone, a northwest dipping paleo-slope is inferred (Carrigy, 1966). Sections constructed parallel to the paleo-slope were expected to show greater lateral consistency and therefore provide an easier means of correlating across the basin. Sections constructed perpendicular to the paleo-slope were expected to show the architecture of the basin filling processes resulting from the series of relative sea-level changes occurring during the deposition of the Mannville Group. Correlations of the Lower Mannville from sub-basin to sub-basin are primarily restricted to paleo-valleys that follow the north-northwest grain of the Alberta Foreland basin.

The grid spacing is approximately 50 kilometres (Figure 13). Closer grid spacing down to Township spacing (10 Km.) was required in the Cold Lake to Lloydminster area to accurately correlate across the area. Each well along the line of section was included and the top of the Mannville Group was used as a datum. From the working database of cross-sections a smaller network (Figure 14) was selected for graphic representation. A summary cross-section (Figure 15) is an attempt to illustrate the dominant architecture, significant regional variations in the architecture and the relationship between strata isolated in separate basins.

The gamma ray logs of these sections were digitized on LOG DIGITIZER (Ranger, ©1989) and then transferred to the computer assisted drafting package CANVAS 3.01 (Denaba Corp.). Within CANVAS 3.01 correlations and facies relationships were constructed on the framework of gamma ray logs. Following the drafting of the cross-section, the gamma ray logs were hidden in a separate drafting layer. The overlay layer containing the interpreted correlations and distribution of facies was then compressed horizontally and vertically to generate a visual aid (Appendix A, Cross-section 2) concentrating otherwise spread out data (Appendix A, Cross-section 1 part A and part B).

The Upper Mannville above the Sparky Member was correlated in less detail. To the north of

Township 60 time was spent on the correlation of distinct shale beds or unconformity surfaces whereas to the south only coal beds were noted and indicated on the cross-sections.

Flooding and unconformity surfaces interpreted from the grid of cross-sections provide the basis for the reconstruction of a series of paleotopograhic interpretations in the study area, shown in the context of other authors' paleotopograhic interpretations of selected time slices in the Mannville Group.

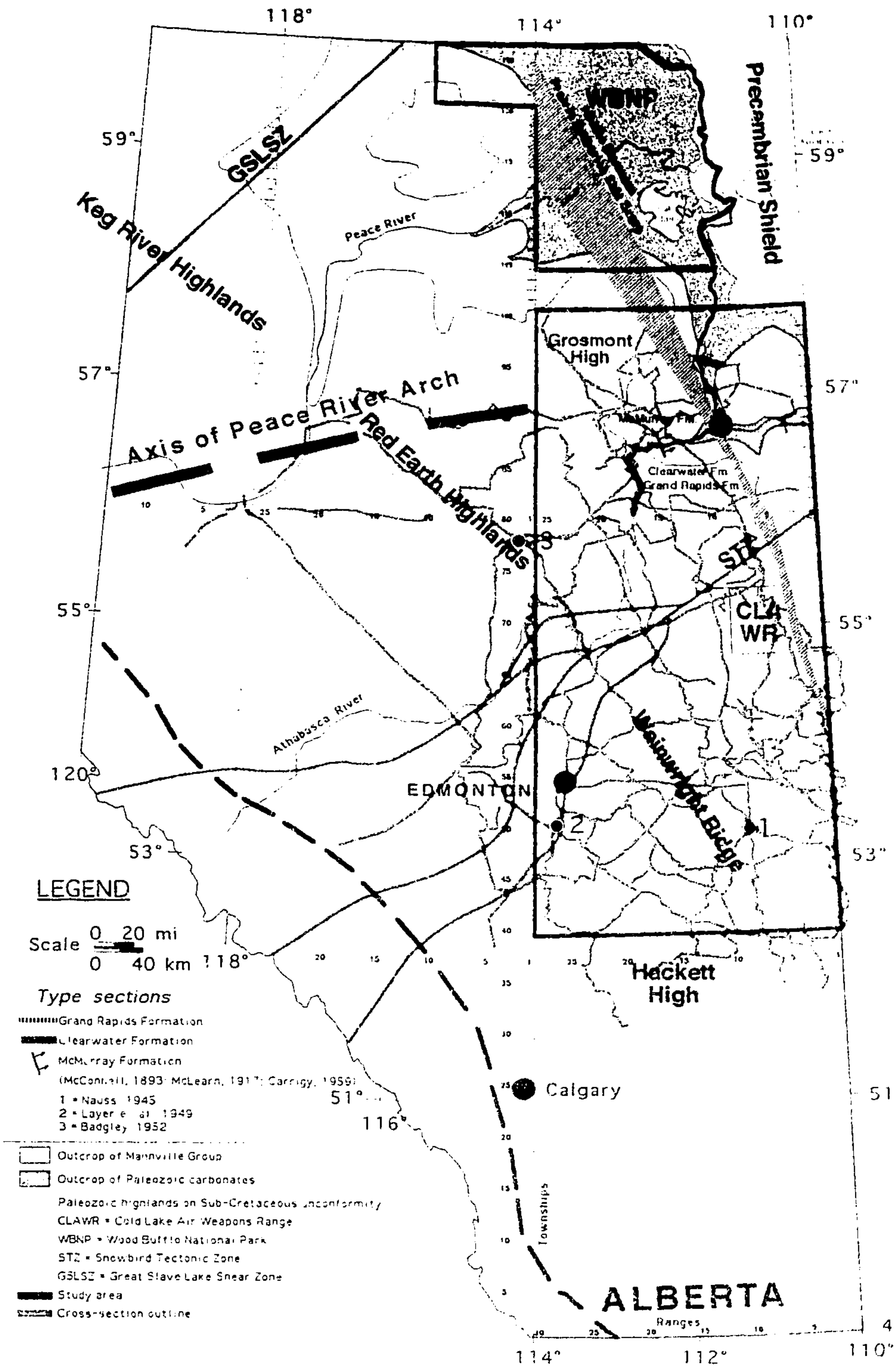

FIGURE 13 Distribution of cross-section database shown in relation to: the study area, sub-Cretaceous Highs, Precambrian basement faults, and outcrops of the Mannville Group, Paleozoic strata and the Precambrian Shield (modified from: Rudkin, 1964; Green, 1972; Ross and Stephenson, 1989; Leckie and Smith, 1992; Ranger, 1994).

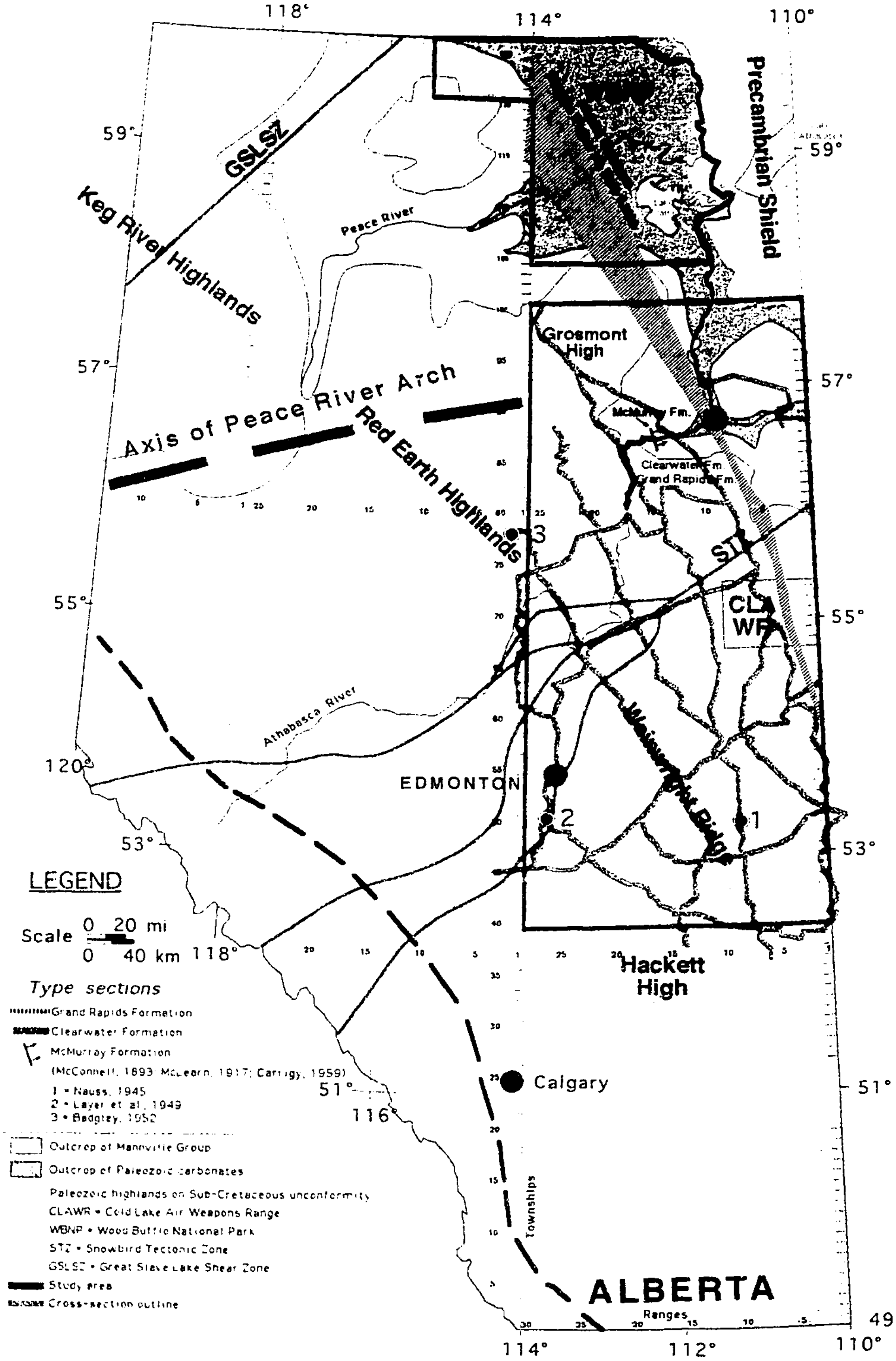

FIGURE 14 Location of cross-sections built of digitized gamma ray well logs on a computer assisted mapping package (CANVAS) show in relation to: the study area, sub-Cretaceous Highs, Precambrian basement faults, and outcrops of the Mannville Group, Paleozoic strata and the Precambrian Shield (modified from: Rudkin, 1964; Green, 1972; Ross and Stephenson,1989; Leckie and Smith, 1992; Ranger, 1994).

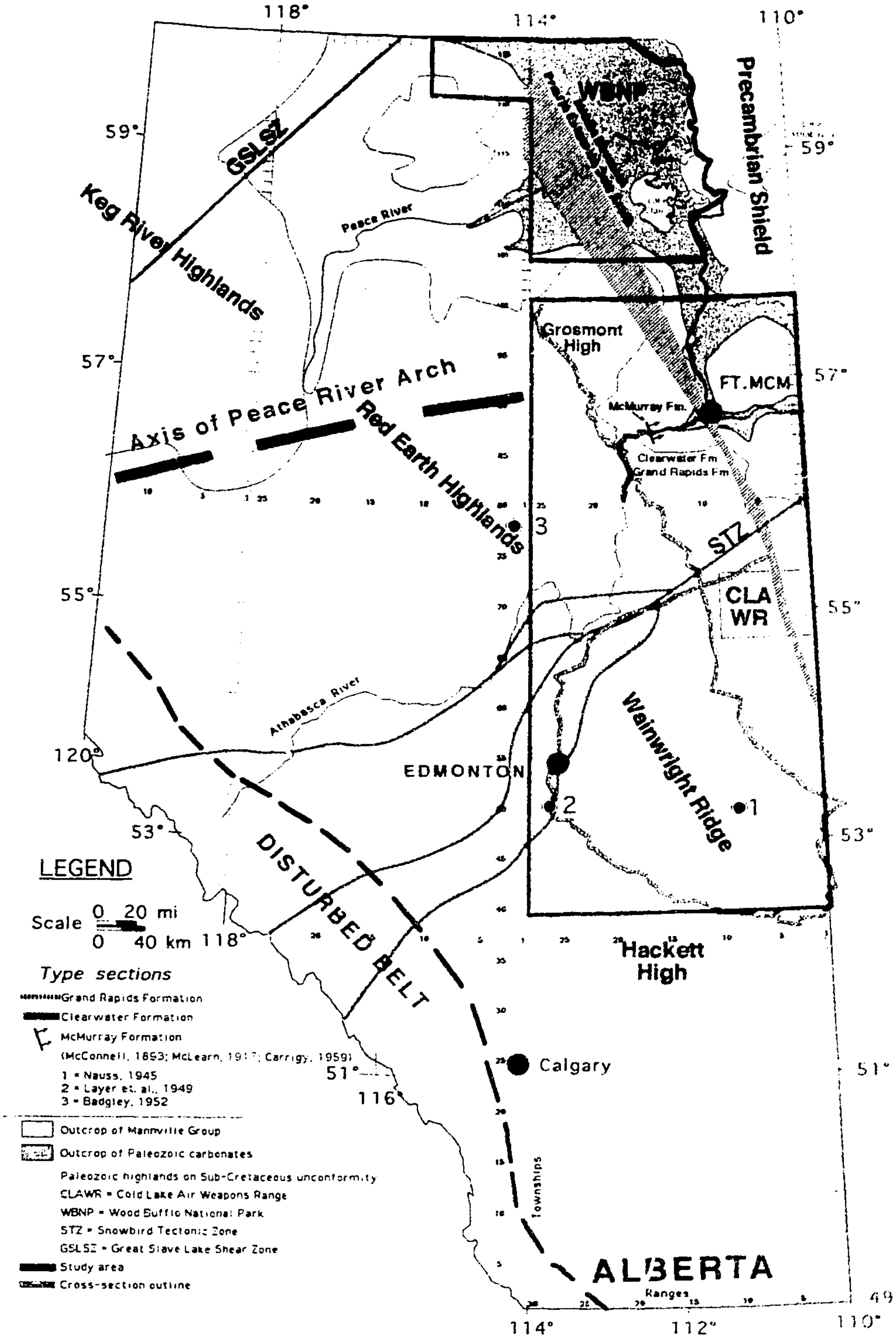

FIGURE 15 Study area and outline of summary cross-section shown in relation to sub-Cretaceous Highs, Precambrian basement faults, and outcrops of the Mannville Group, Paleozoic strata and the Precambrian Shield (modified from: Rudkin, 1964; Green, 1972; Ross and Stephenson,1989; Leckie and Smith, 1992; Ranger, 1994).

2 Interpretation of the Stratigraphic Succession

2.1 Lower Mannville Succession - 3rd Order Transgressive Systems Tract

The subdivision of the Mannville succession is discussed in ascending order through a series of paleogeographic maps (figures 16-39), a regional well log section (Appendix A, Cross-section 1part A and part B) and a condensed schematic of the well log section (Appendix A, Cross-section 2).

The Lower Mannville succession is the result of a gradual Lower Cretaceous marine transgression during the Aptian to lowest Albian stages. By late Aptian time the Boreal Sea consisted of two lobes separated by the emergent part of an axial high trend of pre-Cretaceous strata extending to the northwest across Alberta (Jackson 1984). This stage of the transgression referred to as the Bullhead Sea is considered by Caldwell (1983) to be the initial stage of an ensuing rise in sea level beginning in Late Aptian time and continuing through all of Albian time.

2.1.1 Phase 1 - Relative Sea-level Rise - fluvial aggradation - infilling of Paleozoic topographic valleys - (Dina Member, Ellerslie, Lower McMurray, Cadomin/Gething Formations)

The sub-Cretaceous unconformity in the study area is locally overlain by a shaly succession up to 25 m in thickness. Maximum thickness of succession occurs in topographic depressions ≥ 80 m below the top of the McMurray Formation and equivalents, along and to the east of the Prairie Evaporite Salt Scarp (Figure 11 and 16). Petrophysically, the unit is a massive shale or interbedded shale and sandstone succession. The higher density of the shale relative to overlying shale beds may indicate its source to be residual from local erosion of the surrounding carbonate strata. The accumulation of the thicker shale successions along the Prairie Evaporite Salt Scarp may reflect penecontemporaneous salt dissolution. The stratigraphic position of the unit and its dominantly shaly character indicate that it may be an equivalent of the Deville (Detrital) Formation (Badgley, 1952).

The shaly succession (Deville Formation ?) is abruptly overlain by a dominantly clean (15 - 30 API) sandstone succession which fines-up abruptly to a thin, widespread shale. The sandstone succession up to 45 m in thickness, is the result of fluvial aggradation within two subbasins separated by the Wainwright

Ridge (Figure 16). Communication between the subbasins only occurred toward the end of the phase of deposition, with the lowest topographic area along the highlands being at the southeastern end of the Wainwright Ridge. Relative to the Wainwright Ridge, the succession forms the Ellerslie Formation to the southwest, the Gething/Cadomin Formations to the northwest, the Dina Member to the east (Lloydminster area), and the lower McMurray Formation to the northeast.

2.1.2 Phase 2 - Relative Sea-level Rise - Transgression of the Bullhead Sea - Broad Brackish Embayments Formed - (Ostracode Member, lower part of Cummings Member, Upper part of McMurray Formation)

The shale unit overlying the sandstone succession described above reflects the first episode of regional flooding resulting in the development of widespread, shallow, brackish seas extending down to the 49th parallel and beyond (Figure 17). Communication between the seas occurred in at least three or four localities along the axis of Paleozoic highlands, with the lowest topographic area of the highlands being at the southeastern end of the Wainwright Ridge. The petrophysical characteristics of the succession from each subbasin, differ. In the subbasin to the east of the Wainwright Ridge, the gamma ray log describes one to two upward-coarsening successions that are laterally extensive. The lower sheet, averaging 12 to 15 metres in thickness, tends to be cleaner and thicker. On the schematic and well log cross-sections (Appendix A, Cross-section 1 part A; Cross-section 2), the succession forms the lower two thirds of the Upper McMurray "member" in the northeast and the lower half of the Cummings Member in the southeast. On the western side of the Wainwright Ridge, the lateral equivalent is the brackish-bay shales, fine-grained sandstones, and argillaceous limestones of the Calcareous/Ostracode Member (Glaister, 1959; Banerjee and Davies, 1988) (Appendix A, Cross-section 1 part B; Cross-section 2). Petrophysically, the succession is characterized by a negative SP, higher density and resistivity relative to surrounding strata with a similar gamma ray reading. The gamma ray response indicates two slightly upward-coarsening units. Banerjee and Davies (1988) suggested that the embayment was twice inundated by an advancing sea. The greater shale content plus the carbonate beds may reflect a sediment starved brackish basin. This phase of deposition closed with a relative drop in sea-level, the retreat of the Bullhead Sea.

2.1.3 Phase 3 - Relative Sea-level Fall - Regional Incision - Post Ostracode Time

Depth of incision and the extent of the region incised was probably restricted to areas outside the

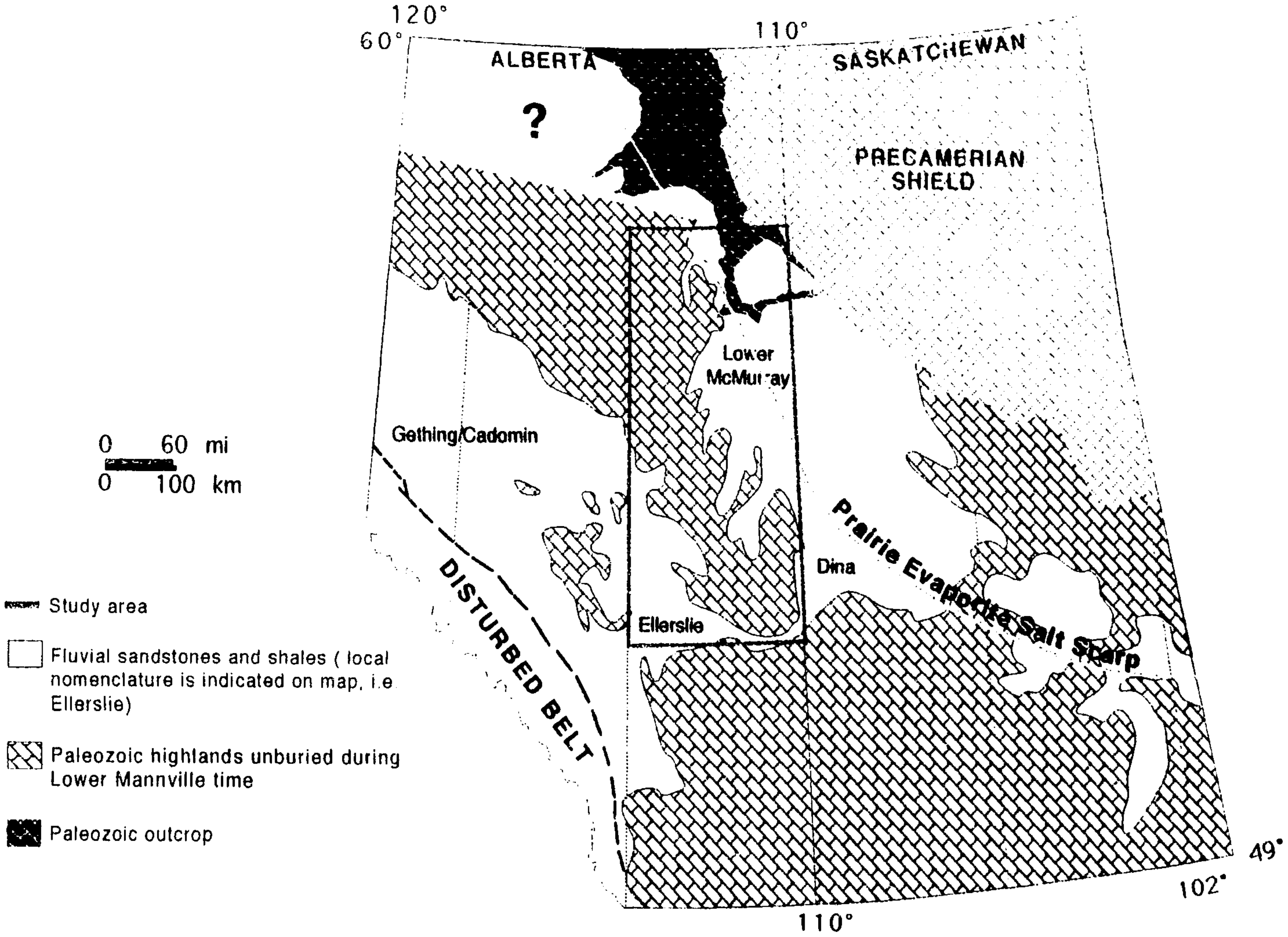

Figure 16 Lower Mannville paleography at the time of the first major flooding event of the foreland basin by the Boreal Sea (modified from Green, 1972; Hayes et. al., 1994)

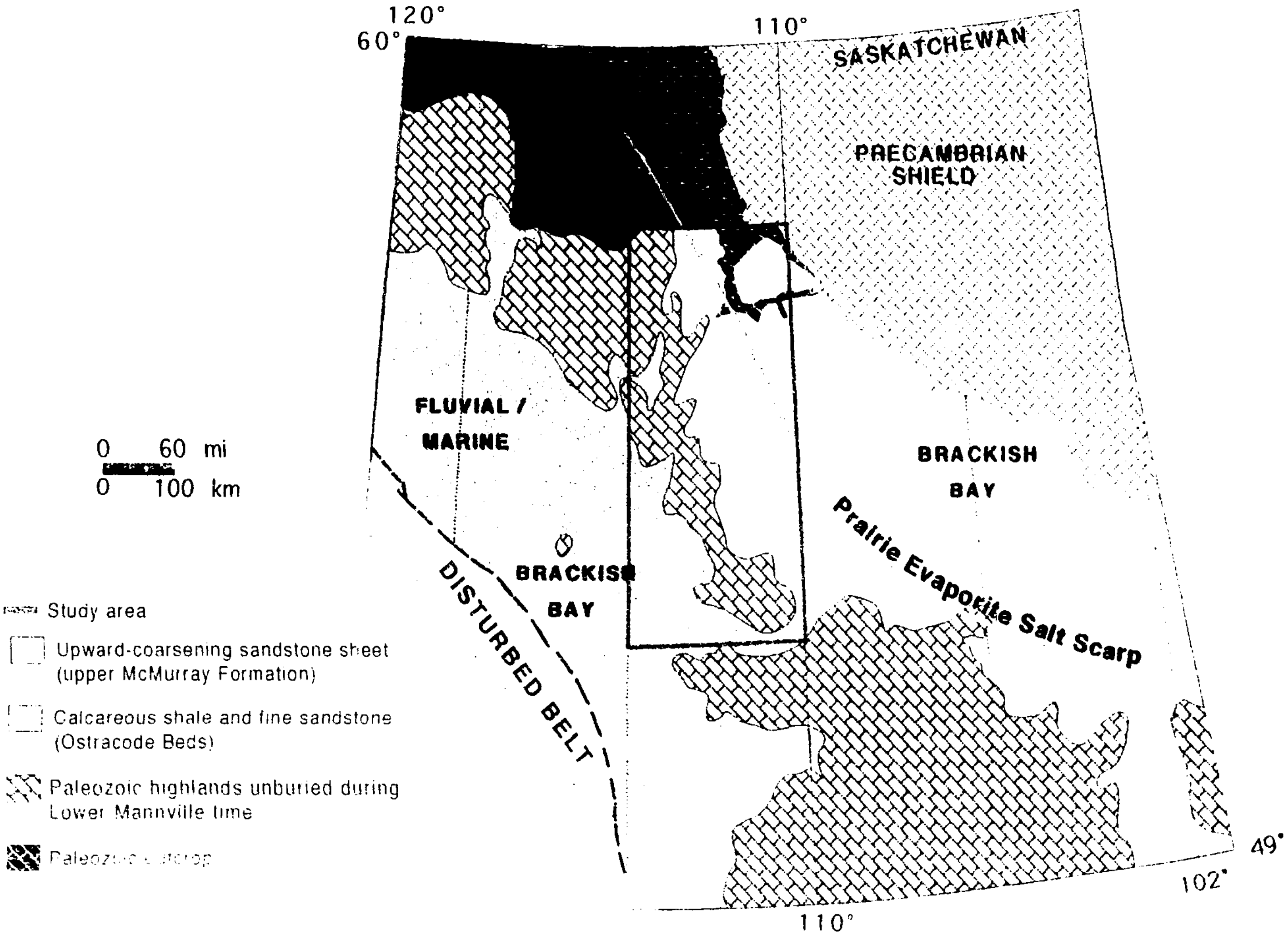

Figure 17 Paleography during deposition of the Calcareous, Ostracode, lower part of the Cummings Member, and upper part of the McMurray Formation paleography (modified from Hayes *et al.*, 1994; Leckie and Smith, 1992; Christopher, 1980; Flach, 1984; Mcphee, 1986)

subsiding centre of the Peace River Arch. Two areas of incision are documented (Figure 18). To the northeast of the Wainwright Ridge, along the axis of the Prairie Evaporite Salt Scarp, the entire upper McMurray unit, the lateral equivalent of the Ostracode Member, was removed.

On the southern flank of the Wainwright Ridge, valleys were incised through the Ostracode Member into the underlying Ellerslie Member. The incision follows the axis of the sub-Cretaceous paleo-valley, then abruptly ends or switches direction to the northeast along the trend of the southernmost of several faults diverging to the southwest from the main Snowbird Tectonic Zone (STZ) (Figure 19) (Ross and Stephenson, 1989). To the north of this inferred fault or ductile shear zone, further incision was not observed in the cross-sections used in the study. Within the STZ, the Drayton Valley Complex or the Bigoray sandstone is described as being entirely encased in shale and overlying the Ostracode Member (Rosenthal, 1988; Jackson, 1984). Correlations of this sandstone succession indicate that it is composed of a series of prograding, downlapping units. It is suggested that it may not have formed during the phase of fluvial incision but rather on the rise of relative sea-level, as the landward limit of the succession onlaps onto upward-fining estuarine (?) valley fill. The sediment flush associated with the phase of lowstand incision may have been the source of the Bluesky Formation further to the northwest.

2.2 Transgression of the Moosebar/Clearwater Sea

2.2.1 Phase 4 - Relative Sea-level Rise - Flooding of incised valleys and shallow coastal plain - (estuarine valley fill of incised valleys in the Ostracode Member and the upper part of the McMurray Formation)

The close of the lowstand phase is associated with the advance of the Moosebar/Clearwater Sea culminating in a period of maximum marine incursion (figures 20 and 21). In the initial phase of sea-level rise, incised valleys of the previous lowstand phase became estuarine embayments (Pemberton *et.al.*, 1982; Rennie, 1987; Mattison, 1987; Karvonen, 1989). Pemberton *et al.*, (1982) have identified at least ten ichnogenera from outcrops along the Steepbank River (Tp. 100, R. 8W4) for the middle and upper parts of the McMurray Formation. The ichnogenera include *?Dolopichnus, Lockeia, Monocraterion, Palaeophycus, Planolites, ?Rosselia, Skolithos, Teichichnus* and vertical escape structures. They suggest that the deep channel complex in which the sediments were deposited was closely associated with a nearby marine shoreline. The palynological evidence suggest some saline influence in many of the interchannel

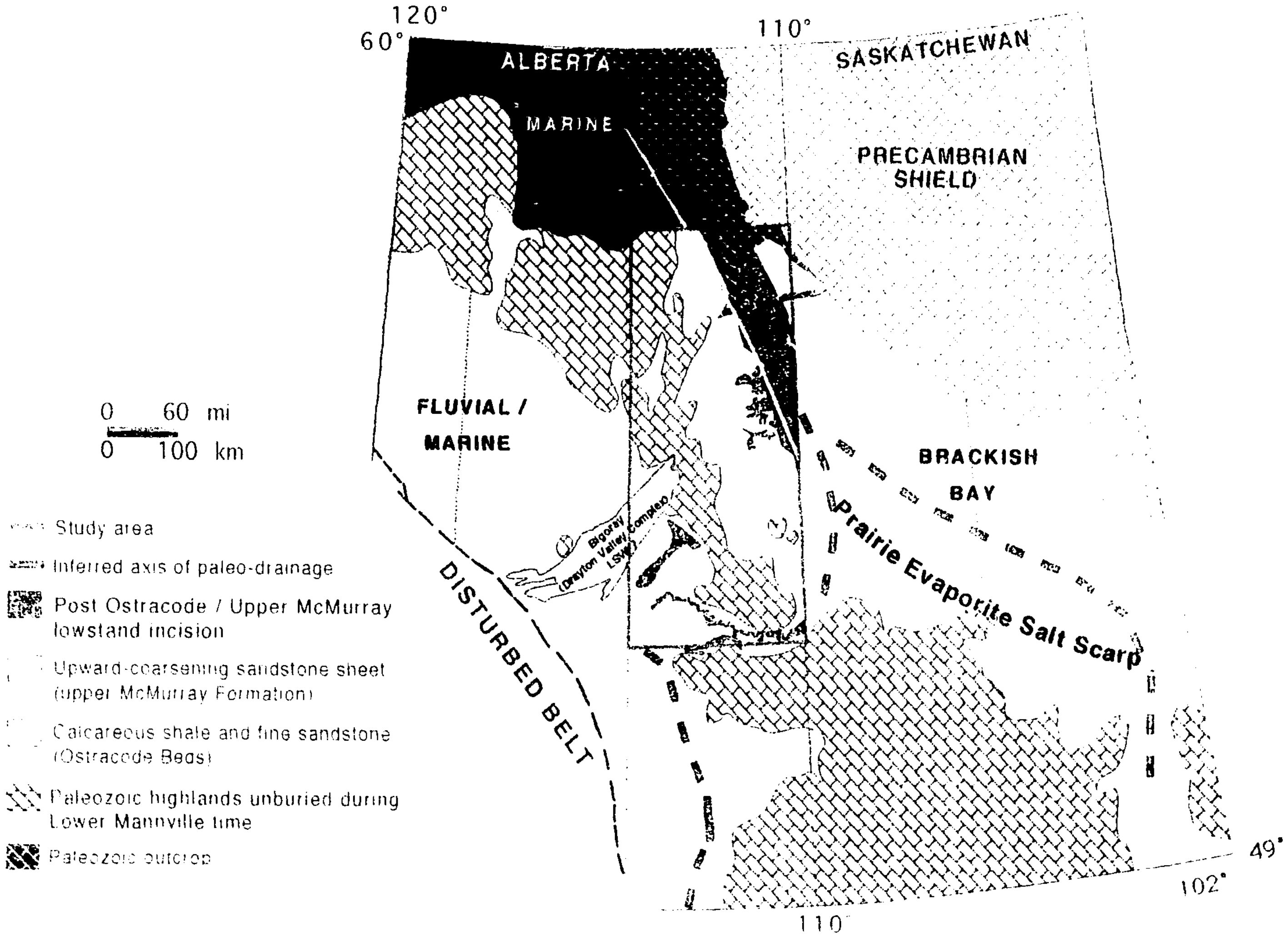

Figure 18. Lowstand incision following deposition of the Ostracode Beds, lower part of Cummings Member, and the upper part of McMurray member time (modified from Green, 1972, Jackson, 1984, Rennie, 1987, Rosenthal, 1988, Leckie and Smith, 1992, Hayes et al., 1994).

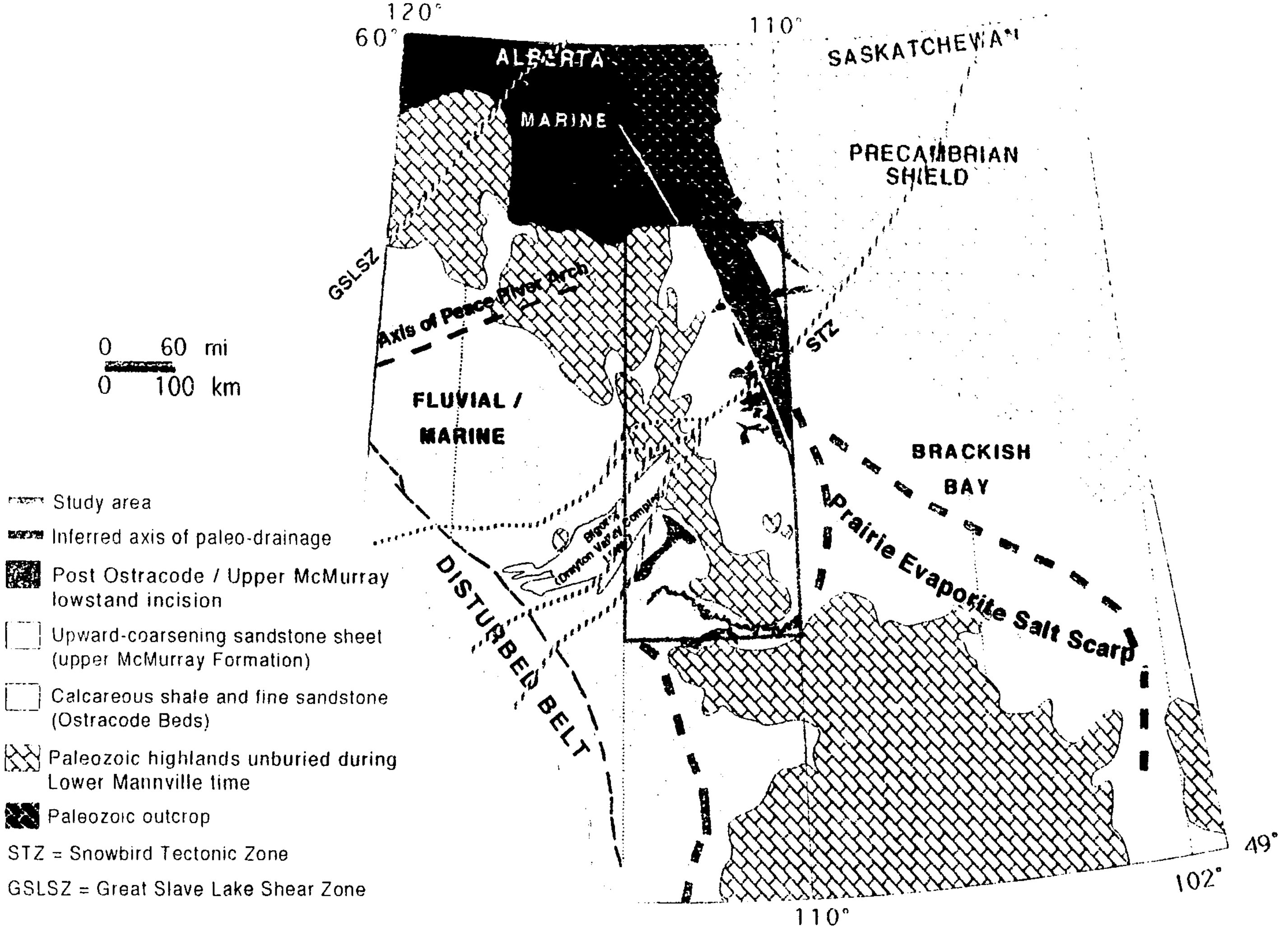

Figure 19 Lowstand incision: post- Ostracode, Cummings, and upper McMurray time relative to the Snowbird Tectonic Zone (modified from Green, 1972; Jackson, 1984; Rennie, 1987; Rosenthal, 1988; Ross and Stephenson, 1989; Leckie and Smith, 1992; Hayes *et. al.*, 1994).

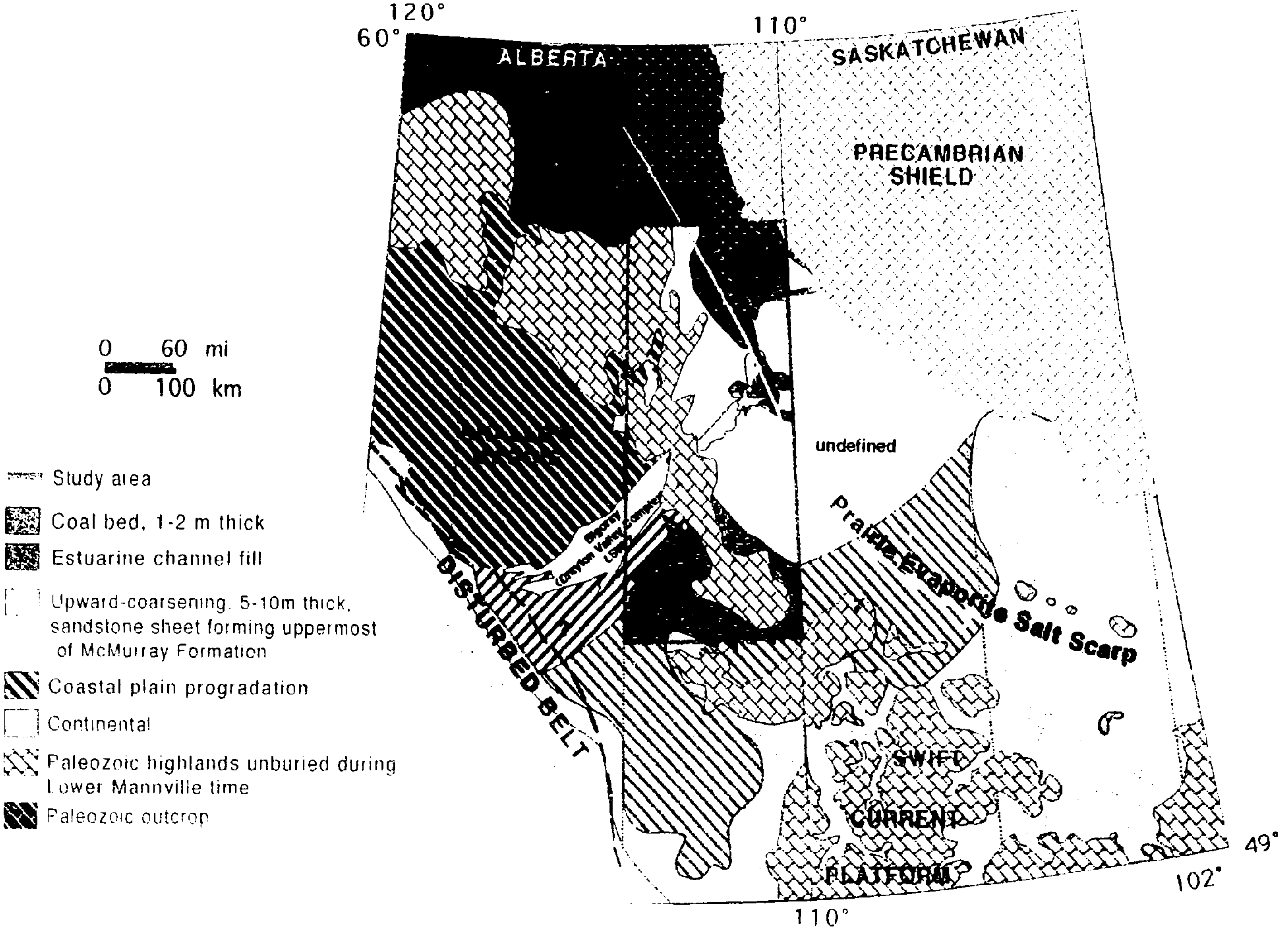

Figure 20 Initial transgressive phase of the Moosebar / Clearwater Sea: upper Cummings member, upper most McMurray Formation, basal Glauconite and Wabiskaw members (modified from Green, 1972; Christopher, 1980; Jackson, 1984, Chiang, 1984, Rennie, 1987, Leckie and Smith, 1992; Rosenthal, 1988, Hayes *et al.*, 1994)

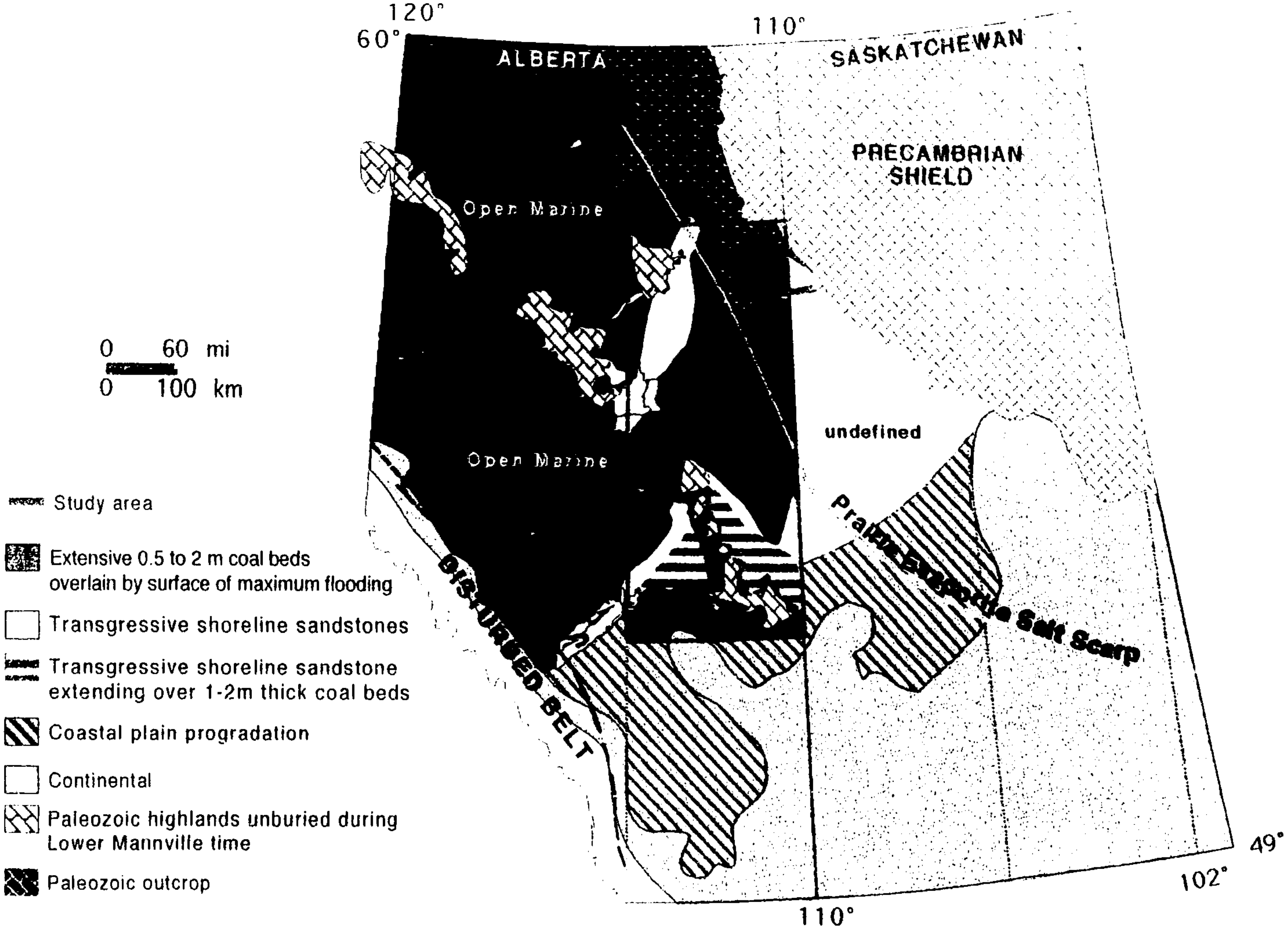

Figure 21 Time of maximum transgressive phase of the Moosebar / Clearwater Sea: upper part of Cummings Member, lower Glauconite B unit (Hoadley Barrier), and basal glauconitic sandstone of the Wabiskaw member (modified from Green, 1972; Jackson, 1984; Christopher, 1980; Chiang, 1984; Leckie and Smith, 1992; Ranger, 1994).

sediments of the middle McMurray, but the degree of marine influence is still open to question (Flach 1984; Rennie 1987).

In the upper half of the McMurray Formation in the Fort McMurray area (T. 89, R. 9W4M), Mattison (1987) identified sixteen ichnogenera which include: *Planolites, Palaeophycus, Ophiomorpha, Cylindrichnus, Teichichnus, Skolithos, Bergaueria, Thalassinoides, Conichnus, Conostichnus, Asterosoma, Monocraterion, Trichichnus, Gyrolithes, Rosselia* and escape structures. Of the three facies he recognized in the upper McMurray, two usually contained twelve ichnogenera while the third only contained three. From both the middle and upper part of the McMurray Formation, the more common ichnogenera include *Planolites, Palaeophycus, Cylindrichnus, Teichichnus, Skolithos.* On the basis of the ichnogenera present, he interpreted the upper part of the McMurray Formation as being deposited in a shoreface or nearshore shoal settings.

With continued sea-level rise, shallow, broad, brackish embayments formed both to the northeast (Ranger and Pemberton, 1988) and southwest (G[illegible]d Pemberton, 1994) of the Wainwright Ridge (Figure 20). Evidence of marine incursions are reported by L[illegible]r et al. (1987) and Ranger and Pemberton (1988) roughly 200 km to the south and paleo-geographically [illegible]ward from Fort McMurray (T. 89, R. 9W4M) in the Primrose Area (T. 72, R. 6 W4M). Ranger and Pemberton (1988) identified six ichnogenera in the middle and upper parts of the McMurray of Primrose Area which include: *Planolites, Skolithos, Teichichnus, Cylindrichnus* and *Chondrites.* The ichnogenera are interspersed with a widespread shale facies containing thin coals and rootlets. A preliminary interpretation of the vertical succession in this area led Ranger and Pemberton (1988) to suggest a restricted marine estuary, dominated by brackish water conditions, with intermittent development of brackish to freshwater marsh environments.

In the embayment to the southwest of the Wainwright and along the southeastern flank of the Wainwright Ridge, coastal marsh environments formed. In association with the marsh environments, a 6 to 10 m thick, upward-coarsening sheet prograded to the north across the northeastern embayment. This sheet forms the upper unit of the upper McMurray member to the northeast of the Wainwright Ridge. The regional correlations indicate that the lateral equivalent to this unit, west of the Wainwright Ridge, is the Drayton Valley Complex (Rosenthal, 1988) or Bigoray sandstone (Jackson, 1984). A regional strike section extending from T. 54, R. 18W4M to T. 63, R. 1W5M defines the Drayton Valley/Bigoray sandstone as a series of northwest prograding shoreline sheet-sandstones. To the south of this complex a linear, northeast trending incision of the Ostracode member is filled with a fining-upward sandstone succession probably representing fluvial/estuarine fill behind an aggrading shoreline system. In summary this phase of deposition began with the flooding of incised valleys, with continued sea-level rise leading to more widespread inundation of the coastal plain, followed by widespread progradation of a thin shoreface succession.

2.2.2 Phase 5 - Relative Sea-level Rise - Open marine separated from brackish lagoons by extensive barrier systems

Continued sea-level rise of the Moosebar/Clearwater Sea is associated with the widespread deposition of the initial occurrence of glauconitic (McLearn, 1917; Badgley, 1952; Carrigy, 1963; Rosenthal, 1988) in association with sediment intensely bioturbated by a wide range of ichnogenera (Mattison, 1987; O'Connell, 1988; Male, 1992) indicating the onset of a fully open marine environment across the region (Figure 21).

Study of the environments of deposition in which modern deposits of glauconite have been found suggests that at least five conditions must be maintained for the formation of glauconite. These are: (1) normal sea water, (2) suitable parent material, (3) slightly reducing conditions, such as are produced by decaying organic matter, (4) slow rate of detrital influx, and (5) moderate to shallow depth of water (Cloud, 1955). Among the suitable parent materials listed by Takahashi (1939) are hydrated and gelatinized fragments of volcanic glass, opaline silica, faecal pellets, feldspars, and possibly micas.

Within the Mannville Group, the initial occurrence of glauconite is associated with the first major influx of lithic sediment derived from the newly evolving mountain range (Columbian Orogeny) to the west. The slow rate of detrital influx associated with the formation of modern glauconite has led stratigraphers to the conclusion that ancient glauconite beds may mark stratigraphic discontinuities representing a lack of deposition for considerable intervals of time over wide areas (Weller, 1960).

Throughout most of the northern two-thirds of the study area, the initial occurrence of glauconite occurs in a 2 to 3 m thick, lithic sandstone overlying quartz-rich sandstone and is overlain by a 4 to 6 m thick marine shale (Badgley, 1952; Carrigy, 1963; Carrigy, 1971; Clack, 1967; Dekker *et al.*, 1981; Flach, 1984, McPhee, 1986; Ranger and Pemberton, 1988). The glauconitic unit is intensely bioturbated by a suite of ichnogenera (Mattison, 1987; Ranger and Pemberton, 1988) indicative of fully marine conditions. The petrophysical response of the glauconitic unit consists of a high density spike, approximately 1 m thick, an abrupt increase in resistivity, and generally a corresponding decrease in the permeability relative to the underlying quartz rich sandstone. Regional well log correlations of this glauconitic unit together with observations of core data (O'Connell, 1988; Moslow and Pemberton, 1988; Male, 1992; Bradley and Pemberton, 1992) indicate that it was deposited over most of central Alberta in a very thin uniform sheet beneath a widespread overly marine shale. This observation in conjunction with both the high degree of burrowing and range of ichnogenera lends support to the suggestion that the presence of glauconite in high concentrations may mark periods of very low sedimentation for considerable intervals of time over wide areas.

The southern limit of the foregoing succession of glauconitic sandstone and overlying marine shale occurs along the Hoadley Barrier and along the eastern flank of the Wainwright Ridge. Behind the Hoadley Barrier and along the flanks of the Wainwright Ridge the approximate lateral equivalent of the glauconitic sandstone is an extensive coal unit up to 2 metres in thickness. On the southwestern flank of the Wainwright Ridge, the coal unit overlies the Ostracode Member and the estuarine fill (i.e. Bellshill Lake deposit in T. 41, R. 12W4) of the lowstand valley incised into the Ostracode Member. Progressing eastward into the embayment the coal unit grades eastward to organic rich mudstone with an average thickness of 3-5 m (Geier and Pemberton, 1994; Ford, (PanCanadian) per. comm.). This coal unit confined behind the axis of the Hoadley Barrier, testifies to the existence of an extensive fresh water bay.

The base of the Hoadley Barrier overlies upward-fining channel fill of the aforementioned northeast trending valley incised into the Ostracode Member, and approximately coincides with the southern arm of the Snowbird Tectonic Zone (Figure 19). It is suggested here that the Hoadley Barrier developed along the inflection point between greater basin subsidence to the northwest and lesser subsidence to the southeast. Correlations of the coal unit across the Wainwright Ridge indicate that an equivalent of the Hoadley Barrier developed to the northeast and parallel to the axis of the Wainwright Ridge. The barrier/shoreline deposit of both barrier systems consists of a clean, massive, 10-15 m thick sandstone which abruptly overlies the coal unit, and wedges out onto the flanks of the Wainwright Ridge. Progressing to the east within the embayment to the southeast of the Wainwright Ridge, this barrier/shoreline deposit tapers into the thin (3-5 m thick), laterally extensive, organic rich mudstone, the lateral equivalent of the coal unit. In some areas a thin ($\leq$ 1 m thick) coal bed overlies the barrier/shoreline sandstone. Both the lower and upper coal beds merge along the axis of the Wainwright Ridge with a combined thickness of 1 to 3 metres. The barrier/shoreline sandstone on the eastern flank of the Wainwright Ridge appears to be equivalent to the upper half of the Cummings Member, and on the southwestern flank, equivalent to the lower cycle of the

Glauconite B unit of Rosenthal (1988).

2.2.3 Phase 6 - Relative Sea-level Fall - deposition of upper Wabiskaw Member Lowstand Wedge

Lowstand incision of both the lower succession of the Glauconite B unit (Hoadley Barrier) and the upper half of the Cummings Member (Cold Lake area on eastern flank of Wainwright Ridge), is interpreted to represent the first major drop in relative sea-level following the onset of the transgression of the Moosebar/Clearwater Sea (Figure 22). Lowstand shoreline deposition formed a northward thickening wedge 15 to 20 m in thickness. The northern flank of the lowstand wedge tapers over less than a township into a widespread succession consisting of a lower 2 to 3 metre thick, silty to very-fine grained, wave rippled sandstone and an overlying 1 to 2 metre thick bentonite bed. Approaching the Grosmont and Red Earth Highlands the 2 to 3 metre thick sandstone units thickens, translating into an extensive, upward-coarsening sheet that onlaps the Paleozoic highs but does not cover them. The distal part of this lowstand succession forms the upper of three shoreline sheets that merge into one stacked sandstone succession approaching the southeastern end of the Red Earth Highlands (Ranger, 1994). Badgley (1952) defined the interval of the stacked sandstone succession as the type section for the Wabiskaw Member, the basal member of the Clearwater Formation. The lateral equivalent of the Wabiskaw Member type section, to the east and south, consists of a laterally extensive succession consisting, in ascending order, of a basal 2 - 3 m thick glauconitic unit, a 4 - 6 m thick marine shale, and a 2 - 3 m thick silty sandstone and a 1 - 2 m thick bentonitic unit. In this study the glauconitic unit overlies the top of the McMurray Formation and the bentonitic unit is referred to as the Wabiskaw Shale Marker (W sm). The 'W sm' is laterally continuous across the northern half of the study area but gradually becomes indistinct as the underlying 2 - 3 m thick silty sandstone thickens to the south and northwest.

2.2.4 Phase 7 - Relative Sea-level Rise - deposition of upper Glauconite B unit and the Lloydminster Member

The regional correlations indicate that the ensuing transgression flooded the foreland basin southward to the Hoadley Barrier and its lateral equivalent, the lower part of the Clearwater C unit, on the eastern side of the Wainwright Ridge (Figure 23). Landward of the barrier, a lateral equivalent of the

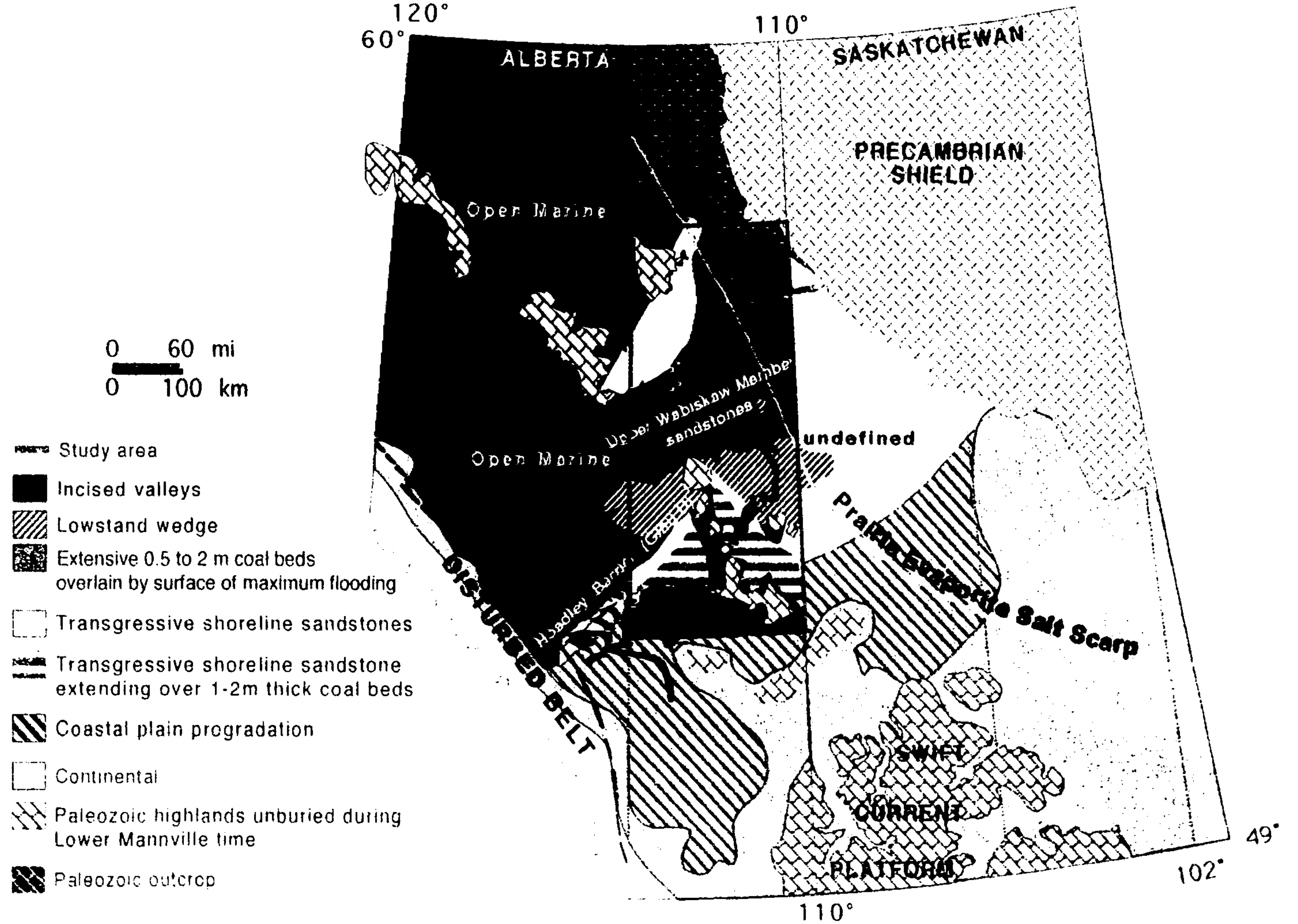

Figure 22 First lowstand phase after the transgression of the Moosebar/Clearwater Sea. Lowstand shoreline deposits formed around northern part of Wainwright Ridge (lower part of Clearwater C unit, Cold Lake) and around the southern flanks of the Red Earth and Grosmont Highs (A and B sands of Wabiskaw Member (modified from Green, 1972, Christopher, 1980, Gross, 1980; Chiang, 1984, Jackson, 1984, Rosenthal, 1988)

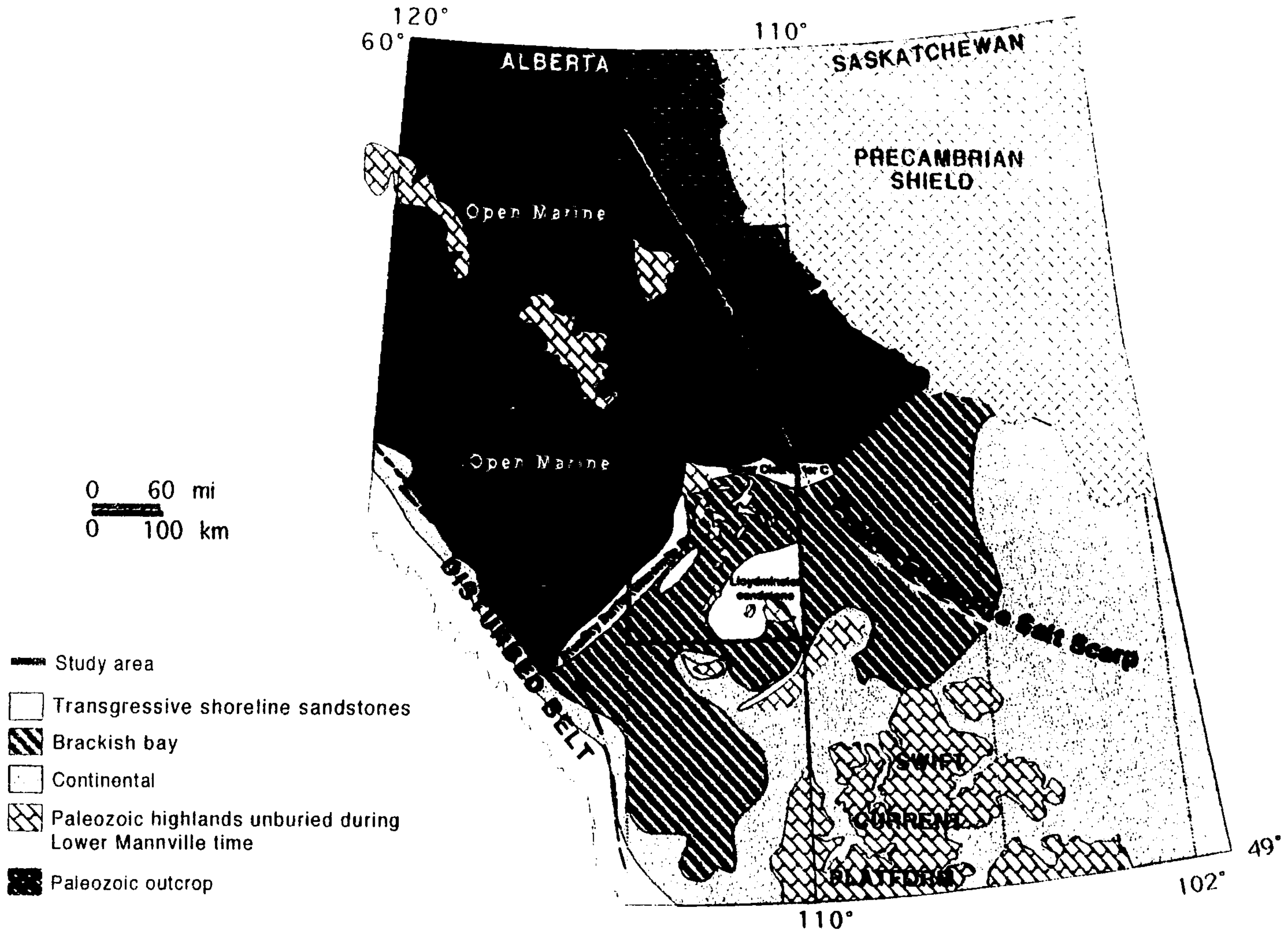

Figure 23 Second highstand phase of the Moosebar / Clearwater Sea: deposition of the barrier sandstones of the Upper Glauconite B (Hoadley Barrier) and Clearwater C unit (Cold Lake), and the shoreline sandstone of the Lloydminster member (modified from Green, 1972; Christopher, 1980; Gross, 1980; Chiang, 1984; Jackson, 1984; Rosenthal, 1988).

flooding event is recognized as a thin 1-2 m thick shale interpreted to have formed in a brackish to shallow marine environment (Geier and Pemberton, 1994). This shale correlates to the shale separating the Cummings Member from the Lloydminster member in the Lloydminster - Vermillion region. Biostratigraphic analysis of the shale by Nauss (1945, 1947) shows it to be marine in origin. Further evidence for the existence of a marine environment is based on ichnogenera recognized in the sandstone interval immediately underlying this shale in well 11-2-50-2W4.

The regional correlations show that there are two distinct sandstone successions associated with the flooding. These include the upward-coarsening sandstone facies of the Lloydminster Member and the upper succession of the Glauconite B unit of the Hoadley Barrier (Rosenthal, 1988). The sandstone facies of the Lloydminster Member is localized around small remnant Paleozoic outcrops of the southern end of the Wainwright Ridge while the Hoadley Barrier is localized along the southern flank of the Snowbird Tectonic Zone (Figure 24). The lack of sedimentation prior to the deposition of the shale southeast of the Hoadley Barrier indicates that flooding behind the barrier occurred early in the transgressive phase.

The low lying coastal plain of Cape Hatteras and Cape Lookout area of the North Carolina Coast (Heron *et al.*, 1984) (Fig. 25) may present a possible modern analogue. Along this coastline the highest wave energy occurs where the landmass projects further seaward. The barrier system along the North Carolina Coast is characterized by linear barriers flanking an extensive lagoonal system. Due to high wave energy, few tidal inlets cut the barriers. Tidal inlet processes are dominated by large flood-tidal deltas as a result of the microtidal range. Both transgressive and regressive processes operating in an overall transgressive system are controlled by the rate of sediment supply.

The quartzose sandstone of the Lloydminster Member (O'Connell, 1988), the feldspathic sands of the Clearwater C unit in the Cold Lake area (T 60-66, R 1-15W4M) (Harrison *et al.*, 1981; Putnam and Pedskalny, 1983) and the lithic sands of the Hoadley barrier (Rosenthal, 1988) point to widely divergent sources.

North of the Clearwater C barrier system, the Wabiskaw marker shale is overlain by a muddy succession that gradually tapers to a few metres in the northwest from a maximum thickness of 25 metres in the south. Informally within industry and the Energy Resources Conservation Board, this muddy succession forms the lower part of the B unit of the Clearwater Formation. Within this study, it is referred to as the Clearwater B2 unit.

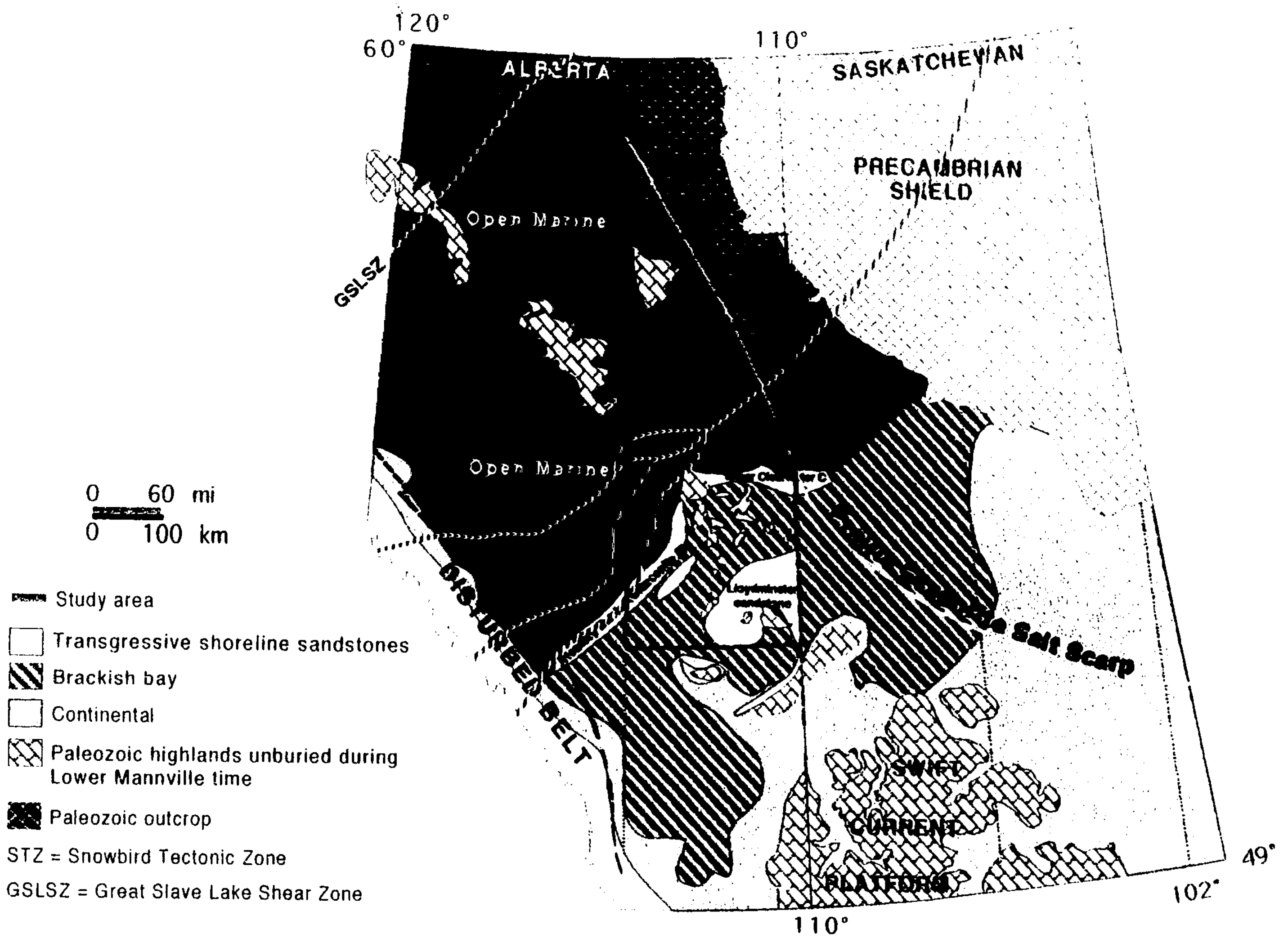

Figure 24 Second highstand phase of the Moosebar / Clearwater Sea: deposition of the barrier sandstones of the Upper Glauconite B (Hoadley Barrier) and Clearwater C unit (Cold Lake), and the shoreline sandstone of the Lloydminster member shown in relation to the STZ (modified from Green, 1972; Christopher, 1980; Gross, 1980; Chiang, 1984; Jackson, 1984; Rosenthal, 1988; Ross and Stephenson, 1989).

2.2.5 Phase 8 - Relative Sea-level Fall - Deposition of upper Clearwater C lowstand wedge

Both the Hoadley - Clearwater C barrier system and the Lloydminster sandstone are incised by channels (Figure 26) (Chiang, 1984; Rosenthal,1988; Gross, 1980; O'Connell, 1985, 1988). On the basis of the foregoing, channels within the barrier system may have been tidal inlets. Evidence of sea-level lowering is found just north of the Cold Lake area (T 66-70, R 1-6W4M). Here, the Clearwater B2 unit is incised. Progressing north of the area of incision, a thin 5 to 10 m thick, clean sandstone sharply overlies the Clearwater B2 unit. This lowstand deposit formed to the north of Township 71, Range 1-15W4M is suggested to have formed the locus of a new barrier system during the phase next phase of relative sea-level rise. This barrier system, up to 40 m in thickness, is referred to here as the Clearwater B1 sandstone.

The stratal context and the petrophysical characteristics of the upper surface of the Clearwater B2 unit are similar to the glauconitic sandstone, the basal unit of the Wabiskaw Member. Petrophysically, the upper 3 to 5 metres of the Clearwater B2 unit is more resistive, less dense and cleaner than the underlying part of the unit and is capped by a moderately distinctive, 2-5 metre thick shale referred to here as the Clearwater B2 shale marker (B2 sm) (Figure 27). The Clearwater B2 shale marker is not developed over the area of the lowstand shoreline sandstone. The upper surface of the Clearwater B2 unit is interpreted as a transgressive surface of erosion on the basis of the incised valley, the regionally consistent petrophysical characteristics of its upper surface, and its stratal context.

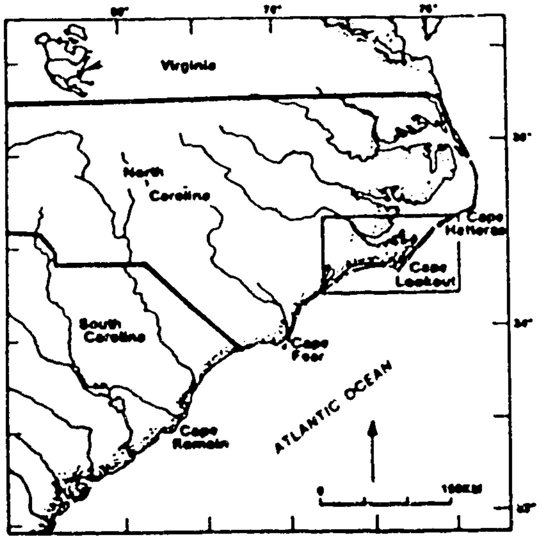

Figure 25 Morphology of the southern United States coastline showing major cuspate forelands and cape systems (modified from Heron *et. al.*, 1984).

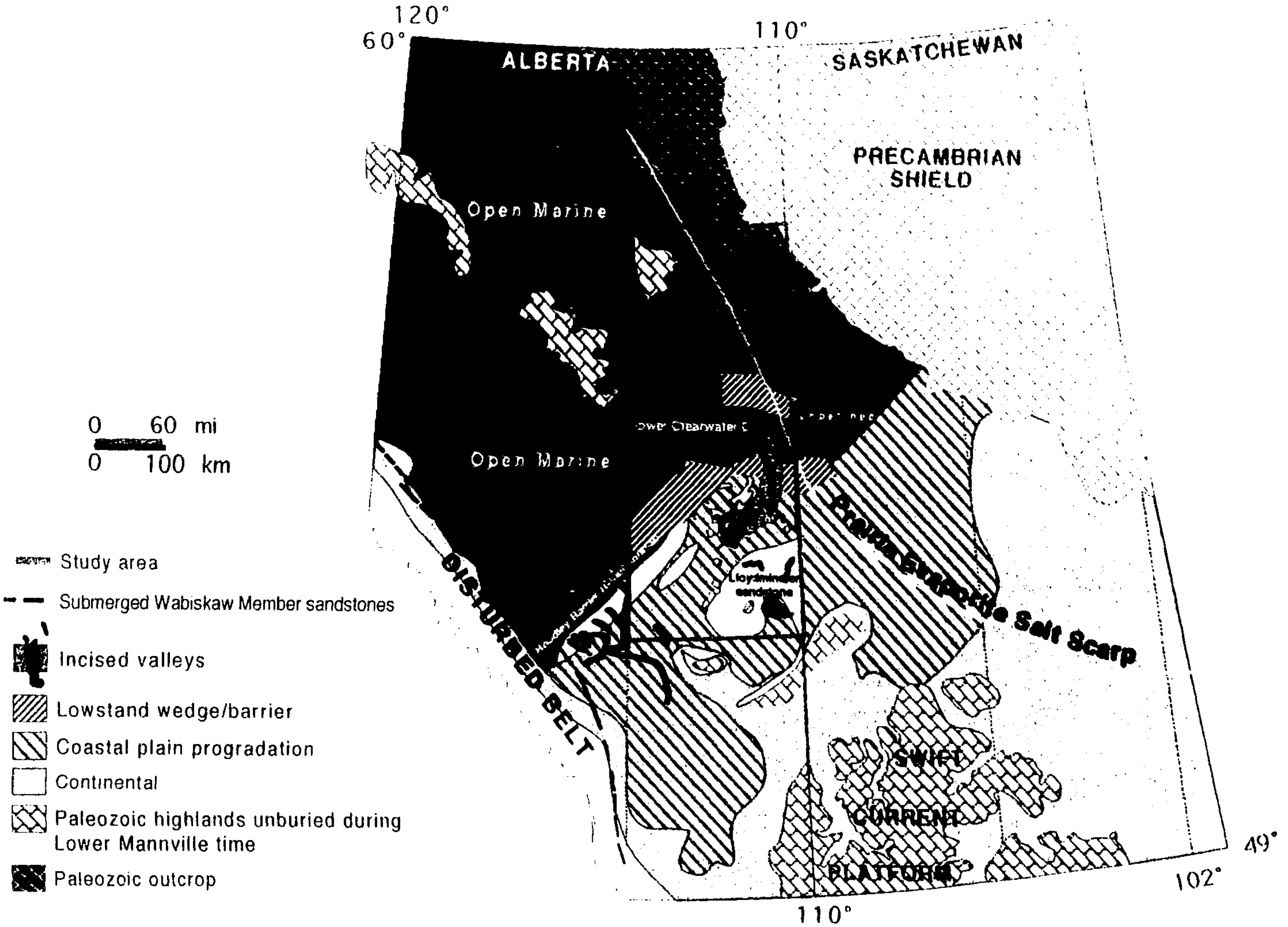

Figure 26 Second lowstand phase of the Moosebar / Clearwater Sea: incision of the barrier sandstones of the upper Glauconite B (Hoadley Barrier) and Clearwater C unit (Cold Lake), and the shoreline sandstone of the Lloydminster Member (modified from Green, 1972; Gross, 1980; Christopher, 1980; Jackson, 1984; Rosenthal, 1988).

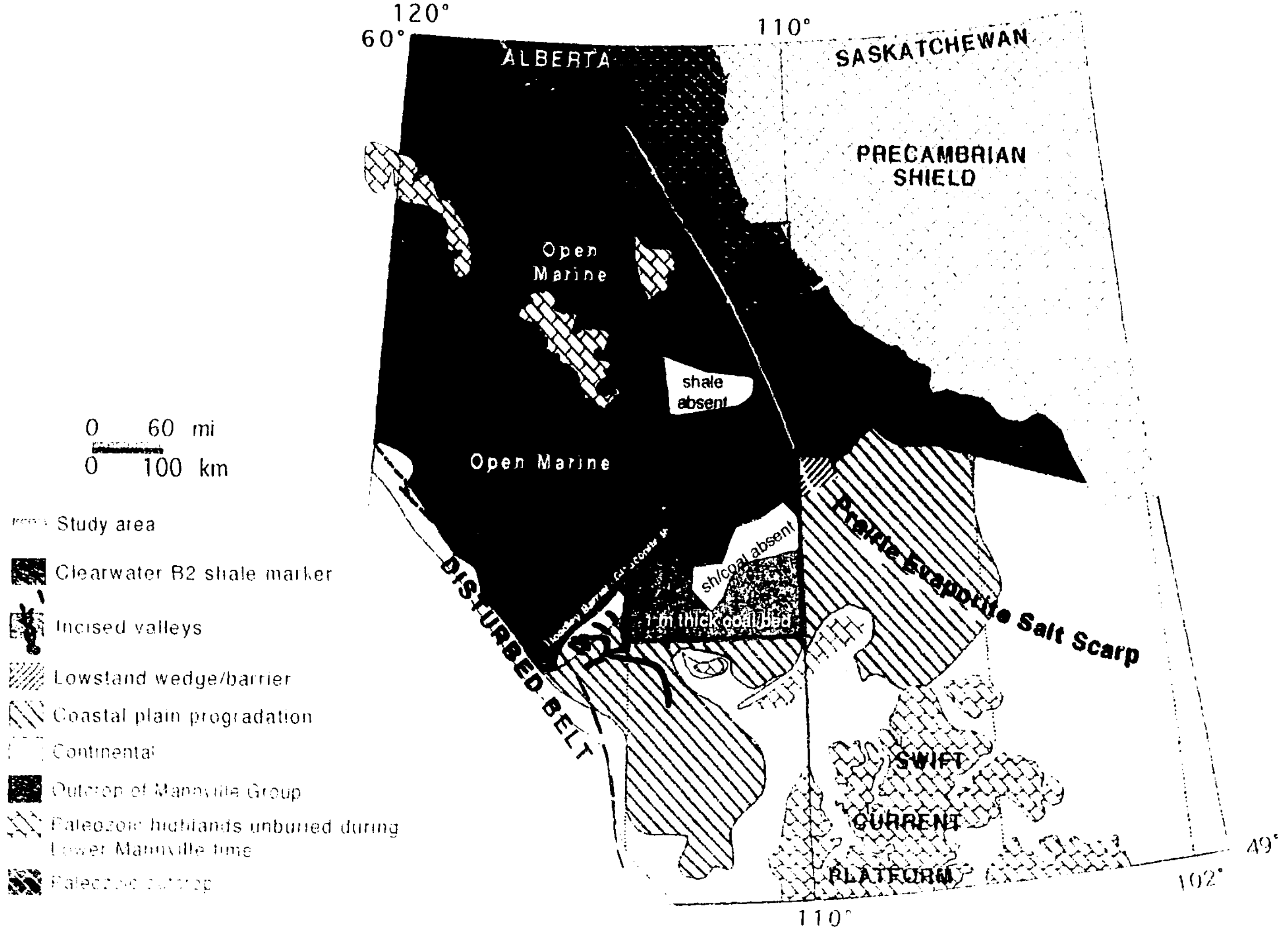

Figure 27 Third highstand phase of the Moosebar/Clearwater Sea, resulting in the widespread distribution of Clearwater B2 shale marker and Lloydminster coal overlying the Lloydminster Member (modified from Green 1972, Christopher, 1980, Gross, 1980, Jackson, 1984, Rosenthal, 1988)

2.2.6 Phase 9 - Relative Sea-level Rise - Deposition of Clearwater B1 unit and the Rex Member

The interpretation of well log data and core reveal a complex history of deposition during this phase of sea-level rise. Progressing to the north, the Clearwater B1 sandstone barrier rapidly translates into an upward-coarsening muddy sandstone succession that onlaps the Grosmont High but does not cover it (Figure 28). The muddy succession of the Clearwater B1 unit abruptly translates into a 20 m thick, clean sandstone on the northeastern flank of the Grosmont High. Progressing toward the Red Earth Highlands, the Clearwater B1 sandstone barrier translates into a 20 m thick muddy succession containing several thin sand stringers.

Progressing south of the Clearwater B1 sandstone barrier system, the lateral equivalent consists of a succession of muddy sandstone sharply overlain by a clean to muddy upward-fining sandstone (Figure 29). Further to the southeast the succession translates into an upward-coarsening succession grading still further to the southeast into a clean, blocky sandstone (Figure 30) which in turn grades into the muddy to upward-coarsening sandstone succession of the Rex Member in the Lloydminster region (T 50 along the 4th Meridian).

Observation of core (in well 10-13-64-15W4) from the muddy unit of the Clearwater B1 unit, approximately 20 km south of the Clearwater B1 barrier system, indicate sediment deposited in a brackish to brackish-marine environment (Pemberton, pers. comm.). Only an indirect link can be made between this muddy unit and the brackish sediments of the Rex Member (O'Connell, 1985, 1988) to the southeast. There is no distinctive shale or coal bed that extends between the two areas. Inference is made instead on the stratal relationships of shale, coal and sandstone successions between the two areas.

In order to explain the relationship of the Clearwater B1 barrier sandstone, the low lying coastal plain of Cape Hatteras and Cape Lookout area of the North Carolina Coast (Heron *et al.*, 1984) (Fig. 25) is again suggested to present a possible modern analogue. It is suggested that as the barrier aggraded with sea-level rise, it was separated from the shoreline sandstones of the Rex Member by an extensive brackish-marine lagoon (Figure 28). Analysis of the well logs east of range 12W4 and west of Range 12W4 in the 100 km wide band south of the barrier does not indicate the presence of channels in the muddy lower unit of the B1 overlying the Clearwater B2 shale marker. Instead the muddy lower unit of the B1 gradually translates toward the south into the muddy, upward-coarsening succession of the Rex Member.

The upper surface of the muddy lower unit of the B1 and the Rex Member provide evidence of a

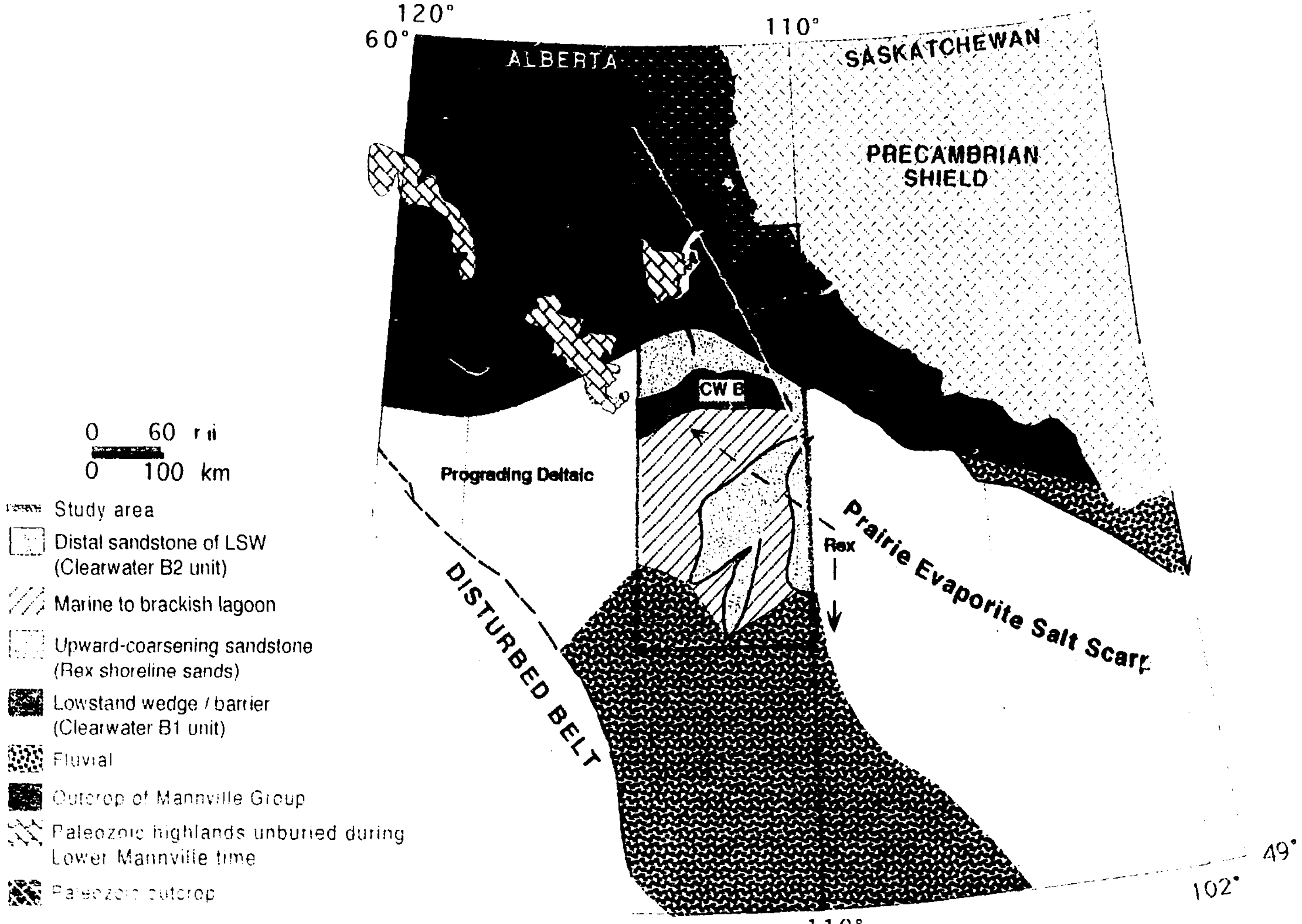

Figure 28 Early phase in the evolution of a barrier - lagoon-attached shoreline system during the third highstand phase of the Moosebar/Clearwater Sea. Distribution of the Rex Member and the Clearwater B sandstone barrier (modified from Green, 1972; Leckie and Smith, 1992)

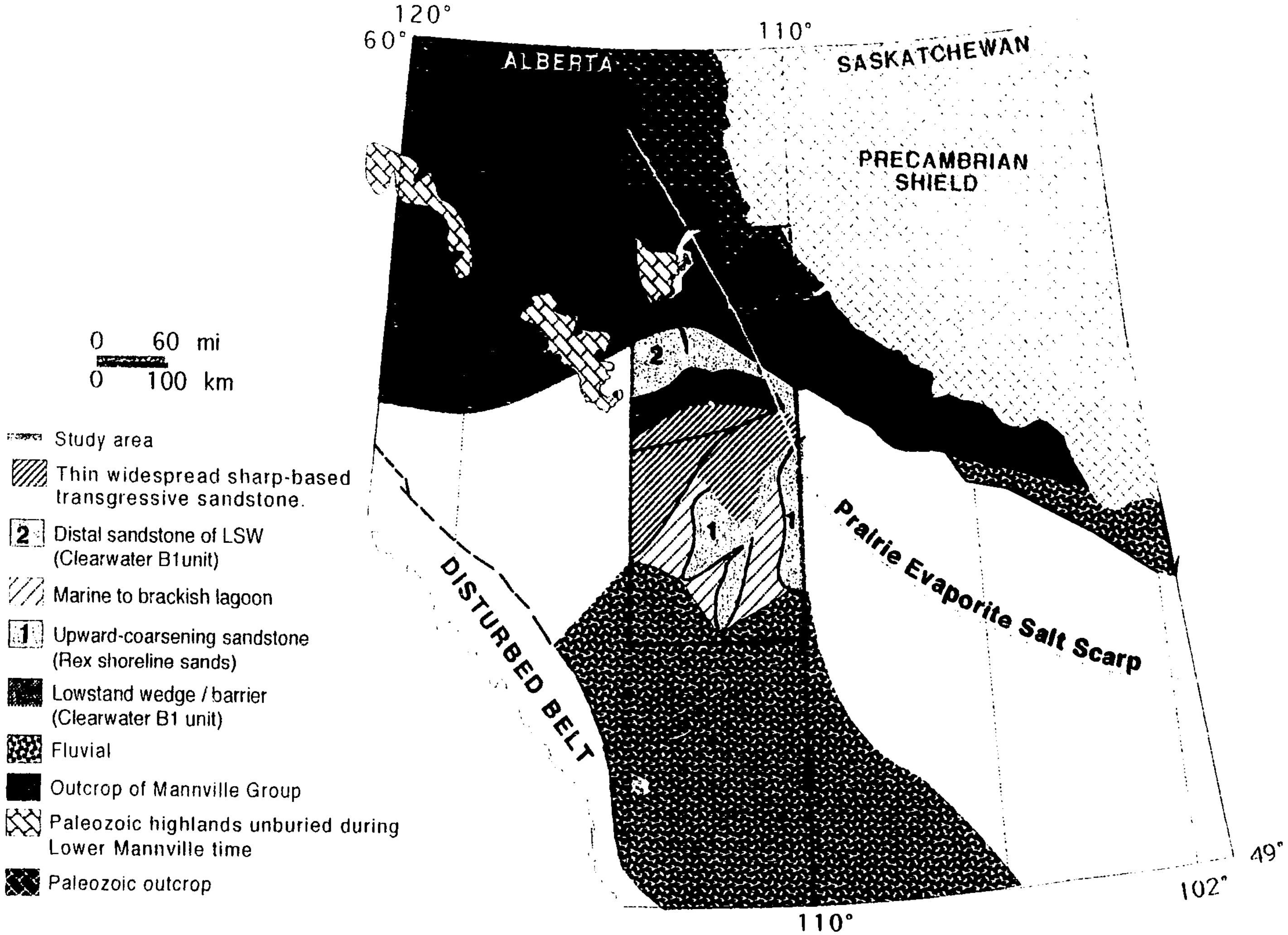

Figure 29 Third lowstand phase of the Moosebar/Clearwater Sea; ensuing fourth highstand forms widespread ravinement surfaces overlain by thin sharp-based transgressive sandstones (upper part of the Clearwater B1 unit) (modified from Green, 1972; Leckie and Smith, 1992).

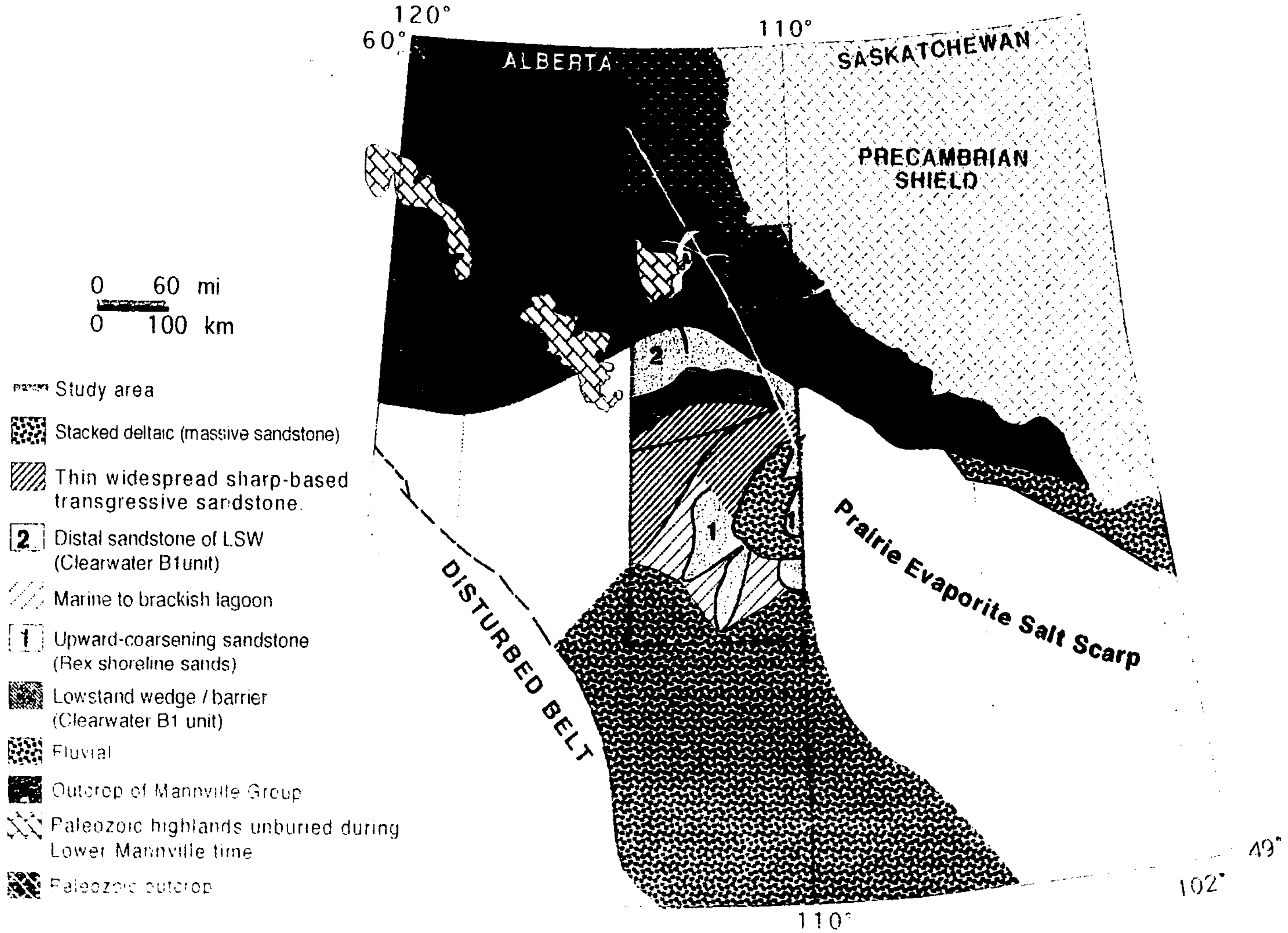

Figure 30 Peak of fourth highstand phase of the Moosebar/Clearwater Sea shoreline retrogrades and aggrades forming a stacked massive sandstone succession (upper part of the Rex Member) Clearwater B barrier sandstone remains stationary, aggrading during the phase of relative sea-level rise (modified from Green 1972, Leckie and Smith, 1992)

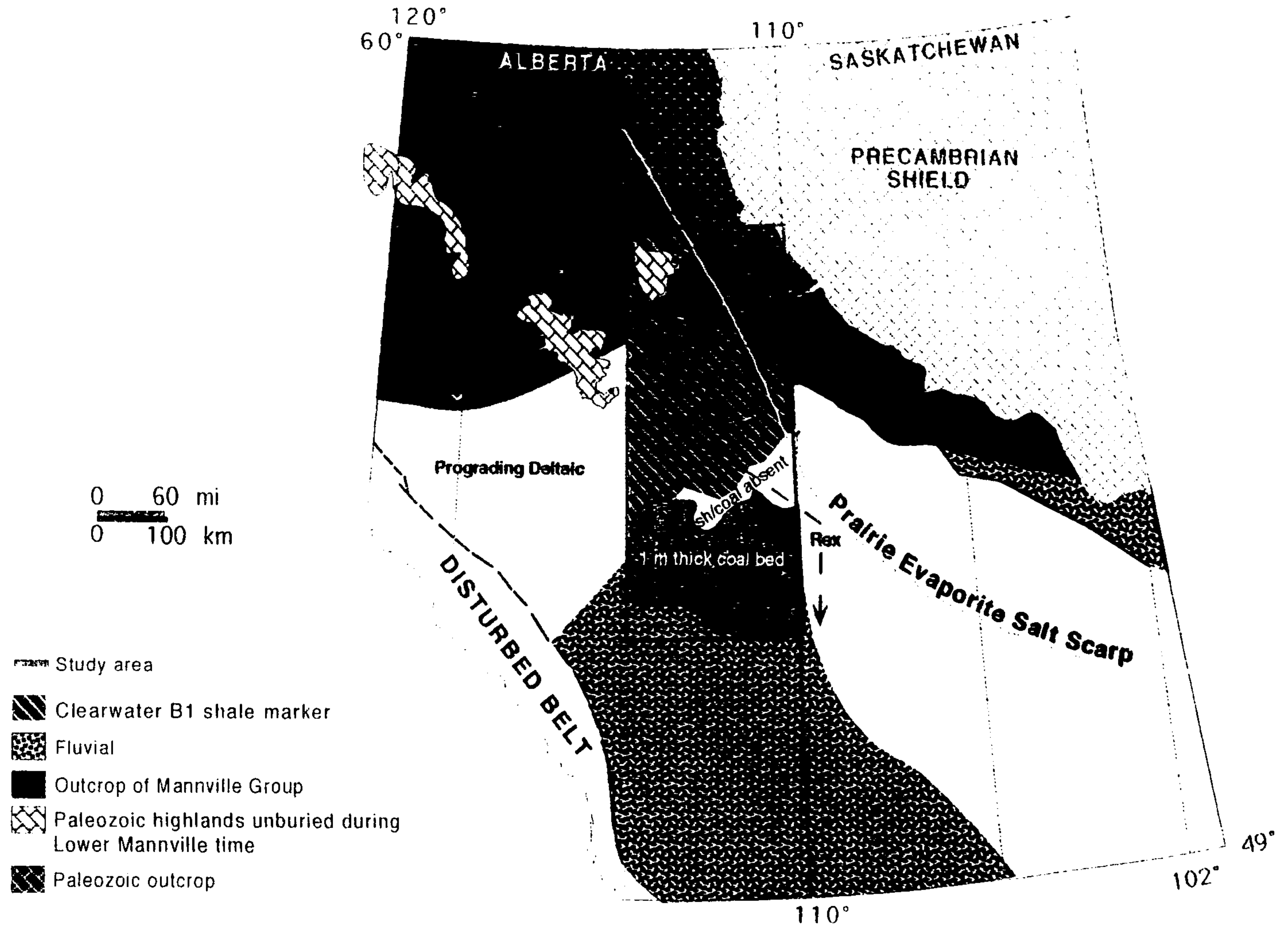

Figure 31 Distribution of the Clearwater B1 shale marker and its lateral equivalent, coal beds overlying the Rex Member resulting from widespread flooding during the fourth highstand phase (modified fromGreen, 1972; Leckie and Smith, 1992).

major lowstand surface of erosion. Shale and sand filled channels extend from the Lloydminster area (T 50, along the 4th Meridian) in a north-northwest direction up to Township 65. In the 75 to 150 km wide band (Figure 29) south of the Clearwater B1 barrier system, the lower muddy sub-unit of the Clearwater B1 is sharply overlain by at least two retrogradational, southward thinning, 5 to 15 metre thick, upward-fining sandstone successions. It is suggested that the laterally extensive contact at the base of the upward-fining sandstone successions was produced by ravinement processes during the next phase of relative sea-level rise.

Progressing to the southeast, the upward-fining sandstone succession forms the basal part of a 20 to 30 metre thick, clean, blocky sandstone succession sharply overlying the erosional surface of muddy strata of the Rex Member. The widespread 2 to 3 metre thick Clearwater B1 shale marker (B1 sm) (Figure 31) overlying the Clearwater B1 unit merges into the middle of the stratigraphic interval of this blocky sandstone succession. The shale bed also coincides stratigraphically with a 0.5 to 1 m thick coal bed present within the upper part of the blocky sandstone succession. Stratigraphically this coal correlates to the coal bed forming the upper surface of the Rex Member.

2.3 Upper Mannville Succession - post Clearwater B unit-Rex Member

Deposition of the Mannville succession, above the Clearwater B1 - Rex succession, is interpreted to have been a function of tectonic subsidence along the northern flank of the Snowbird Tectonic Zone (STZ) (Figure 32). South of the STZ, the succession is characterized by thin, 5 to 10m thick, upward-coarsening successions, capped by thin organic beds. Along, and to the north, of the STZ, semi-linear, 25 to 40 m thick, blocky sandstone successions parallel the STZ and the axis of the Peace River Arch. Four distinct sandstone wedges successively prograde and aggrade to the north-northwest. In ascending order they include the Clearwater A sandstone (CW A), Grand Rapids C sandstone (GR C), Grand Rapids B sandstone (GR B), Grand Rapids A sandstone (GR A) (Kramers and Prost, 1986). The thicker sandstone successions are interpreted to be lowstand wedges on the basis of their stratigraphic position relative to their thinner lateral equivalents to the south, their onlap and downlap patterns, and the extensive incision of the thinner equivalents to the south. In the Lloydminster region, the thinner equivalents have been subdivided in ascending order into the General Petroleums, Sparky, Waseca, McLaren and Colony.

The General Petroleums is interpreted as the earliest phase of shoreline progradation following a significant period of relative sea-level rise during the flooding of the Clearwater B1 unit. At least six offlapping lowstand successions (Figure 33) are recognized and referred to as 1 to 6, with increasing numbers equating with successively younger deposits. Lowstand incision is interpreted to have cut through units 1 to 3 depositing unit 4. Unit 5 may have had a more easterly source. Unit 6 is a thin, sharp-based, upward-fining, 10 m thick sandstone sheet deposited out on the open shelf. This progradational cycle closes with regional flooding submerging units 5 and 6, and onlapping deposits units 3 and 4.

During the transgression, a barrier system was localized on deposits units 3 and 4 (Figure 34). South of the barrier system, the lateral equivalent is correlated with the Sparky Member. Beyond the type location in the Lloydminster area, the Sparky Member is recognized as an extensive succession consisting of a lower 2 to 3 metre thick shale and an overlying 9 to 15 thick, upward-coarsening sandstone. South of Township 55, the succession is commonly overlain by a 0.5 to 1 m thick coal unit or a 5 to 10 m thick muddy succession containing thin coal beds (Figure 35). From the observed stratigraphic relations it is suggested that the localization of the barrier system resulted in the development of an extensive lagoon across which a thin shoreline sandstone rapidly prograded. Infilling of the lagoon led to shoreline progradation to the northwest of the barrier system. Flexure along the SnowBird Tectonic Zone resulted in the aggradation of a 40 m thick, stacked shoreline succession, the Grand Rapids C unit. A similar process contributed to the Waseca Member-Grand Rapids B unit (Figure 36); the McLaren Member-Grand Rapids ? unit; and the Colony Member-Grand Rapids A unit (Figure 37).

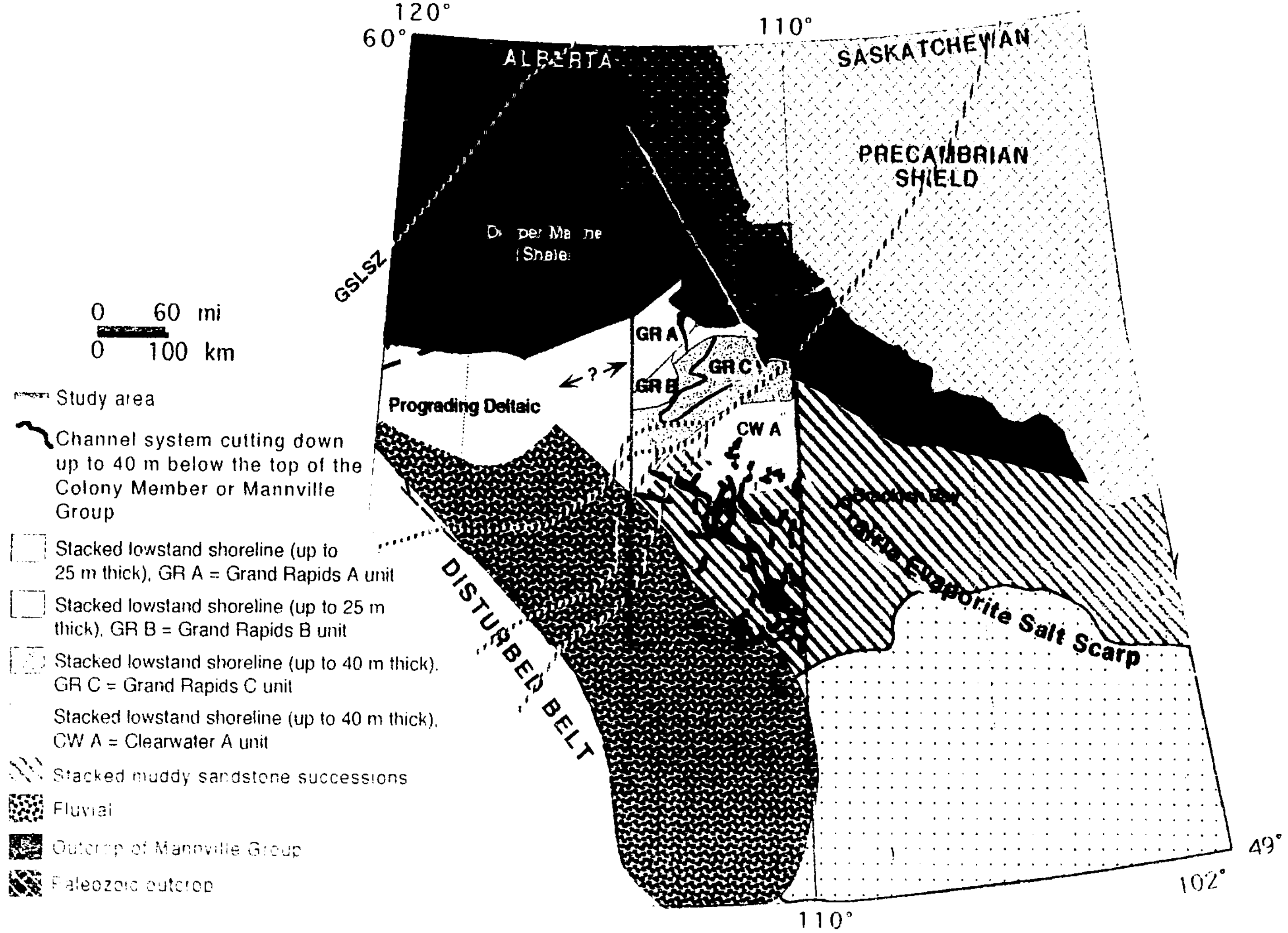

Figure 32 Generalized distribution of post-Sparky succession (Upper Mannville) shown in relation to the Snowbird Tectonic Zone (modified from Green, 1972, Gross 1980, Jackson 1984, Kramers, 1986).

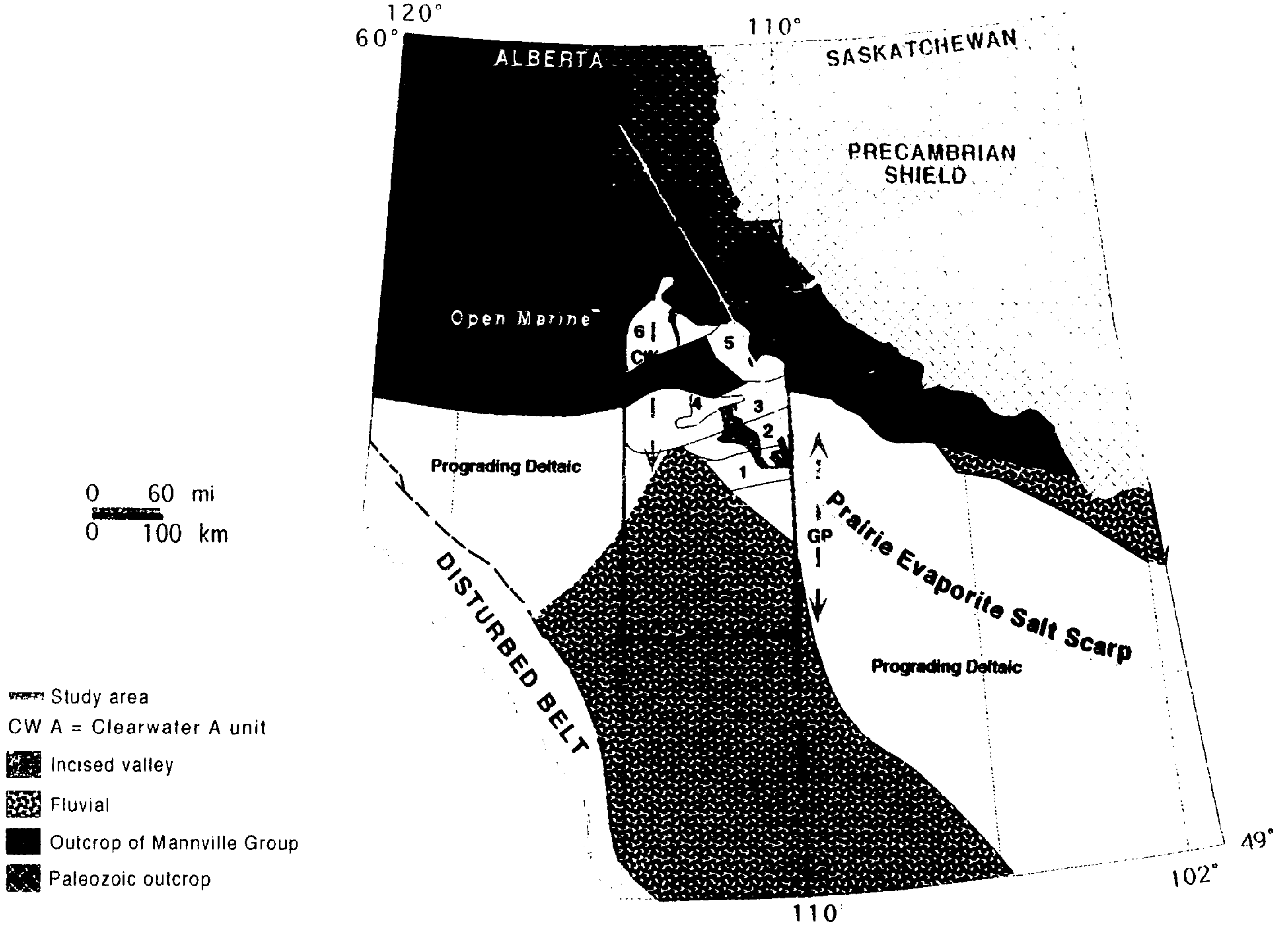

Figure 33 Distribution of thin (5 m thick) muddy sandstone sheets of General Petroleums Member shown translating into the downlapping lowstand wedges1 to 6 of the Clearwater A unit (modified from Green, 1972; Christopher, 1980; Gross, 1980Rosenthal, 1988; Jackson, 1984;).

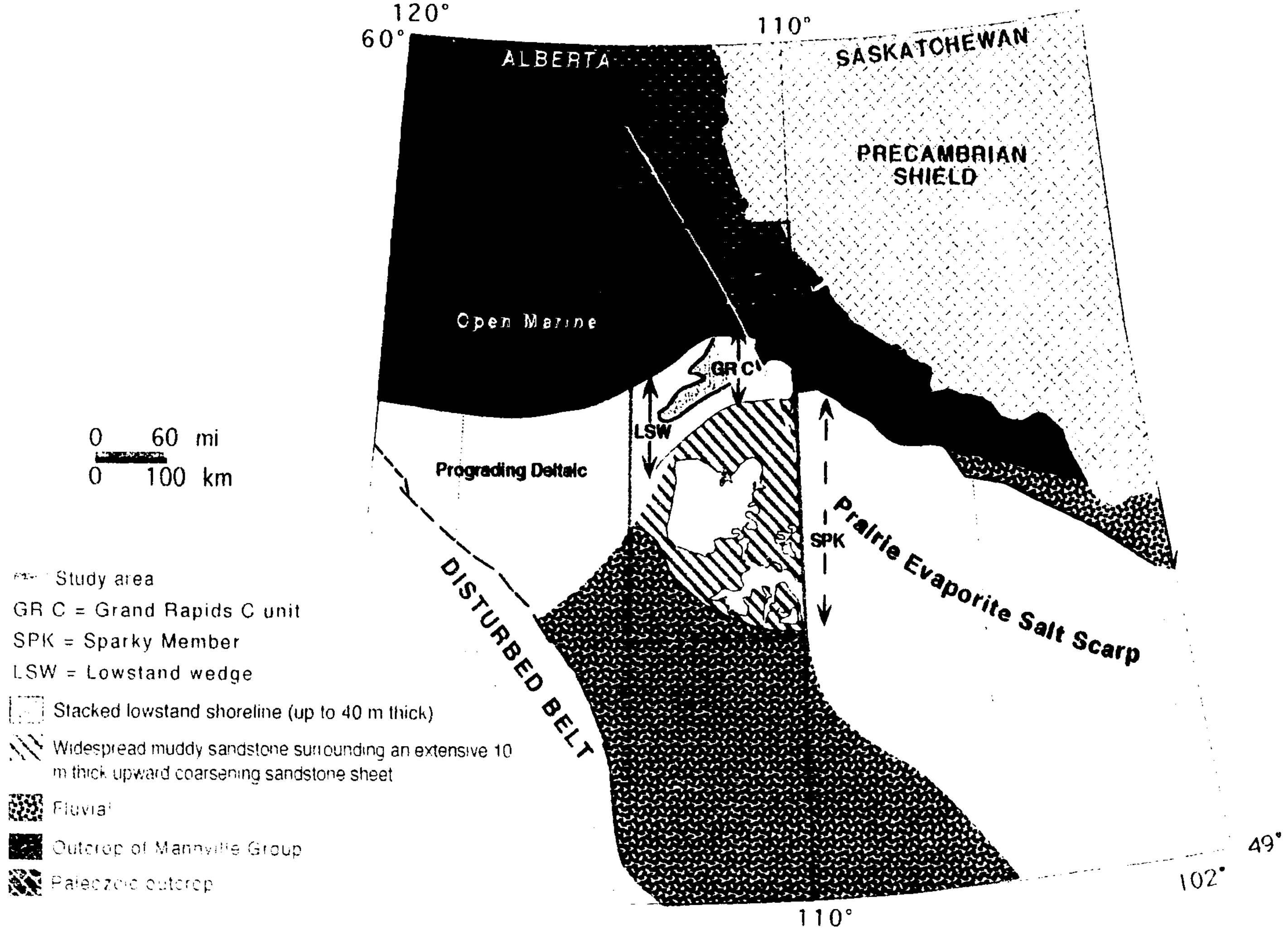

Figure 34 Distribution of Sparky member shown merging with Grand Rapids C barrier sandstone (modified from Green, 1972, Gross 1980, Kramers, 1986, Leckie and Smith 1992.)

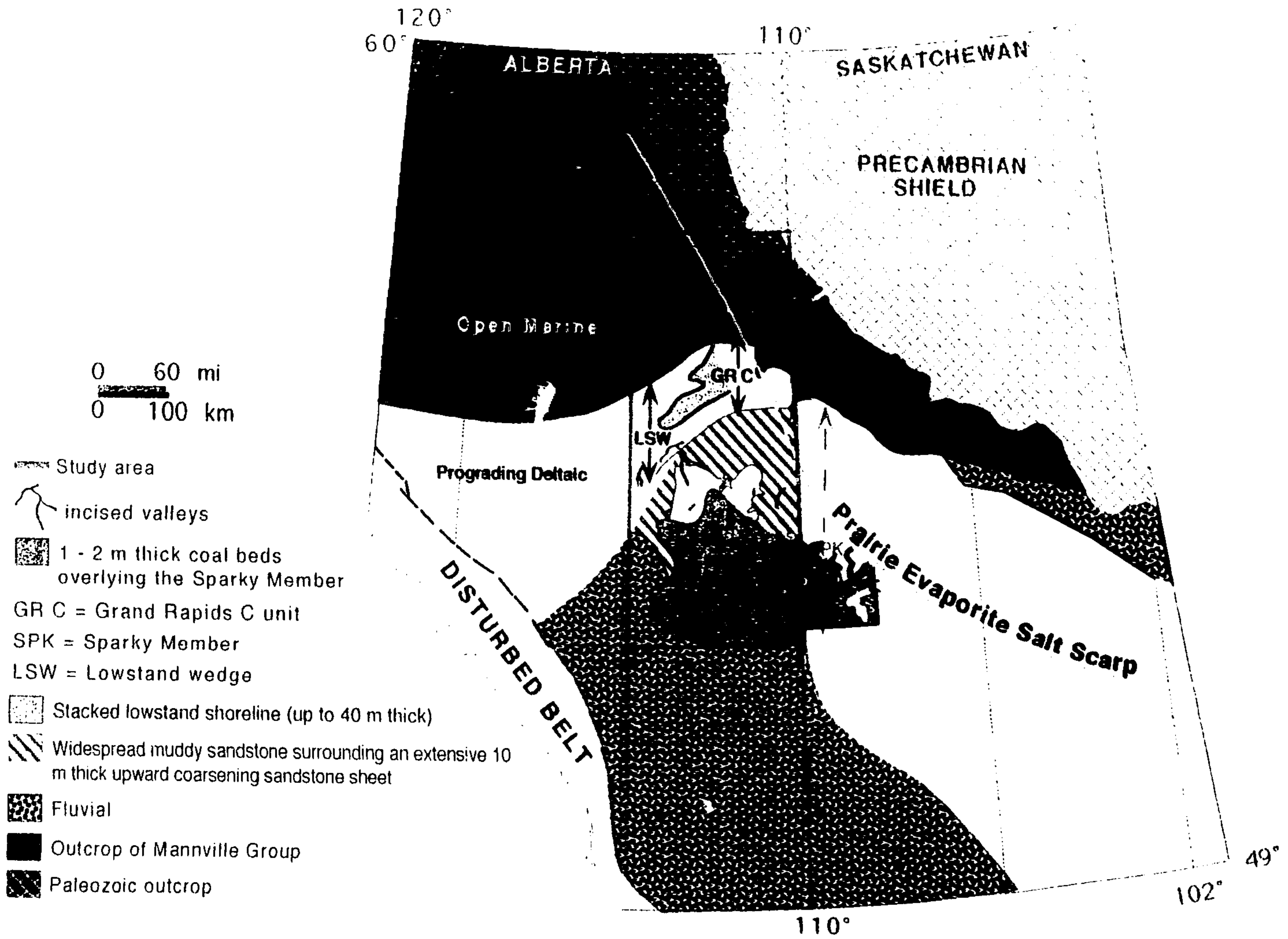

Figure 35 Distribution of Sparky coal overlying Sparky Member (modified from Green, 1972; Gross, 1980; Smith *et. al.*, 1984; Kramers, 1986; Leckie and Smith, 1992).

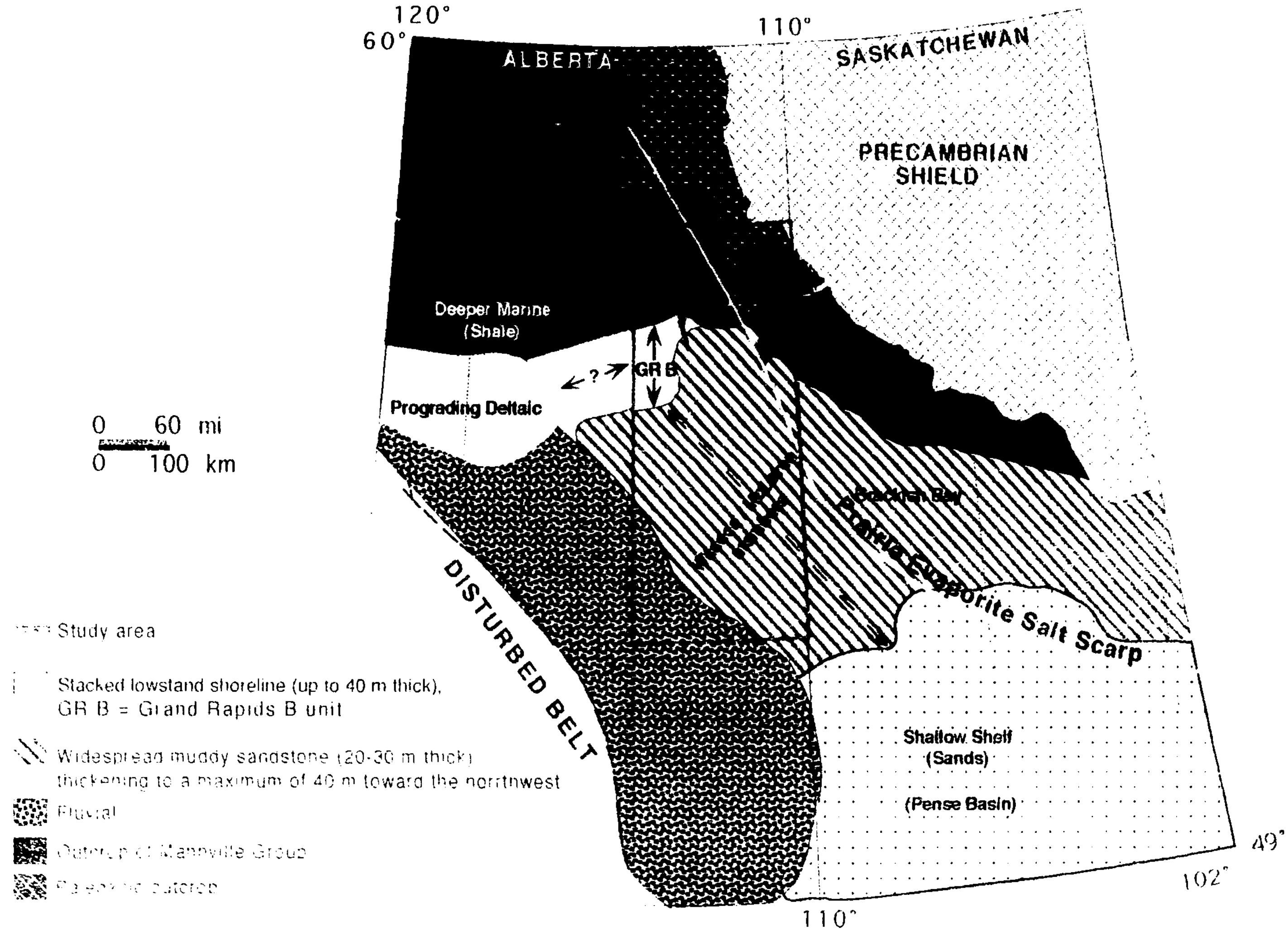

Figure 38. Distribution of muddy Waseca and McLaren member shown merging with Grand Rapids B barrier sand stone (modified from Green, 1970; Gross, 1980; Kramers, 1986; Leckie and Smith, 1992)

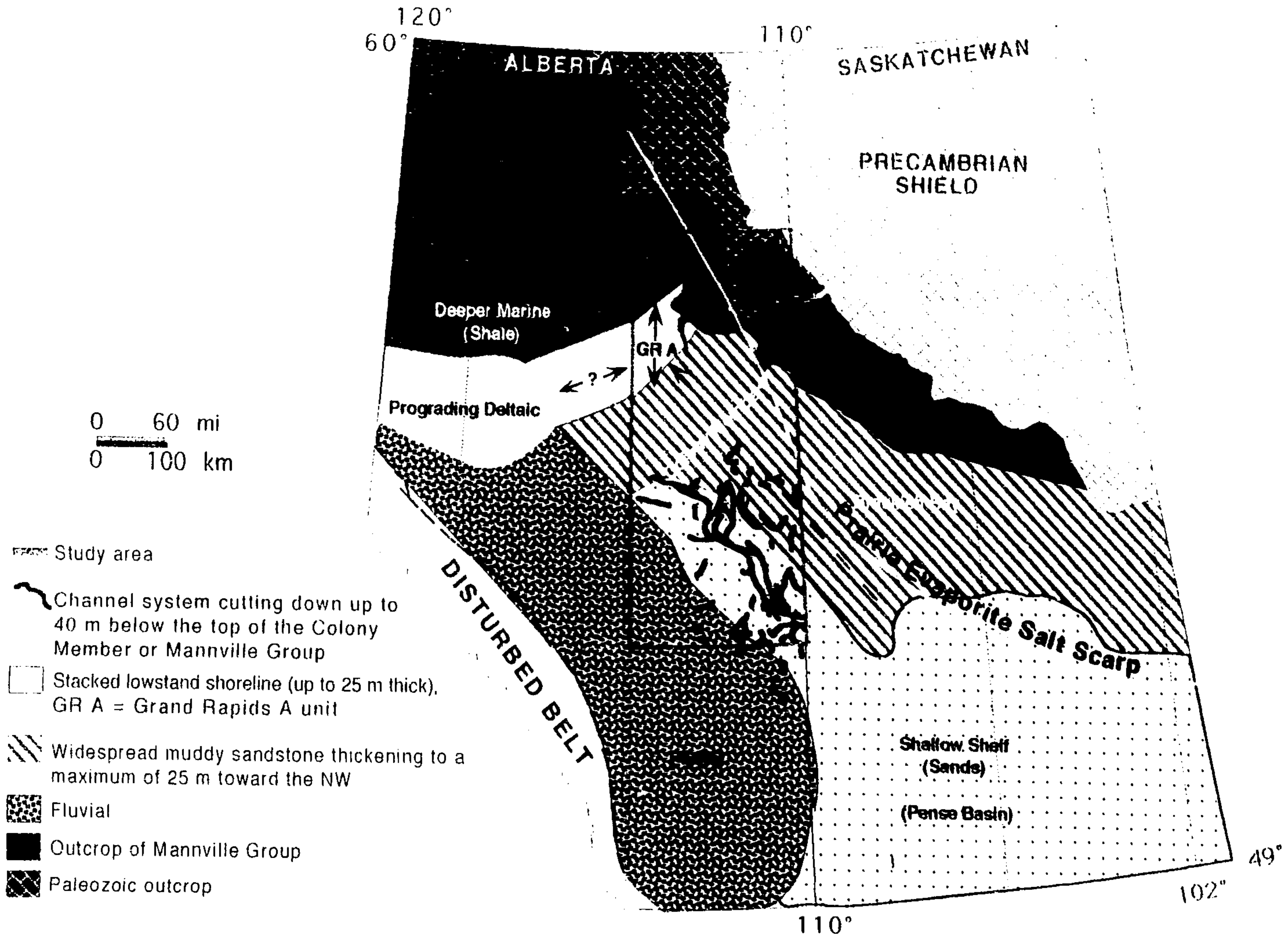

Figure 37 Distribution of muddy Colony Member shown merging with Grand Rapids A barrier sand stone (modified from Green, 1972; Gross, 1980; Kramers, 1986; Leckie and Smith, 1992).

3 Discussion and Conclusions

Within the first order Zuni Sequence, the Mannville Group is a second order sequence comprised of a lower "Transgressive Systems Tract" and an upper "Highstand Systems Tract" of third order. The transition between the two systems tracts is based on stratal geometry, reflecting a change from retrogradation to progradation. Fourth to fifth order transgressive/regressive cycles are superimposed on both of these systems (Figure 12).

The Lower Cretaceous Mannville Group of eastern Alberta is subdivided on the basis of surfaces reflecting relative sea-level change. A review of the stratigraphic record through the correlation of geophysical well log data indicates there are at least nine fourth order cycles of relative sea-level rise that flooded the region. The lower three flooding events subdivide a retrogradational succession while the upper six subdivide a dominantly progradational succession.

The initial flooding event is associated with the transgression of the Boreal Sea during which time paleo-valleys on the sub-Cretaceous unconformity were filled with fluvial deposits. The flooding of broad fluvial plains forming the top of the Dina member, the mid to lower McMurray Formation and the Ellerslie Formation left a widespread, 1 to 5 m thick shale succession. Infilling of flooded embayments was a function of sediment supply. During the ensuing highstand of the sea, embayments closer to the foredeep of the foreland basin were more sediment-starved compared to those toward the Precambrian Shield. The flooding event is followed by a major drop in sea-level contributing to deep incision. The second flooding event transforms incised valleys into long estuaries which later forms broad estuaries as sea-level rises above the coastal plain. During the relative still-stand of the sea, shoreline advance resulted in the deposition of a widespread, 10 to 15 thick, sandstone sheet. The third flooding event marks the time of maximum transgression, during which an open marine environment covered the northern half of the Alberta Foreland Basin.

During Upper Mannville time the factors of relative sea-level rise, basin subsidence and sediment input resulted in a succession that is both aggradational and progradational. The succession can be subdivided on the basis of six flooding surfaces reflecting temporary periods of widespread transgression. Laterally, the succession between flooding events, is comprised of three components. The more landward component (southeastern area) is a 15 to 25 m thick succession extending up to 300 km in width and consisting of an upward-shoaling, muddy to sandy facies often capped by a thin 0.5 to 2 m thick coal. Progressing to the north-northwest, the landward component translates over a few kilometres into a 20 to

40 m thick, clean, blocky sandstone wedge forming a linear, 20 to 100 kilometre wide band, trending northeast -southwest. Progressing to the north-northwest, the blocky sandstone wedges translate gradually over 20 to 30 kilometres into laterally extensive mud dominated successions containing laterally extensive thin sandstone stringers.

The transition from the upward-shoaling, muddy to sandy landward component to the thicker blocky sandstone wedge occurs along the length of the Snowbird Tectonic Zone (STZ). Relative to the STZ, lowstand incision is prevalent to the south but difficult to recognize to the northwest. It is suggested that the STZ marks the southeastern limit of Precambrian basement subsidence associated with the collapse of the Peace River Arch during the Lower to Upper Cretaceous. Regionally, accommodation space formed during each flooding event is assumed to be a function of the limit of basement flexure along the STZ. Southeast of the STZ, the accommodation space is primarily a function of the extent of relative sea-level rise whereas to the northeast of the STZ, the accommodation space is a function of both the extent of relative sea-level rise and the rate of basement subsidence.

If the above reasoning is valid the following scenario is proposed for the evolution of the Upper Mannville succession of eastern Alberta. During the stillstand, following each transgressive phase, the rate of shoreline progradation would slow or stop as it advanced a region of greater subsidence. With constant sea-level, a stacked shoreline sandstone would evolve while the coastal plain would be incised by shallow fluvial systems. If sea-level dropped or sediment input increased the shoreline would move seaward with an increase in the depth of regional incision. If sea-level rose, a stranded barrier system may have been localized along the former shoreline position with an extensive brackish /marine lagoon formed behind it. In general, analysis of the cross-section data, supports a cycle of sea-level rise, standstill and sea-level fall. The area to the south of the STZ was dominated by shallow, marine to brackish, lagoonal environments while the area to the north was dominated by deeper marine environments.

The Lloydminster, Rex, and General Petroleum members are the initial phase of shoreline progradation culminating in thick lowstand wedges included in the Clearwater Formation. The Sparky, Waseca, McLaren, and Colony members are the initial phase of shoreline progradation culminating in thick lowstand wedges included in the Grand Rapids Formation.

The mapping of each cycle of relative sea-level rise is based on the correlation of thin, distinctive marine shale beds in the northern part of the region, and in the south, by less distinct marine to brackish shale beds that often overlie distinctive regional coal beds. Ambiguity in the correlation of each flooding event especially above the McMurray - Cummings level occurs between the thinner muddy to sandy upward-shoaling succession to the south and the thicker blocky, sandstone wedge to the north. In this zone neither marine shale beds nor coal beds are well developed. In these areas, widespread erosional surfaces, where developed, and the stratal geometry of the Upper Mannville succession, both to the north and south, must be used to infer stratigraphic equivalence.

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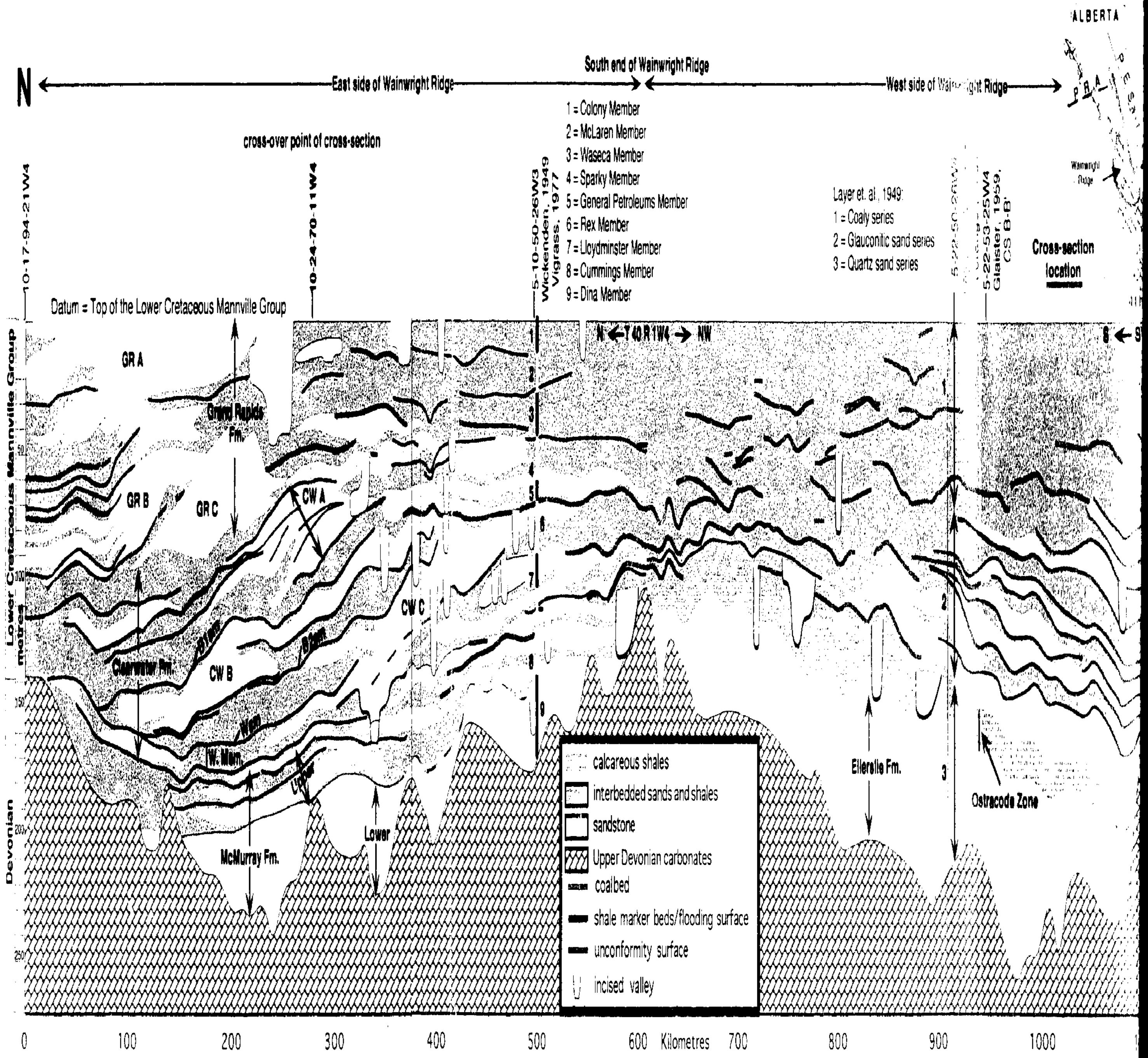
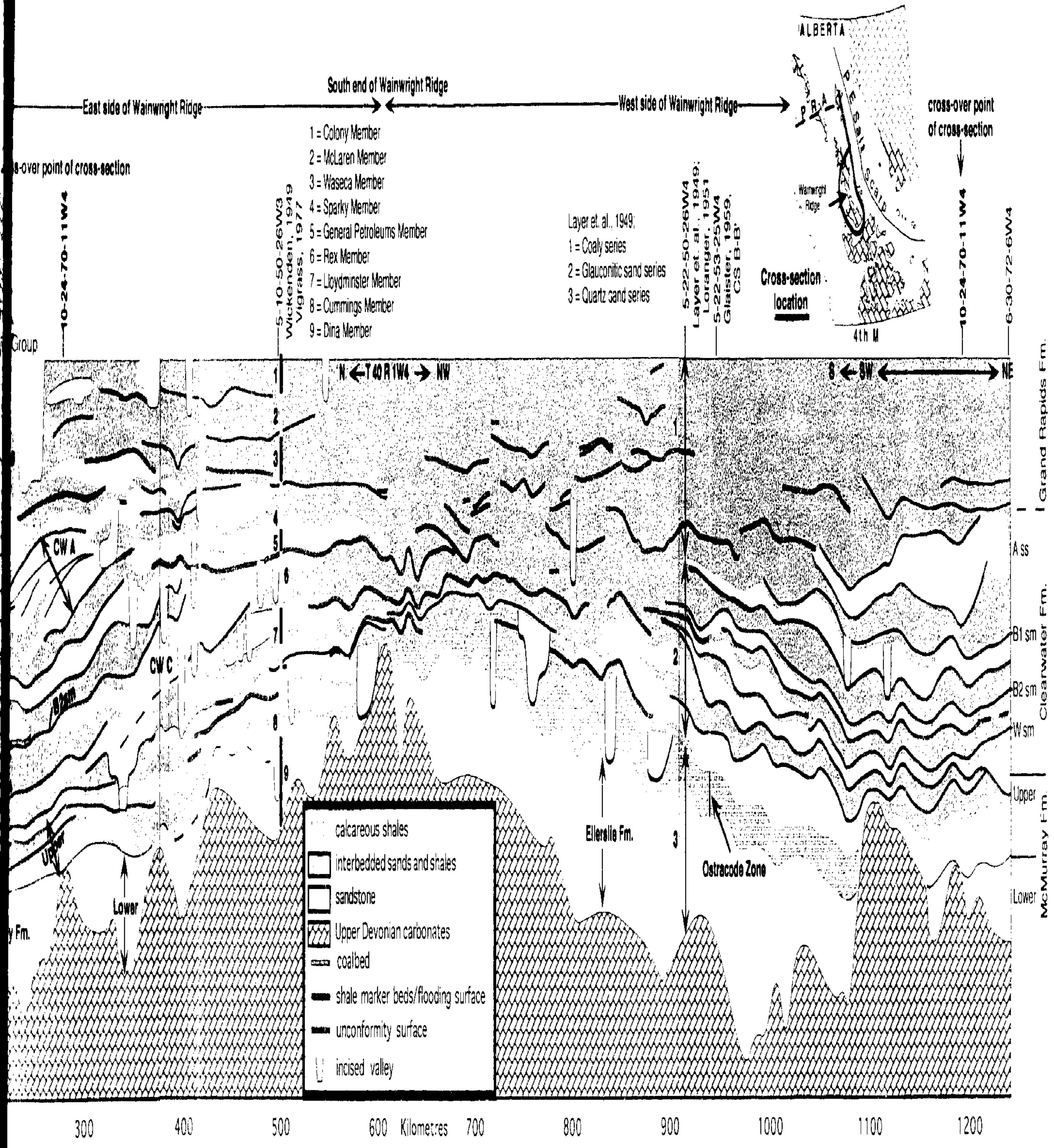
Appendix A

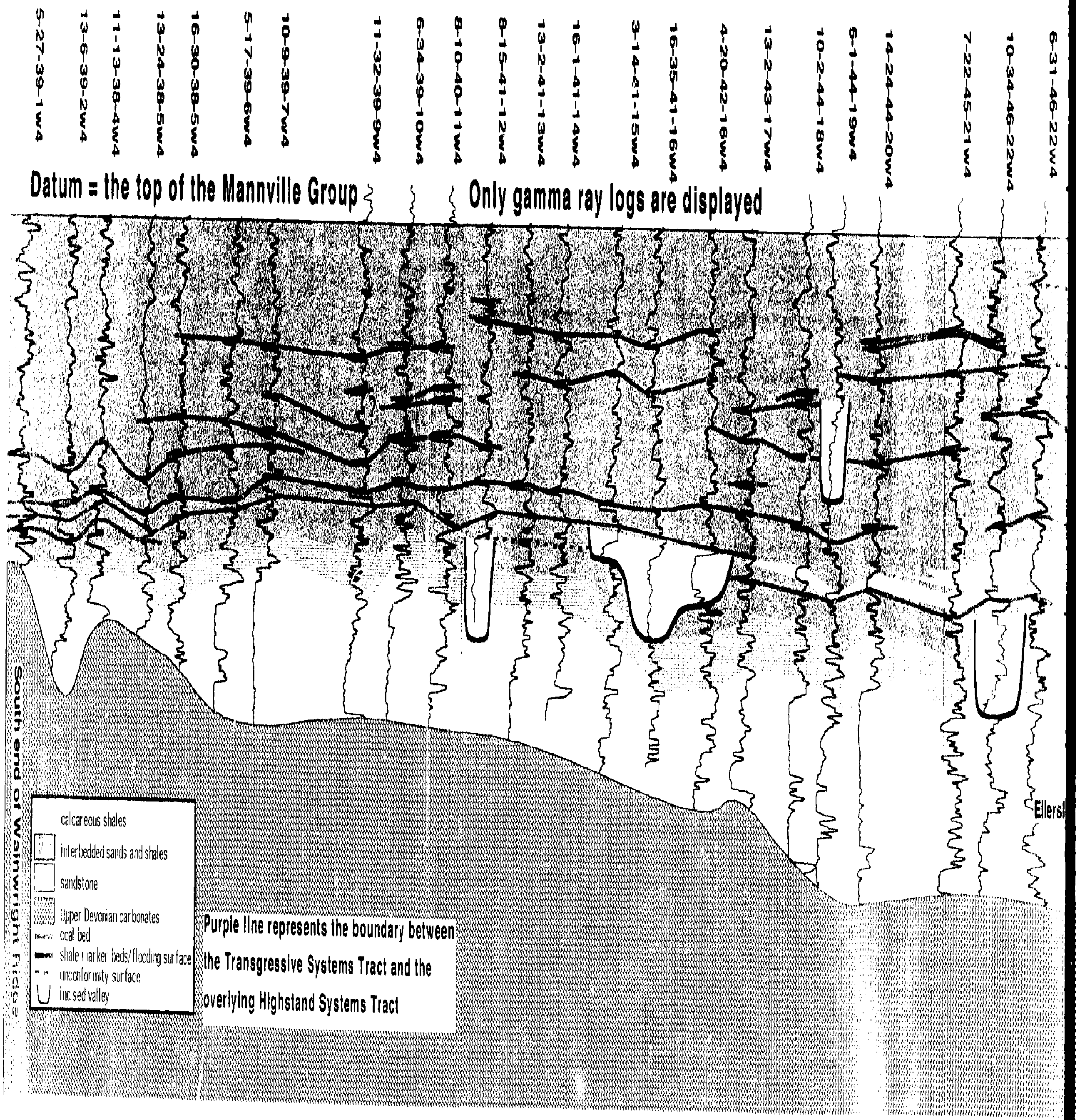


Appendix A CS 2 Schematic cross-section illustrating the sequence stratigraphy of the Mannville Group of east-central Alberta (GR = Grand Rapids ; sm = shale marker ; CW = Clearwater; W = Wabiskaw)

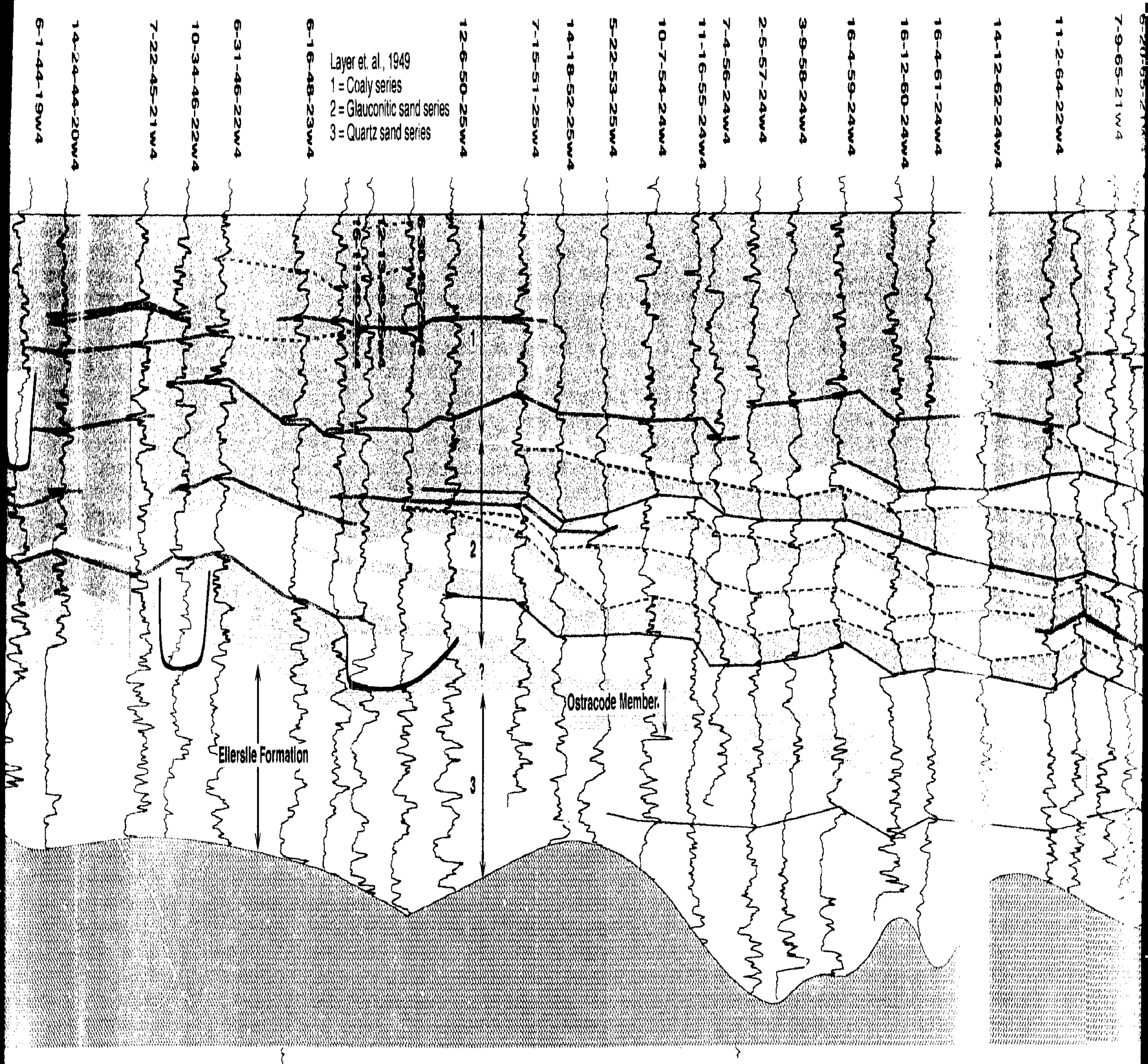


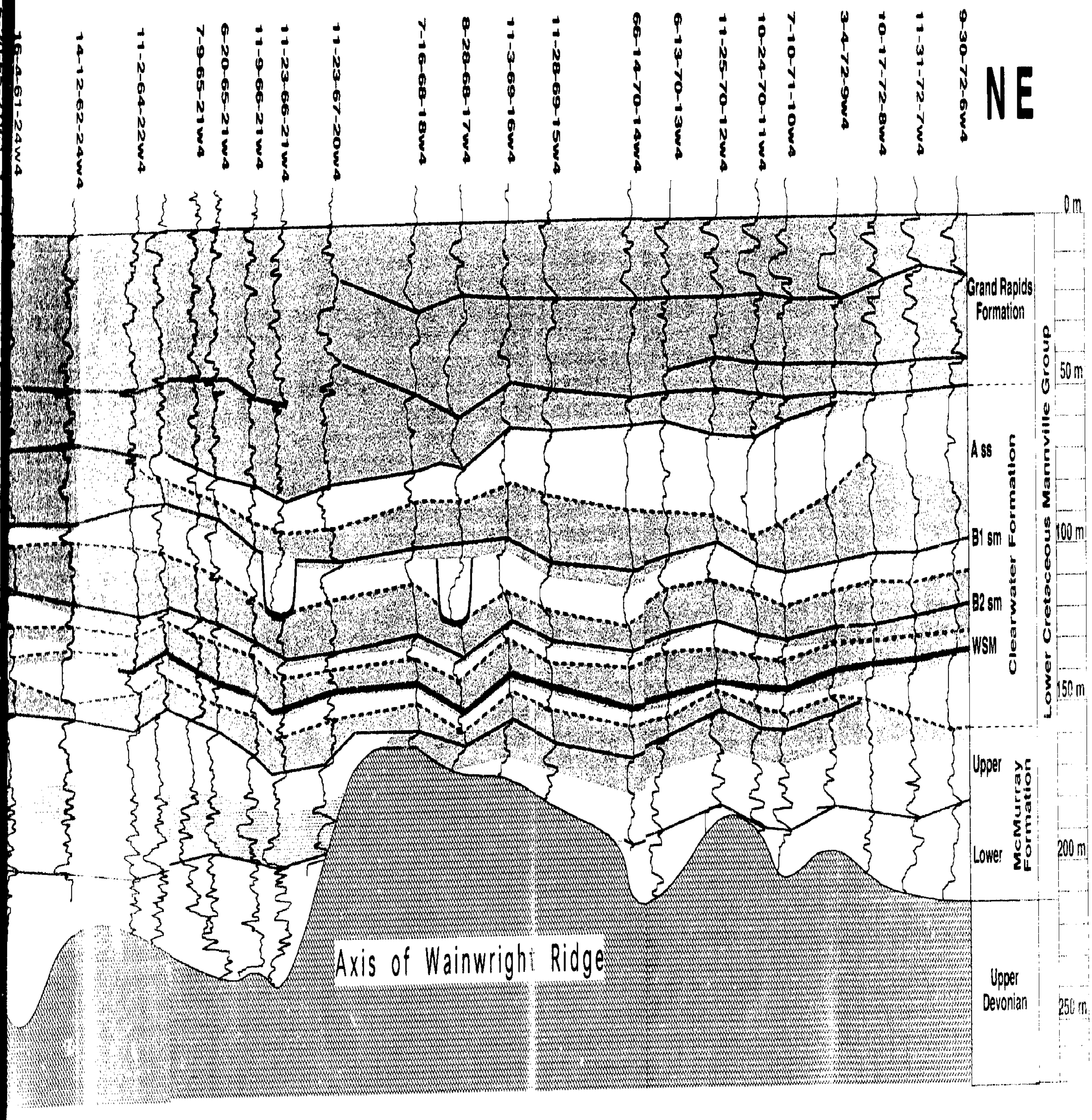
g the sequence stratigraphy of the Mannville Group of east-central Alberta (GR = Grand Rapids ; sm = shale marker ; CW = Clearwater; W = Wabiskaw)

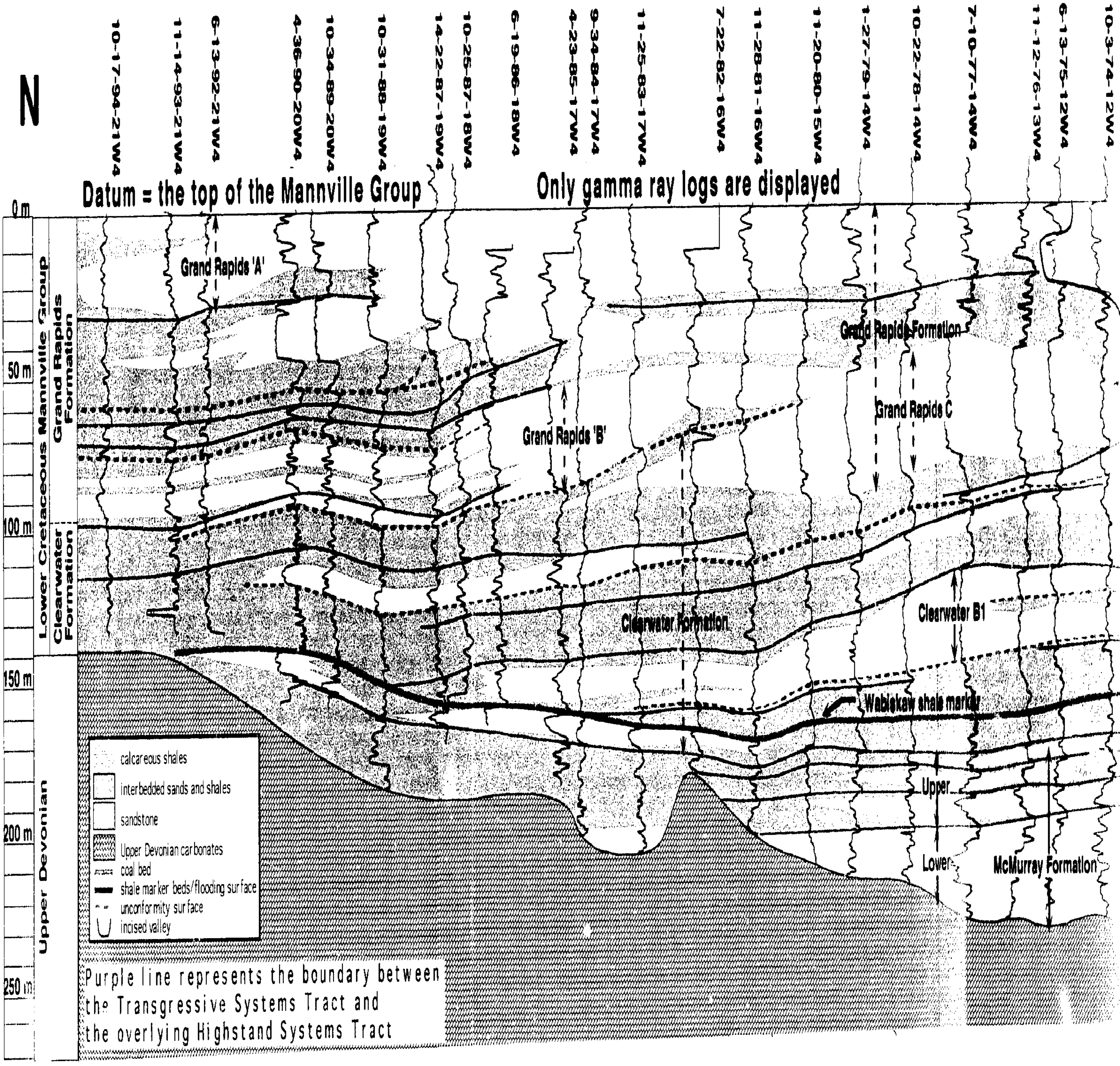
vertical exaggeration = 1200



Appendix A Cross-section 1, part B

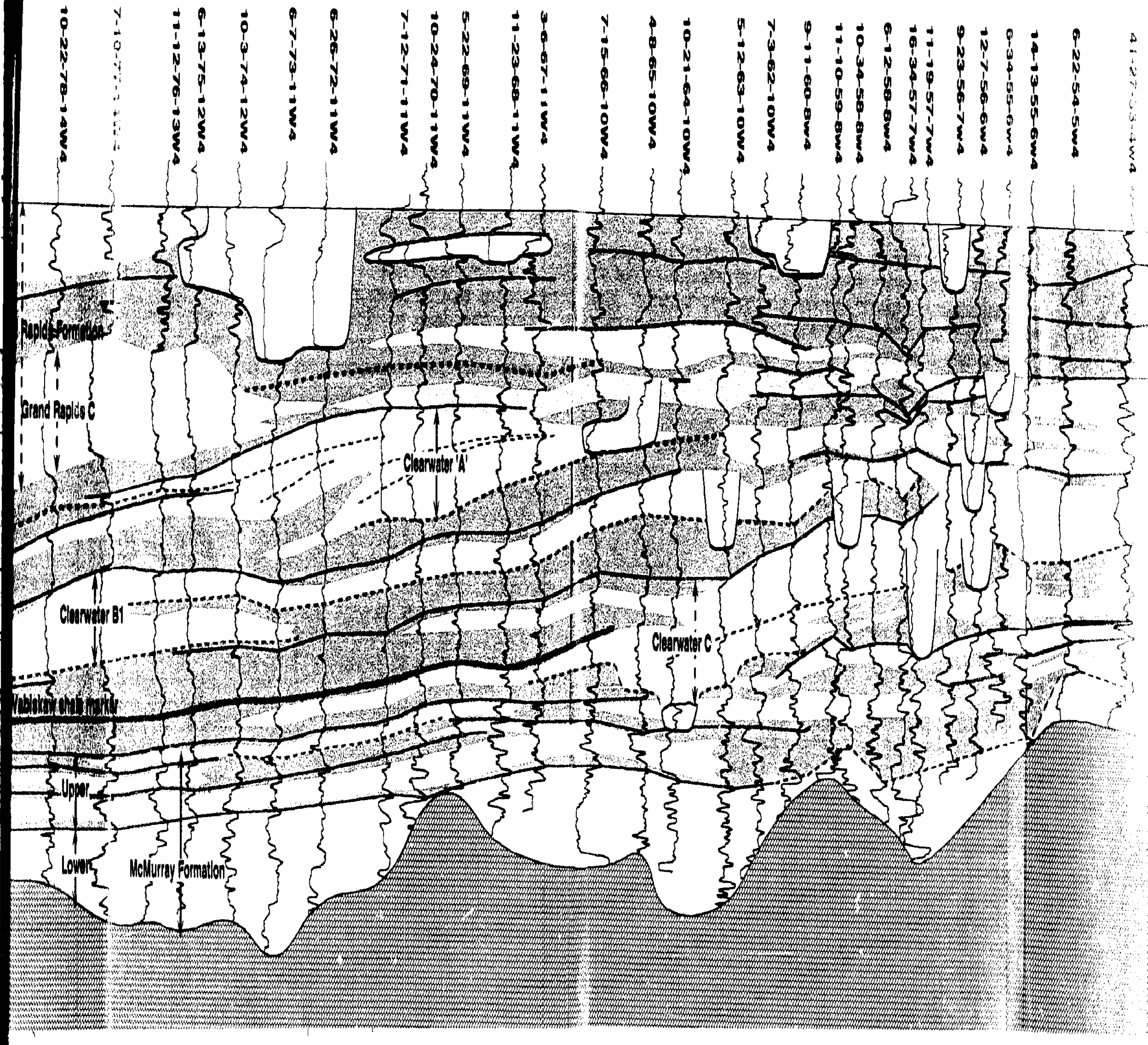

6-1-44-19w4
14-24-44-20w4
7-22-45-21w4
10-34-46-22w4
6-31-46-22w4
6-16-48-23w4
12-6-50-25w4
7-15-51-25w4
14-18-52-25w4
5-22-53-25w4
10-7-54-24w4
11-16-55-24w4
7-4-56-24w4
2-5-57-24w4
3-9-58-24w4
16-4-59-24w4
16-12-60-24w4
16-4-61-24w4
14-12-62-24w4
11-2-64-22w4
7-9-65-21w4
Layer et. al., 1949
1 = Coaly series
2 = Glauconitic sand series
3 = Quartz sand series
1
2
?
3
Ostracode Member.
Ellerslie Formation


NE
16-4-61-24w4
14-12-62-24w4
11-2-64-22w4
7-9-65-21w4
6-20-65-21w4
11-9-66-21w4
11-23-66-21w4
11-23-67-20w4
7-16-68-18w4
8-28-68-17w4
11-3-69-16w4
11-28-69-15w4
66-14-70-14w4
6-13-70-13w4
11-25-70-12w4
10-24-70-11w4
7-10-71-10w4
3-4-72-9w4
10-17-72-8w4
11-31-72-7w4
9-30-72-6w4
0 m
50 m
100 m
150 m
200 m
250 m
Grand Rapids Formation
A ss
B1 sm
B2 sm
WSM
Clearwater Formation
Lower Cretaceous Mannville Group
Upper
Lower
McMurray Formation
Upper Devonian
Axis of Wainwright Ridge

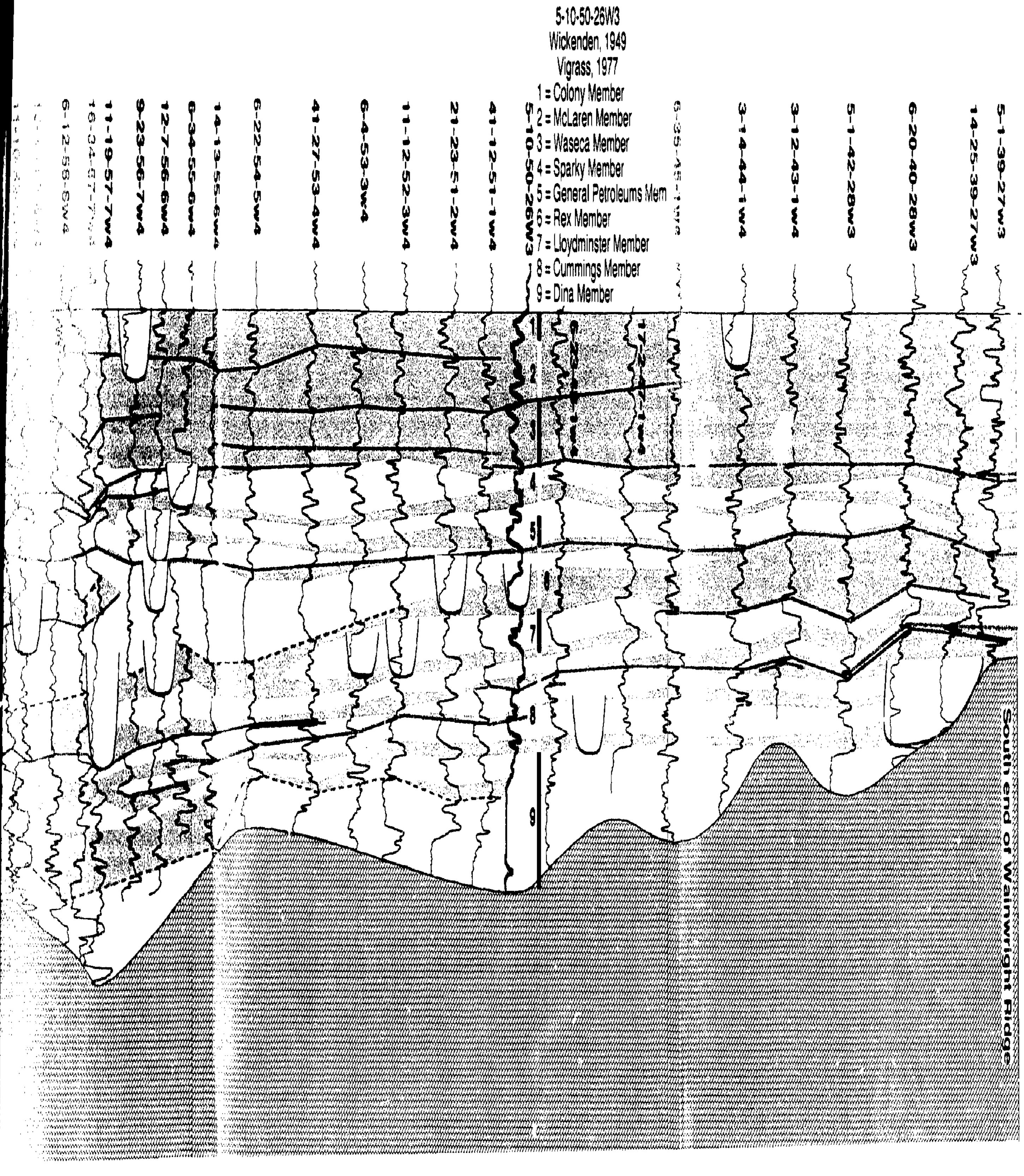


Purple line represents the boundary between the Transgressive Systems Tract and the overlying Highstand Systems Tract

Appendix A Cross-section 1, part A



10-22-78-14W4
11-12-76-13W4
6-13-75-12W4
10-3-74-12W4
6-7-73-11W4
6-26-72-11W4
7-12-71-11W4
10-24-70-11W4
5-22-69-11W4
11-23-68-11W4
3-6-67-11W4
7-15-66-10W4
4-8-65-10W4
10-21-64-10W4
5-12-63-10W4
7-3-62-10W4
9-11-60-8W4
11-10-59-8W4
10-34-58-8W4
6-12-58-8W4
16-34-57-7W4
11-19-57-7W4
9-23-56-7W4
12-7-56-6W4
6-34-55-6W4
14-13-55-6W4
6-22-54-5W4
Rapids Formation
Grand Rapids C
Clearwater 'A'
Clearwater B1
Clearwater C
Wabiskaw shale marker
Upper
Lower
McMurray Formation


5-10-50-26W3
Wickenden, 1949
Vigrass, 1977
1 = Colony Member
2 = McLaren Member
3 = Waseca Member
4 = Sparky Member
5 = General Petroleums Mem
6 = Rex Member
7 = Lloydminster Member
8 = Cummings Member
9 = Dina Member
6-12-56-8w4
16-34-57-7w4
11-19-57-7w4
9-23-56-7w4
12-7-56-6w4
6-34-55-6w4
14-13-55-6w4
6-22-54-5w4
41-27-53-4w4
6-4-53-3w4
11-12-52-3w4
21-23-51-2w4
41-12-51-1w4
5-10-50-26W3
6-35-45-1w4
17-2-47-1w4
3-14-44-1w4
3-12-43-1w4
5-1-42-28w3
6-20-40-28w3
14-25-39-27w3
5-1-39-27w3
1
2
3
4
5
6
7
8
9
South end of Wainwright Ridge