Chapter 23 – Cretaceous Cardium Formation of the Western Canada Sedimentary Basin

F.F. Krause - The University of Calgary, Calgary
K.B. Deutsch[1] - The University of Calgary, Calgary
S.D. Joiner[2] - The University of Calgary, Calgary
J.E. Barclay[3] - Geological Survey of Canada, Calgary
R.L. Hall - The University of Calgary, Calgary
L.V. Hills - The University of Calgary, Calgary

Overview and Geologic Framework

The Cardium Formation, exposed along the Rocky Mountain Foothills and present beneath the Alberta Plains, comprises a terrigenous, muddy, sandy, and conglomeratic clastic wedge that accumulated during the Turonian and Coniacian stages of the Late Cretaceous along the western margin of the Alberta Foreland Basin. This clastic wedge is a complex lithostratigraphic interval that contains multiple disconformities, paraconformities and diastems of variable regional extent. The formation is encased in a thick succession of black mudstones, the Blackstone/Kaskapau formations below and the Wapiabi/Muskiki formations above. All these formations comprise a sedimentary assemblage assigned throughout Alberta and British Columbia to the Smoky, Alberta, La Biche and Colorado groups.

In plan view the formation is arranged in an arcuate strip, approximately 1000 km long, that swings through a 90 degree arc from Waterton Lakes National Park and Canada-U.S. border, past Grande Prairie, Alberta and beyond to Dawson Creek, British Columbia (Fig. 23.1). In the foothills, the formation has been brought to the surface by multiple, juxtaposed, east verging thrusts. In the plains it is confined to the subsurface within allochthonous and autochthonous intervals of the Colorado/Alberta/Smoky/La Biche groups. The clastic wedge projects approximately 200 km into the basin's interior from the British Columbia-Alberta boundary, is 150 m thick in foothills exposures, thins in the subsurface of the plains to less than 50 m, and becomes indistinct along its easternmost terminus, melding into the mudstones (Fig. 23.2). The formation's dominant rock types are mudstone and sandstone, with small but important conglomerate fractions.

The Cardium Formation is of significant geological interest for two principal reasons: 1) it represents a complex stratotectonic pulse that alternated between sandy and muddy stages during the period of maximum inundation of the Mesozoic North American foreland basin, and 2) it possesses a colossal hydrocarbon storage capacity, manifest in a series of stratigraphic traps, the largest of which is the supergiant Pembina Field (Fig. 23.2) (Nielsen and Porter, 1984; Krause et al., 1987a, b).

Sedimentological responses identified within the formation indicate that accumulation took place in muddy and sandy inner and outer shelf, shoreface, lagoonal, tidal, estuarine and coastal plain settings. The deposits alternated between coarse- and fine-grained stages that were controlled by both autocyclic and allocyclic processes, such as delta avulsion, compaction-driven subsidence, tectonically-driven subsidence, tectonically-controlled sediment sources, and tectonic and eustatically controlled changes in sea level. These processes contributed to the development of a complex sedimentary mosaic containing varied and abundant stratigraphic traps and reservoirs. Hydrocarbons stored in these reservoirs appear to have been derived from neighboring rocks, and are typically light and sweet (Deroo et al., 1977; Creaney and Allan, 1992). Reservoirs have been found at depths ranging between 1200 and 2700 m.

Previous Work

Literature on the Cardium Formation and its hydrocarbon reservoirs is considerable, exceeding 400 references (see Krause et al., 1987a; Leggitt et al., 1992). This literature comprises an array of geological and engineering studies published in academic and trade journals, oil company submissions to Alberta's Energy Resources Conservation Board, Geological Survey of Canada reports and maps, and university theses and technical memoranda.

Engineering. The formation has been described in a variety of engineering studies. The following are of regional stratigraphic interest: Groeneveld (1964), Gillund (1969), Alpay (1972), Chakravorty et al. (1978), McLeod (1978), Purvis and Bober (1979), Krause and Collins (1984) (see Krause et al., 1987a, b for other references).

Geophysics. Geophysical studies considered here are of regional stratigraphic interest. These studies have established characteristic seismic reflection signatures for the formation, in the search for stratigraphic traps and the description of triangle zones; namely, those by Wren (1984), Slatt et al. (1987), Chappell (1989), MacKay (1991) and Nazar (1992).

Mineralogy and Diagenesis. Information on the diagenesis and mineralogy of the formation is sparse. Notable studies include Sinha (1970), Machemer (1984), Krause et al. (1987b), Staley (1987), Machemer and Hutcheon (1988) and Selim et al. (1990).

Paleontology. There are not many paleontological studies of the Cardium Formation and it has only been studied systematically in the past decade: Pemberton and Frey (1984) - trace fossils; Sweet and McIntyre (1988) - palynomorphs; Heise (1987) - palynomorphs; Vossler and Pemberton (1988) - trace fossils; Hall et al. (1991) - ammonites.

Sedimentology. Contributions to our present understanding of the Cardium Formation since the advent of modern sedimentological practices have been many. They include Berven (1966), Michaelis and Dixon (1969), Swagor et al. (1976), Griffith (1981), Wright and Walker (1981), Krause (1982), Walker (1983a, b, c; 1984; 1985), Krause and Nelson (1984, 1991), Krause et al. (1987b, *in press*), Plint and Walker (1987), Plint et al. (1987), Plint (1988), Bergman and Walker (1987), Walker and Eyles (1988, 1991), Leggitt et al. (1990), Joiner (1991), Keith (1985, 1991), Pattison and Walker (1992), and Deutsch (1992).

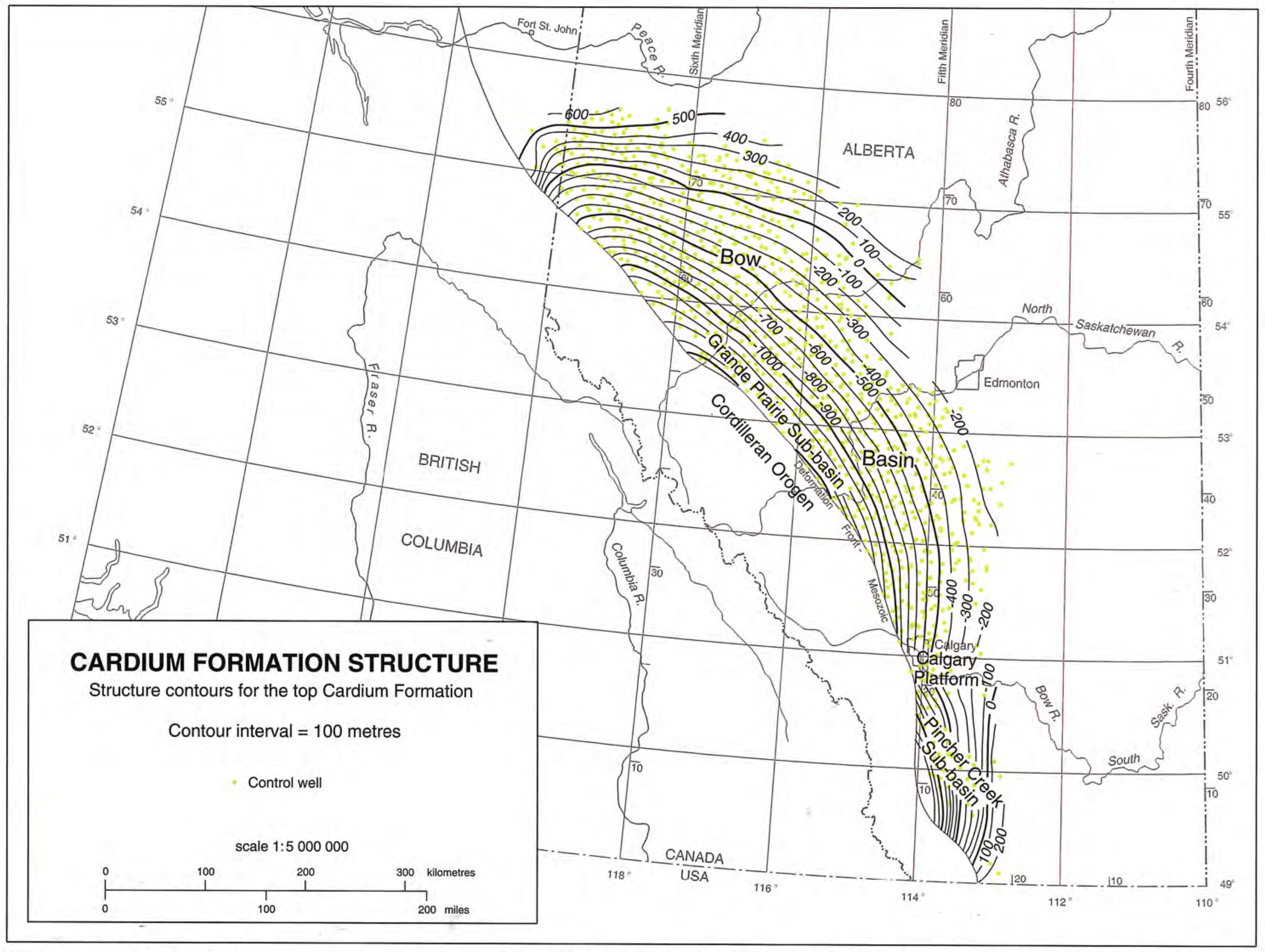

Figure 23.1 Cardium Formation structure map, illustrating present regional dip to the southwest, caused mainly by thrust sheet loading from the Cordilleran Orogen to the southwest. The dominant tectonic element on this map is Bow Basin. Subsidiary tectonic elements are Calgary Platform (Williams and Burk, 1964) and Grande Prairie and Pincher Creek sub-basins.

Stratigraphy. Extensive stratigraphic studies of the Cardium Formation in the subsurface and in outcrop, by the oil industry and the Geological Survey of Canada, followed the discovery of the supergiant Pembina oilfield in 1953 (Michaelis, 1957; Nielsen, 1957; Stott, 1963, 1967). More recently, regional characteristics of the formation have been discussed by Duke (1985) and Plint et al. (1988). Stratigraphic schemes for the subsurface and correlations to outcrop have been presented by Michaelis (1957), Swagor (1975), Krause and Nelson (1984), Plint et al. (1986, 1988), Hall et al. (*in press*).

As outlined in Figures 23.3a and 23.3b, three schemes for subdividing the formation into members are presently in use. Two classifications are lithostratigraphic, one proposed for outcrops by Stott (1963, 1967) and one designed for the subsurface by Krause and Nelson (1984). A third scheme is an informal allostratigraphic classification proposed by Plint et al. (1986, 1987, 1988). Significantly, this latter classification correlates outcrop with subsurface strata, but discards all previous proposals. Recently, Deutsch (1992) and Deutsch and Krause (1990) have shown that the Ram and Moosehound members of Stott (1963) can be extended to the subsurface, thus casting doubt on the need to eliminate previous work and confirming Stott's (1967) correlations into the subsurface (see also the Stratigraphy discussion below). Other previous and formally established stratigraphic intervals are also correlatable between outcrop and subsurface, but their stratigraphic characterization is presently under review.

Structure. Structural analysis of the formation has proceeded from a dual perspective: 1) mesoscale examination of the distribution and orientation of fractures in outcrop, notably by Muecke and Charlesworth (1966) and Barton (1983), and in the subsurface by McLeod (1978) and Bell and Gough (1981); and 2) macro- and mega-scale studies of outcrops in the foothills and subsurface of the plains, where the Cardium Formation can be used as a marker horizon. These studies have focused on geological mapping and on geometric characterization of imbricate and east-verging thrusts, horses and duplexes, and triangle zone thrusts and passive roof duplexes; e.g., Martin (1956), Irish (1965), Bally et al. (1966), Ollerenshaw (1966, 1968a,b, 1970, 1972a,b, 1974, 1976a,b, 1978), Teal (1983), MacKay (1991), Skuce et al. (1992).

Stratigraphy

Stratigraphic Nomenclature

Cardium member names were established for outcrops in the foothills of Alberta and British Columbia by Stott (1963, 1967). He recognized seven members: Ram, Kiska, Cardinal, Leyland, Sturrock, Moosehound and Baytree (Figure 23.3a). He identified the Moosehound and Baytree members as being of continental and

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Present addresses: 1. Amoco Canada Petroleum Co. Ltd.; 2. Mobil Oil Canada; 3. also at The University of Calgary

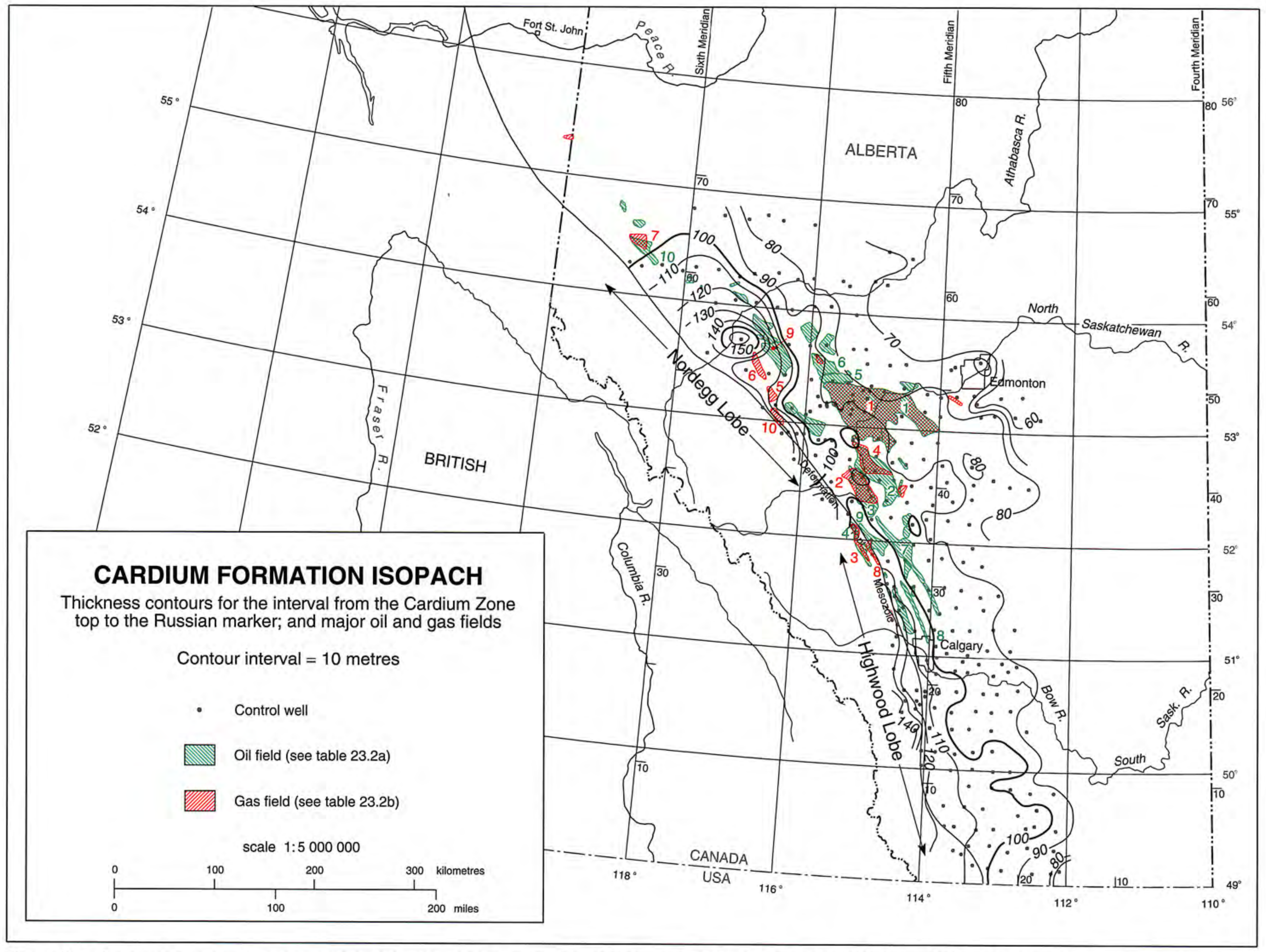


Figure 23.2 Cardium Formation isopach map highlighting the regional distribution of the formation between 49° and 55°N latitude. Note that the formation wedges eastward and has two depositional lobes (Nordegg and Highwood). Map also illustrates distribution of major Cardium Formation oil and gas fields.

Table 23.2a

Oil Production from the Cardium

Oil production from the Cardium is concentrated in southwestern Alberta adjacent to the disturbed belt. Pembina, Canada's largest oil field, produces from the Cardium and is truly a giant oil field.

There are 14 Cardium oil fields with Initial Established Recoverable Oil Reserves of over 1 x 10^6 m^3 (6 MMBbls). The ten largest Cardium oil fields, listed in order of Initial Established Recoverable Reserves, are shown in Table 1. Cumulative production data for Alberta are updated to the end of 1990.

Table 1. Ten Largest Cardium Oil Fields (in units of 10^6m^3).

No.	Field	Formation	No.of Pools	Initial Established Marketable Reserves	Initial Established In-place Volume	Cumulative Production	Discovery Year
1	Pembina	Cardium	20	231.3	1187.2	172.1	1953
2	Willesden Green	Cardium	9	25.8	124.7	18.0	1954
3	Ferrier	Cardium	12	12.3	77.5	7.4	1954
4	Ricinus	Cardium	49	6.6	49.8	4.1	1968
5	Cyn-Pem	Cardium	16	5.5	18.8	3.8	1962
6	Carrot Creek	Cardium	23	3.9	17.3	1.6	1963
7	Garrington	Cardium	14	3.5	34.7	3.1	1953
8	Crossfield	Cardium	3	3.1	26.1	3.0	1956
9	Caroline	Cardium	10	2.4	10.5	1.8	1961
10	Kakwa	Cardium	6	2.1	9.3	1.2	1957

All of these fields occur in stratigraphic traps, in sandstones and conglomerates deposited in thin sheets as at Pembina or in elongate marine scours as at Garrington and Crossfield. All fields contain light to medium gravity oil.

Total recoverable oil reserves in the Cardium are estimated at 305.0 x 10^6m^3, of which 220.9 x 10^6m^3 have already been produced. Pembina alone comprises over 75 percent of the recoverable reserves. Initial Established In-Place Volume of Cardium oil reserves totals 1648 x 10^6m^3. There are 297 Cardium pools in 42 fields, with an average 1027 x 10^3m^3 recoverable oil reserves/pool. When Pembina is deleted from this calculation, the average drops to 266 x 10^3m^3. Table 2 lists the distribution of Cardium oil reserves according to In-Place Pool Size.

Table 2 - Size Distribution of Cardium Oil Pools (in units of 10^6m^3)

In-Place Pool Size Class	No.of Pools	Recoverable Reserves	Cumulative Production
less than 0.1	76	0.40	0.19
0.1 to 1	174	5.04	2.54
1.0 to 10	37	20.25	12.74
10.0 to 100	8	22.59	15.47
100.0 to 1000	1	25.73	17.93
over 1000	1	231.00	171.99
Total	297	305.00 x 10^6m^3	220.86 x 10^6m^3

Table 23.2b

Gas Production from the Cardium

Gas production from the Cardium is concentrated in southwestern Alberta adjacent to the disturbed belt. As well, minor gas production occurs in western Saskatchewan. Included are fields producing from the Cardium in Alberta and the St Walburg Sand in Saskatchewan.

There are 12 Cardium gas fields with Initial Established Marketable Gas Reserves of over 1000 x 10^6m^3 (35 BCF). The ten largest Cardium gas fields, listed in order of Initial Established Marketable gas reserves, are shown in Table 1. Cumulative production data for Alberta are updated to the end of 1990.

Table 1. Ten Largest Cardium Gas Fields (in units of 10^6m^3).

No.	Field	Formation	No.of Pools	Initial Established Marketable Reserves	Initial Established In-place Volume	Cumulative Production	Discovery Year
1	Pembina	Cardium	5	20,566	113,714	15,165	1953
2	Ferrier	Cardium	26	18,333	34,931	14,431	1956
3	Ricinus	Cardium	49	16,538	22,441	2,303	1968
4	Willesden Green	Cardium	8	5,946	24,743	3,388	1962
5	Minehead	Cardium	6	3,390	5,644	277	1965
6	Ansell	Cardium	8	3,076	14,910	393	1976
7	Kakwa	Cardium	6	2,878	4,423	178	1978
8	Caroline	Cardium	10	2,654	8,070	1,413	1965
9	Edson	Cardium	12	2,025	4,124	1,081	'1963
10	Hanlan	Cardium	5	1,263	1,642	0	1969

Much of the gas production from the Cardium is closely associated with oil production, with both often being produced from the same field.

Total recoverable gas reserves in the Cardium are estimated at 88.3 x 10^9m^3, of which 30.8 x 10^9m^3 have already been produced. Initial Established In-Place Volume of Cardium gas reserves totals 263 x 10^9m^3. There are a total of 289 Cardium gas pools, with an average 305 x 10^6m^3 recoverable gas reserves/pool. Table 2 lists the distribution of Cardium gas reserves according to In-Place Pool Size.

Table 2 - Size Distribution of Cardium Gas Pools (in units of 10^6m^3)

In-Place Pool Size Class	No.of Pools	Recoverable Reserves	Cumulative Production
1.0 to 10	8	28	5
10 to 100	134	3,977	572
100 to 1000	124	20,465	2,338
1000 to 10000	18	16,728	3,711
over 10000	5	47,087	24,148
Total	289	88,285 x 10^6m^3	30,774 x 10^6m^3

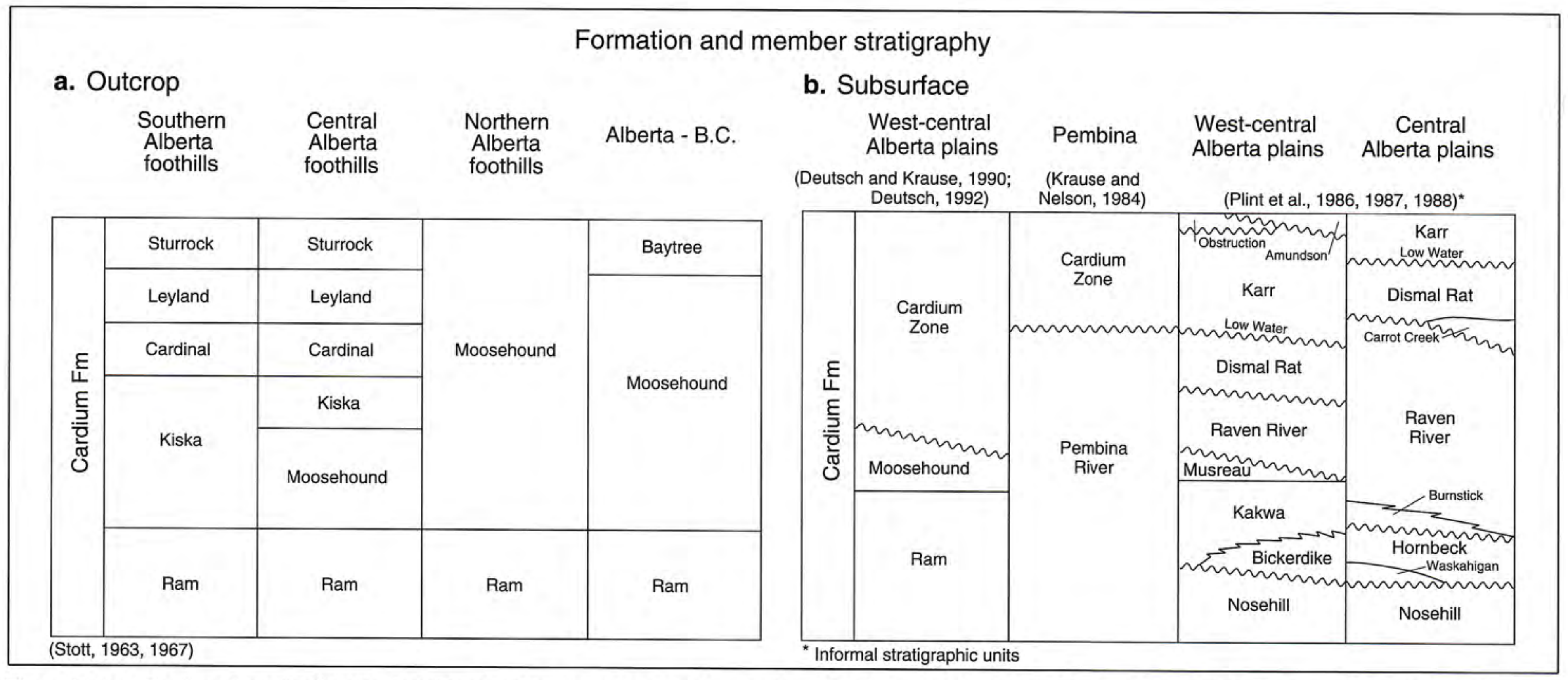


Figure 23.3 **a.** Cardium Formation lithostratigraphic member subdivisions in outcrops of the Alberta and northeast British Columbia foothills (after Stott, 1963, 1967). **b.** Cardium Formation stratigraphic subdivisions in the subsurface, lithostratigraphic and allostratigraphic (Krause and Nelson, 1984; Deutsch and Krause, 1990; Deutsch, 1992) and allostratigraphic (Plint et al., 1986, 1987, 1988).

coastal plain origin, the former containing predominantly coals, mudstones and sandstones, and the latter conglomerates. The Baytree Member conglomerates have recently been studied by Hart and Plint (1989), who indicate that they represent shoreface and beach deposits. In contrast, the Ram, Cardinal and Sturrock members are dominantly sandy, while the Kiska and Leyland members are predominantly shaly; all five are of marine nearshore and shoreface origin. Stott (1963, p. 61 and 73, and his Fig. 5) also noted, in north-south regional transects, that the Kiska, Cardinal, Leyland and Sturrock members "replaced" the Moosehound Member from south to north because of transgression and onlap (see Fig. 23.3a).

Two lithostratigraphic units characterize the Cardium Formation in the subsurface of central Alberta - the Pembina River Member below and the Cardium Zone Member above (Fig. 23.3b) (Krause and Nelson, 1984; Krause et al., 1987b). The Pembina River Member includes the informal Cardium "A" and "B" sandstones used by industry to designate, respectively, an upper and a lower producing zone. The Pembina River Member consists of one or more coarsening-upward sequences that grade from shales to sandstones and then to variably thick conglomerates. The Cardium Zone Member also comprises coarsening-upward sequences, but in contrast to the Pembina River Member contains predominantly shales with lesser amounts of fine-grained sandstone and conglomerate. Both members are marine sediments, having been molded by wave, tidal and geostrophic currents and reworked by the activities of euryhaline and stenohaline bottom-dwelling organisms (Krause and Nelson, 1984; Vossler and Pemberton, 1988; Keith, 1991; Krause and Nelson, 1991; Krause et al., *in press*).

The Pembina River Member comprises stacked, but offlapping, progradational parasequence sets and the Cardium Zone Member stacked retrogradational and progradational parasequence sets (Keith, 1985, 1991; Plint et al., 1988; Joiner, 1991; Deutsch, 1992). The basal part of the Cardium Zone Member is transgressive, onlapping erosional surfaces that truncate underlying Pembina River Member units. The middle and upper Cardium Zone Member units offlap and onlap each other (Deutsch, 1992).

As shown by Joiner (1991) in the Pembina Field area, the upper Pembina River Member sandstones represent an eastward prograding and clinoforming parasequence set formed during a period of relative sea-level fall. A similar stratigraphic relation was noted by Keith (1985, 1991) in the Willesden Green Field area. Pembina River Member progradational parasequences are truncated at their updip edge by a major transgressive, marine erosion surface that is overlain and underlain by conglomerates. This unconformity is regional in extent and was first mapped by Griffith (1981), Krause and Collins (1984) and Keith (1985), and questionably (see below) by Leggitt et al. (1990). Unconformities with similar stratigraphic relations have been noted in outcrop at various levels (e.g., Michaelis, 1957; Wright and Walker, 1981; Krause and Nelson, 1984; Duke, 1985; Plint et al., 1988), but it has been demonstrated only recently, using ammonite biostratigraphy, that the sandstone parasequences in the upper Pembina River Member are correlative with the Cardinal Member in outcrop (Fig. 23.3) (Hall et al., 1991). Thus, the unconformity at the top of the Cardinal Member may be equivalent to the one observed at the Pembina Field (Hall et al., 1991, *in press*; Joiner, 1991).

The Cardium Zone Member has been traced by Deutsch (1992) and Deutsch and Krause (1990, 1991) in the subsurface of the Kakwa area. In this area, marine shales of the Cardium Zone Member interfinger and interface with coastal plain shales of the Moosehound Member. These relations are interpreted as resulting from transgression, erosion and truncation of Moosehound Member units, unroofing in the hinterland of thick upper Paleozoic carbonate sequences, and sedimentation processes typically found along muddy shorelines and shelves (Heise, 1987; Krause et al., 1987b, 1992; Deutsch and Krause, 1991). An alternative interpretation of these relations is proposed by Plint et al. (1988, Figs. 1 and 2), who suggest instead that the juxtaposition of coastal plain and marine shales is unconformable, the result of a fall in relative sea level and subsequent subaerial exposure, fluvial erosion and development of lowstand, coarse-grained shoreline deposits. Subsequently, relative sea level rose, resulting in shoreface erosion and removal and basinward redistribution of coarse-grained sediments.

A second, informal, subsurface member subdivision and correlation scheme has evolved over the past decade using a mixture of allostratigraphic and lithostratigraphic concepts (see Fig. 23.3b), (Plint et al., 1986, 1987, 1988). In this scheme, two members are lithostratigraphic, the Kakwa and Musreau (equivalent to the Ram and Moosehound members of Stott, 1963, 1967), and twelve are allostratigraphic: Nosehill, Bickerdike, Waskahigan, Hornbeck, Burnstick, Raven River, Carrot Creek, Low Water, Karr, Dismal Rat, Amundson and Obstruction (the first seven are equivalent to the Pembina River Member and the last five are equivalent to the Cardium Zone Member of Krause and Nelson, 1984). Plint et al. (1987, 1988) proposed that their allostratigraphic members are separated by regional unconformities that developed in response to eustatic sea-level drops and widespread subaerial exposure of the shelf. More recently, Leggitt et al. (1990) and Walker and Eyles (1991) suggested that the unconformity separating the Raven River and Carrot Creek allomembers was formed by combined eustatic and tectonic controls. Plint et al. (1988) accept that these unconformities provide the opportunity for intraformational correlation. Published discussions and replies relating to the allostratigraphic subdivision and correlation scheme proposed by Plint et al. (1986, 1987) have been provided by Hayes and Smith (1987), Rine et al. (1987), and Plint et al. (1987). Recent work by Walker and Eyles (1991) and Pattison and Walker (1992) goes as far as to indicate that these unconformities are basinwide. The unconformities may be basinwide, but to date evidence to substantiate this proposal has not been unearthed. It is worth noting that the Cretaceous Western Interior Seaway, the basin in which the Cardium Formation was deposited, extended from the Gulf of Mexico to the Arctic Ocean during the Turonian and Coniacian (Williams and Burk, 1964; Williams and Stelck, 1975).

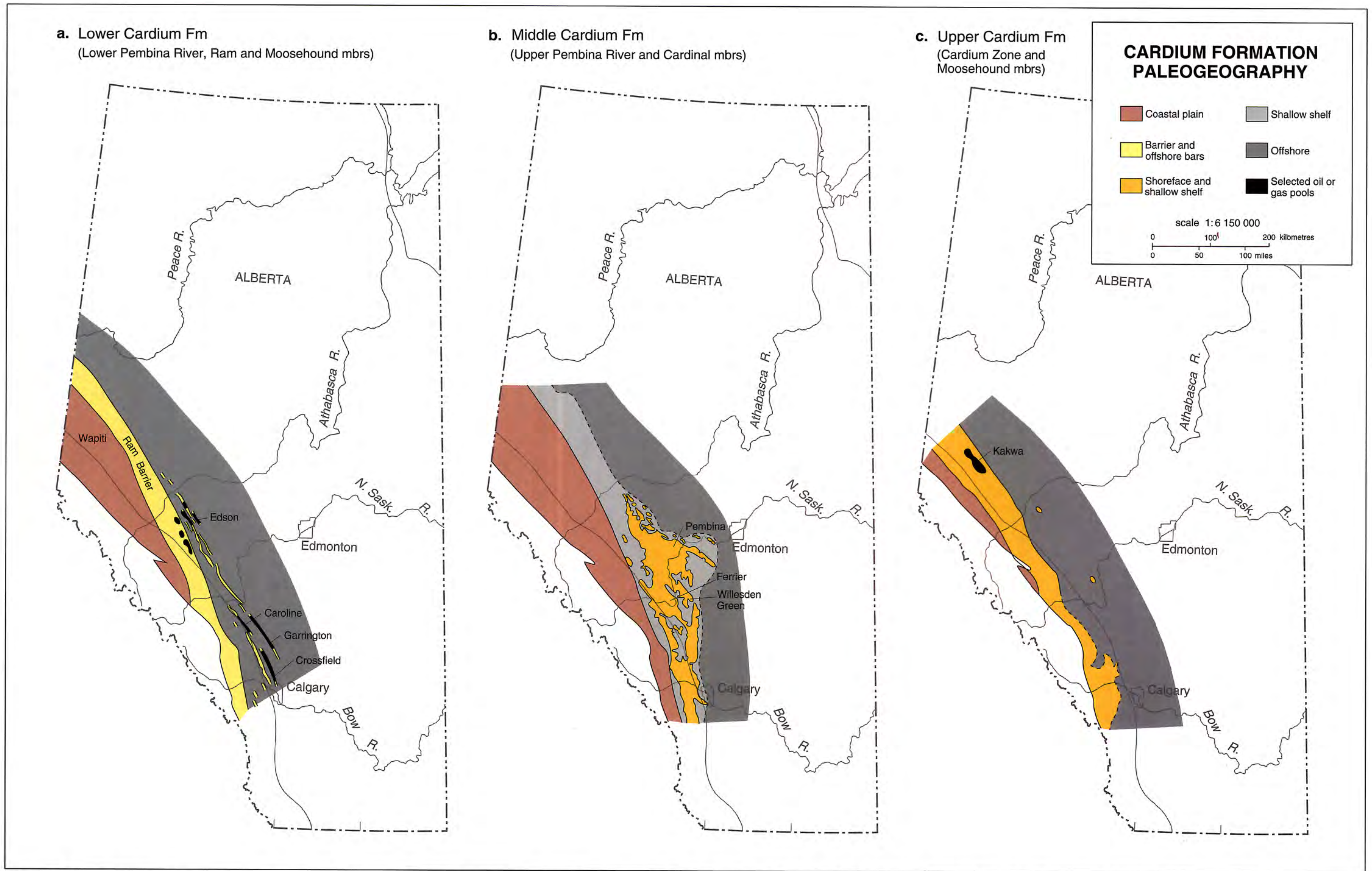


Figure 23.4 Cardium Formation paleogeographic maps depicting distribution of five major lithosomes. **a.** Inferred paleogeography during early Cardium Formation deposition, including the Ram, Moosehound and lower Pembina River members. The Ram and Moosehound members contain a succession of lithosomes that are progradational and are representative of shoreface, beach, backshore, lagoon, marsh and paleosol, and tidal channel deposits. Lower Pembina River Member rocks encompass offshore (inner and outer shelf) and offshore bar lithosomes. **b.** Inferred paleogeography during middle Cardium Formation deposition, including the Kiska, Cardinal, Mooosehound and upper Pembina River members. The distribution of lithosomes reflects a seaward shift of sedimentation in response to sea-level fall. **c.** Inferred paleogeography during late Cardium Formation deposition, following a landward shift of sedimentation in response to sea-level rise. Stratigraphic units included in this interval are the Leyland, Sturrock, Moosehound and Cardium Zone members. Lithologies associated with this stage of deposition reflect dominant mudstone and lesser sandstone accumulation. Lithosome successions and associations are typical of muddy inner and outer shelves, muddy and sandy shorefaces, and muddy coastal plains. Figure courtesy Canadian Hunter Exploration Ltd., Mr. D. Smith.

Stratigraphic History

The depositional history of the Cardium Formation is summarized in three slice maps (Fig. 23.4), depicting paleogeography.

Ram, Moosehound and Lower Pembina River Members (Lower Cardium Formation). Initial Cardium Formation deposition (Fig. 23.4a) is represented by a progradational sedimentary assemblage (Ram and Moosehound members) marked predominantly by internal autocyclic discontinuities. Ram Member deposits are typified by extensive offshore, bioturbated and current-bedded mudstones that give way upward to crossbedded, shoreface, foreshore and tidal inlet sandstones of the "Ram Barrier", a prograding barrier island and strandplain system. In turn, "Ram Barrier" deposits are capped by mudstones and sandstones of backbarrier, lagoonal, tidal and coastal plain origin of the Moosehound Member (Stott, 1967; Duke, 1985; Plint, 1988; Plint and Walker, 1987; Deutsch and Krause, 1990, 1991; Deutsch, 1992). In front of the barrier island and strandplain system, to the east, are complexes of very long and narrow, northwest-southeast oriented, sandy and conglomeratic inner shelf ridges, sandwiched between bioturbated mudstones (Berven, 1966; Pattison, 1987; Krause and Nelson, 1991). Biostratigraphic data indicate that these ridges are younger than the Ram Member and older than the Cardinal Member (Heise, 1987). They may therefore have developed in a variety of ways: in response to relative sea-level fall, fluvial transport and complete modification during subsequent sea-level rise, as beach and shoreface deposits (Berven, 1966; Pattison and Walker, 1992); as offshore ridges along a muddy shoreline receiving fluvial input, but transported and reworked by tidal and storm currents, and subsequently decapitated and left stranded during sea-level rise (Krause and Nelson, 1991); or as tidal ridges (Off, 1963). Beyond the ridge complex, eastward and seaward, muddy outer shelf deposits dominate.

Upper Pembina River, Kiska, Cardinal and Moosehound Members (Middle Cardium Formation). The extensive sandy barrier island, strandplain and muddy lagoonal-coastal plain system that typified early Cardium Formation deposition gave way during middle Cardium deposition to muddy and sandy coastal plains and shelves (Fig. 23.4b). Both were widespread and contain significant estuarine, shoreface and inner shelf sandstones and conglomerates that accumulated in response to the lowering of relative sea level (Krause and Nelson, 1984; Keith, 1985, 1991; Krause et al., 1987b; Joiner, 1991). Typically, sandstones are overlain unconformably by conglomerates. Both deposits form an irregular and anastomosing sheet of variable thickness that has been mapped as a single unit across most of Alberta using resistivity logs and a 30 ohm m cut-off (Fig. 23.4b). Deposition of these sediments resulted in the sandstone and conglomerate reservoirs in the supergiant Pembina Field, and the Willesden Green, Ferrier, Ricinus, Carrot Creek and smaller fields (see Fig. 23.2). Sandstones in these fields are marine, prograde eastward and southeastward into the basin, and represent a response to lowered relative sea level (Krause et al., 1987b; Keith, 1985, 1991; Joiner, 1991). West of the hydrocarbon fields, mudstones, conglomeratic mudstones and fine-grained sandstones accumulated in marine, muddy, inner shelf, nearshore and swampy, coastal-plain settings. In contrast, thick conglomerate deposits accumulated in deep northwest-oriented scours cut into underlying

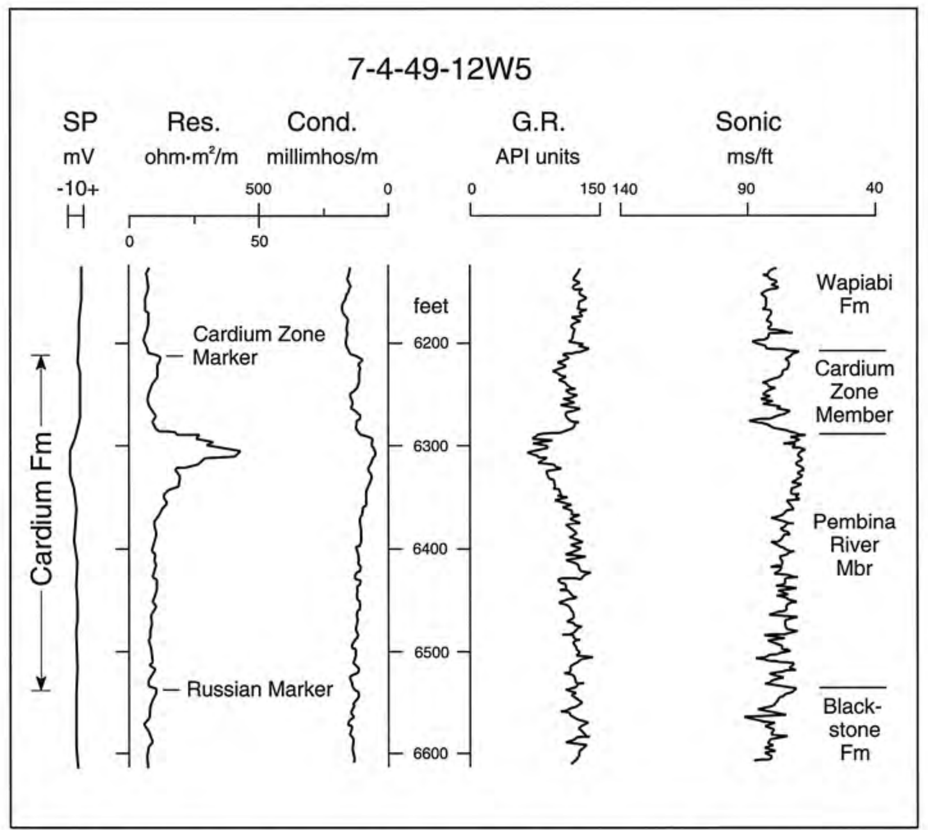
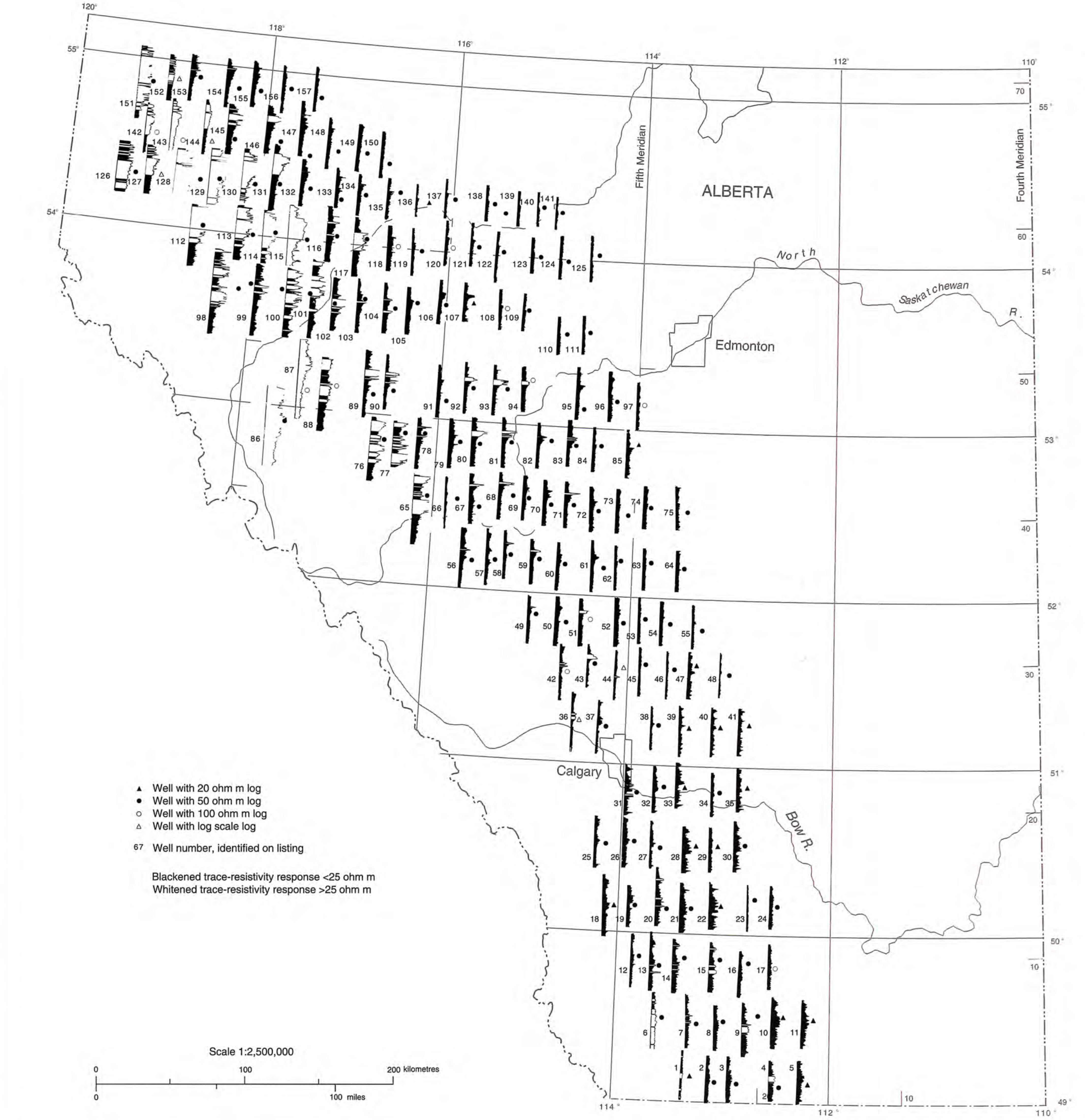


Figure 23.5 Self potential, resistivity, conductivity, gamma-ray and sonic log traces for the Cardium Formation in well 7-4-49-12W5. Note that the vertical scale (1:2150) is larger than the Atlas standard for reference logs (1:3000). Log traces illustrate responses for the Cardium Zone Member and the Pembina River Member. The Cardium Zone Marker defines the top of the formation and the Russian Marker highlights the base of the formation. Wireline log responses for the formation are typical of central and eastern areas of Nordegg Lobe. Note that SP logs of the Cardium Formation are normally recorded at 4 millivolts, not 10 millivolts as has been done for this well. Furthermore, in older Cardium Formation fields, available wireline log suites are typically restricted to self potential, resistivity, conductivity and radioactivity logs.

sands and muds by repeated wave, storm and tidally induced currents. Scouring processes operated autocyclically during periods when relative sea level was stable and basin filling was taking place by progradation of sandstones. Subsequently, during rising relative sea level, scouring processes operated allocyclically as nearshore deposits were decapitated by transgression and modified by storm and inner and outer shelf processes (Swagor et al., 1976; Krause and Nelson, 1984; Joiner, 1991; Keith, 1991; Krause et al., *in press*). Scour and fill sediments accumulated in estuarine, shoreface and nearshore marine settings (Swagor et al., 1976; Krause et al., 1987b, *in press*; Bergman and Walker, 1987; Leggitt et al., 1990; Keith, 1991).

Cardium Zone, Leyland, Sturrock and Moosehound Members (Upper Cardium Formation). During late Cardium Formation deposition, the western margin of the foreland basin was characterized by extensive muddy coastal plain and shelf sedimentation along northwest-southeast oriented depositional belts (Fig. 23.4c). This style of sedimentation appears to have developed in response to extensive uplift and erosion of Devonian, Carboniferous and Permian limestone and dolostone strata in the orogenic wedge of the Mesozoic foreland. Support for this inference is provided by the almost exclusive occurrence of reworked palynomorphs of these ages in rocks of the Cardium Zone Member (Heise, 1987). In contrast, rocks of the Pembina River Member contain predominantly Permo-Triassic palynomorphs (Heise, 1987). These relations suggest that the stratigraphic order is inverted, perhaps as a result of progressive unroofing of the orogenic wedge (Deutsch, 1992; Krause et al., 1992). Thus, the supply of terrigenous material became restricted with time to very fine-grained sandstones, abundant muddy fractions and lesser cherty conglomerates. Fine-grained sandstones accumulated in lower and middle shoreface settings as inner shelf ridges, oriented northwest-southeast and



Resistivity log listing for wells used in electrofacies map

1. 14-28-2-25W4
2. 14-18-2-23W4
3. 5-16-2-22W4
4. 13-3-2-19W4
5. 7-9-2-17W4
6. 3-27-6-27W4
7. 9-14-6-25W4
8. 6-22-6-23W4
9. 6-25-6-20W4
10. 10-35-6-19W4
11. 2-24-6-17W4
12. 3-25-10-29W4
13. 8-8-10-27W4
14. 2-31-10-25W4
15. 10-28-10-23W4
16. 13-21-10-21W4
17. 11-9-10-19W4
18. 10-10-14-1W5
19. 6-11-14-29W4
20. 6-2-14-27W4
21. 14-10-14-25W4
22. 13-15-14-23W4
23. 7-35-14-21W4
24. 11-16-14-19W4
25. 16-14-18-2W5
26. 4-26-18-29W4
27. 10-9-18-27W4
28. 14-13-18-25W4
29. 10-21-18-21W4
30. 8-16-18-23W4
31. 11-1-22-29W4
32. 13-13-22-27W4
33. 2-18-22-25W4
34. 11-2-22-23W4
35. 6-20-22-21W4
36. 10-34-26-4W5
37. 6-16-26-2W5
38. 10-22-26-27W4
39. 13-21-26-25W4
40. 14-26-26-23W4
41. 6-36-26-21W4
42. 12-2-30-5W4
43. 9-26-30-3W5
44. 10-22-30-1W5
45. 10-35-30-28W4
46. 5-27-30-26W4
47. 8-4-30-24W4
48. 16-8-30-22W4
49. 11-35-33-7W5
50. 4-16-33-5W5
51. 7-19-33-3W5
52. 16-21-33-1W5
53. 7-34-33-28W4
54. 9-23-33-26W4
55. 6-11-33-24W4
56. 5-13-37-12W5
57. 10-16-37-10W5
58. 10-31-37-9W5
59. 4-22-37-7W5
60. 16-28-37-5W5
61. 4-11-37-3W5
62. 11-30-37-1W5
63. 10-29-37-27W4
64. 16-16-37-25W4
65. 10-26-41-15W5
66. 7-15-41-13W5
67. 6-5-41-11W5
68. 11-33-41-9W5
69. 4-28-41-8W5
70. 1-19-41-6W5
71. 10-22-41-5W5
72. 10-4-41-3W5
73. 6-4-41-1W5
74. 14-20-41-27W4
75. 16-13-41-25W4
76. 4-3-45-18W5
77. 3-12-45-17W5
78. 1-28-45-15W5
79. 6-11-45-13W5
80. 10-7-45-11W5
81. 7-17-45-9W5
82. 12-25-45-7W5
83. 4-22-45-5W5
84. 14-17-45-3W5
85. 11-24-45-1W5
86. 7-34-45-25W5
87. 2-18-48-23W5
88. 14-8-48-21W5
89. 6-1-48-19W5
90. 11-17-48-17W5
91. 8-2-48-14W5
92. 7-4-49-12W5
93. 1-10-49-10W5
94. 11-27-49-8W5
95. 16-6-48-4W5
96. 2-28-48-2W5
97. 13-11-48-28W4
98. 7-26-54-1W6
99. 7-36-54-28W5
100. 10-30-54-25W5
101. 7-12-54-24W5
102. 7-6-54-22W5
103. 10-23-54-20W5
104. 10-12-54-18W5
105. 6-29-54-16W5
106. 10-28-54-14W5
107. 10-31-54-12W5
108. 3-25-54-10W5
109. 12-29-54-8W5
110. 11-11-53-6W5
111. 5-16-53-4W5
112. 11-20-58-4W6
113. 6-14-58-1W6
114. 5-14-58-27W5
115. 11-10-58-24W5
116. 11-27-58-22W5
117. 4-26-58-20W5
118. 6-13-58-18W5
119. 10-9-58-16W5
120. 11-26-58-14W5
121. 7-33-58-12W5
122. 9-20-58-10W5
123. 5-14-58-8W5
124. 16-10-58-6W5
125. 7-25-58-4W5
126. 10-28-61-9W6
127. 2-20-61-7W6
128. 5-26-61-5W6
129. 6-31-61-3W6
130. 5-27-61-1W6
131. 10-34-61-26W5
132. 2-26-61-24W5
133. 6-1-61-22W5
134. 10-21-61-20W5
135. 7-36-61-18W5
136. 7-13-61-16W5
137. 10-22-61-14W5
138. 6-22-61-11W5
139. 10-5-61-10W5
140. 5-25-61-8W5
141. 10-18-61-6W5
142. 6-25-64-8W6
143. 10-10-64-6W6
144. 6-15-64-4W6
145. 10-30-64-2W6
146. 11-22-64-26W5
147. 12-1-64-24W5
148. 10-23-64-22W5
149. 10-26-64-20W5
150. 5-5-64-18W5
151. 10-1-68-9W6
152. 7-14-68-7W6
153. 9-30-68-5W6
154. 11-11-68-3W6
155. 4-8-68-1W6
156. 14-20-68-25W5
157. 1-8-68-23W5

Figure 23.6 Electrofacies map highlighting characteristic and variable resistivity responses of the Cardium Formation in Nordegg and Highwood lobes. Note that resistivity responses greater than 25 ohm m are more common in Nordegg Lobe than in Highwood Lobe, a consequence of greater abundance of porous deposits over this area (see also Figure 23.4b - middle Cardium Formation deposition map). Note further that the distinct resistivity shoulder of the Cardium Zone Member top in the Nordegg Lobe is replaced by a broader and complex shoulder with several small but recurring peaks. Geometric symbols identify a well's geographic location and the resistivity log's arithmetic and logarithmic scales.

offlapping to the northeast and southeast (Deutsch and Krause, 1990, 1991; Krause, 1990; Deutsch, 1992). Sandstones were imprinted predominantly by oscillatory current and bioturbate bedding, the latter represented typically by *Cruziana* and *Skolithos* ichnofacies (Deutsch, 1992).

Reference Logs

Characteristic Cardium Formation wireline log responses in Bow Basin are illustrated in Figures 23.5 and 23.6. Well 7-4-49-12W5 from the Pembina Field, which contains the most important Cardium Formation reservoir, illustrates a set of wireline tool records that includes gamma ray (G.R.) and sonic responses, in addition to the more commonly available spontaneous potential (SP), resistivity and conductivity log records (Fig. 23.5). The SP log in the reference well is not typical, having been logged at 10 millivolts instead of 4 millivolts, as is standard. Cardium Formation sandstones and conglomerates are commonly indistinguishable if recordings were obtained at 20 millivolts, the standard voltage used for SP logs in the subsurface of Alberta.

Formation Boundaries. In the subsurface, the top of the Cardium Formation was recognized early and defined consistently on resistivity logs (Sproule, 1954; Parsons, 1955; Warke, 1955; Nielsen, 1957; see also Krause and Nelson, 1984). The formation top is characterized, particularly in the Nordegg Sub-basin (discussed below), by a simple, distinct resistivity shoulder in what is an otherwise continuous mudstone interval (Fig. 23.5). This shoulder has become known throughout industry as the Cardium Zone Marker and the unit below as the Cardium Zone (Parsons and Nielsen, 1954; Nielsen, 1957; and Krause and Nelson, 1984). In cores, the resistivity shoulder originally identified on logs is represented by a scoured mudstone that is pebbly and sideritized with a griotte fabric (Parsons, 1955; Krause and Nelson, 1984). In Highwood Lobe, the resistivity shoulder is broader and more complex and is characterized by several small but recurring peaks (Fig. 23.6). In outcrop, the top of the formation was placed at the highest sandstones of the Sturrock Member and below the muddy or sandy pebbly grits at the base of the Wapiabi/Muskiki formations (Stott, 1963).

Throughout Bow Basin the base of the Cardium Formation remained poorly defined until this present study. Thus, particularly in the subsurface, the thickness over its known area of occurrence was unknown (Figs. 23.2 and 23.6). As recognized here, the base of the formation is identified by a widespread resistivity double shoulder that resembles the Russian alphabet letter "z". This marker occupies approximately a 5 to 10 m interval and is identified informally herein as the "Russian Marker" (Fig. 23.5). These formational boundaries differ from boundaries previously established in outcrop, formally by Stott (1963, 1967) and informally by Duke (1985). Stott (1963, p.63) acknowledged that the base of the formation and Ram Member was gradational and defined it restrictively, placing it at the sole of the first "thick", laterally continuous, "massive", or currrent bedded sandstone. Thus, he limited its use to areas that encompass his definition. Identification of the basal boundary of the formation has always been difficult and equivocal. Basal sandstones with the characteristics defined by Stott (1963) are present only in outcrop and the subsurface in a narrow belt paralleling the thrusts closest to the Front Ranges. Recently, Deutsch (1992) traced the Ram Member in the subsurface of the plains in the Kakwa area and confirmed Stott's (1967) correlation. However, Deutsch (1992) also noted that the base was transitional and placed it within the underlying mudstones of the Blackstone/Kaskapau formations. Comparisons with published maps of the eastern foothills indicate that other workers have experienced similar difficulties in identifying formational boundaries; in particular, choosing the base of the formation (e.g., MacKay, 1991; Ollerenshaw, 1972a, b, 1976a).

Formation Distribution. The distribution of the Cardium Formation in the subsurface of most of western Alberta is illustrated in Figure 23.6, using 157 resistivity logs. These logs display formational resistivity changes in this portion of the foreland basin and reflect not only lithological changes but also formation fluid compositions. Across the basin resistivity logs should be used with care, because the resistivity has been recorded on four different scales. On Figure 23.6 these different scales are signposted by a geometric symbol next to the log trace (see legend). In addition, resistivities greater than 25 ohm m are in white and responses less than 25 ohm m are in black.

Age

The Late Turonian age assigned to the Cardium Formation is based partly on its stratigraphic position between the Blackstone and Wapiabi formations, both of which have been well dated by their contained ammonite faunas (Stott, 1963, p. 62; 1967, p. 37). The upper parts of the Blackstone yield ammonites representing the zone of *Prionocyclus woollgari* and possibly the zones of *P. hyatti*, *P. macombi* and *Scaphites warreni* (Stott, 1963, p. 52, 53), of Middle and early Late Turonian age. The basal parts of the overlying Wapiabi Formation (Muskiki Member) lie within the zone of *Scaphites preventricosus* (Stott, 1963, p.93) which is now assigned to the Early (but not earliest) Coniacian (Cobban, *pers. comm.*, 1992).

Macrofossils are rare in the Cardium Formation, but those that have been recorded generally support this age assignment for the formation. Stelck (1955) referred to the following specimens: *Scaphites preventricosus* in the topmost sandstone of the formation from the foothills just west of Pembina, Alberta; *S.* cf. *corvensis* from the middle shales in northeastern British Columbia; and a *Prionocyclus* said to be close to *Prionocyclus wyomingensis* from the Highwood River in southern Alberta. These ammonites indicate the presence of strata of Late Turonian and Early Coniacian ages. Parsons (1955) recorded the presence of *P. wyomingensis* in a core from the Pembina area. Stott (1963, p.63) mentioned specimens of *Scaphites* from the upper part of the Cardium Formation on the Sheep River, southern Alberta, which he compared with *S. mariasensis* and *S. impendicostatus*. These would again indicate a Late Turonian to Early Coniacian age. Ammonites identified as *S. preventricosus* were noted from the Leyland Member on the Bow River west of Calgary by Barton (1983) and another specimen from the top of the Cardinal Member in the same area was identified as *P. wyomingensis*. None of the above specimens has ever been illustrated or described.

Several large specimens of *P. wyomingensis* recently collected from the top bed of the Cardinal Member at Seebe confirm its correlation with the Late Turonian zone of *P. wyomingensis*. The presence of a fragment of *P. ?quadratus/germari* in a concretion within the lower parts of the Leyland Member, 4.5 m above the top of the Cardinal Member at Seebe, indicates correlation with the uppermost Turonian zone of *P. quadratus*. Two metres higher in the Leyland Member is the first occurrence of *Scaphites preventricosus*, which is of Early (but not earliest) Coniacian age. Partial specimens of *P. wyomingensis* have been recovered from cores in the upper Pembina River Member from the Pembina Field. These ammonites indicate correlation with the Cardinal Member in the foothills outcrop belt (Hall et al., *in press*).

Structure

Stratotectonic elements that controlled sedimentation during deposition of the Cardium Formation are shown in Figures 23.1 and 23.2. The bulk of Cardium Formation deposits is contained in a bow-shaped basin that follows an elongate, compound arc with north to northwest trend, delimited by the 49° and 56°N latitudes (Canada-U.S. border to Grande Prairie area). This basin is identified herein as Bow Basin, after its bow shape and after the Bow River, which dissects it in the south. Bow Basin is further partitioned into two structural lows that are separated by a high at approximately the 51°N latitude. These structural features were noted by Williams and Burk (1964), who named the dividing high the Calgary Platform, and the lows in between the Central Alberta and Southern Alberta basins. We have chosen not to retain the last two names, because similar terms have also been used for other sub-basins in different geographic locations, in different rock intervals of the Alberta Basin (e.g., Moore, 1989). We propose instead to name the low to the north of the Calgary Platform the Grande Prairie Low, drawing attention by this name to the change in direction of structure contours in the subsurface in the vicinity of the city of Grande Prairie. The low to the south of the Calgary Platform we propose to name the Pincher Creek Low, for the town of the same name in southwestern Alberta.

Bow Basin is a distinct structural entity and is a sub-basin of the Alberta Basin. Bow Basin's main characteristics are: its bow shape; northwest-southeast orientation; structure contours that swing to the west over its northern perimeter near the Alberta/British Columbia boundary (between 54° and 55° 30'N latitude, and 118° and 122°W longitude); separation by Calgary Platform, near 51°N latitude, into two sub-basins; and long geological history, in existence from the Early Cretaceous to the early Tertiary (Second White Specks marker to the Paskapoo Formation) (Burk, 1962; Taylor et al., 1964, Fig. 13-1; Williams and Burk, 1964, Fig. 12-15). The east-west orientation of structure contours in the north, beneath the general area of Grande Prairie, may be a result of Late Cretaceous reactivation of the Peace River Arch, or possibly vertical displacement along the Hay River Fault Zone to the north. Reactivation of the Peace River Arch into a positive element may have commenced as early as Early Cretaceous (see sub-Mannville unconformity structure contour map; Fig. 19.3, *this volume*).

Thickness

Formation thickness across the western subsurface of Alberta is illustrated in Figure 23.2. This isopach map illustrates the formation's thickness distribution in the subsurface along the western margin of Alberta from 49° to 55°N latitude. Isopachs are from resistivity logs (Figs. 23.5, 23.6) using the Cardium Zone Marker and the Russian Marker for the top and base of the formation respectively. The thickness of the formation in Bow Basin across and along strike is not uniform. However, in general, the isopachs indicate that the formation wedges toward the east, with a thickness greater than 165 m in the west and decreasing to a thickness less than 50 m in the east (Fig. 23.2). The formation's maximum and minimum thickness at its margins are unknown, because the formation has been eroded in the orogenic thrust belt to the west and lacks definition on wireline logs along its eastern boundary, where the sandy lithofacies merge eastward into mudstones undifferentiated from mudstones above and below the Cardium Formation interval (Fig. 23.6).

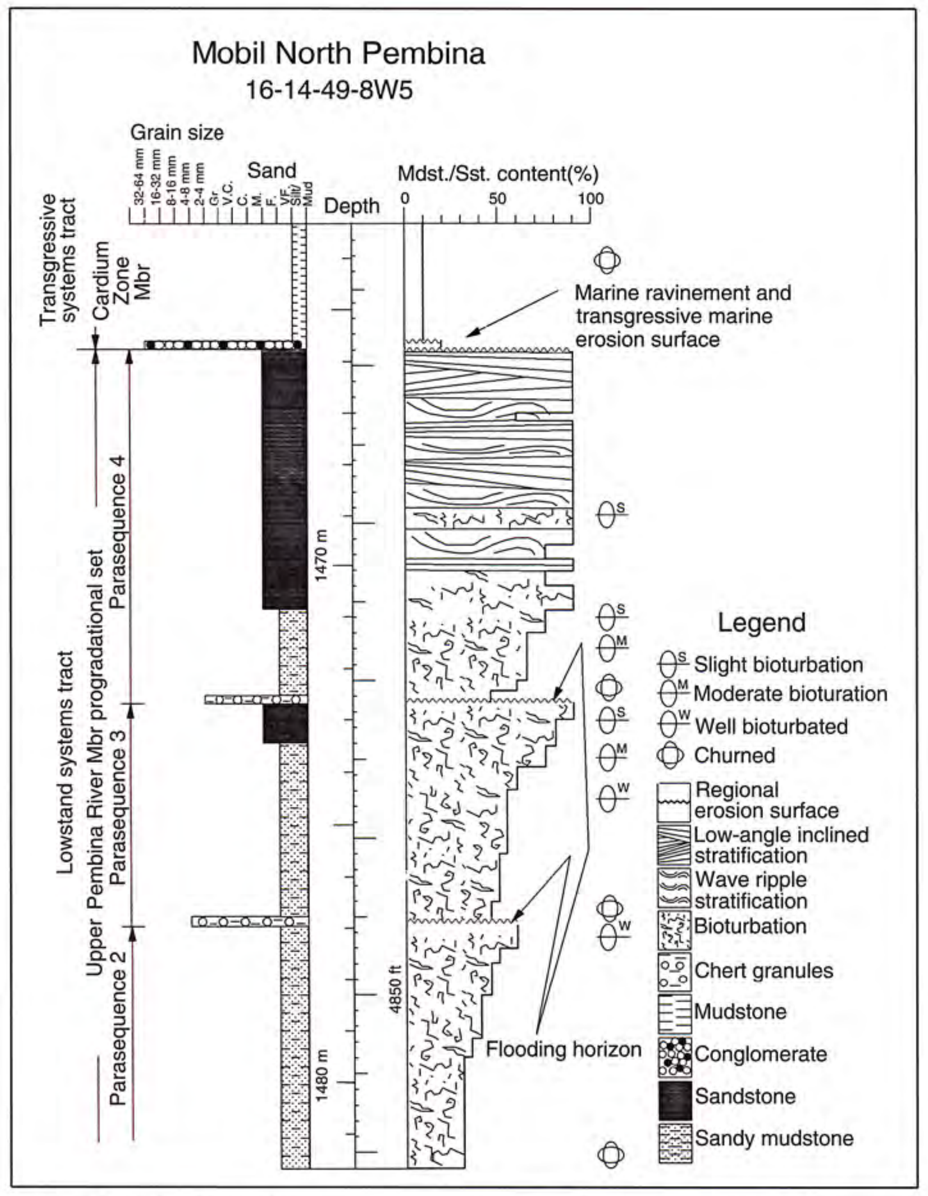


Figure 23.7 Lithological log based on core from the Pembina reservoir, well 16-14-49-8W5, illustrating sandy parasequence sets in the upper Pembina River Member (for additional details see Joiner, 1991).

Across the map area from north to south, two thick lobate wedges are apparent, named here the Nordegg Lobe in the north and the Highwood Lobe in the south (Fig. 23.2). The two lobes are separated by a saddle highlighted by decreasing isolines north of Calgary, across Townships 30-40, slightly north of 52°N latitude and seemingly not coincident with Calgary Platform. These lobes reflect separate depocenters), the Nordegg Lobe localized to the Grande Prairie Low and the Highwood Lobe centered over the Pincher Creek Low and southern margins of the Grande Prairie Low.

North of Township 65, isolines also thin progressively northward and westward (Fig. 23.2). Similar isopach changes have been noted farther north (approximately 55°N latitude) by Burk (1962), and Hart and Plint (1990), using different Cardium Formation marker horizons. Hart and Plint (1990) have attributed these changes to vertical syntectonic movements of rejuvenated Peace River Arch normal faults and uplift parallel with the axis of the ancestral arch. An alternative is that the observed stratigraphic differences could be responses to thrusting associated with development of passive roof duplexes and triangle zones, which are common elsewhere in the basin in this stratigraphic interval and are associated with modern uplift of the Rocky Mountains (Teal, 1983; Skuce et al. 1992).

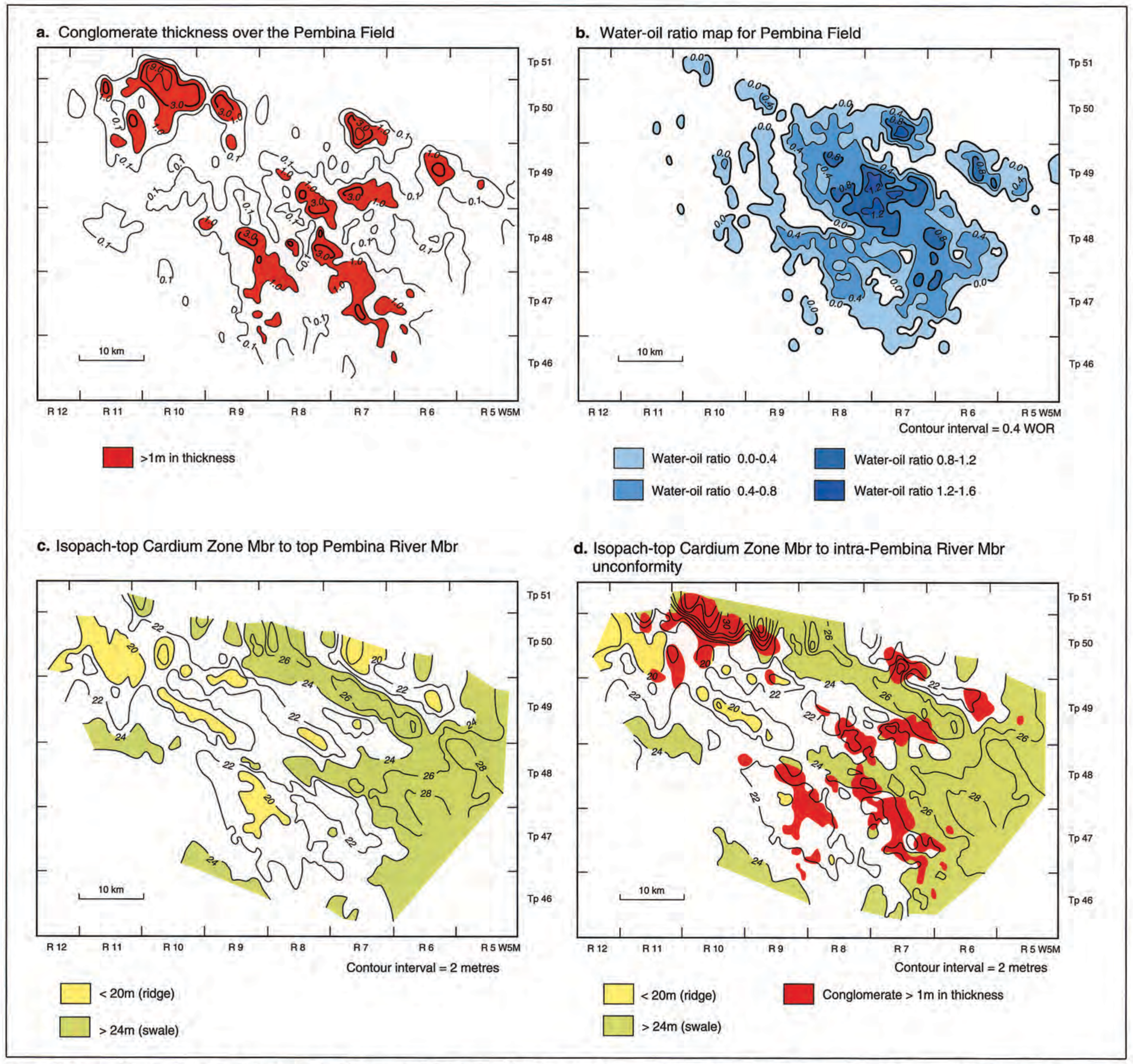


Figure 23.8 Pembina Field maps. **a.** Conglomerate thickness and distribution. Note that conglomerate distribution is discontinuous and patchy, varying in thickness and lateral extent. The map database consists of approximately 1400 cored wells. Contours are set at 0.1, 1.0, 3.0, and 9.0 m. **b.** Water-oil ratio map for 1982 (ERCB production data). The unit of measurement is Log WOR. The contour interval is 0.4 m^3/m^3. Note that areas of high WOR are associated with areas of thick conglomerate. **c.** Isopach map of the Cardium Zone Member (top datum) illustrating ridge and swale topography on the top of the Pembina Field reservoir. Because the datum is at the top, larger isopach values represent greater distances from the datum and thus isolines with larger values highlight topographic lows on the underlying surface. Conversely, lower isoline values represent topographic highs. The surface topography highlighted by this map includes areas with conglomerate and sandstone and reflects the transgressive marine erosion surface remaining after sea level rose. Following transgression, as water depth increased, bottom shear stresses were insufficient to continue reworking conglomerates and sandstones. As a result, mudstones accumulated instead, burying and sealing underlying deposits and draping the transgressive erosion surface. The contour interval is 2 m. **d.** Isopach map of the interval from the Cardium Zone Marker (top datum) to the unconformity that separates sandstones from conglomerates in the Pembina River Member. This map illustrates the subdued ridge and swale topography that separates capping conglomerates from underlying sandstone parasequences. This surface is a composite unconformity that resulted from autocyclic erosion during progradation of the sandstone parasequence set and ravinement during sea-level rise. Note again, as above (Fig. 23.8c), that larger isopach values represent lows in the basal surface. The contour interval is 2 m. Conglomerates thicker than one metre, that overlie sandstones beneath the composite unconformity are highlighted in red (for additional details see Krause et al., 1987b).

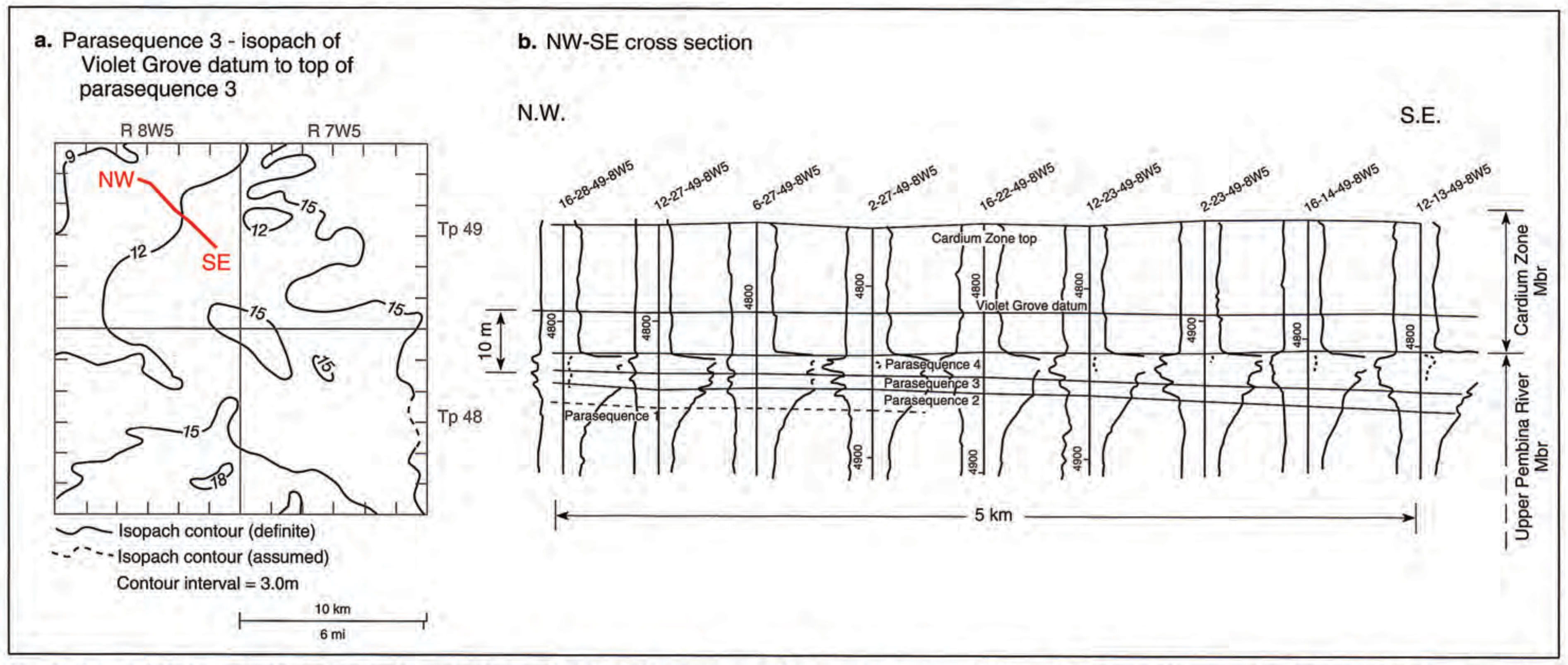


Figure 23.9 **a.** Isopach map of sandy parasequence 3 in the Tp 48-49, R 7-8W5 area of the Pembina reservoir. Datum is the Violet Grove marker (Joiner, 1991). Note that the datum is at the top; thus on the underlying surface larger and smaller isopach values are lows and highs, respectively. The map illustrates offlap to the southeast. In addition, this parasequence has a broad saddle with a northwest-southeast axis in Township 48. **b.** Electric log cross section, 5 km long, oriented in the northwest-southeast direction, highlighting offlapping parasequences 1-4.

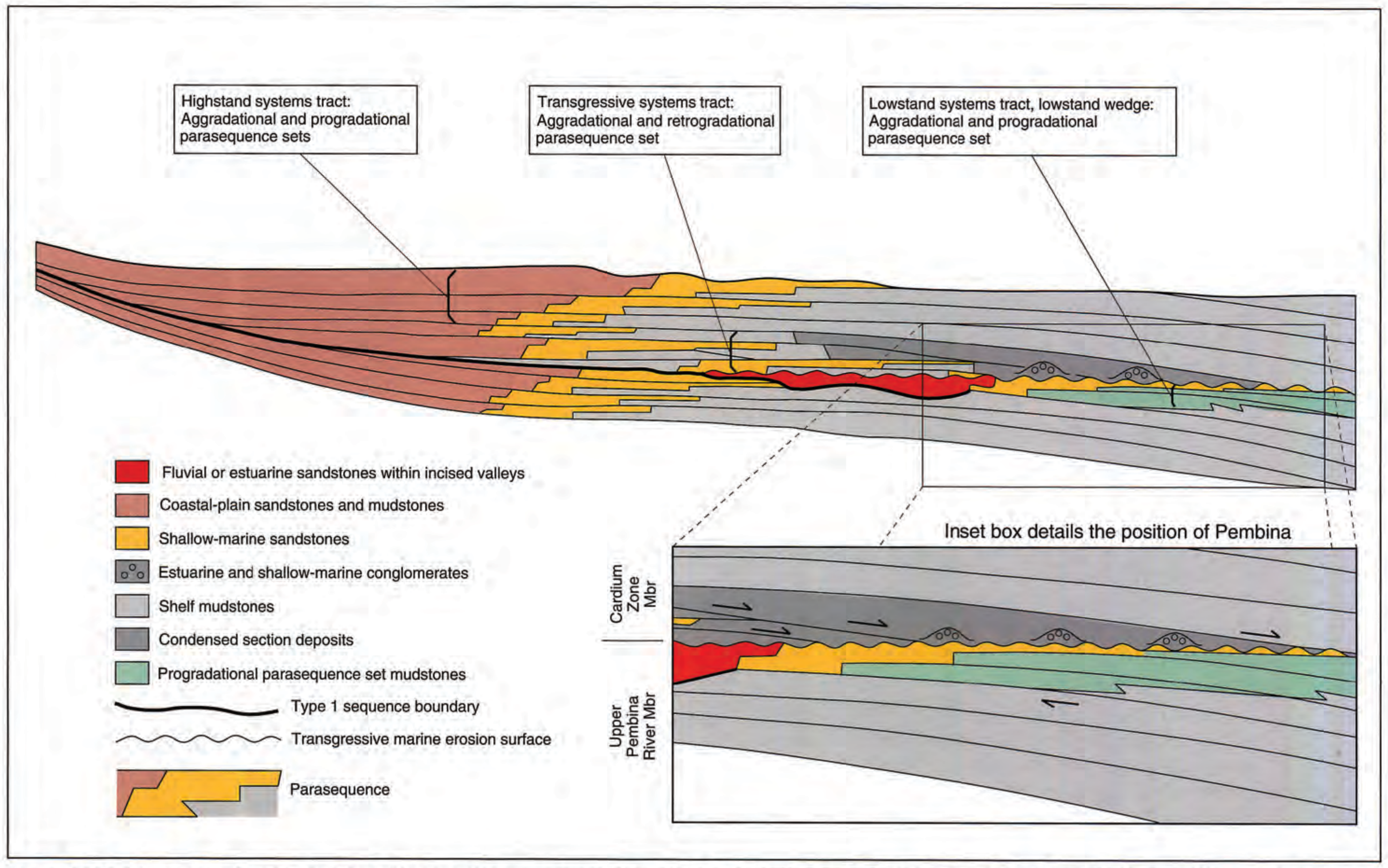


Figure 23.10 Sequence stratigraphic depiction of the geometric arrangement of lowstand, transgressive and highstand systems tracts, modified from van Wagoner et al. (1990). Inset box illustrates interpreted sequence stratigraphic setting in Pembina Field deposits. Note that sandstones represent the lowstand wedge of a lowstand systems tract and conglomerates above the unconformity are predominantly elements of the retrogradational parasequence set of a transgressive systems tract (Joiner, 1991; Joiner and Krause, 1991).

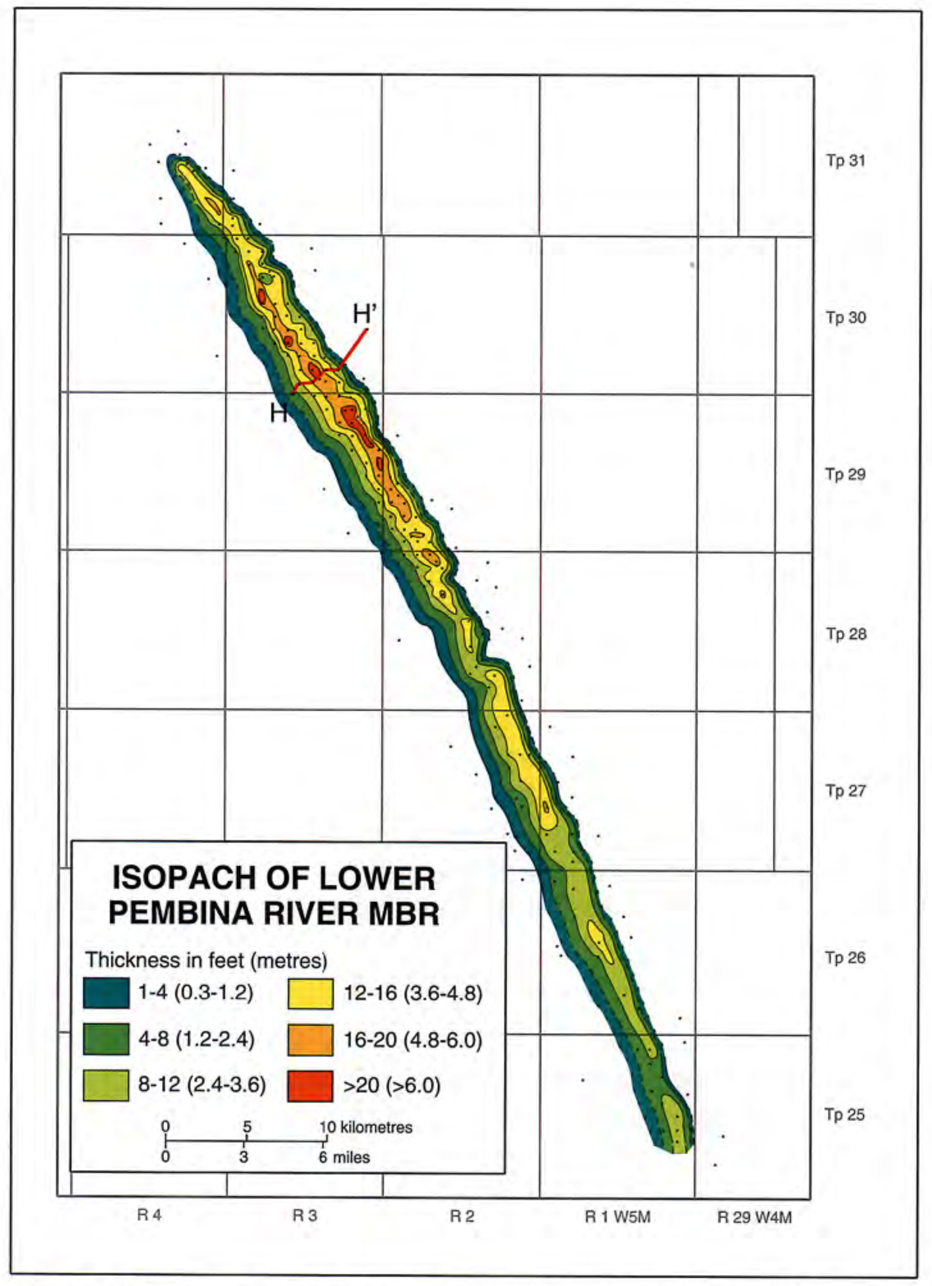


Figure 23.11 Isopach map of the lower Pembina River Member, Crossfield reservoir. This deposit is a sandstone and conglomerate body that accumulated on the Turonian seafloor as a submarine ridge (for additional details see Krause and Nelson, 1991).

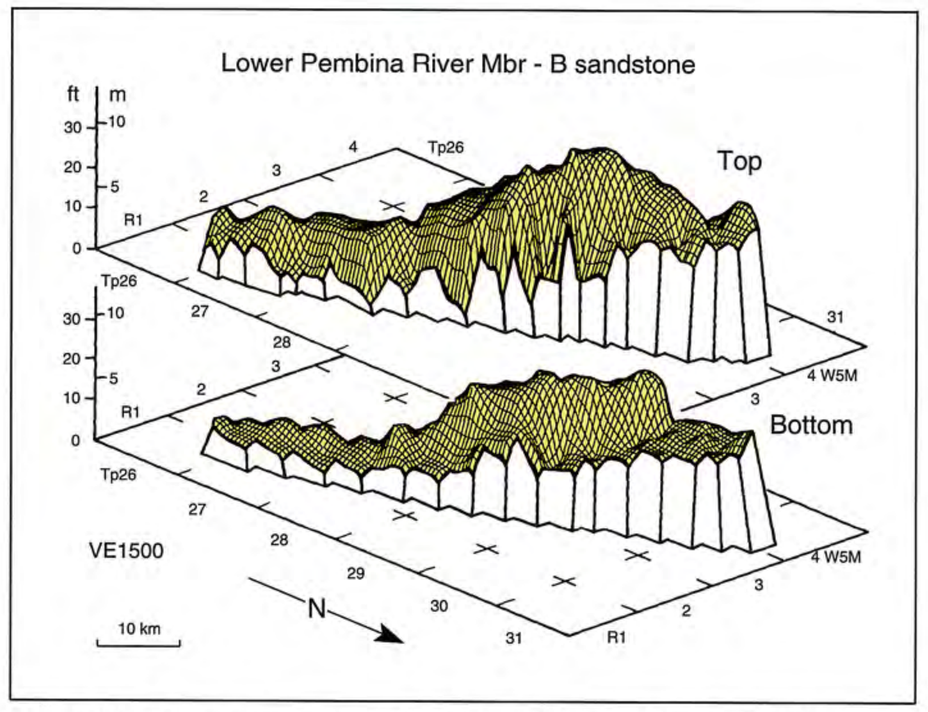


Figure 23.12 Perspective diagram of the Crossfield reservoir submarine ridge. Surfaces generated from resistivity log markers above and below the reservoir. Datum is the Cardium Zone Member top marker, viewing angle is 22° above the horizon (Krause and Nelson, 1991). Note development of the ridge over a topographic inhomogeneity and eastward and southward progradation.

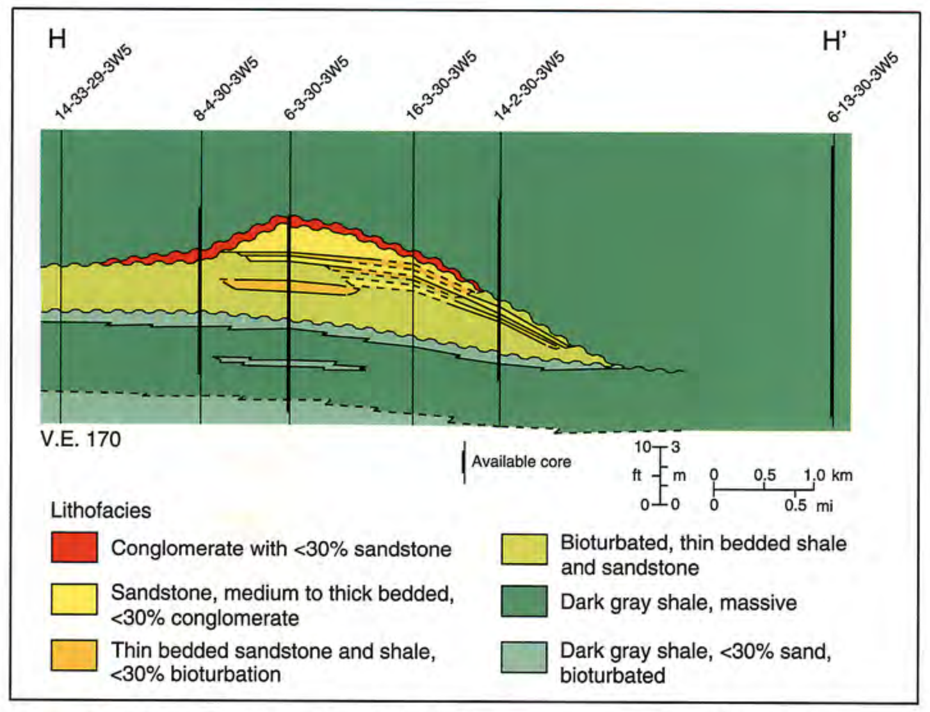


Figure 23.13 Southwest-northeast lithofacies cross section of the Crossfield reservoir along line H-H′ highlighted on Figure 23.11 (for details see Krause and Nelson, 1991). Note that the reservoir is encased in shale and thus the field represents a stratigraphic trap. As illustrated in Figures 23.11 and 23.12, Crossfield is a ridge that is shaped as an asymmetrical wedge, pinching-out to the east, grading into bioturbated sandstones and mudstones to the west, coarsening and shoaling upward.

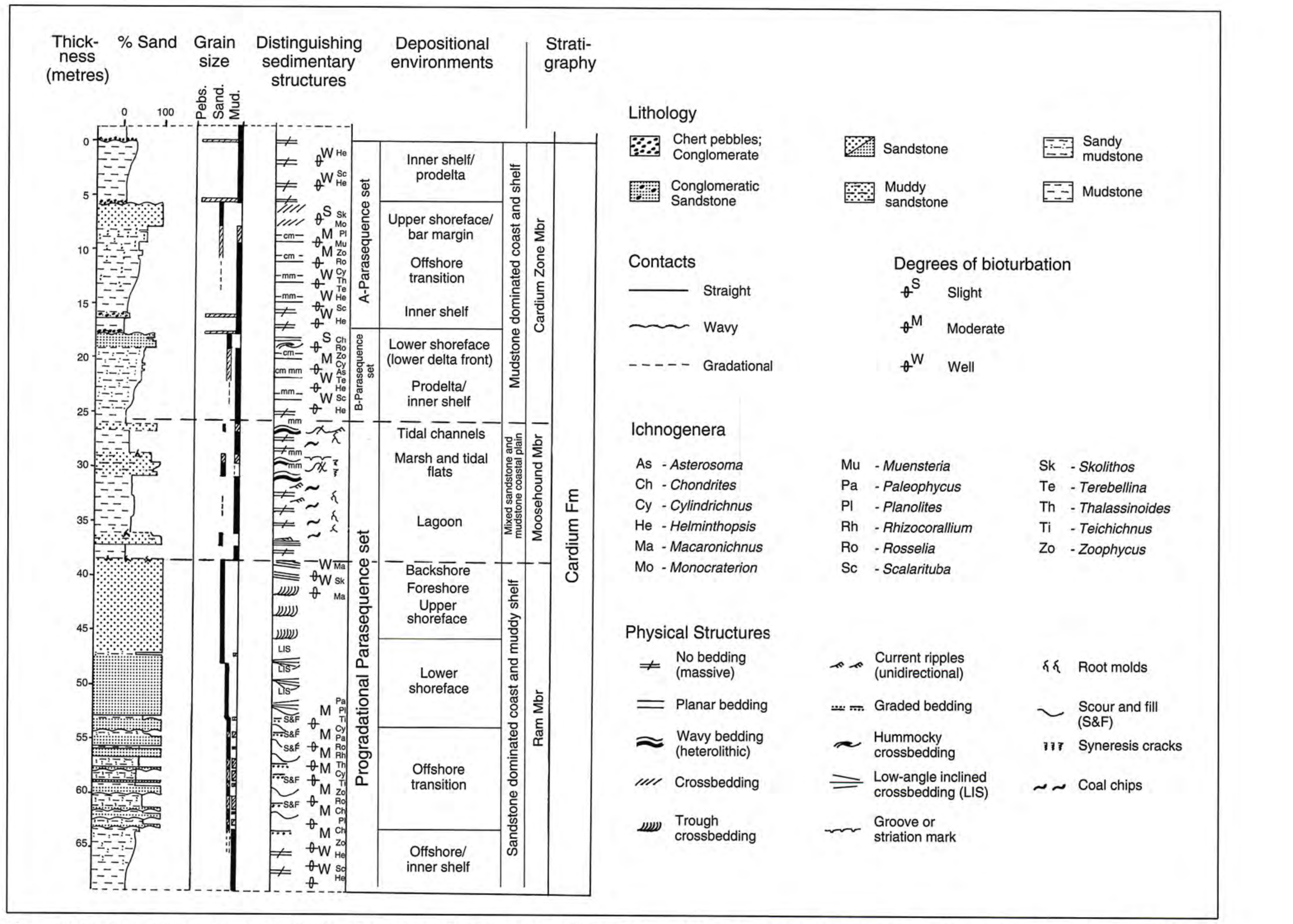


Figure 23.14 Composite lithology log for Cardium Formation in the Kakwa region, illustrating thickness, relative percentage sandstone, approximate grain sizes, characteristic sedimentary structures, interpreted sedimentary environments and stratigraphic subdivisions (for additional details see Deutsch, 1992). Note sandstone-dominated Ram Member and mudstone-dominated Moosehound and Cardium Zone members.

Subregional and Local Relations

Pembina Field and Vicinity - Upper Pembina River Member Reservoir

In the Pembina Field the Cardium Formation reservoir consists, in broad terms, of two stacked, terrigenous clastic reservoirs; a lower sandstone reservoir and an upper conglomerate reservoir, separated by a regional unconformity (Fig. 23.7; Krause et al., 1987b). Sandstones have high storage capacity (-h), but low to moderate flow capacity (kh), whereas conglomerates have low storage capacity (-h), but high flow capacity (kh) (Groeneveld, 1964; Gillund, 1969; Krause et al., 1987b). These conglomerates, as mapped over most of the Pembina Field, are arranged as discontinuous and patchy sheets ranging from less than 0.1 m to greater than 9.0 m in thickness (Fig. 23.8a; Krause et al., 1987b). It is significant that, locally, conglomerates present severe production problems as "thief zones" for secondary and enhanced recovery schemes, a response which is particularly evident where they form thick, pod-like accumulations (Fig. 23.8a, b; Gillund, 1969; Krause et al., 1987b, their Figs. 8 to 11).

The top of the Pembina reservoir, including the conglomerate, is characterized by a ridge and swale topography oriented northwest-southeast (Fig. 23.8c; Nielsen, 1957; Groeneveld, 1964; Krause, 1982; Krause et al., 1987b; Leggitt et al., 1990). The unconformity surface that separates the conglomerates from the underlying sandstones also displays a ridge and swale topography (Fig. 23.8d; Krause and Collins, 1984; Krause et al., 1987b). This surface is identified as the "E-5 erosion surface" by Leggitt et al. (1990) who mapped it using resistivity logs. There is continuing controversy over how conglomerates and sandstones can be distinguished on available resistivity logs (as discussed above) and thus over whether the capping conglomerates are included or excluded in their Figure 5 map (Leggitt et al., 1990, p. 1169). Nonetheless, using this map and core descriptions, they interpreted the origin of the "E-5" surface to be the result of southwest uplift and rotation of the basin floor, followed by subaerial exposure. Subsequently, the surface was modified by incision of underlying sandstones to produce a series of subparallel, shoreface steps during slow transgressions or stillstands, as the basin floor rotated backward and downward (Leggitt et al., 1990).

Sandstones underlying the erosion surface comprise a parasequence set composed of at least ten clinoforming, prograding and offlapping parasequences, bounded by disconformities (Joiner, 1991). Below the disconformities, parasequences consist of very fine-grained sandstones imprinted with current bedding, commonly low-angle inclined cross-stratification ("LIS" – Krause and Nelson, 1984). Above the disconformities, parasequences display bioturbated mudstones and very fine-grained sandstones, with medium to granule sized chert grains and griotte siderites (Figs. 23.7; 23.9; Joiner, 1991; Joiner and Krause, 1990, 1991). Disconformities could have formed by autocyclic shoreface erosion during periodic pauses in sedimentation, through temporary abandonment, sediment starvation, compactional subsidence and subsequent flooding and ravinement.

The unconformity separating the sandy parasequence sets from the overlying conglomerates is not a simple erosion surface, but consists instead of at least two disconformities (Joiner, 1991; Krause et al., *in press*): a lower disconformity present only locally and an upper one that is widespread throughout the Pembina Field. The lower, more local disconformity, is characterized by asymmetrical, parallel, northwest-southeast oriented, channel-like scours, up to 5 m deep, 3 km wide and 10-20 km long. These scours contain well sorted, crossbedded sandy conglomerates and poorly sorted, conglomeratic, muddy sandstones with marine trace fossils (Joiner, 1991; Krause et al., *in press*). The well sorted, crossbedded conglomerates are marine and appear to have been sculpted by tidal currents (Krause et al., *in press*). These deposits are incised and overlain by poorly sorted conglomerates that are associated with the upper disconformity. The lower erosion surface is truncated along the margins of the asymmetrical channel-like scours by the upper erosion surface. The aggregate of these surfaces is the unconformity separating sandstones from overlying conglomerates. The subdued ridge and swale topography of this surface is depicted in Figure 23.8d (Krause et al., 1987b; Joiner, 1991; Joiner and Krause, 1991).

The lithological characteristics and the spatial relations of the various deposits and unconformities at Pembina and the immediate vicinity are analogous to ones observed in modern subaqueous deltas and marine-outer-central estuary settings (Joiner, 1991; Joiner and Krause, 1991). Sandstones prograded into the seaway during sea-level lowstand, as a result of general relative sea-level lowering, as first suggested by Keith (1985, 1991) for the Willesden Green Field to the southwest of Pembina. In contrast, most of the overlying pebble conglomerates were derived from estuarine storage areas to the west during ravinement and shoreline incision as relative sea level rose (Fig. 23.10; Joiner, 1991; Joiner and Krause, 1991). The unconformity separating sandstones from conglomerates, as indicated above, is complex. It formed initially in response to autocyclic reworking by tidal and wave erosion processes, as underlying sandstones prograded into the basin and, subsequently, by allocyclic shoreface incision through ravinement and storm wave processes as sea level rose (Joiner, 1991; Joiner and Krause, 1991; Krause et al., *in press*).

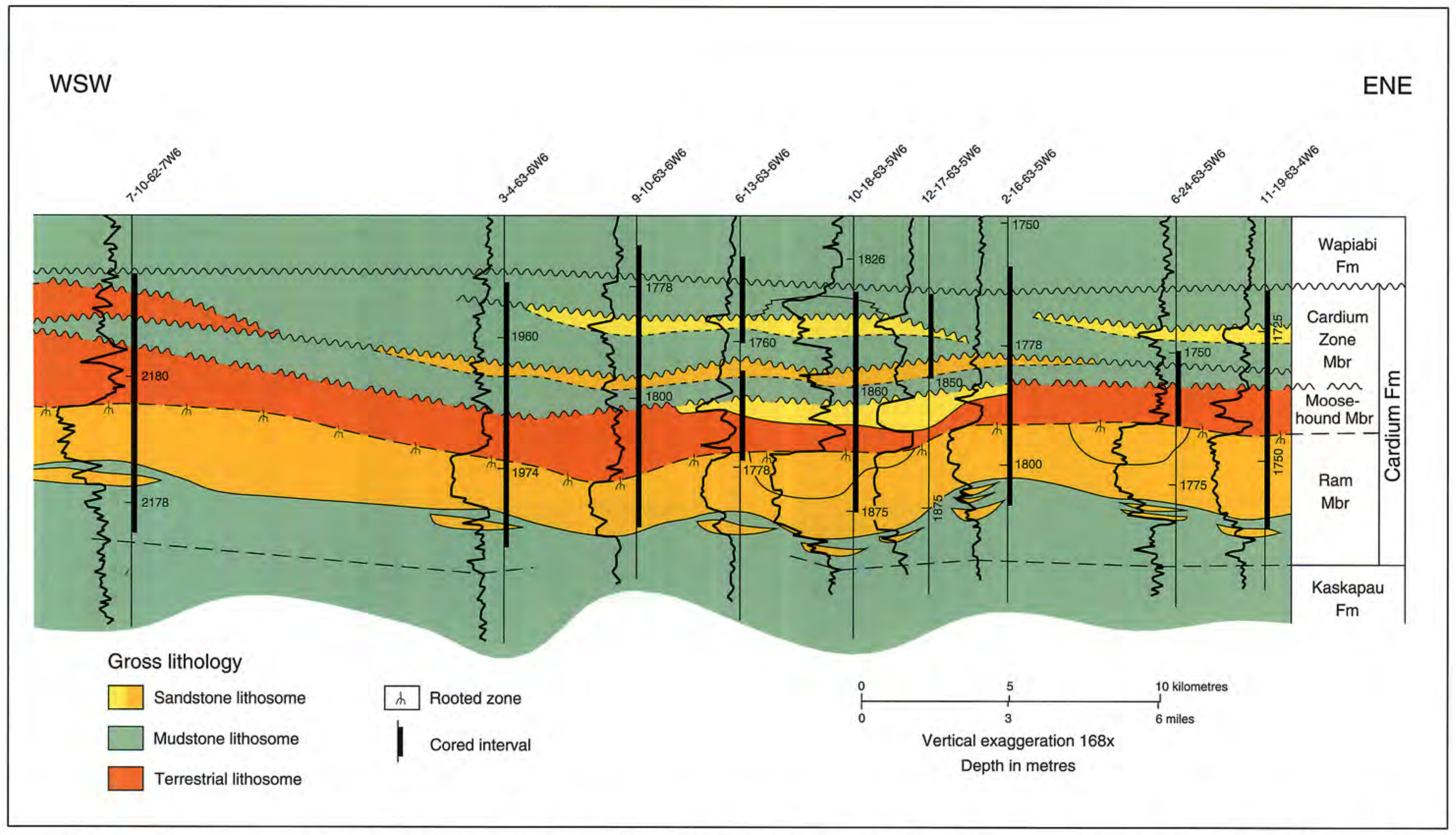


Figure 23.15 Stratigraphic cross section (core and wireline log) of the Cardium Formation in the Kakwa region, illustrating regional characteristics of the Ram, Moosehound and Cardium Zone members (Deutsch, 1992). Note the variable base of the Ram Member and a regional autocyclic unconformity separating the Ram and Moosehound members. The contacts between the members, however, are transitional in terms of lithofacies and lithosome successions - environments change progressively, from shoreface and beach environments to lagoon and tidal marsh environments (see also Figure 23.14). Note also the channel complexes within the Moosehound Member and a regional allocyclic unconformity between the Moosehound and Cardium Zone members. In this instance, lithofacies and lithosome succession shift is sharp, changing from coastal plain to inner shelf and prodelta mudstones. In addition, note the multiple, variably continuous unconformities and sandstone lithosomes within the Cardium Zone Member; and a regional allocyclic unconformity at the top of the Cardium Zone Member, marking the top of the formation.

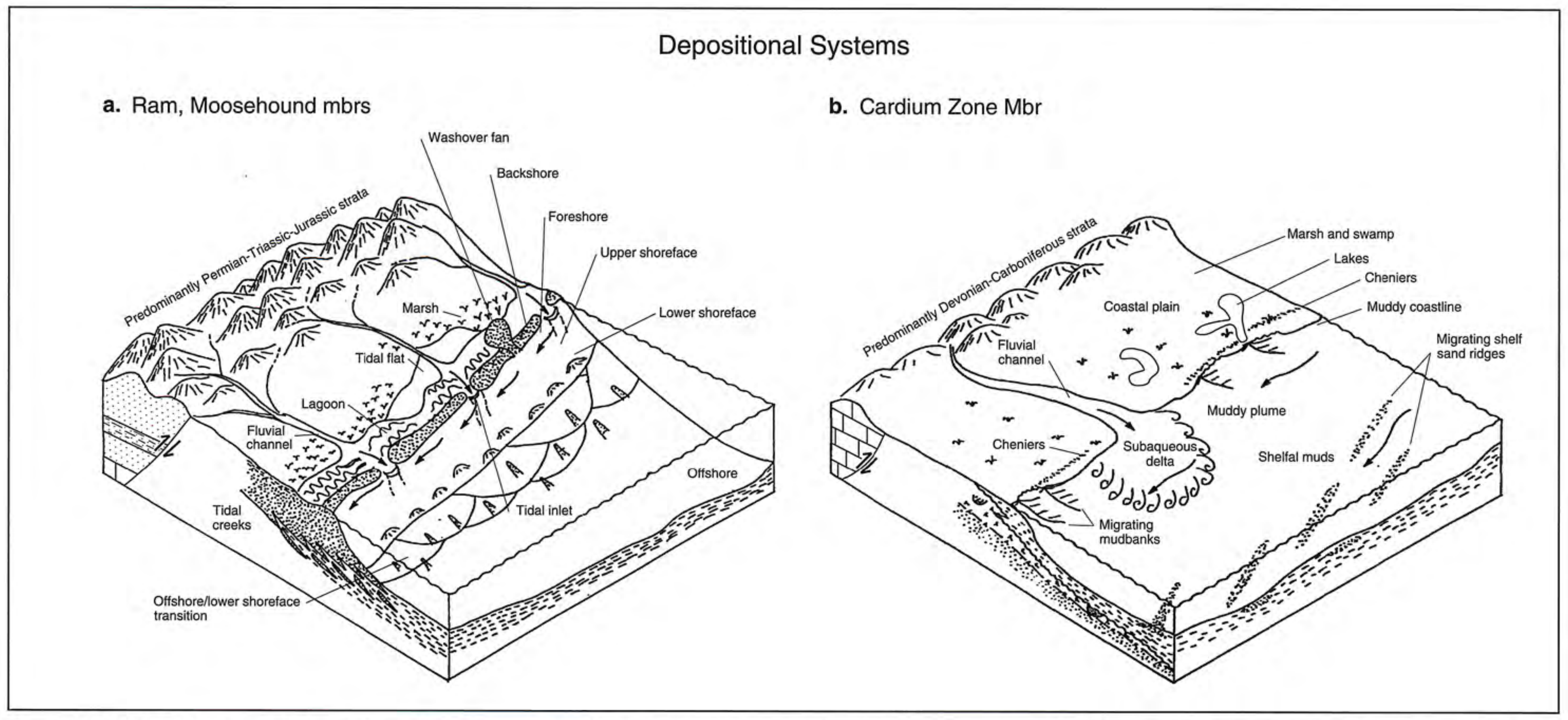


Figure 23.16 Block diagrams depicting depositional scenarios envisioned for accumulation of the Cardium Formation in the Kakwa region of Alberta (for additional details see Deutsch, 1992). **a.** Setting during accumulation of the Ram and Moosehound members; diagram illustrates sandy progradational shoreface and coastal plain regime typical of early Cardium Formation deposition. **b.** Setting during accumulation of the Moosehound and Cardium Zone members; diagram illustrates the muddy coastline regime typical of late Cardium Formation deposition.

Crossfield Field and Vicinity - Lower Pembina River Member Reservoir

The Crossfield reservoir is a 72 km long, 2.5 to 5 km wide sandstone and conglomeratic sandstone ridge that accumulated on the Late Turonian seafloor (Figs. 23.11, 23.12; Berven, 1966; Pattison, 1987; Krause and Nelson, 1991, Pattison and Walker, 1992). The reservoir is areally restricted, encased in mudstones, complexly interlayered and characterized by five, marine, upward shoaling lithofacies that have been described and interpreted by Krause and Nelson (1991) (Fig. 23.13). The ridge may have been initiated during a relative sea-level lowstand, where inner shelf and lower shoreface, bioturbated and current bedded, mudstones and gritty mudstones were initially deposited on a scoured mudstone in a setting dominated by unidirectional current flow. Subsequently, the ridge shoaled to the point where combined wave and unidirectional current components influenced sedimentation, as indicated by beds with small- and medium-scale, low-angle inclined cross-stratification, plane-parallel laminae, and little or no bioturbation (Krause and Nelson, 1991). Alternatively, the ridge may be transgressive in origin, having accumulated on a topographic inhomogeneity that developed in response to bottom reworking and scour of mudstones as a result of rising relative sea level (see Krause and Nelson, 1991, their Fig. 17). Coarse material, gritty mudstones and sandstones, may have become progressively more abundant as sea level continued to rise and shoreline deposits to the west and northwest were incised by ravinement processes and transported offshore. Deposits eventually shoaled sufficiently to be reworked by fair-weather and storm-weather waves and tidal currents. Subsequently, the ridge was abandoned as rising relative sea level peaked and reworking of the ridge by storm-weather waves and currents resulted in a conglomeratic lag at the top. Finally, rising sea level placed the ridge beneath average storm wave-base and fine-grained sedimentation resumed, encasing the ridge in mudstones. In addition, the sediment flux of the basin may have been such that fine-grained sediment input and transport overwhelmed coarser grained sediments (see below).

As discussed by Krause and Nelson (1991, their Fig. 17), the ridge developed on a topographic inhomogeneity and over time grew upward, eastward and southward. This pattern of growth indicates that dominant current directions on the Late Turonian seafloor were ridge-parallel with across ridge components, directed from the northwest to the southeast (Figs. 23.11, 23.12; Krause and Nelson, 1991). Processes such as these have been reported for the Atlantic inner, storm-dominated shelf of the United States by Swift and Field (1981). As suggested by Swift and Niedoroda (1985), tidal sediment transport processes are similar to storm transport processes and would have similar responses. The sediment transport processes could also intensify if storm and tidal currents are combined (Swift and Niedoroda, 1985). Combined storm and tidal processes may have fashioned the Crossfield reservoir into a ridge. Observed lithofacies clearly point to modification by storm flows and the dimensions of the ridge are similar to dimensions observed in modern tidal settings (as was originally pointed out by Off, 1963). Moreover, thick, black, massive, laminated and bioturbated mudstones, which enclose the ridge, reflect an overabundance of muds and silts at the time of deposition. These mudstone sequences may have formed in response to nearshore mud transport and depositional systems, as observed today along the shelves and coasts of Suriname, south Louisiana, the East China and Yellow seas, and Malabar (Wells and Coleman, 1981; Rine and Ginsburg, 1985; Wright et al., 1988; Krause and Nelson, 1991).

Kakwa Field and Vicinity - Cardium Zone Member Reservoir

The Cardium Formation in the Kakwa region is subdivided into three formal units, from base to top, the Ram, Moosehound and Cardium Zone members (Fig. 23.14; Deutsch, 1992). The basal, sandstone-dominated Ram Member is relatively uniform, with northwest- to southeast-trending thin and thick zones. The middle unit, the Moosehound Member, is an eastward thinning terrestrial mudstone and sandstone that is onlapped in the Kakwa area by the Cardium Zone Member and farther west intertongues with it (Fig. 23.15; Plint, 1988; Deutsch, 1992; Deutsch and Krause, 1990, 1991). In the Kakwa area (Nordegg Lobe), the Ram and Moosehound members represent a progradational parasequence that advanced in response to lowering relative sea level (Deutsch, 1992). Plint (1988) has also suggested that two types of shoreface sequences are present in the Ram Member: gradational and sharp based. The former can be attributed to progradation, as above. However, Plint (1988) has further proposed that sharp based shoreface sequences are not only progradational, but form in response to rapid lowering of sea level. The end result envisioned by Plint (1988) for these deposits is their proposed stranding and isolation on the shelf as sea level rises and transgression occurs. This attractive, but unconfirmed, interpretation has become the "type study" for the "forced regressions" of sequence stratigraphers (see Posamentier et al., 1992). Alternatively, sharp-based deposits could be the result of reworking by transgression, driven by subsidence, as has been described for the Mississippi Delta by Penland et al. (1988).

The Ram Member grades upward from bioturbated sandy mudstones at its base through a sequence of rhythmites and gutter casted, low-angle inclined, trough and planar tabular cross-stratified sandstones, capped by an extensively bioturbated, crossbedded and massive sandstone with rooted and pedogenically altered profiles. The lithological sequence of the Ram Member represents

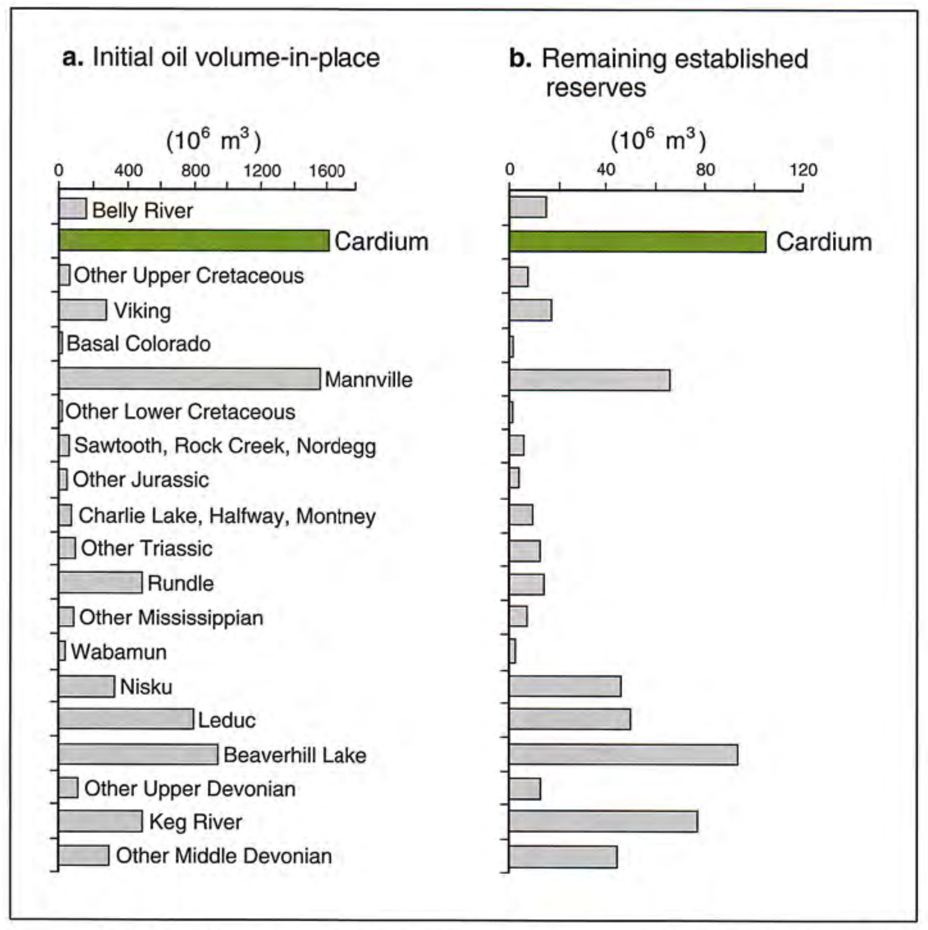


Figure 23.17 Cardium Formation hydrocarbon volumes. **a.** Initial known volume of hydrocarbons stored in the Western Canada Sedimentary Basin of Alberta (ERCB 870-17). **b.** Established known remaining reserves of hydrocarbons in the Western Canada Sedimentary Basin of Alberta (ERCB 87-18). Note that in both instances the Cardium Formation represents approximately 20 percent of the hydrocarbons identified in the Western Canada Sedimentary Basin as initial volume-in-place and as remaining established reserves. This hydrocarbon volume, stored in approximately 42 reservoirs, places this unit in the category of a supergiant formation.

depositional environments that change progressively upward from inner shelf and offshore transition to lower-, middle-, and upper-shoreface, foreshore and backshore environments (Figs. 23.15, 23.16; Plint, 1988; Deutsch, 1992; Deutsch and Krause, 1990, 1991). In contrast, the Moosehound Member consists of extensive deposits of carbonaceous and pelecypod-rich mudstones, interbedded and commonly pedogenically altered mudstone and sandstone, and wave and unidirectional current-bedded sandstones (Plint and Walker, 1987; Deutsch, 1992; Deutsch and Krause, 1991, 1992; Krause et al., 1992). The lithofacies architecture of these two members can be interpreted as representing a prograding, mesotidal barrier and backbarrier system that was influenced by fair-weather and storm-weather wave, tidal and riverine processes (Fig. 23.16a; Deutsch, 1992; Deutsch and Krause, 1990). Alternatively, Plint and Walker (1987) have interpreted the Ram and Moosehound members as being characteristic of a regressive and progradational, microtidal, barrier-lagoon system maintained by close interplay between subsidence and sedimentation.

The overlying Cardium Zone Member accumulated in a shallow shelf setting characterized by several parasequences, bound by disconformities. These contacts place bioturbated mudstones over current-bedded sandstones and represent deepening events. Toward the top of the Cardium Zone Member, parasequences become sandier and these deposits form areally restricted, long, linear, northwest-southeast-oriented ridges. To the west, Cardium Zone Member deposits interfinger with mudstones of the Moosehound Member (Figure 23.16b; Deutsch, 1992; Deutsch and Krause, 1991). The sedimentary and stratigraphic relations observed suggest that these rocks accumulated in mud-dominated settings, such as are observed in modern environments of Suriname, south Louisiana, the East China and Yellow seas, and the Malabar coast (Wells and Coleman, 1981; Rine and Ginsburg, 1985; Wright et al., 1988; Deutsch, 1992; Deutsch and Krause, 1991; Krause et al. 1992).

The Kakwa area is particularly important in understanding the depositional history of the formation, because these rocks preserve two very different, but juxtaposed, sedimentation styles – the nearshore to coastal plain sandstone-dominated Ram/Moosehound members and the nearshore to coastal plain mudstone-dominated Cardium Zone/Moosehound members. This juxtaposition of lithologies and similar depositional environments appears to be the product of differences in available erodable materials from the orogenic wedge of the Mesozoic Rocky Mountain Foreland Basin, rather than juxtaposition due to oscillations of relative sea level and erosion of sandstones during sea-level rises and concomitant ravinement (Figs. 23.16; Heise, 1987; Plint et al., 1987; Plint, 1988; Deutsch, 1992; Krause et al., 1992). Heise (1987), in a palynological study of the formation in outcrop and subsurface elsewhere in the basin, has shown that Upper Cretaceous palynomorphs succeed each other in normal stratigraphic order, but reworked palynomorphs of Triassic, Permian, Carboniferous and Devonian ages are inverted stratigraphically. Abundant Paleozoic palynomorphs are found in higher intervals of the formation and lower Mesozoic palynomorphs are found in lower intervals. The relations observed by Heise (1987) indicate that Paleozoic carbonate rocks contributed progressively more sediment to the foreland basin during Cardium Formation sedimentation as the orogenic foreland wedge continued to be uplifted, unroofing older rocks, and the locus of foreland basin subsidence migrated toward the foreland. Thus, ample supply of fine-grained sediment and diminishing terrigenous coarse clastic supply would have contributed to increasing accumulation of mudstone deposits later in the history of the formation.

Economic Geology

The volume of light hydrocarbons stored in the Cardium Formation is enormous (Fig. 23.17). Established reserves are greater than 1.6×10^6 m^3 of oil ($>10 \times 10^9$ BOIP; ERCB 87-18). Cardium Formation light hydrocarbon reserves also dominate foreland basin oil reserves. The known initial in-place oil volume contained in the Cardium Formation is almost one quarter of the total oil volume of the Western Canada Sedimentary Basin and this oil is predominantly light (ERCB 87-18). The initial oil in-place is represented by at least 42 fields producing from the Ram, Moosehound, lower and upper Pembina River and Cardium Zone members (Fig. 23.17a). Presently remaining reserves, accessible with currently available technology, amount to 20 percent of the remaining reserves of the Western Canada Sedimentary Basin (Fig. 23.17b; ERCB 87-18). Oil recovery from the formation is low and on average amounts to approximately 20 percent (McLeod, 1978; Purvis and Bober, 1979; Krause et al., 1987b). The low oil recovery factor makes this formation Canada's single largest conventional petroleum reserve. Thus, the Cardium Formation is deserving of continued study by the geological and engineering community.

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Frontispiece 24.0 Upper Cretaceous strata of the plains. Badlands eroded into the Campanian Belly River/Judith River succession in the valley of the Red Deer River, Dinosaur Provincial Park, north of Brooks, Alberta. The Belly River clastic wedge represents the first of the great foreland progradational cycles produced by Laramide orogenesis in the Cordillera to the west. Photograph by I.A. Campbell.