Chapter 16 – Triassic Strata of the Western Canada Sedimentary Basin

Authors:
D.E. Edwards - Krishelle Enterprises Ltd., Calgary
J.E. Barclay - Geological Survey of Canada, Calgary
D.W. Gibson - Geological Survey of Canada, Calgary
G.E. Kvill - North Canadian Oils Ltd., Calgary
E. Halton - Retired, Calgary

Overview

Triassic strata of the Western Canada Sedimentary Basin (Figs. 16.1-16.3) occur in four main physiographic provinces: the Rocky Mountains, the Rocky Mountain Foothills and the Interior Plains of northeastern British Columbia and northwestern Alberta (Gibson and Barclay, 1989), and the Interior Plains of southern Saskatchewan and Manitoba. The Alberta-British Columbia rocks of the Alberta Basin (Fig. 16.1) are separated from the Williston Basin rocks by the Sweetgrass Arch (see Porter et al., 1982). This chapter treats these two basins separately because their strata are quite different and also because Williston Basin strata may or may not be Triassic in age (Fig. 16.4a,b). The Williston Basin in Canada comprises two connected sub-basins, the Watrous and Amaranth sub-basins (Figs. 16.1, 16.5).

Alberta Basin

In the Alberta Basin, Triassic strata were deposited in one large, central sub-basin, the Peace River Embayment, which extended eastward from the western ocean onto the North American craton. The Embayment was connected to the Liard sub-basin in the north and to deposits in the Rocky Mountains and foothills in the south.

In the Alberta Basin, Triassic strata are up to 1200 m thick and thin eastward to an eroded zero edge (Fig. 16.2). They consist of marine to marginal-marine siliciclastic and carbonate rocks and lesser amounts of evaporites. These strata form a westward-deepening stable continental shelf and shoreline, inherited from the Carboniferous and Permian of the western passive margin of the North American craton. The strata range in age from Early Triassic Griesbachian to Late Triassic Norian (Fig. 16.6). Triassic rocks in the Alberta Basin extend from the United States border to the Liard River area of northeastern British Columbia and southern Yukon. The Liard sub-basin contains a thick section of Lower Triassic shales overlain by Cretaceous shales.

Throughout most of the Alberta Basin the Triassic is overlain unconformably by marine strata of Jurassic age (Figs. 16.7 - 16.9). In the extreme northwestern foothills of British Columbia and along the northern erosional edge of Triassic deposition in both Alberta and British Columbia, the Triassic is overlain by Lower Cretaceous strata (Figs. 16.7, 16.8). Triassic rocks are underlain unconformably by marine strata of Permian or Carboniferous age (Figs. 16.6 - 16.8).

Alberta Basin Triassic sediments were deposited as a series of three major transgressive-regressive ("T-R") third- or fourth-order cycles (Figs. 16.6, 16.8; Podruski et al., 1988; Gibson and Barclay, 1989).

The first (lowermost) cycle involves sediments deposited along a tidally influenced, deltaic coastline with corresponding deep-marine and distal shelf deposits. Depositional environments of the second cycle show similarities to barrier island/tidal coastlines such as those along the modern Texas Gulf Coast, the Persian Gulf and the New Brunswick coast (e.g., Fig. 16.10). The Western Canada Sedimentary Basin was situated at approximately 30° N during Triassic time and the paleoclimate probably ranged from mid-temperate to sub-tropical (Gibson and Barclay, 1989), similar to the modern Persian Gulf. The region was arid and dominated by winds from the west (Habicht, 1979). The third major cycle is dominated by shallow-water carbonate deposits.

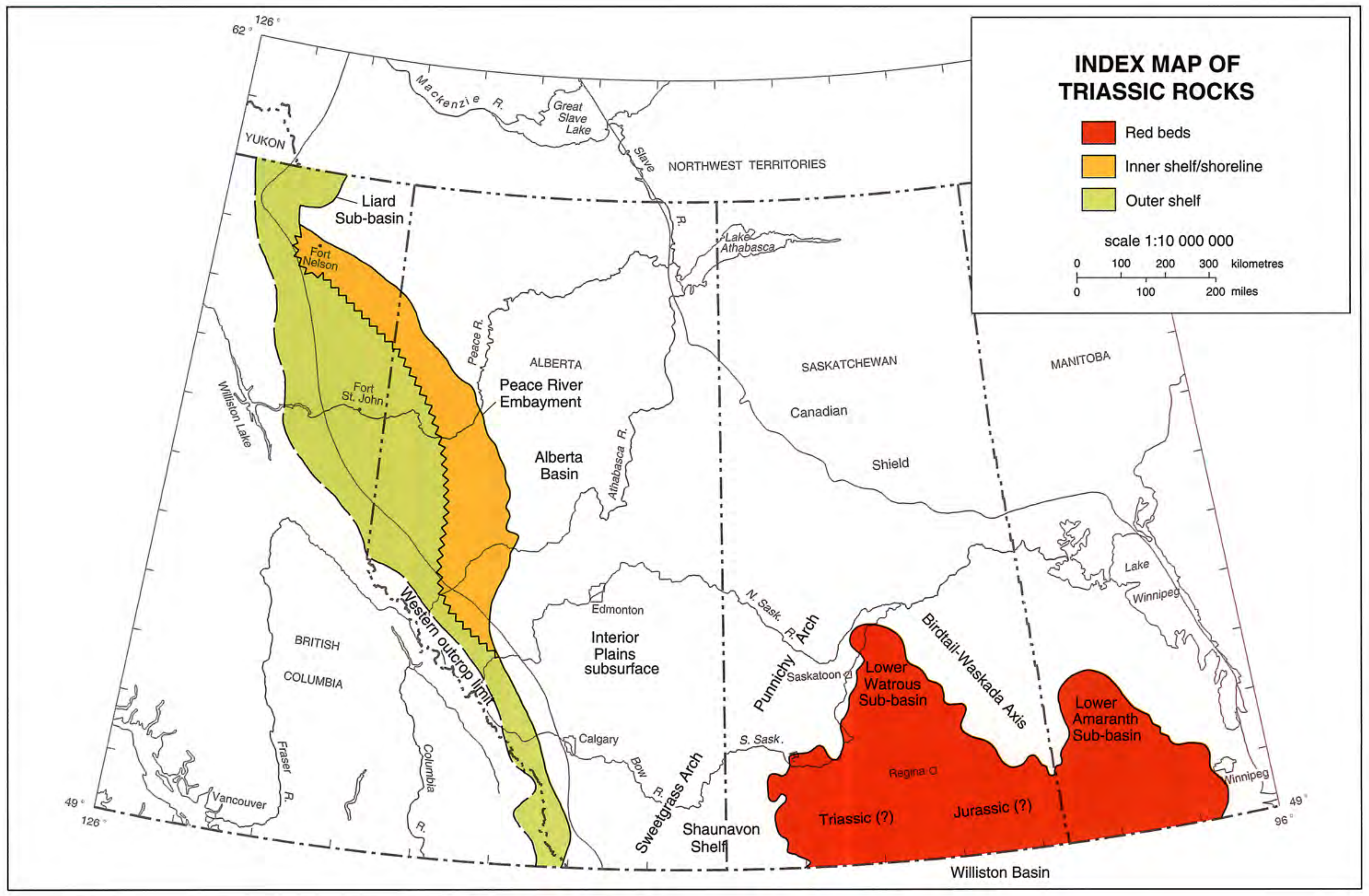


Figure 16.1 Index map of Triassic rocks in the Western Canada Sedimentary Basin.

Triassic strata contain substantial proven and potential hydrocarbon reserves in 105 oil fields and 217 gas fields. Triassic gas was discovered in 1950 within the Peace River Embayment at Whitelaw, Alberta. Exploration accelerated as a result of oil discoveries from 1952 to 1957 at Fort St. John, Sturgeon Lake South, Boundary Lake and Milligan Creek (Fig. 16.2). Alberta Basin recoverable oil reserves are 127.4 x 10^6 m^3, and marketable gas reserves are 278.7 x 10^9 m^3 (Tables 16.2a and 16.2b). These fields account for about 4 percent of Western Canadian oil reserves (Podruski et al., 1988) and about 8 percent of the gas reserves. The Triassic remains an active exploration target as shown by drilling activity and recent discoveries at Spirit River (Aukes and Webb, 1986), Brassey (Higgs, 1990a,b) and Ring-Border (Sturrock and Dawson, 1990).

Previous Work

Most of the early Triassic stratigraphic and paleontological studies undertaken in the Rocky Mountain Foothills of northeastern British Columbia were summarized by McLearn and Kindle (1950). This paper reviewed a substantial body of work (see reference list in Barss et al., 1964), which was done principally by McLearn from 1918 onward, and provided a stratigraphic and paleontological framework for the Triassic outcrop belt. Subsequent surface investigations of Triassic rocks in Alberta and British Columbia were made by Pelletier (1960, 1961, 1963, 1964, 1965), Tozer (1961, 1963a,b, 1967, 1982a,b, 1984) and Gibson (1970, 1971a, b, 1972, 1975).

Prompted by the gas and oil discoveries in the Peace River region, subsurface studies were published by such workers as Hunt and Ratcliffe (1959), Clark (1961), Armitage (1962), Fulton (1966), Fitzgerald and Peterson (1967), Mothersill (1968), Sharma (1969), Roy (1972) and Miall (1976). An important synthesis of Triassic surface and subsurface information was published in 1964 by Barss, Best and Meyers in the original geological atlas of Western Canada. This paper still serves as the fundamental reference to the Western Canada Triassic. A more recent synthesis of Triassic stratigraphy in the Peace River area was published by Gibson and Edwards (1990a, b).

In the foothills and Rocky Mountain Front Ranges between Jasper and the United States border, reports concerning Triassic rocks have been prepared by Kindle (1944), Warren (1945) and Gibson (1968a,b, 1969, 1971b, 1974). More recent papers concerning mainly the subsurface Triassic include McAdam (1979), Barss and Montandon (1981), Halton (1981), Cant (1984, 1986), Aukes and Webb (1986), Campbell and Horne (1986), Podruski et al. (1988), Brack et al. (1989), Gibson and Barclay (1989), Bever (1990), Gibson and Edwards (1990a,b), Higgs (1990a,b), Shell Canada Limited (1990), Sturrock and Dawson (1990) and Gibson (*in press*).

Early Triassic fish have been described by Schaeffer and Mangus (1976), from the Wapiti Lake area of British Columbia. The fish assemblages of Wapiti Lake are of significance in evolutionary terms because of the appearance of *Parasemionotiformes*, a group that is intermediate between the primative bony fish (*Paleonisciformes*), which are typical of Paleozoic assemblages, and the advanced groups (holosteans), which dominate in the Late Triassic. Work on the Western Canada Ichthyosaur fauna has been published by Callaway and Brinkman (1989).

Geological Framework

The Peace River Embayment of Alberta and British Columbia developed during Early Carboniferous and Permian time, coinciding with the area occupied by the Precambrian to Devonian Peace River Arch and present Peace River Arch. The Carboniferous-Permian embayment subsided as a broad downwarp with a large central half-graben complex along the axis of the arch, with subsidence accompanied by intense block faulting (Richards, 1989; Henderson, 1989; Barclay et al., 1990; O'Connell et al., 1990). During Triassic time, the Embayment persisted and subsided as a broad downwarp associated with minor block fault rejuvenation, particularly in the Monias area and southwest of Fort St. John. The rejuvenated faults influenced local sedimentation patterns.

Locally, sediment loading, indicated by deformed bedding and slump structures, and also localized small-scale (10-20 m) faulting normally formed in subparallel sets, were factors in Triassic deposition (see Cant, 1984; 1986; Wittenberg and Moslow, 1991). The fault sets also commonly control fluid distributions within reservoirs (e.g., Ring-Border, Wembley and Cecil fields; Figs. 16.2, 16.25).

To date there is no convincing evidence of a major highland or sediment source area for Triassic sediments west of the Alberta Basin. Triassic rocks in the present British Columbia Cordillera represent islands of the western ocean known as Panthalassa. The islands may have existed off the edge of the craton but these rocks are interpreted to have been accreted to North America during Jurassic to Cretaceous orogeny (Tozer, 1982a, b; Gibson and Barclay, 1989). Swelling claystones in the Montney Formation, Ring-Border Field area (Fig. 16.2; northeast British Columbia and western Alberta), might be bentonitic and thus volcanically-derived, and hint perhaps at western volcanism and thus possible highlands west of the Western Canada Sedimentary Basin (D.L. Sturrock, pers. comm., 1990).

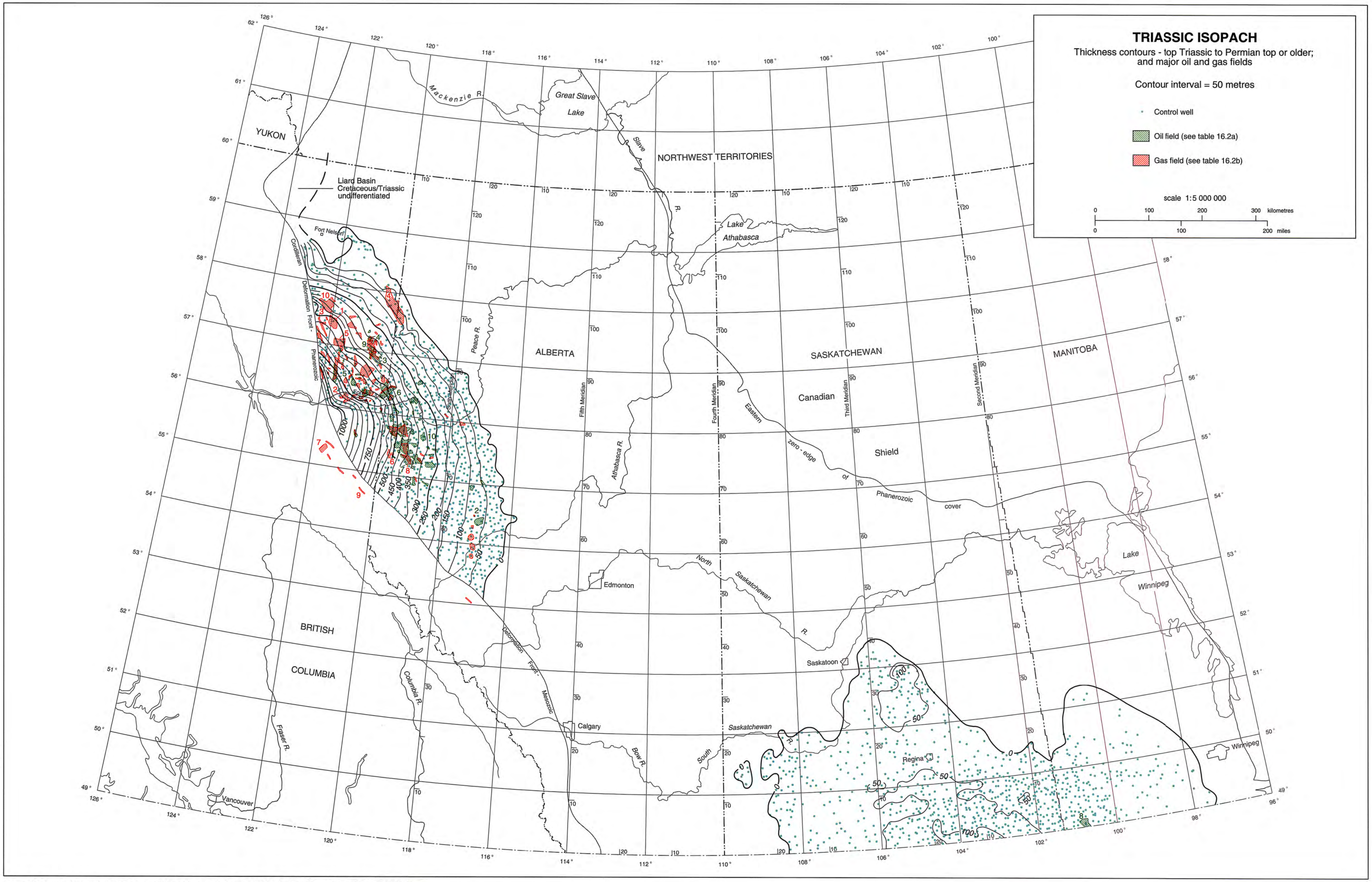


Figure 16.2 Total Triassic isopach map, with major producing fields highlighted (see tables 16.2a and 16.2b).

Table 16.2a

Oil Production from the Triassic

Major oil production from the Triassic is primarily derived from northeast B.C., western Alberta and southwest Manitoba. Most of the fields occur along erosional wedge edges within the Triassic. Included is the Waskada field in southwest Manitoba, which produces from the Amaranth formation.

There are 20 Triassic oil fields with Initial Established Recoverable Oil Reserves of over 1 x 10^6m^3 (6 MMBbls). The ten largest Triassic oil fields, listed in order of Initial Established Recoverable oil reserves, are shown in Table 1. Cumulative production data for Alberta and British Columbia are updated to the end of 1990.

Table 1 - Ten Largest Triassic 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	Boundary Lake	Bndry L Mbr	6	34.7	85.0	28.4	1954
2	Kaybob South	Montney	1	17.8	34.9	13.5	1961
3	Peejay	Halfway	4	11.1	28.2	9.8	1959
4	Milligan Creek	Halfway	1	7.2	13.8	6.9	1957
5	Inga	Inga	2	6.2	18.5	5.8	1962
6	Boundary L South	Bndry L Mbr	10	5.8	21.3	3.9	1963
7	Wembley	Charlie Lk	13	5.1	28.3	2.3	1978
8	Waskada	Amaranth	5	3.5	n.a.	1.6	1980
9	Weasel	Halfway	7	3.3	7.1	3.1	1961
10	Rycroft	Charlie Lk	11	3.1	10.0	1.2	1982

Five of these fields are in B.C., four in Alberta and one in Manitoba. Nine of the fields are in stratigraphic traps, formed by pinchout of porous sandstone or carbonate facies. The Inga field is the only structural trap, and occurs on an anticlinal structure.

Total recoverable oil reserves in the Triassic are estimated at 127.4 x 10^6m^3, of which 89.1 x 10^6m^3 (i.e. 70%) have already been produced. Initial Established In-Place Volume of Triassic oil reserves totals 427 x 10^6m^3. There are 337 Triassic oil pools, with average recoverable oil reserves of 378 x 10^3m^3/pool. Table 2 lists the distribution of Triassic oil reserves according to In-Place Pool Size.

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

In-Place Pool Size Class	No. of Pools	Recoverable Reserves	Cumulative Production
less than 0.1	84	0.60	0.25
0.1 to 1	195	7.75	3.59
1.0 to 10	50	32.00	15.82
10.0 to 100	8	87.09	69.44
over 100	-	-	-
Total	337	127.43 x 10^6m^3	89.10 x 10^6m^3

Table 16.2b

Gas Production from the Triassic

Major gas production from the Triassic is restricted to northeast B.C. and western Alberta. Many of the fields occur along erosional wedge edges within the Triassic or in structural highs related to foothills faulting. There are 45 Triassic gas fields with Initial Established Marketable Gas Reserves of over 1000 x 10^6m^3 (35 BCF). The ten largest Triassic gas fields, listed in order of Initial Established Marketable gas reserves, are shown in Table 1. Cumulative production data for Alberta and British Columbia are updated to the end of 1990.

Table 1 - Ten Largest Triassic 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	Laprise Creek	Baldonnel	3	24,942	29,130	16,647	1957
2	Monias	Halfway	1	18,090	20,100	4,384	1979
3	Jedney	Baldonnel/Hfwy	5	16,279	19,025	10,567	1958
4	Ring	Blsk/Gtng/Montny	1	15,307	20,409	14	1980
5	Nig Creek	Baldonnel	3	13,196	18,843	8,086	1953
6	Sinclair	Doig	9	10,562	15,635	2,360	1977
7	Sukunka	Baldonnel	6	9,946	14,309	3,238	1964
8	Wembley	Halfway/Doig	10	7,903	12,780	365	1978
9	Ojay	Baldonnel	1	7,870	9,838	0	1974
10	Tommy Lakes	Halfway	1	7,699	19,247	1	1960

Seven of these largest Triassic gas fields occur as stratigraphic wedge edge traps, and the remaining three, namely Jedney, Sukunka and Ojay, are in structural traps along the foothills disturbed belt. Eight of these ten fields occur in B.C., and Sinclair and Wembley in western Alberta. The most recent major Triassic gas discovery was the Ring field, discovered in 1980.

Total recoverable gas reserves in the Triassic are estimated at 278.7 x 10^9m^3, of which 94.4 x 10^9m^3 have already been produced. Initial Established In-Place Volume of Triassic gas reserves totals 382.4 x 10^9m^3. There are a total of 674 Triassic gas pools, with an average 414 x 10^6m^3 recoverable gas reserves/pool. Table 2 lists the distribution of Triassic gas reserves according to In-Place Pool Size.

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

In-Place Pool Size Class	No. of Pools	Recoverable Reserves	Cumulative Production
1.0 to 10	13	62	38
10 to 100	310	10,976	1,703
100 to 1000	302	65,026	21,283
1000 to 10000	41	101,269	35,090
over 10000	8	101,377	36,284
Total	674	278,710 x 10^6m^3	94,398 x 10^6m^3

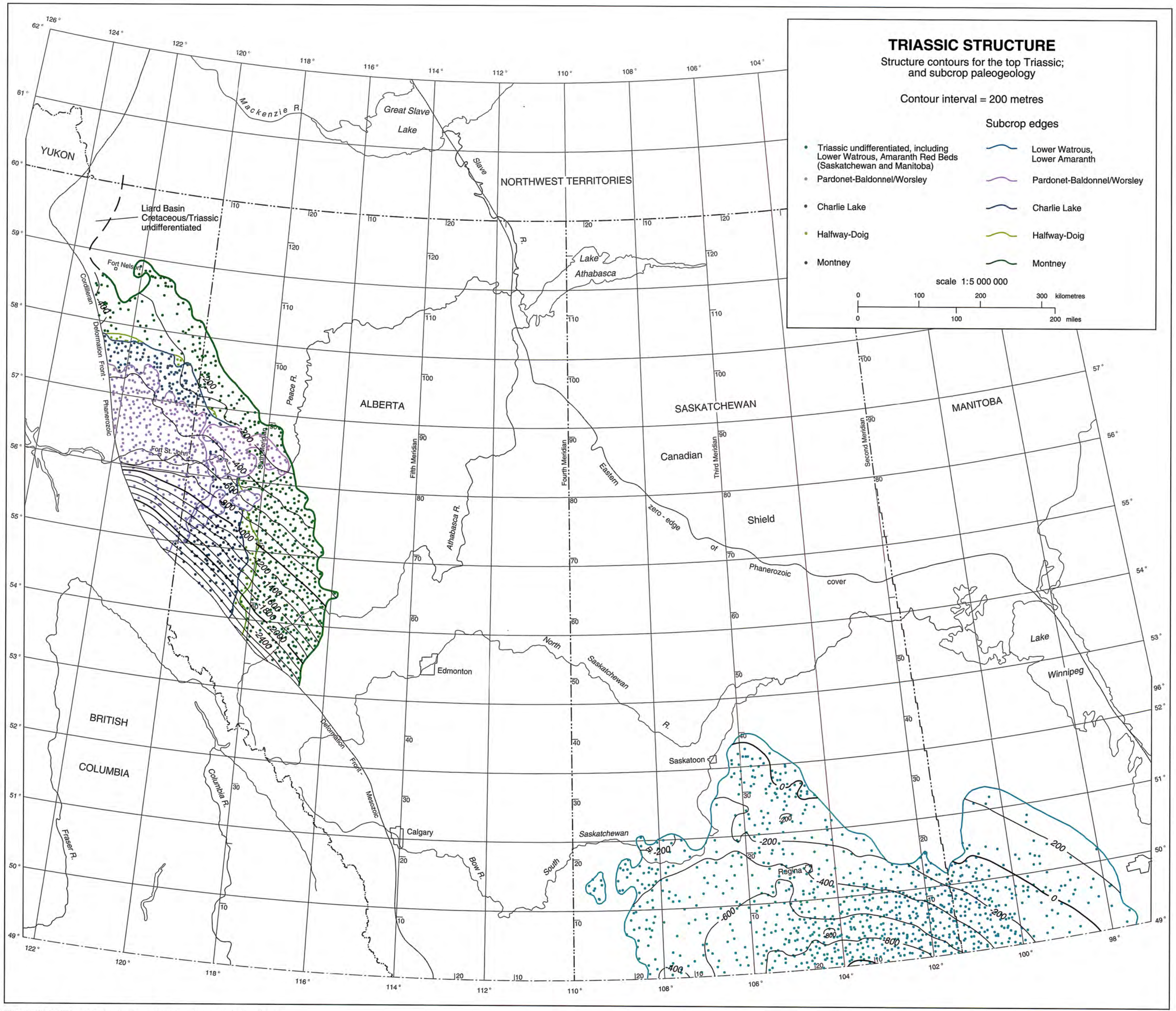


Figure 16.3 Triassic structure map, and subcrop paleogeology.

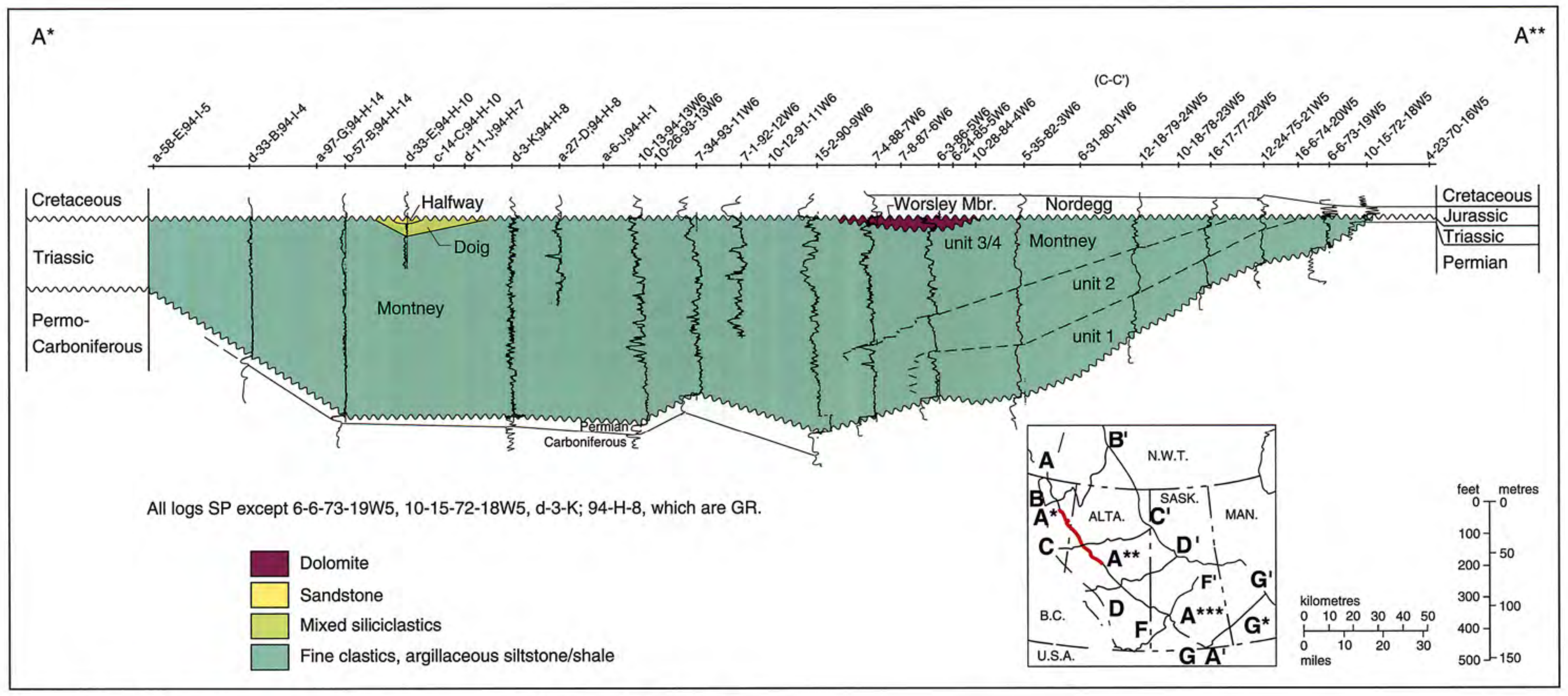


Figure 16.4a Northwestern portion of Atlas cross section A-A′, in the Alberta Basin.

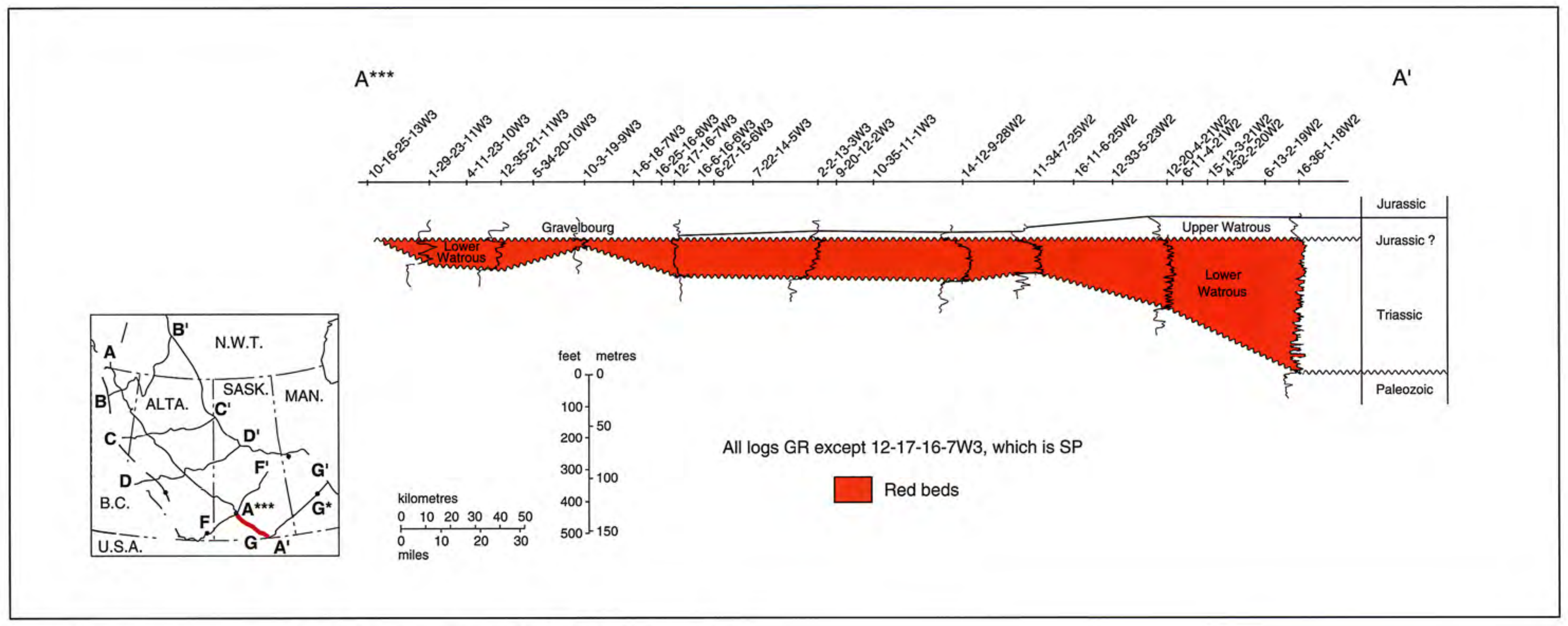


Figure 16.4b Southeastern portion of Atlas cross section A-A′, in the Williston Basin.

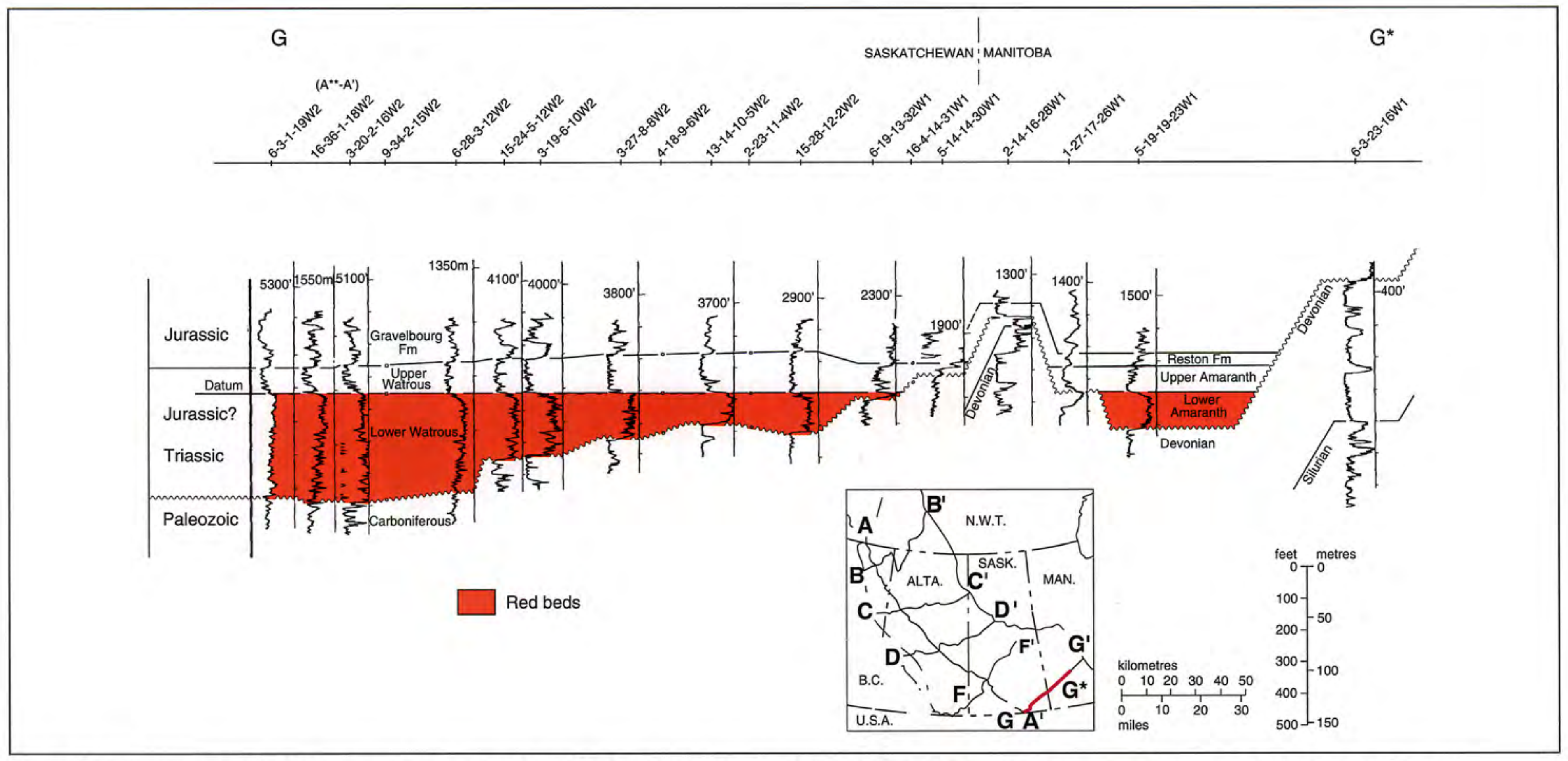


Figure 16.5 Cross section G-G*, showing the separation of the Williston Basin Triassic into the Watrous Sub-basin in the west and the Amaranth Sub-basin in the east, separated by the Birdtail-Waskada Axis.

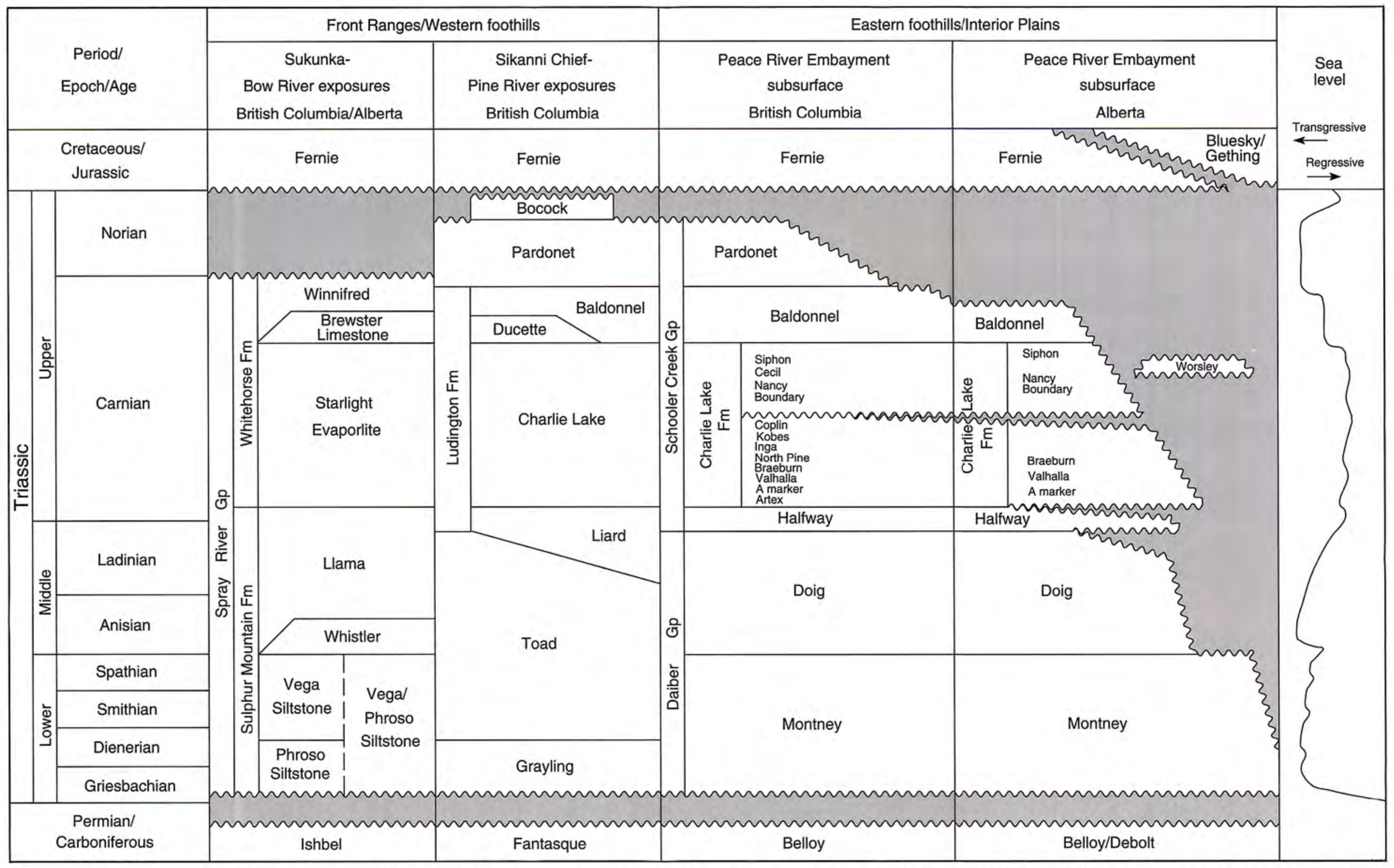


Figure 16.6 Triassic nomenclature and correlation chart for the Alberta Basin portion of Western Canada Sedimentary Basin, from the Rocky Mountain Front Ranges, through the foothills to the Interior Plains, Alberta and British Columbia.

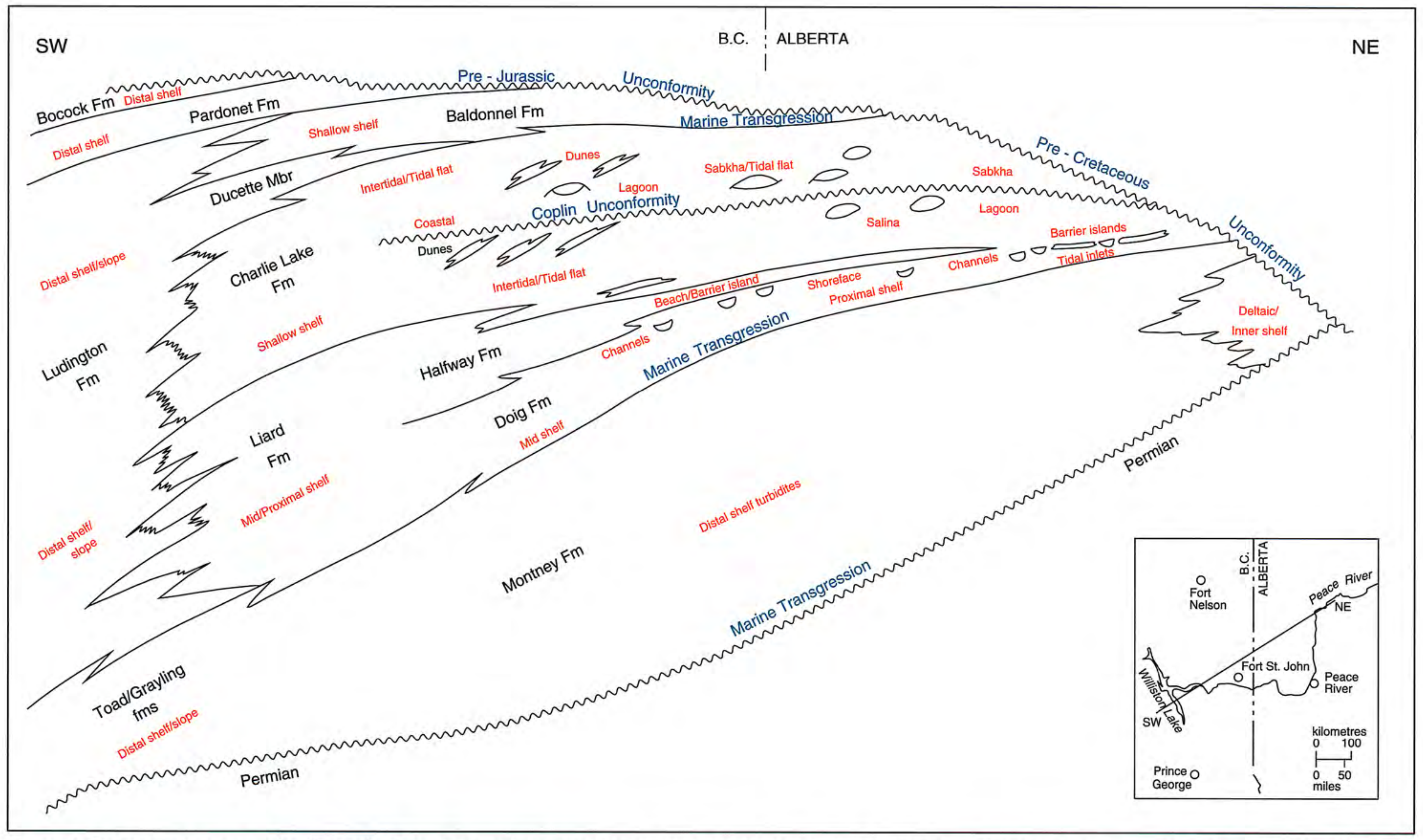


Figure 16.7 Schematic cross section illustrating Triassic formations, stratigraphic relations and depositional environments, Peace River Embayment area, northeastern British Columbia outcrop (SW) to the Peace River subsurface (NE), (modified from Gibson and Edwards, 1990b).

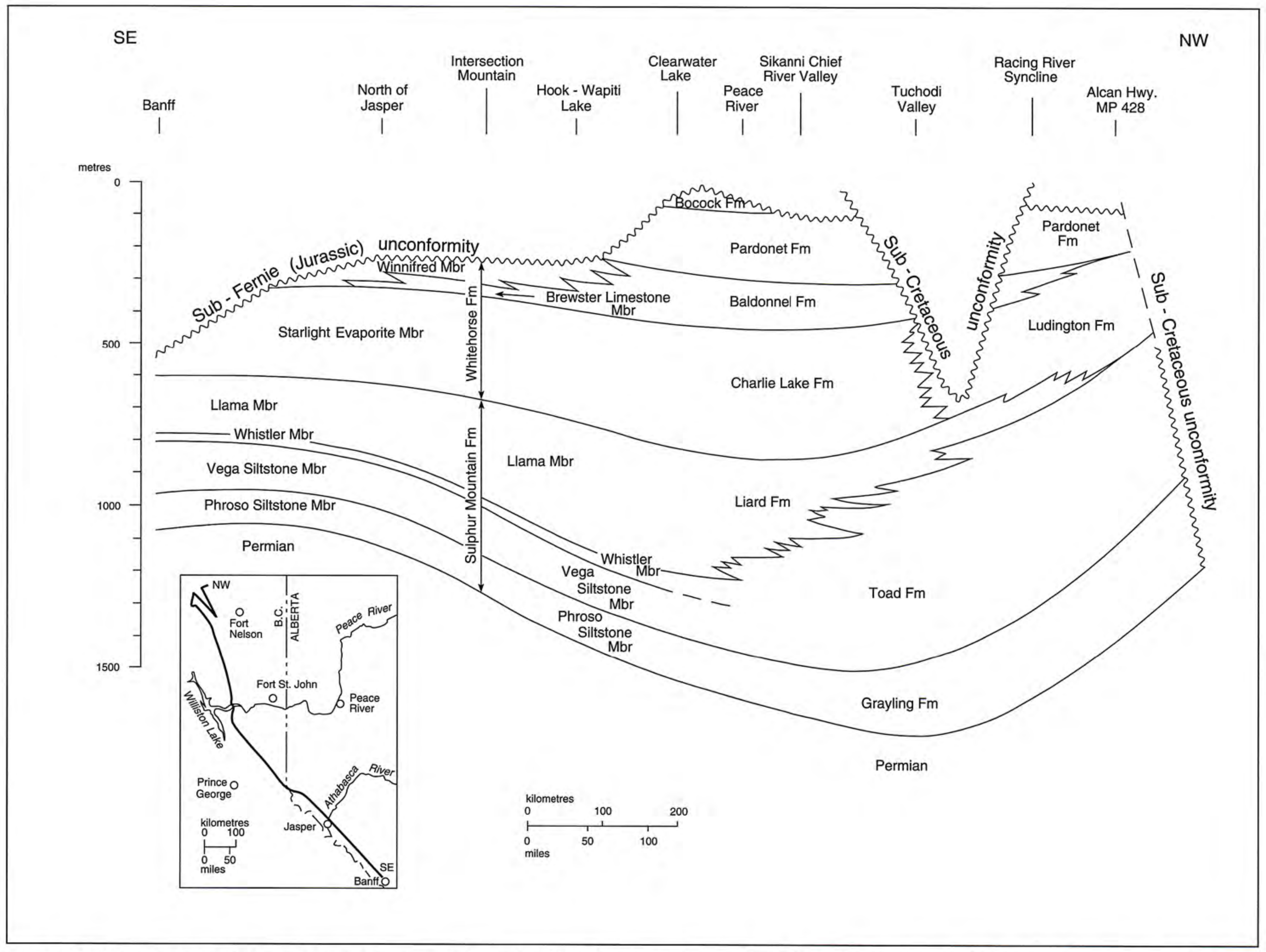


Figure 16.9 Schematic longitudinal section illustrating nomenclature and stratigraphic relations between Banff, Alberta (SE) and the Alaska Highway in northeastern British Columbia (NW) (prepared by E.T. Tozer, modified from Gibson and Barclay, 1989).

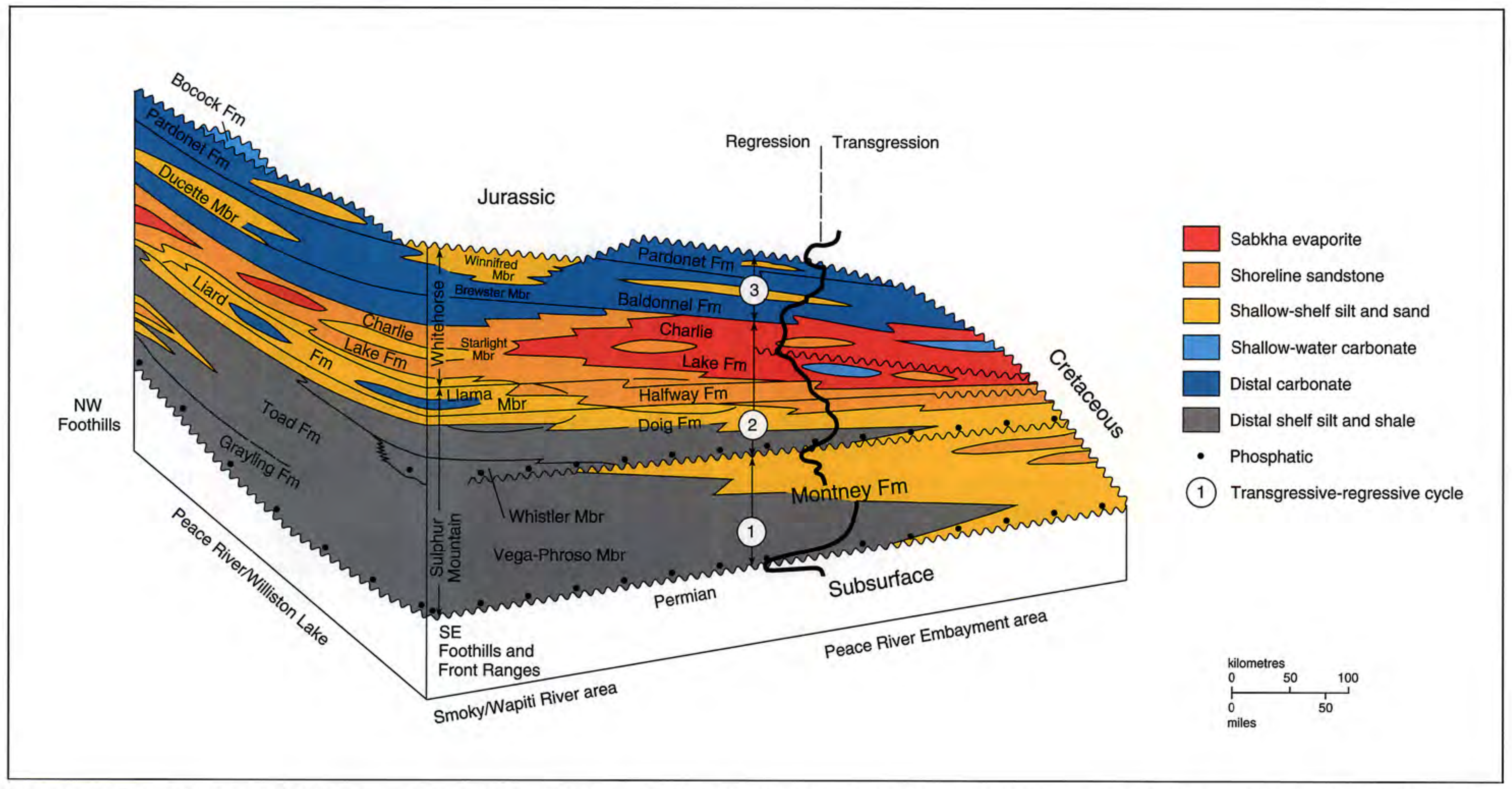


Figure 16.8 Generalized stratigraphic cross section, illustrating Triassic lithologies and regional relations between Rocky Mountain Front Ranges, foothills and subsurface plains of Alberta and British Columbia. Lithofacies assemblages 1, 2 and 3 correspond to broad regional transgressive-regressive packages and are related to relative sea-level changes. Major unconformities include the sub-Triassic, sub-Jurassic and sub-Cretaceous surfaces. The heavy black curve depicts relative sea level.

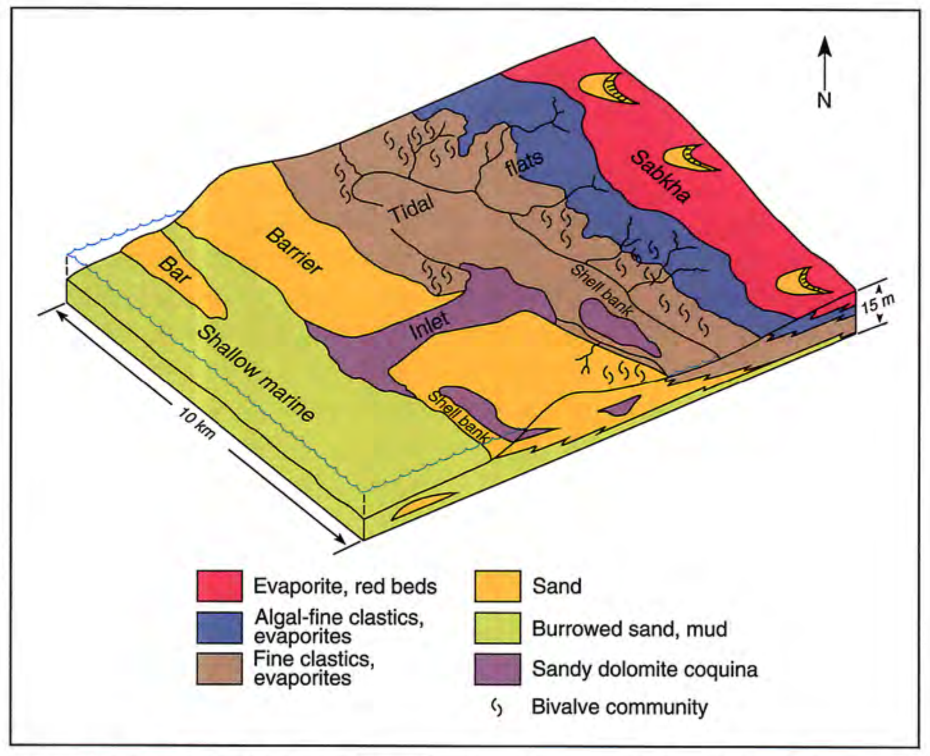


Figure 16.10 Model of inferred depositional environments for the Doig, Halfway and Charlie Lake formations, northeastern British Columbia. This scenario depicts progradation of a barrier-tidal inlet complex (Halfway Fm) over offshore shelf shale, siltstone and sandstone (Doig Fm). The barrier is capped by Charlie Lake sabkha facies (after Barclay and Leckie, 1986).

In the western foothills and Rocky Mountain Front Ranges, Triassic rocks have been subjected to the Jura-Cretaceous Columbian and Upper Cretaceous-lower Tertiary Laramide orogenies, resulting in a series of imbricate thrust faults and folds. In northeast British Columbia, some of these structures provide large gas traps, such as at Sukunka, Jedney, Bubbles and Beg fields (Fig. 16.2; Fitzgerald and Peterson, 1967; Barss and Montandon, 1981; Podruski et al., 1988; Brack et al., 1989).

Structure

In the Peace River Embayment, tectonic activity during the Paleozoic resulted in numerous block faults, which displayed a rejuvenated but diminished activity during Triassic time. Faulting was much reduced by the time of Halfway deposition and is most evident in the Fort St. John/Monias area near the end of Triassic time (Fig. 16.3). Triassic strata drape over underlying Paleozoic faults in a number of areas (e.g., Pouce Coupe, Tp 78 R12W6). Some of these rejuvenated faults are important in hydrocarbon production (e.g., Cecil and Ring-Border fields). Small-scale "load or gravity faults" occur in the Halfway and Doig interval (Cant, 1984, 1986; Wittenberg and Moslow, 1991) but are too small to appear on regional-scale structure and isopach maps. Tectonic activity associated with the Cretaceous Laramide Orogeny produced a number of thrust faults and folds seen in the west and southwest of the Peace River Embayment. These faults and folds act as important anticlinal hydrocarbon traps, such as at Sukunka, Beg and Jedney fields in British Columbia.

Structure on top of the Triassic sediments forms a peneplain surface except along the subcrop edge, where the surface is influenced by Lower Cretaceous channeling (Fig. 16.3).

Stratigraphy

Stratigraphic Nomenclature

Triassic stratigraphy, nomenclature and nomenclatural relations in the Alberta Basin are summarized and discussed by McLearn and Kindle (1950), Hunt and Ratcliffe (1959), Barss et al. (1964), McAdam (1979), Stewart (1984), Tozer (1984), Gibson and Barclay (1989), Gibson and Edwards (1990a, b), Glass (1990) and Gibson (*in press*) (see Figs. 16.6 - 16.8).

For mapping purposes in this chapter (Figs. 16.24, 16.27, 16.31 and 16.34), the Triassic of the Peace River Embayment is subdivided into four map units, based mainly on geophysical well logs. These map units are, in ascending order, the Montney Formation, the Doig plus Halfway formations, the Charlie Lake Formation, and the Baldonnel plus Pardonet formations (see Figs. 16.6, 16.7). Because of the gradational nature and consequent difficulty in recognizing some formational contacts, and the spread of Atlas well control (1 well per township = 1 well/100 sq. km), a more refined subdivision is difficult to apply regionally and consistently. The Montney map unit represents the first Alberta Basin Triassic transgressive-regressive (T-R) cycle, the Doig-Halfway and Charlie Lake map units the second T-R cycle, and the Baldonnel-Pardonet map unit the third T-R cycle (Fig. 16.8; see Podruski et al., 1988; Gibson and Barclay, 1989).

In the foothills outcrop belt between the Sukunka and Liard rivers, northeastern British Columbia, Triassic rocks are subdivided into eight formations, some of which display sufficient internal lithological variation for subdivision into members of basin-wide or local extent. These are, in ascending order, the Grayling, Toad, Liard, Charlie Lake, Baldonnel, Pardonet and Bocock formations (Fig. 16.9). In the western foothills, north of Williston Lake, the Liard and Charlie Lake formations and part or all of the Baldonnel Formation grade westward into the Ludington Formation (Fig. 16.7) (N.B., Williston Lake, British Columbia, should not be confused with the Williston Basin of Saskatchewan and Manitoba). South, and near Williston Lake, the Baldonnel Formation is further divided into an unnamed upper unit and a lower unit, the Ducette Member (Fig. 16.7). In the foothills and front ranges between Sukunka River and the United States border, Triassic rocks are divisible into two distinctive and contrasting formations, a lower Sulphur Mountain Formation and an upper, Whitehorse Formation (Fig. 16.9). Each of these two formations is subdivided into members.

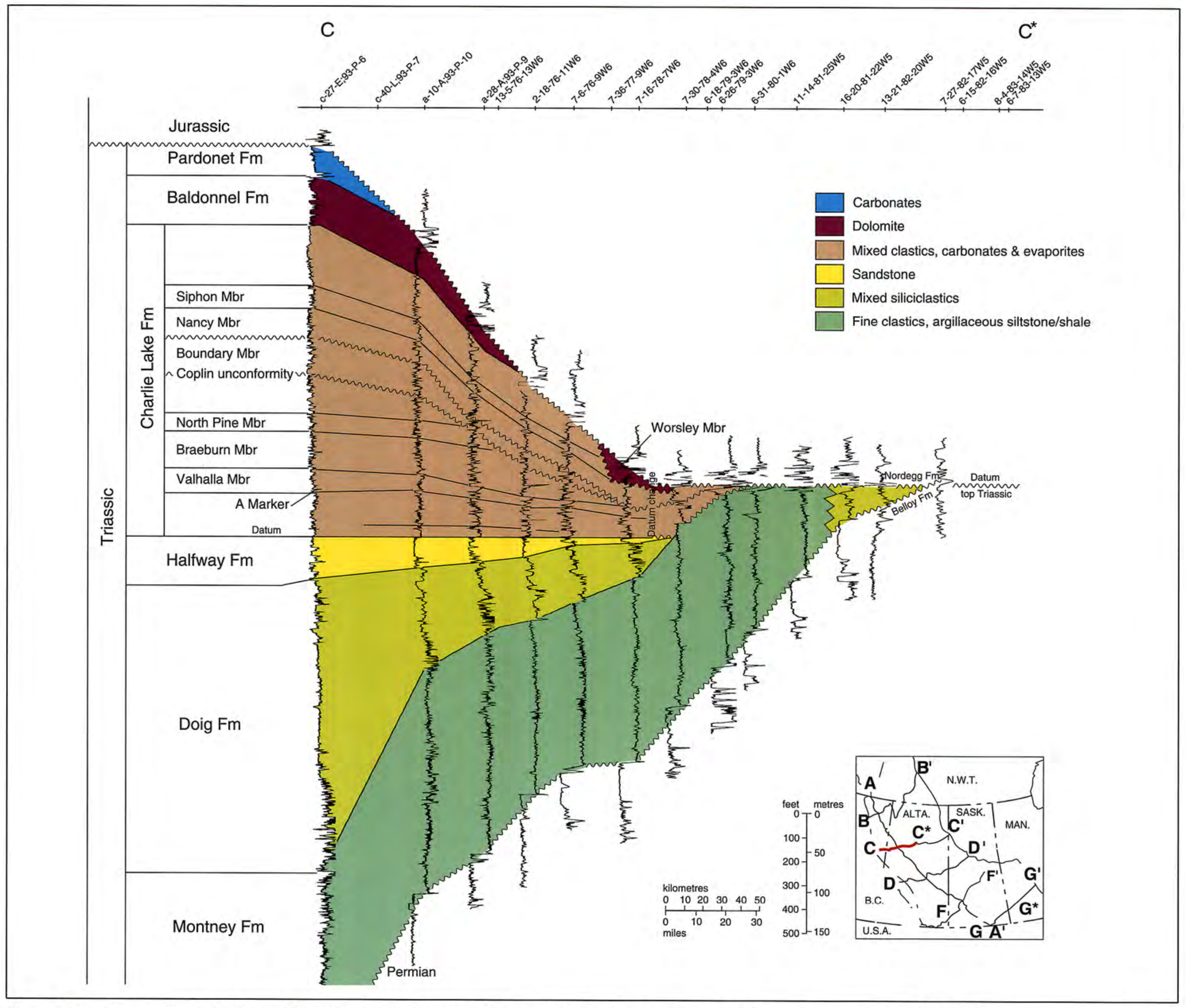


Figure 16.11 Cross section C-C*, Peace River Embayment. The datum is the top Halfway in the west and the sub-Jurassic unconformity in the east.

In the subsurface of the Peace River Embayment, six formations are present. In ascending order these are the Montney, Doig, Halfway, Charlie Lake, Baldonnel and Pardonet formations (Figs. 16.6-16.8). The Charlie Lake Formation is subdivided into a number of formal and informal members (Fig. 16.22; see Torrie, 1973; McAdam, 1979; Stewart, 1984; Glass, 1990).

Unconformities or disconformities occur locally at the base of the Halfway Formation (Barss et al., 1964), locally at the base of the Charlie Lake Formation (Aukes and Webb, 1986; Campbell et al., 1989), and within the Charlie Lake Formation (Fig. 16.6). The Charlie Lake Formation contains at least three significant unconformities, informally named the Coplin, Boundary Lake and Siphon unconformities as a result of common usage (see Roy, 1972; Torrie, 1973). The Charlie Lake unconformities are most evident along the eastern margin of the basin (Aukes and Webb, 1986), possibly reflecting basin margin uplift events. The Coplin unconformity occurs regionally and subdivides the Charlie Lake into informal upper and lower units (see Fig. 16.6; note break shown between Coplin and Boundary members; see also Figs. 16.11 -16.13).

The "Worsley Member" or "Tangent Dolomite" is poorly understood and is recognized only in the eastern subsurface of the Peace River Embayment of Alberta. It is generally thought to be Triassic (Late?) in age (Figs. 16.6, 16.11) but there is no fossil evidence. The Worsley is underlain unconformably by the Charlie Lake or the Montney Formation and overlain unconformably by the Jurassic Fernie Formation. The "Worsley Member" has not been assigned to a formation and no type section has been designated. Hassler (1990) suggested well PCP et al. Rycroft 6-17-77-5W6, 1382-1385 m, as a reference section. The Worsley (Tangent) Dolomite may be equivalent to any of the Triassic strata, such as the Baldonnel, Pardonet, Bocock, or Charlie Lake formations, or perhaps the base of the Jurassic Fernie Formation (Podruski et al., 1988, p. 82). The Worsley can also be interpreted as a unit of the Toad/Grayling or Montney Formation (e.g., Shell Canada Ltd., 1990). However, the Worsley is herein suggested to be a facies of the Charlie Lake Formation because of interpreted facies transition to the Charlie Lake (Hassler, 1990) and a closer lithological similarity to the Charlie Lake than to other strata.

Stratigraphic History – Peace River Embayment

In the Alberta Basin, Early Triassic deposition began with a major marine transgression eastward onto an eroded Carboniferous and Permian peneplain surface and was followed by a regression. This T-R depositional cycle resulted in the deposition of the Montney, Grayling, lower Toad and lower Sulphur Mountain formations (Fig. 16.8; Gibson and Barclay, 1989; Gibson, *in press*). Initial deposition took place in a westward-deepening, open-shelf marine environment. The sediment source was Permian and Carboniferous sediments on the emergent craton to the east and north (Fig. 16.1; Podruski, et al., 1988). This low-relief area supplied mature, multicycled, quartz-rich sand grains, ultimately from the Precambrian Shield, which dominate all the Triassic clastic deposits.

Over most of British Columbia and Alberta, the Montney, lower Toad and lower Sulphur Mountain formations consist of relatively deep-water, mid- to distal-shelf and slope shales, siltstones and rare limestones (Figs. 16.7, 16.8). Some beds represent tempestites or turbidites. In the westernmost foothills, the lower Toad Formation thins as a result of slower and deeper water deposition, mainly in a distal shelf/slope environment. Approaching the subcrop edge in west-central Alberta, deltaic and/or inner shelf sandstones and dolomitic coquinas in the Montney Formation (Metherell, 1966; Miall, 1976; Brack et al., 1989) and lower Sulphur Mountain Formation (Gibson, 1974) contain hydrocarbons. Also, near or at the subcrop edge in northeastern British Columbia (e.g., Ring-Border gas field at the British Columbia/Alberta boundary, Fig. 16.2), restricted shoreface-lagoonal sandstones, siltstones and shales of the Montney Formation occur.

In the Alberta Basin, the Middle Triassic epoch began with the second of the three T-R cycles, a regional transgression depositing sediments of the Whistler Member (Sulphur Mountain Formation), middle Toad Formation and lower Doig Formation (Figs. 16.7, 16.8). This stratigraphic interval is commonly called the "Phosphate Zone" as it is characterized in many areas by granular phosphate and phosphatic pebble conglomerate (Barss et al., 1964; Gibson and Barclay,1989; Gibson, *in press*). The abrupt basal contact with the Lower Triassic Vega-Phroso and Montney, combined with the occurrence of the phosphatic conglomerates, suggests that the basin may have been subjected to a brief interval of nondeposition or submarine erosion prior to cycle 2 transgression.

Following the transgression, the shelf was again subjected to regression, during which the upper Sulphur Mountain, upper Toad, Liard, upper Doig, and Halfway formations, and the Llama Member were deposited (Figs. 16.7, 16.8). These strata form part of a coarsening-upward profile (see Figs. 16.11, 16.13). The Whistler Member, and upper Toad and lower Doig (Phosphate Zone) formations represent deposition in relatively deep-water distal- to mid-shelf environments. The upper Doig and Halfway formations represent deposition in a prograding micro- to mesotidal barrier island shoreline system with equivalent offshore-shelf marine siliciclastics and lesser limestones to the west. Farther west, equivalent strata of the Liard and upper Sulphur Mountain formations represent mid-shelf to inner-shelf coastal environments.

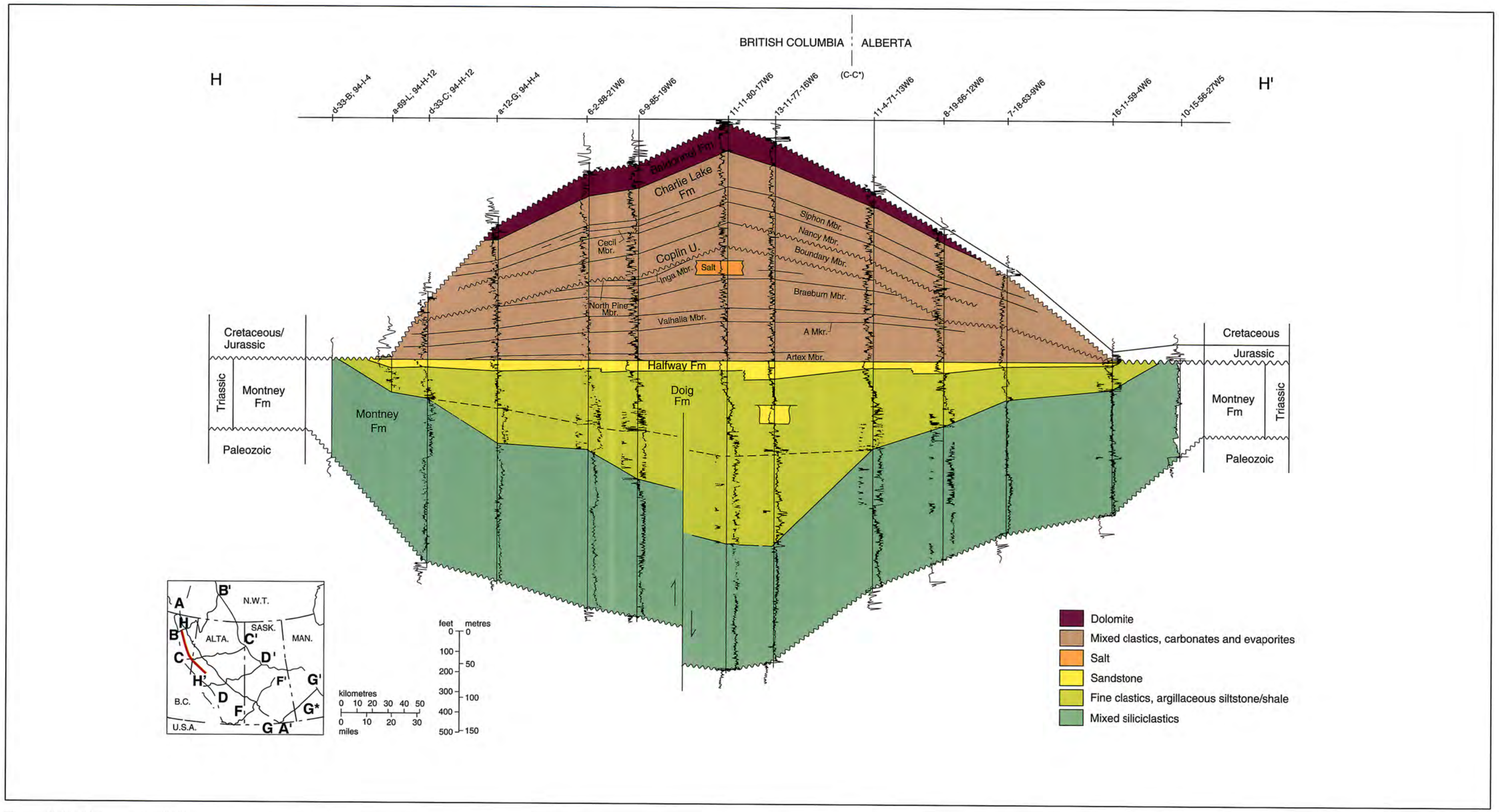


Figure 16.12 Cross section H-H′, northeastern British Columbia to west-central Alberta. Datum is the top of the Halfway Formation, except at the extremities, where the sub-Jurassic unconformity is used as datum.

Hydrocarbon production occurs within the Doig Formation from a series of anomalous, thick sandstone bodies, interpreted as tidal-scoured submarine channels (Gibson and Edwards, 1990a,b) or as shoreface sourced, tectonically controlled, mass wasting features (Wittenburg and Moslow, 1991). In western areas of the foothills and subsurface, the upper Doig-Halfway interval represents lower shoreface sandy deposits gradationally overlain by barrier island and shoreface sandstones. To the north and east in the Peace River Embayment, the Halfway Formation consists of discontinuous sandstone bodies representing various barrier island facies (e.g., lower and upper shoreface, tidal inlet, lagoon) (Fig. 16.10). These sandstones contain significant hydrocarbon reserves, such as at Wembley, Progress, Peejay and Milligan fields (Fig. 16.2) (see Clark, 1961; Fulton, 1966; Mothersill, 1968; Sharma, 1969; Halton, 1981; Cant, 1984, 1986; Barclay and Leckie, 1986; Podruski et al., 1988; Styan and Shaw, 1991).

Toward the west, the Halfway sandstones become thicker and laterally continuous, probably representing stacked shoreface deposits (Figs. 16.11, 16.13, 16.14). In the extreme western foothills of the outcrop belt, the Liard, upper Doig, and Halfway formations grade laterally to deeper water, distal shelf and slope sandstones, siltstones, shales and carbonates of the Ludington Formation (Fig. 16.7).

In the western portion of the Alberta Basin, the Doig-Halfway contact appears generally conformable, but local scour surfaces and basal pebble lags may represent either local erosion at the bases of Halfway tidal channels or an erosional break of regional significance. In the subsurface of the western foothills there is no evidence of an unconformity and Doig-Halfway deposition was continuous. An unconformity separating the Halfway Formation from the overlying Charlie Lake Formation in the eastern portion of the basin has been proposed by many workers (e.g., Armitage, 1962; Aukes and Webb, 1986), suggesting shoreline emergence and subaerial erosion or nondeposition.

Following deposition of the predominantly regressive upper Sulphur Mountain, Liard, upper Doig and Halfway formations, the seas continued to shallow. This produced sediments deposited in shallow inner shelves, coastal bars, tidal inlets, restricted hypersaline lagoons, coastal dunes and extensive tidal flat areas (Figs. 16.7, 16.8, 16.10), representing the final and major regressive phase of the second T-R cycle.

The Charlie Lake Formation and Starlight Evaporite Member (Whitehorse Formation) are dominated by restricted to nearshore marine sedimentation, with deposits accumulating in environments such as sabkhas, coastal dunes, nearshore bars and playas (Fig. 16.8). The Charlie Lake Formation occurs in the subsurface and surface plains and foothills of northeastern British Columbia and west-central Alberta. The Whitehorse occurs in the foothills and Rocky Mountain Front Ranges of southwestern Alberta and southeastern British Columbia (Figs. 16.8, 16.9).

Various informal and formal member names have been assigned to some of the porous and productive sandstone and carbonate units in the Charlie Lake Formation (Fig. 16.6; see Torrie, 1973; McAdam, 1979; Stewart, 1984; Glass, 1990). For example, the Artex, Inga, North Pine, Cecil and Siphon members represent hydrocarbon-bearing coastal dune sandstones. The Boundary Member and the Mica, Nancy, Braeburn, LaGlace, Demmit and Cutbank members (informal) produce hydrocarbons from stratigraphic traps in intertidal algal carbonates and also possibly other carbonate facies (Roy, 1972; Podruski et al., 1988).

In the extreme western foothills north of Williston Lake, the Charlie Lake Formation grades laterally westward into deeper water distal shelf and shelf/slope carbonates and siliciclastics of the Ludington Formation (Fig. 16.7). To the east, in the Laprise Creek area (94-H-5), the upper Charlie Lake unit is a shallow-marine shelf carbonate facies and is similar to the overlying Baldonnel Formation. In the Alberta subsurface, the Worsley (Tangent) Dolomite comprises algal dolomites (locally coquinoid), shale and sandstone, possibly of inner shelf or restricted-marine origin, such as are found within the Charlie Lake Formation (Fig. 16.6; see Podruski et al., 1988; Hassler, 1990).

Following deposition of the lower Whitehorse (Starlight Evaporite Member) and Charlie Lake formations, the environment changed from one of predominantly shallow-restricted marine, to relatively deeper water, open-marine shelf conditions during deposition of the upper Whitehorse (Brewster Limestone Member) and Baldonnel formations (Figs. 16.6, 16.8). Regionally, the Baldonnel Formation, and equivalent Brewster Limestone Member of the Whitehorse Formation are transgressive. However, in the subsurface of the eastern foothills and western plains, the Baldonnel Formation is characterized by several shallowing-upward parasequences, each bounded by hiatal surfaces, recording a series of minor transgressions and regressions. South of Sukunka River, the shelf limestones of the Brewster Limestone Member are overlain by shallow-water inner shelf to restricted-marine strata of the Winnifred Member of the Whitehorse Formation. The Winnifred consists of silty and sandy carbonates, rare sandstones and siltstones, and local solution breccias and redbeds. Thus, the transgression did not eliminate the shallow-water evaporitic conditions everywhere in the basin.

Like the Liard and Charlie Lake formations, the Baldonnel Formation grades westward into deep-water distal shelf/slope siliciclastics and carbonates of the Ludington Formation (Figs. 16.7, 16.8). In the westernmost foothills between the headwaters of Schooler Creek and Halfway River, the Ludington Formation is characterized in some areas by locally thick (up to 167 m), submarine, coquina-filled channel complexes (Gibson and Hedinger, 1989). Throughout much of the Peace River Embayment, the Baldonnel Formation is abruptly overlain by transgressive, deeper water carbonates, siltstones and sandstones of the Pardonet Formation (Figs. 16.7, 16.8).

During deposition of the Pardonet Formation in most areas of the foothills, the seas continued to deepen and transgress the shelf area. However, in the Sukunka River area, the Pardonet Formation is characterized by shallower water carbonates similar to those in the underlying Baldonnel Formation. The Bocock Formation abruptly and possibly erosionally overlies the Pardonet Formation in the extreme western foothills outcrop belt between Williston Lake and Peace River (Figs. 16.7, 16.8). The Bocock represents a possible deep-water slope channel-fill limestone, similar to the Ludington Formation channels mentioned above.

Following deposition of the Pardonet and Bocock formations, the seas continued to transgress in the northern part of the basin, with most areas of the Western Canada Sedimentary Basin overlain by deep-water siliciclastics and carbonates of the Jurassic Fernie Formation. However in the southern half of the basin and plains area to the east, the Triassic appears to have been subjected to pre-Jurassic erosion, prior to transgressive deposition of the deep-water Fernie shales.

Stratigraphic History – Northern Foothills Outcrop Belt

Within the foothills of the Pine River to Liard River area, the Triassic succession differs from that to the east in the Peace River Embayment area and to the south between Pine River and the United States border. In the Pine River-Liard River area, Triassic rocks are divided into seven formations, which in ascending order are: the Grayling, Toad, Liard, Charlie Lake, Baldonnel, Pardonet and Bocock formations (Fig. 16.6, Fig. 16.13). In the western foothills north of Williston Lake, the Ludington Formation is a deep-water lateral equivalent of the Liard, Charlie Lake and Baldonnel formations (Fig. 16.7).

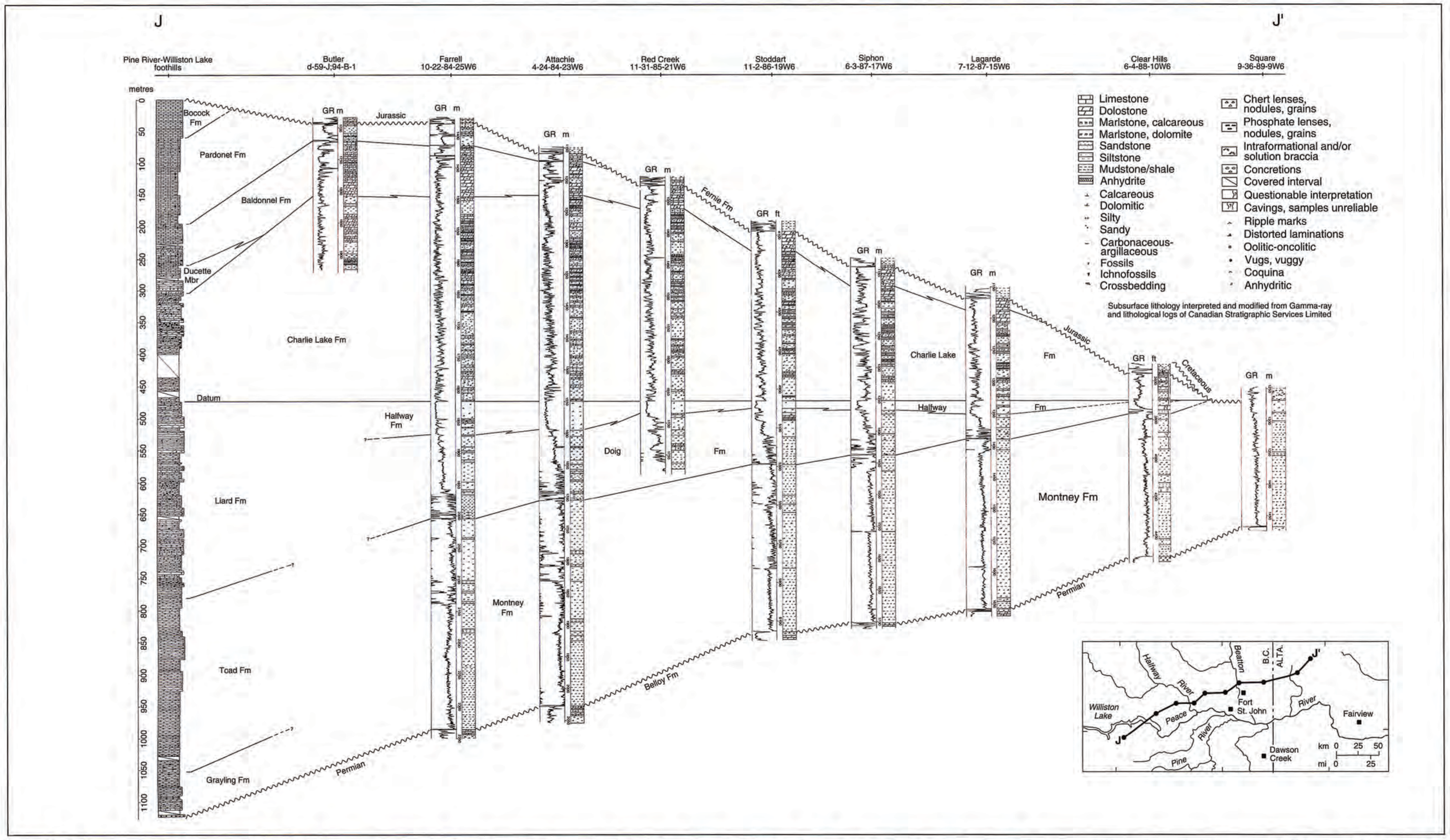


Figure 16.13 Cross section J-J', Pine River/Williston Lake outcrop in northeastern British Columbia to Clear Hills/Osborn subsurface, northwestern Alberta, west-southwest to east-northeast. The vertical scale is Atlas cross section standard (1:6000), but the horizontal scale is expanded.

The Grayling Formation at the base comprises a succession of recessive siltstone, shale, and lesser amounts of limestone, dolostone and very fine-grained sandstone. The Ludington ranges in thickness from a minimum of 35 m to more than 395 m in the vicinity of Liard River. The Grayling disconformably overlies the Permian Fantasque Formation (Fig. 16.6).

The overlying Toad Formation comprises dark gray siltstone, silty limestone, shale and lesser amounts of dolostone and sandstone. The formation ranges in thickness from a minimum of 158 m near Williston Lake to over 825 m near Halfway River (Gibson, 1975, *in press*). The Toad Formation in most outcrop areas is gradationally overlain by the Liard Formation (Fig. 16.7), but in the extreme western foothills north of Williston Lake is overlain abruptly but conformably by the Ludington Formation (Figs. 16.6, 16.7).

The Liard Formation consists of sandstone, siltstone, dolostone and finely crystalline and skeletal limestone. It is equivalent to the Halfway-Doig interval. The Liard Formation ranges in thickness from an erosional pinch-out in the northeast to a maximum of 417 m near Pine River (Gibson, 1975). The Liard Formation is overlain gradationally by strata of the Charlie Lake Formation. The Liard grades laterally westward into strata of the Ludington Formation (Fig. 16.7).

The Charlie Lake Formation, like that in the subsurface eastern foothills and plains, comprises a variegated succession of buff to yellow, gray to orange-brown weathering, dolomitic to calcareous sandstone, siltstone, sandy limestone, dolostone and minor amounts of intraformational and solution breccia. Unlike the Charlie Lake in the subsurface to the east, the formation in the outcrop belt lacks significant anhydrite and gypsum. The Charlie Lake attains a maximum thickness of 405 m near Williston Lake (Gibson,1975, *in press*). Toward the west the Charlie Lake grades laterally into the Ludington Formation (Figs. 16.6, 16.7). The Charlie Lake Formation is overlain gradationally but abruptly by the Baldonnel Formation.

The Ludington Formation in the extreme western foothills between Williston Lake and Liard River, comprises medium to light gray weathering siltstone, silty to sandy limestone, bioclastic limestone and very fine- to fine-grained sandstone. It ranges in thickness from a minimum of 500 m to approximately 960 m in the area of Laurier Pass. The Ludington is overlain abruptly but conformably by the Pardonet Formation (Figs. 16.6, 16.7).

The Baldonnel Formation, unlike that in the subsurface eastern foothills and plains to the east, consists mainly of gray to brownish gray weathering limestone, calcareous and dolomitic siltstone and rare, very fine-grained sandstone. In the Williston Lake area the Baldonnel is characterized by an additional dark weathering siltstone, sandstone and dolostone unit at the base called the Ducette Member (Figs. 16.6, 16.7). The Baldonnel (maximum thickness 145 m) is abruptly overlain by the Pardonet Formation.

The Pardonet Formation has a maximum thickness of 180 m and consists of dark weathering limestone, calcareous and dolomitic siltstone, and shale. Much of the limestone is skeletal and consists of whole and fragmented bivalve shells. The Pardonet ranges in thickness from an erosional pinch-out to a maximum of 137 m south of Williston Lake (Gibson, 1975). In most areas of northeastern British Columbia, including the subsurface of the eastern foothills and plains, the Pardonet is overlain unconformably by dark gray shale, siltstone and limestone of the Jurassic Fernie Formation. However, in the Williston Lake and Pine River area (Figs. 16.1, 16.7-16.9), the Pardonet is overlain abruptly by the Bocock Formation.

The Bocock Formation consists of light gray weathering, finely crystalline to bioclastic limestone, ranging in thickness from an erosional pinch-out to a maximum of 63 m in the west (Gibson, 1975). The Bocock is unconformably overlain by the Jurassic Fernie Formation.

Stratigraphic History – Southern Foothills Outcrop Belt

Triassic rocks in the southern foothills and front ranges, from the United States border to Pine Pass, comprise the Spray River Group. The group is divisible into two distinct and contrasting units, the Sulphur Mountain Formation and the overlying Whitehorse Formation (Figs. 16.6, 16.9). Each formation is further subdivided into several members.

The Sulphur Mountain Formation comprises dark gray to rusty brown weathering siltstone, sandstone and shale, silty to sandy limestone and dolostone, ranging in thickness from an erosional eastern pinch-out to 556 m near the Pine-Sukunka rivers in the west (Gibson, 1975). In most areas, the Sulphur Mountain Formation can be readily divided into four members, in ascending order: Phroso Siltstone, Vega Siltstone, Whistler and Llama (Figs. 16.6, 16.9). In part of the front ranges and foothills of the Athabasca-Bow River region, the Vega Siltstone Member is characterized by an additional unit called the Mackenzie Dolomite Lentil. This distinctive, light coloured dolomite can also be recognized in the subsurface of the plains to the east, and there serves as a hydrocarbon reservoir at the Coalbranch-Basing Field (Fig. 16.2; Bainey, 1990). Between Smoky and Pine rivers, the Phroso and Vega siltstone members cannot be distinguished and must be grouped as the single undifferentiated Vega-Phroso siltstone member of the Sulphur Mountain Formation (Fig. 16.6). The Sulphur Mountain Formation disconformably overlies the Permian Ishbel Group and consists of chert, cherty dolostone and sandstone throughout most of the region (Fig. 16.6). In some eastern foothills localities, the Sulphur Mountain disconformably overlies cherty dolostones of the Carboniferous Rundle Group. The contact of the Sulphur Mountain with the overlying Whitehorse Formation is conformable, ranging from gradational to abrupt.

Regional Cross Sections

The northern part of cross section A-A' (Fig. 16.4a) transects the easterly part of the Peace River Embayment. Units 1, 2, 3 and 4 of the Montney Formation, interpreted as deltaic (Miall 1976) or inner shelf systems, can be seen prograding into the basin south of Township 87. The Doig and Halfway formations occur over a very small area of this cross section. A thin unit of the Worsley (Tangent) Dolomite is shown between Townships 84 and 88.

The pronounced east to west thickening of the Peace River Embayment is illustrated in cross section C-C* (Fig. 16.11). The Montney sandstones can be seen near the subcrop edge. The top of the Halfway/Doig sequence is erosional near its subcrop edge, east of which the Charlie Lake Formation lies unconformably on the Montney Formation. The formal and informal members of the lower Charlie Lake Formation can be seen subcropping against the Coplin unconformity. Convergence of the intraformational unconformities make stratigraphic interpretation very difficult. Carbonates of the Baldonnel and Pardonet formations are truncated eastward by the pre-Jurassic unconformity.

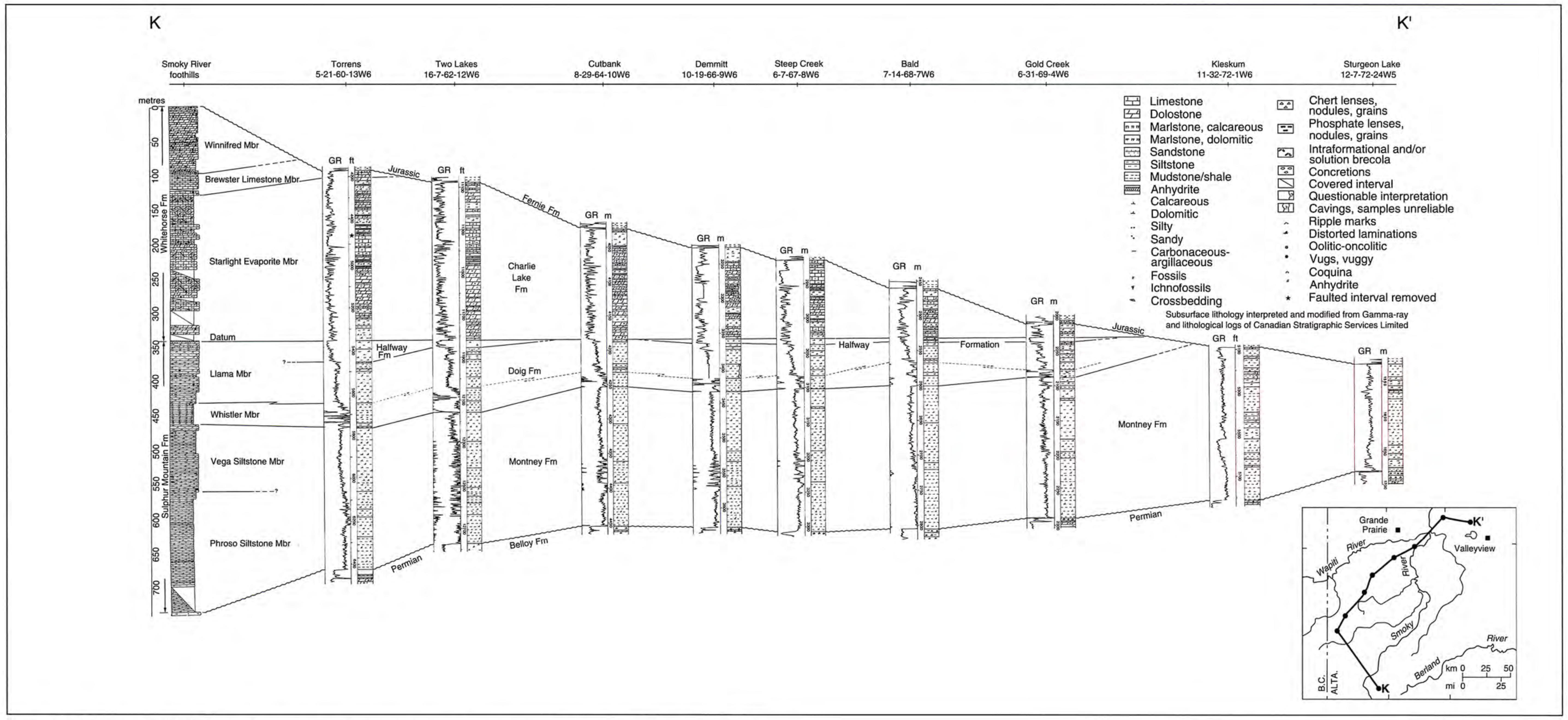


Figure 16.14 Cross section K-K′, Smoky River outcrop to Sturgeon Lake subsurface, west-central Alberta, southwest to northeast.

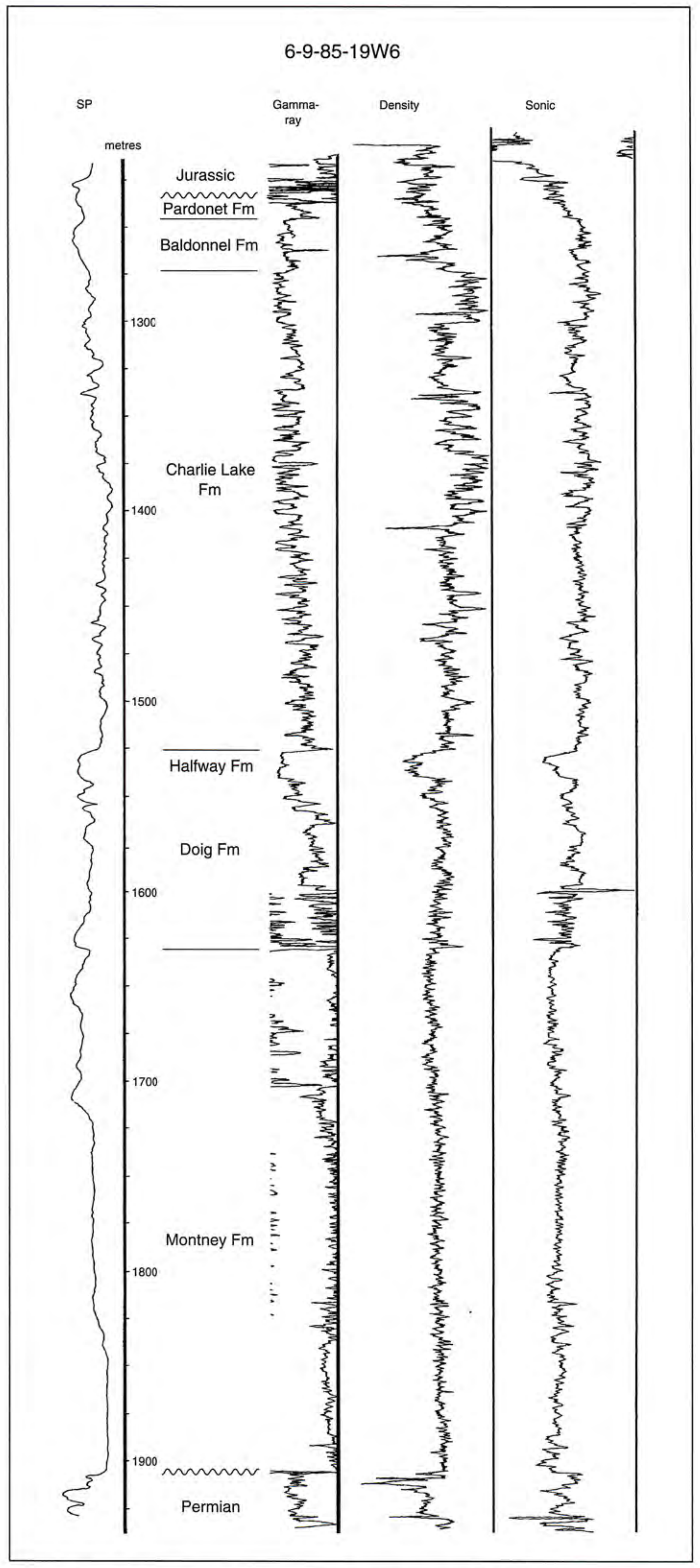


Figure 16.15 Typical spontaneous potential, gamma-ray, density and sonic response for the total Triassic succession in the Peace River Embayment and adjacent areas, Alberta and British Columbia. Vertical scale is 1:3000.

Cross section H-H′ shows the lens-shaped nature of the Peace River Embayment (Fig. 16.12). A reactivated Paleozoic fault is shown in the central part of section H-H′, influencing Halfway and Doig sedimentation with the creation of a distinct thickening on the downthrown side. A Doig Formation anomalous, thick sand body is seen in well 13-11-77-16W6. The Coplin unconformity can be seen truncating some members of the lower Charlie Lake Formation. Gamma-density logs indicate salt in the lower Charlie Lake Formation, in the central portion of the basin (well 11-11-80-17W6). The Baldonnel Formation is preserved only in the central part of section H-H′. The Pardonet Formation and Worsley (Tangent) Dolomite are absent here because of pre-Jurassic erosion and/or nondeposition.

Cross sections J-J′ and K-K′ illustrate the lithological and nomenclatural relations between the foothills outcrop belt and the subsurface foothills and plains in the Peace River Embayment (Figs. 16.13, 16.14). The Smoky River-Sturgeon Lake cross section K-K′ illustrates the relation between the Rocky Mountains Front Ranges and foothills outcrop belt and the subsurface plains to the south in the Deep Basin area of Alberta (Fig. 16.14) (see Masters, 1984). The Triassic nomenclature and lithological relations illustrated on the southern cross section K-K′ are similar to those found in the Jasper, Banff, Kananaskis, Crowsnest Pass and United States border areas (Fig. 16.14). In the Crowsnest Pass and United States border areas, strata of the Whitehorse Formation are not divisible into members (Gibson, 1974).

Reference Well Logs

Peace River Embayment

Total Triassic. Figure 16.15 illustrates typical spontaneous potential, gamma-ray, density and sonic well log signatures for each of the Triassic formations in the Peace River Embayment area of Alberta and British Columbia. Note the abrupt and unconformable contacts with the Permian Belloy at the base and Jurassic Fernie Formation at the top. Other abrupt contacts between formations can be seen, representing transgressive or parasequence boundaries or possibly disconformities (e.g., Halfway and Charlie Lake contact). The prominent high gamma-ray signature at the base of the Doig Formation (Phosphate Zone) represents the contact between the Lower and Middle Triassic and can readily be recognized throughout most areas of the Peace River Embayment.

Montney Formation. A typical gamma-sonic well log illustrating the lithological character of the Montney Formation in the western part of the Peace River Embayment is the type section of the Montney Formation located at 6-26-87-21W6 (Fig. 16.16; Armitage, 1962). The Montney Formation consists of interbedded shale and siltstone representative of distal sediments of large westward prograding sequences. Similar facies can be seen in several of the cross sections (Figs. 16.4a, 16.11 - 16.14). Note the increase in the gamma-ray response at the Doig Formation contact and at the 5700 foot level in the well of Figure 16.16. These gamma-ray peaks may represent major and minor transgressive pulses during deposition of upper Montney sediments.

Figure 16.17 illustrates four distinct gamma-ray and density log deflections in a well from the eastern part of the Montney basin. Each unit represents a coarsening-upward sequence - the shoreward equivalents of the above mentioned prograding sequences. A coquina occurs at the top of Montney unit 3. The presence of phosphate and pyrite in this interval can make the four different Montney units difficult to distinguish on well logs.

Doig Formation. The Doig Formation is generally a mixture of shales and siltstones (well 6-3-87-17W6, Fig. 16.13, cross section J-J′). The lower levels of the Doig Formation are radioactive, whereas the upper levels are not. The Doig/Montney formation contact is generally picked at the base of a prominent radioactive shale or shaly interval (locally termed the "Phosphate Zone"), which can readily be seen on most gamma-ray logs (Figs. 16.11-16.14). The contact between the Doig and Halfway formations is more problematical but is generally assigned to the top of the uppermost prominent shale interval below the distinct and widespread sandstone facies assigned to the Halfway Formation (Fig. 16.18). In places, however, relatively thick sandstones in the upper Doig Formation are developed near or immediately below the Halfway Formation sandstone, and pose a problem in assigning the contact between the two formations. Locally, tidal channels, which are part of the Halfway shoreface, cut into the Doig siltstones and shales, and again create difficulty in distinguishing the two formations. An example of an anomolously thick Doig sandstone that crosscuts the regional expression of the Doig occurs in 6-36-72-12W6 (Fig. 16.19).

Halfway Formation. Three log sections illustrate typical Halfway Formation log responses. In wells 4-24-84-23W6, 6-36-72-12W6 and 6-4-78-6W6 (Figs. 16.18 - 16.20), the Halfway consists predominantly of dolomitic quartzose sandstone displaying a typical "blocky" gamma-ray profile. The log signature denotes sharp contacts with the underlying Doig Formation and the overlying Charlie Lake Formation. In some areas of the basin, these two contacts may represent unconformities or disconformities (Barss et al., 1964; Aukes and Webb, 1986; Campbell et al., 1989). In the western part of the Peace River Embayment, the Halfway Formation western facies is much thicker, more continuous and displays gradational and conformable contacts with underlying and overlying formations (Figs. 16.11 - 16.14). Combined with strata of the Doig Forma-

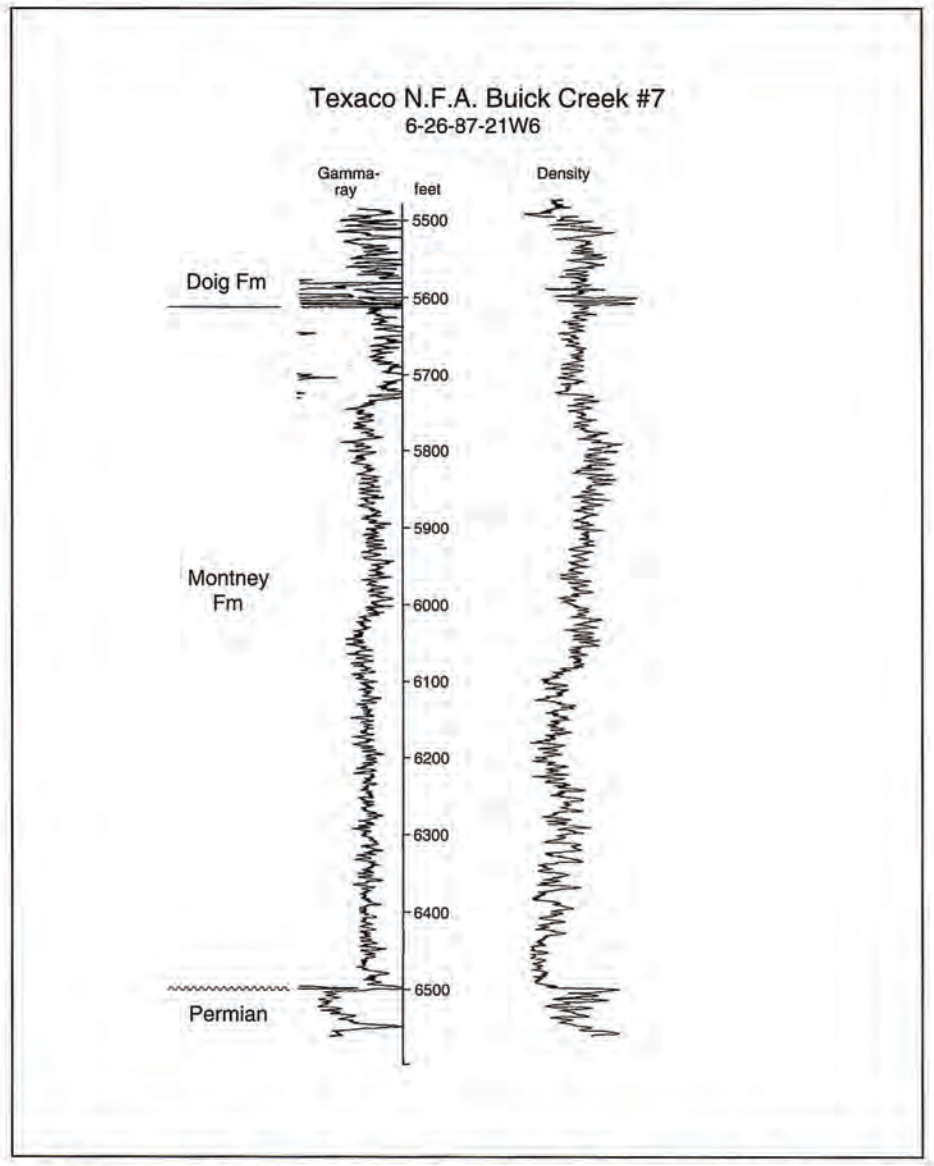


Figure 16.16 Type Montney Formation geophysical gamma-ray/density reference well logs (1:3000 vertical).

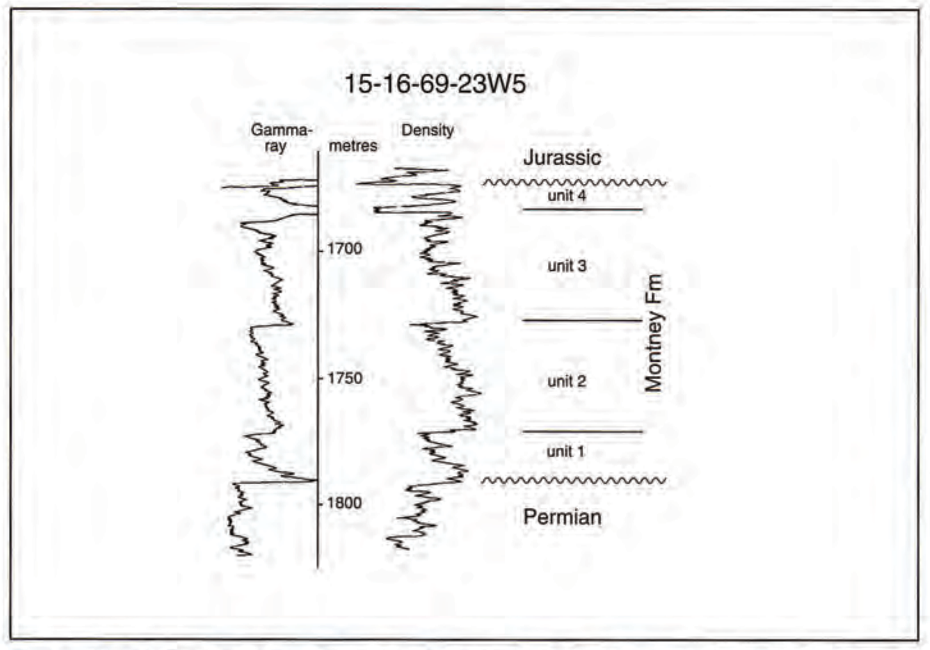


Figure 16.17 Geophysical gamma-ray/density logs of Montney Formation near subcrop edge (1:3000 vertical), illustrating four coarsening-upward, shale to sandstone cycles (units 1 to 4).

tion, a coarsening-upward log sequence profile is visible on most gamma-ray logs (e.g., Figs. 16.18, 16.20).

Well 6-4-78-6W6 (Fig. 16.20) illustrates the eastern nearshore facies of the Halfway Formation (Aukes and Webb (1986) interpret this as a Doig Formation remnant). Here, the Halfway occurs very close to the Coplin unconformity of the Charlie Lake Formation, and the Halfway Formation is predominantly a coquina facies with a similar log response to that of sandstone. A coarsening-upward profile is visible on both the gamma-ray and SP curves. The Charlie Lake/Halfway contact may be unconformable.

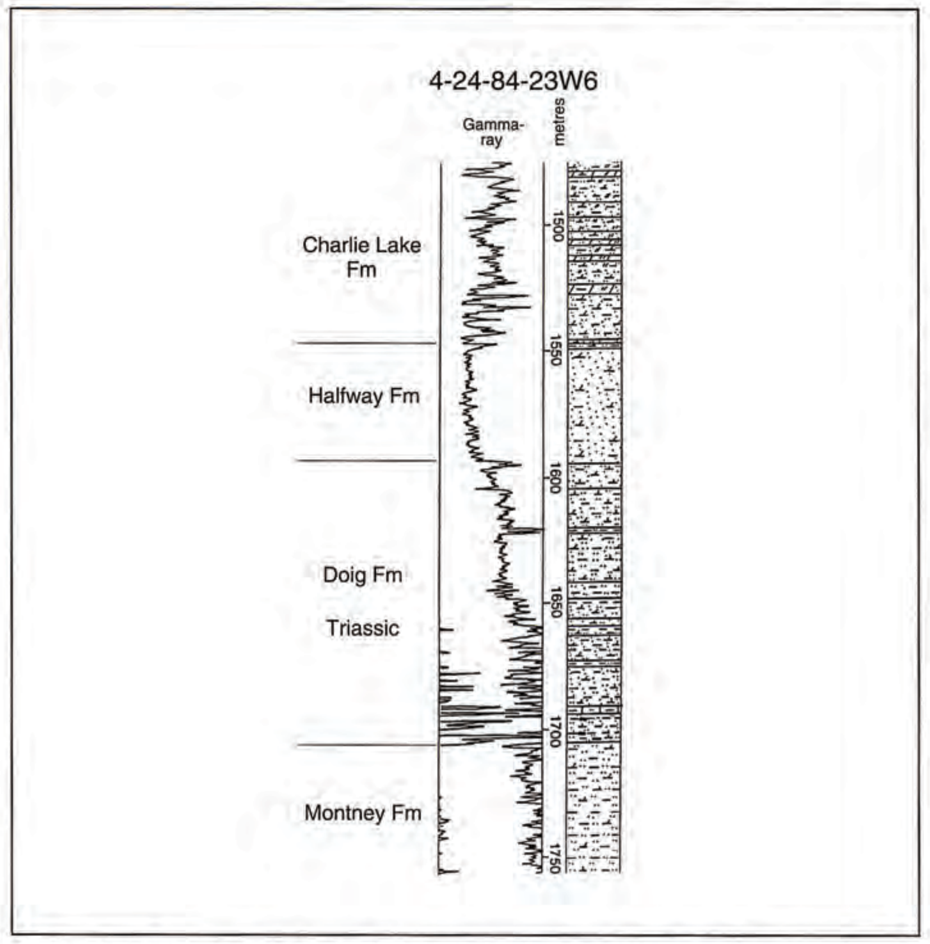


Figure 16.18 Geophysical and lithological reference well logs for the Doig and Halfway formations (see also on cross section K-K', Fig. 16.14). Note the abrupt contact between the Montney and Doig formations, the coarsening-upward character of the gamma-ray signature in the Doig Formation and the blocky gamma-ray profile of the Halfway Formation. Vertical scale is 1:3000.

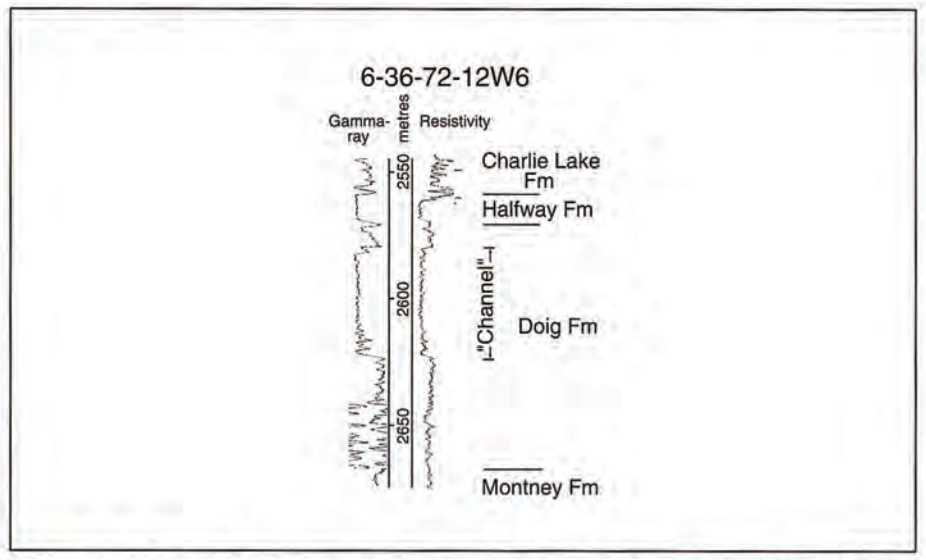


Figure 16.19 Typical geophysical reference well logs of 'channel' sandstone in the upper Doig Formation (1:3000 vertical). Note the typical blocky character of the 'channel' sandstone and the abrupt and possibly unconformable contact with the overlying Halfway Formation.

Charlie Lake Formation. The lower Charlie Lake Formation consists of a variable succession of carbonates, siliciclastics and evaporites. Well log 8-26-83-18W6 (Fig. 16.21) illustrates the Coplin unconformity, its division of the Charlie Lake into upper and lower units, and the presence of several distinct, basin-wide stratigraphic marker units below the unconformity. For example, the Artex and North Pine (shown) and the Inga, Farrel and Blueberry members (not shown) are hydrocarbon-producing facies with the reservoirs consisting mainly of fine-grained sandstone. The A Marker, Valhalla and Braeburn members consist mainly of carbonate that develops good porosity at the subcrop edge. Many of the Charlie Lake members vary lithologically within the basin but nevertheless persist as distinct geophysical log markers.

The upper Charlie Lake Formation above the Coplin unconformity contains four members. In ascending order, these are: the Boundary, Nancy, Cecil, and Siphon members (Fig. 16.6; well 7-5-82-11W6 on Fig. 16.22 shows the Boundary, Nancy and Siphon members; the Cecil is not shown). These stratigraphic units are basin wide throughout the Peace River Embayment. Massive anhydrites overlie the Coplin unconformity in some areas and are capped by the Boundary Member carbonate reservoir. The Nancy member consists mainly of porous carbonate. Where productive, the Cecil and Siphon members consist of sandstones.

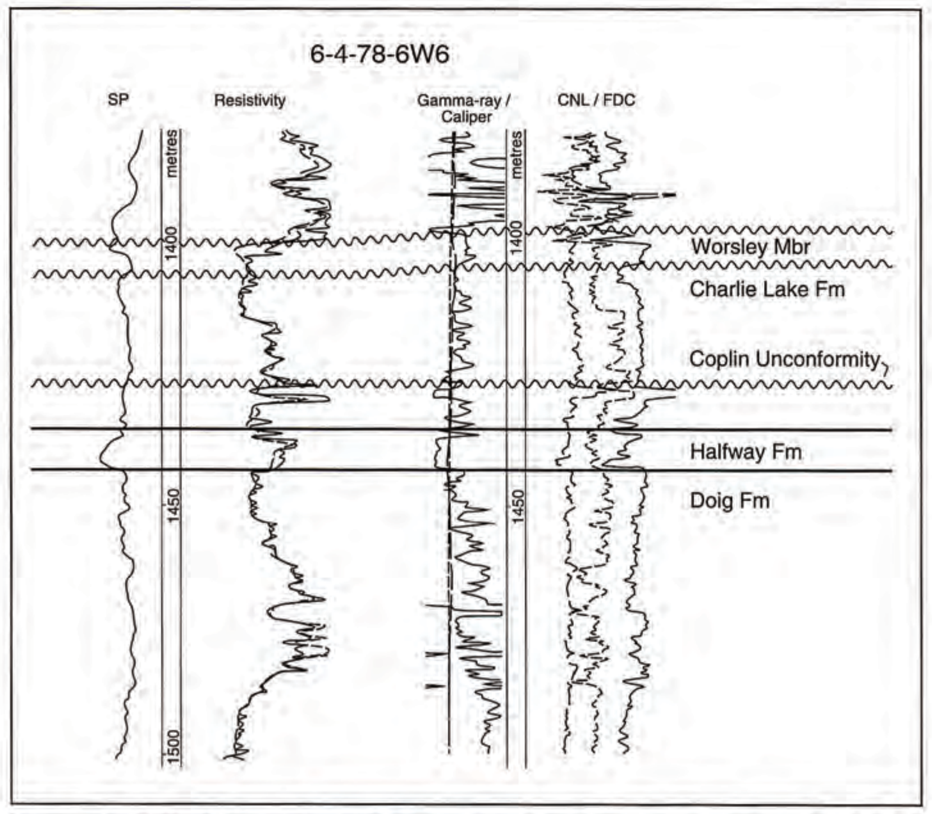


Figure 16.20 Typical geophysical well log signatures of the Halfway Formation and contact signatures with the Doig and Charlie Lake formations. Upper and lower contacts of the Halfway may represent unconformities. Note the lithological signature of the Worsley Member. Note that the vertical scale (1:1500) is expanded from Atlas standard (1:3000).

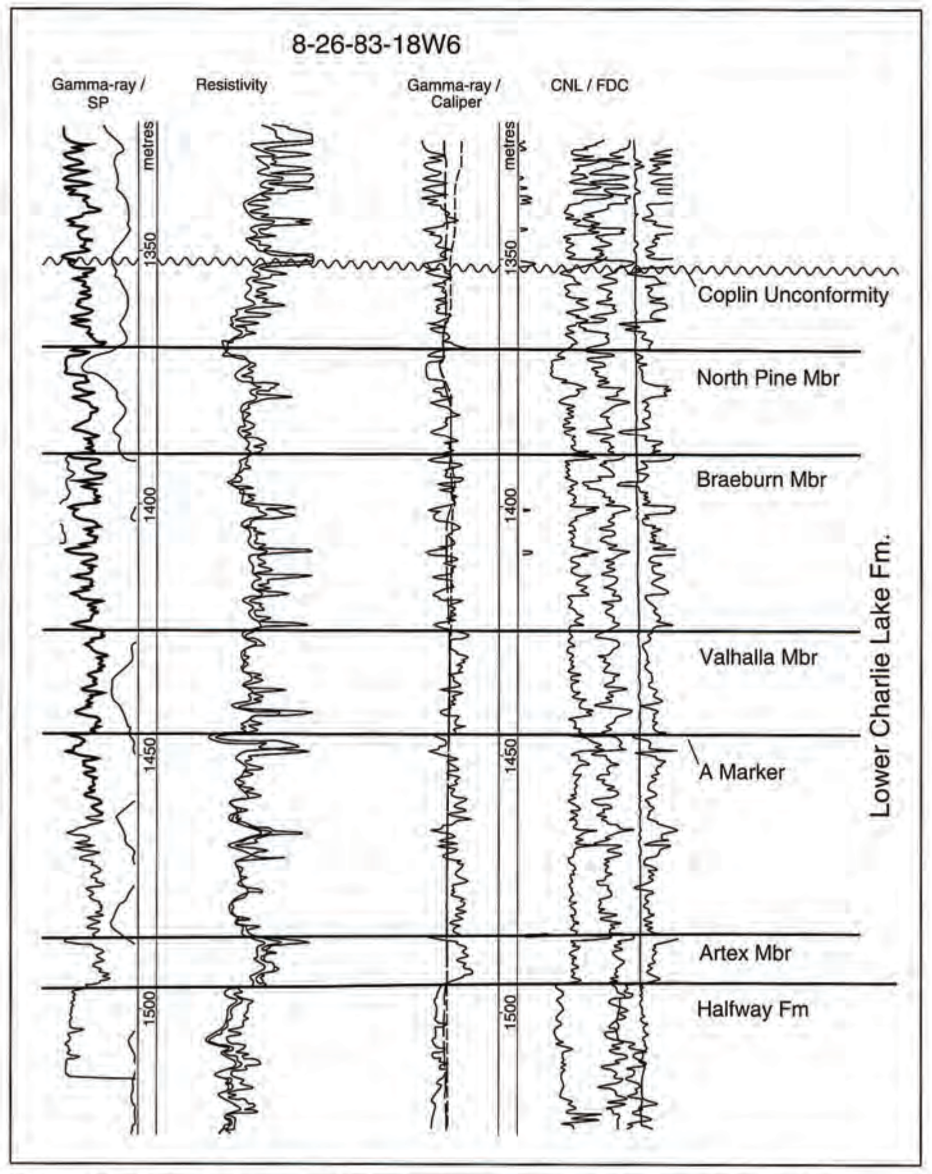


Figure 16.21 Typical geophysical reference well logs of the lower Charlie Lake Formation, illustrating formal and informal members. Note that the vertical scale (1:1500) is expanded from Atlas standard (1:3000).

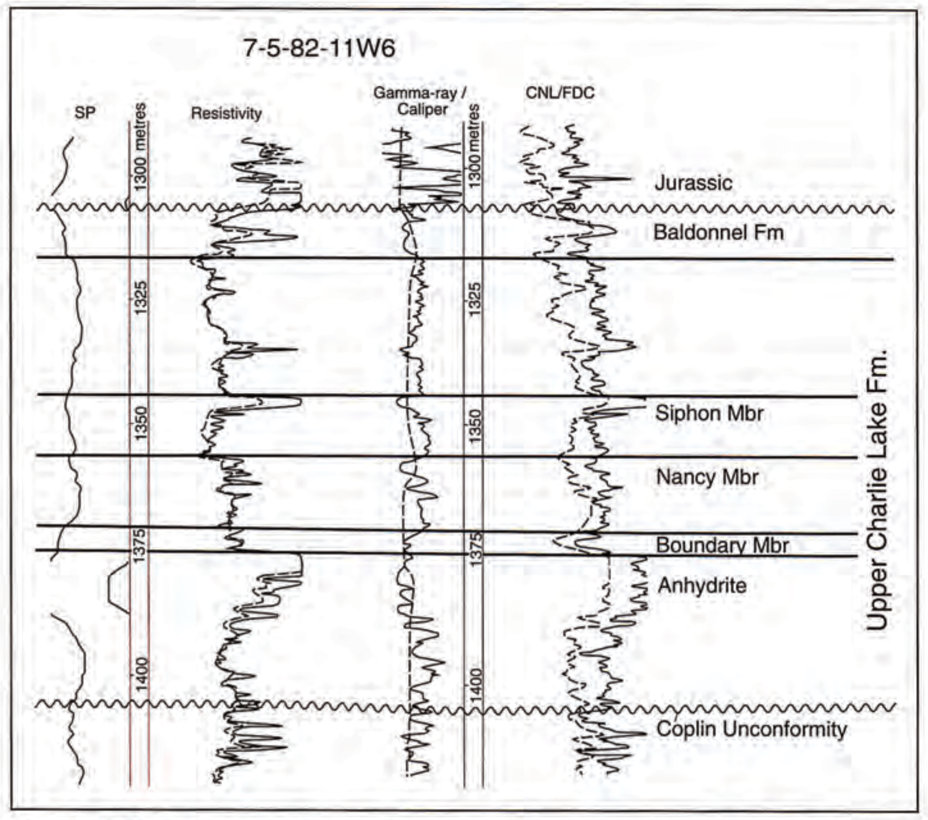


Figure 16.22 Typical geophysical reference well logs of the upper Charlie Lake Formation, illustrating formal and informal members. Note that the vertical scale (1:1500) is expanded from Atlas standard (1:3000).

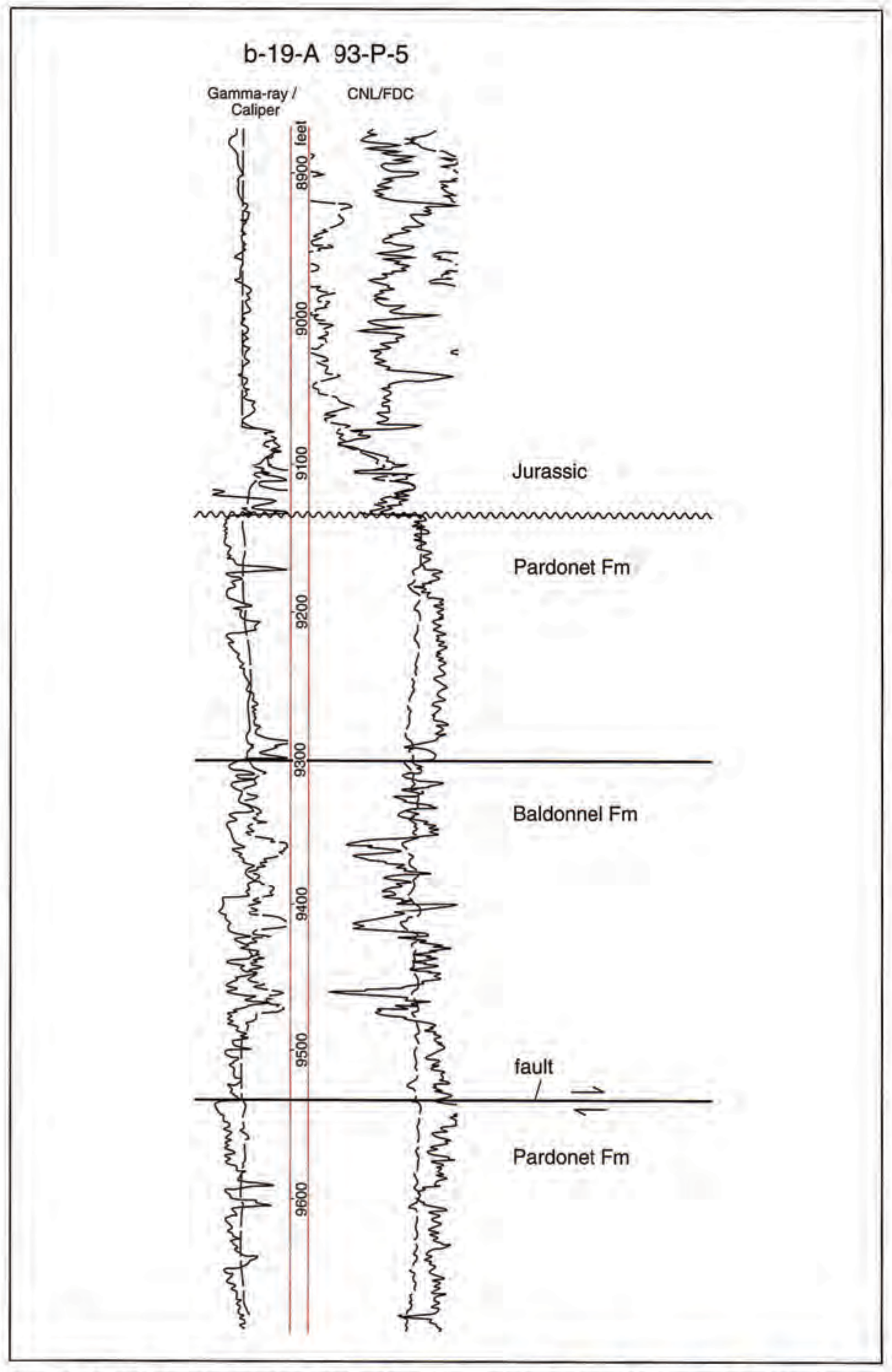
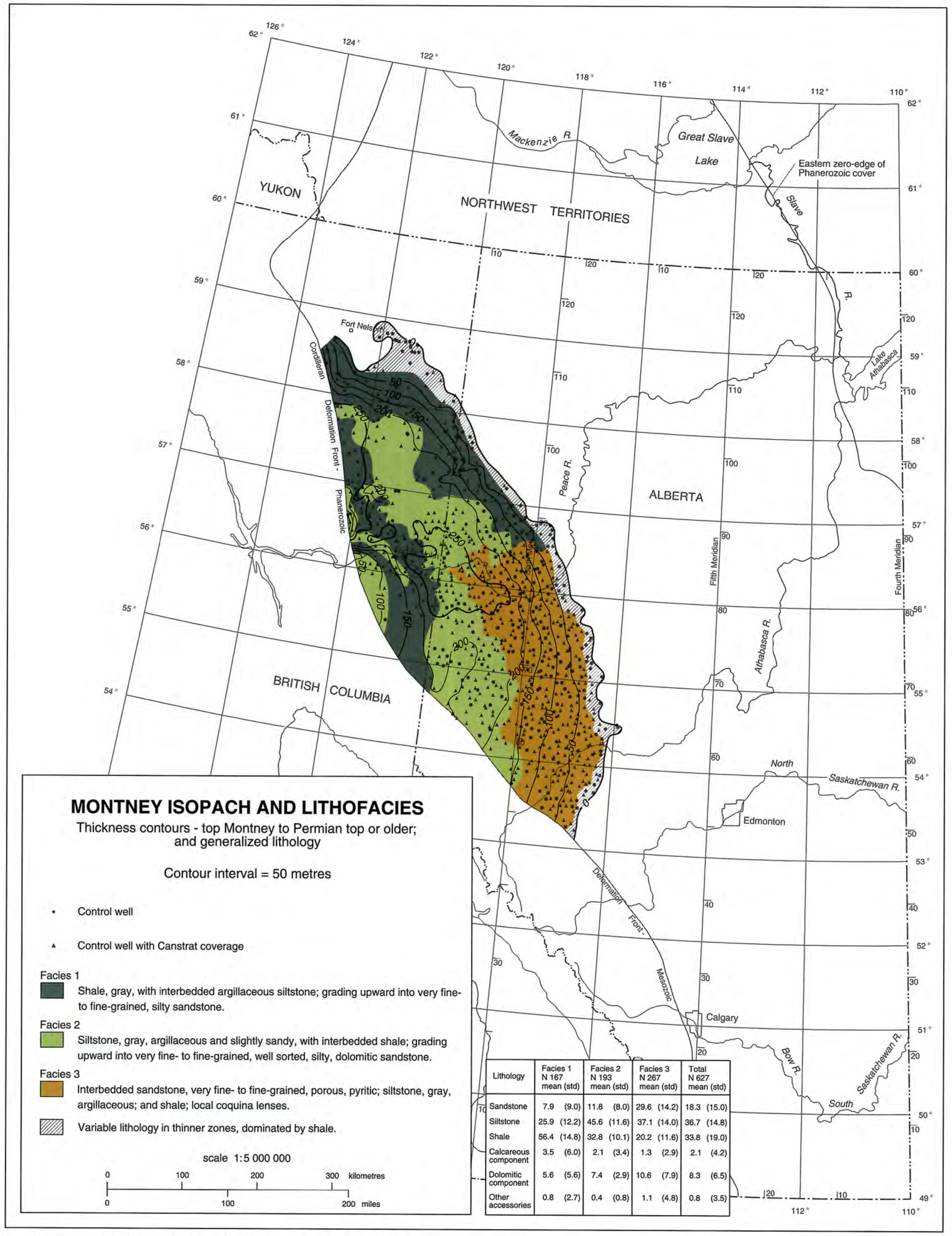


Figure 16.23 Typical geophysical reference well logs of the Baldonnel and Pardonet formations. Note the two regionally distinct high gamma-ray kicks at the base of the Pardonet Formation, and the abrupt contact (unconformable) with the Jurassic Fernie Formation. Note that the vertical scale (1:1500) is expanded from Atlas standard (1:3000).



Lithology	Facies 1 N 167 mean (std)	Facies 2 N 193 mean (std)	Facies 3 N 267 mean (std)	Total N 627 mean (std)
Sandstone	7.9 (9.0)	11.8 (8.0)	29.6 (14.2)	18.3 (15.0)
Siltstone	25.9 (12.2)	45.6 (11.6)	37.1 (14.0)	36.7 (14.8)
Shale	56.4 (14.8)	32.8 (10.1)	20.2 (11.6)	33.8 (19.0)
Calcareous component	3.5 (6.0)	2.1 (3.4)	1.3 (2.9)	2.1 (4.2)
Dolomitic component	5.6 (5.6)	7.4 (2.9)	10.6 (7.9)	8.3 (6.5)
Other accessories	0.8 (2.7)	0.4 (0.8)	1.1 (4.8)	0.8 (3.5)

Figure 16.24 Montney isopach map, and generalized lithofacies distribution.

The Worsley (Tangent) Dolomite occurs only in areas east of the Baldonnel Formation subcrop edge and is shown in well 6-4-78-6W6 (Fig. 16.20).

Baldonnel Formation. Over most of the Peace River Embayment the Baldonnel Formation comprises a cyclical sequence of relatively clean bioclastic or peloidal carbonate (mainly dolostone) with variable concentrations of shale, bitumen and phosphate (well b-19-A/93-P-5, Fig. 16.23). The bases of some of the shales represent probable parasequence boundaries. Note the high gamma-ray peaks at the contact of the Baldonnel and Pardonet formations. A similar abrupt contact is commonly found at the contact with the underlying Charlie Lake Formation.

Pardonet Formation. The gamma-ray log signature of the Pardonet Formation (Fig. 16.23) typifies the stacked, cyclical shallowing-upward, cleaning-upward character of the formation in the Peace River Embayment. However, in the western foothills north of Williston Lake, the log pattern is mainly one of interbedded shaly limestone, dolostone and siltstone. As can be seen in well b-19-A, the Pardonet Formation is separated from the Baldonnel Formation by two prominent radioactive marker units at the base of the Pardonet Formation. Throughout most of the Peace River Embayment, the Pardonet Formation is unconformably overlain by the Jurassic Fernie Formation.

Thickness, Lithology and Petroleum Fields

Peace River Embayment

Montney Formation Isopach

The Montney Formation isopach shows a lens-shaped basin thinning to the east and north because of erosion and nondeposition (Fig. 16.24). Maximum thickness for the Montney is approximately 350 m. The formation also displays a local thinning trend to the west and south, probably because of slower rates of sedimentation.

Along the eastern subcrop edge, the Montney Formation comprises shallow-water marine interbedded sandstone and shale interpreted as being of deltaic origin (Miall, 1976) or of inner shelf origin (Gibson and Barclay, 1989). Local coquina and sandstone units produce oil and gas in the Sturgeon Lake, Kaybob and Sunset fields (Miall, 1976; Podruski et al., 1988). At the northeastern Montney subcrop edge, in the Ring-Border area of northeastern British Columbia and northwestern Alberta (Fig. 16.25), the Montney Formation comprises a succession of shoreface sandstones and restricted lagoonal siltstones and shales (Sturrock and Dawson, 1990, 1991). The shallow-water eastern facies thickens and grades to the west into a deeper water succession of siltstones and shales belonging to middle shelf, outer shelf and shelf-slope environments. In the outcrop belt, Montney-equivalent rocks are called the Grayling and lower Toad formations in the north and the Phroso and Vega Siltstone members of the Sulphur Mountain Formation in the south (Figs. 16.6-16.8).

Ring Field (Fig. 16.25). Natural gas is produced from very fine-grained and well sorted, shoreface sandstones and siltstones. The shoreface sandstones pinch out updip against the pre-Cretaceous unconformity (Fig. 16.26), and are broken along strike by faults and lateral facies changes to siltstone and shale. Reservoir porosities range from 10 to 20 percent, and permeabilities average 10 mD over an average 10 m net pay (Sturrock and Dawson, 1990, 1991).

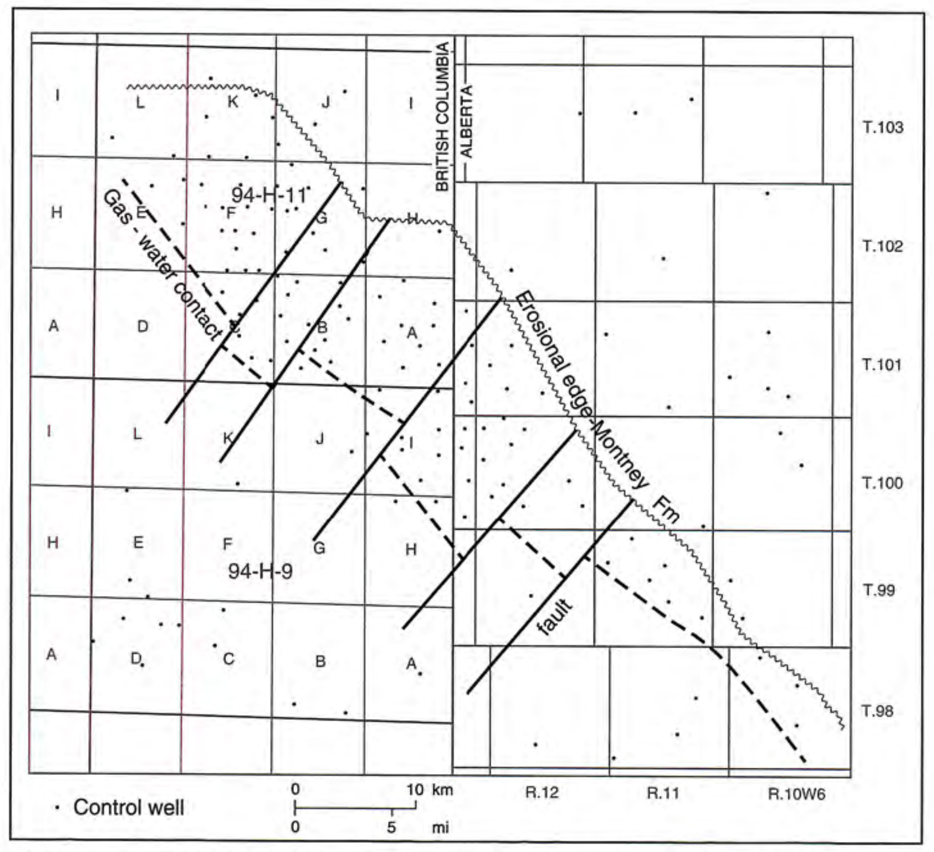


Figure 16.25 Ring-Border Field area, illustrating the erosional edge of the Montney Formation and several small subparallel faults that offset the gas/water interface (after Sturrock and Dawson, 1990).

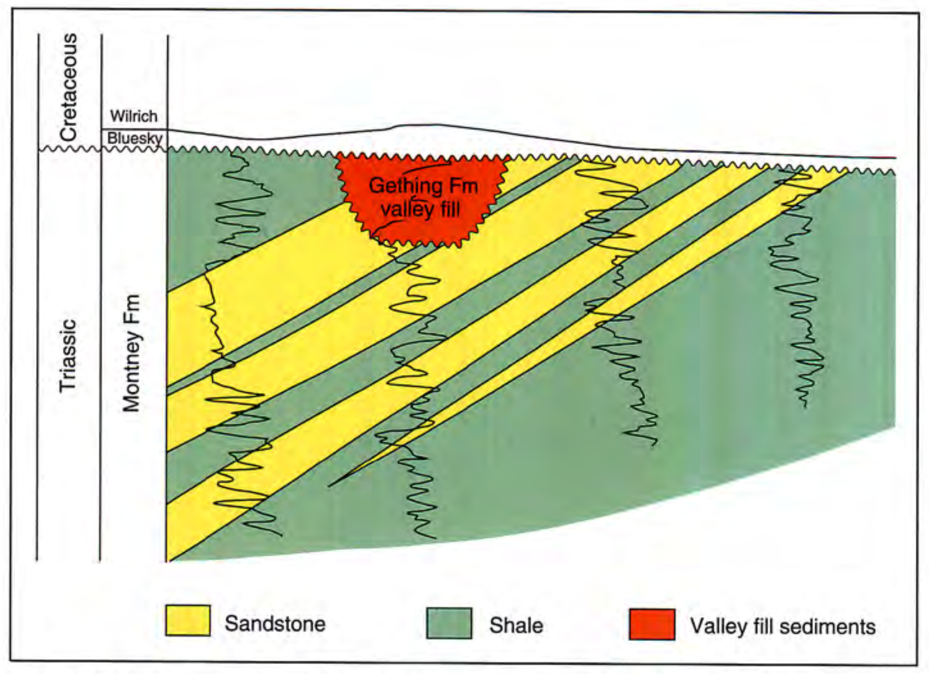
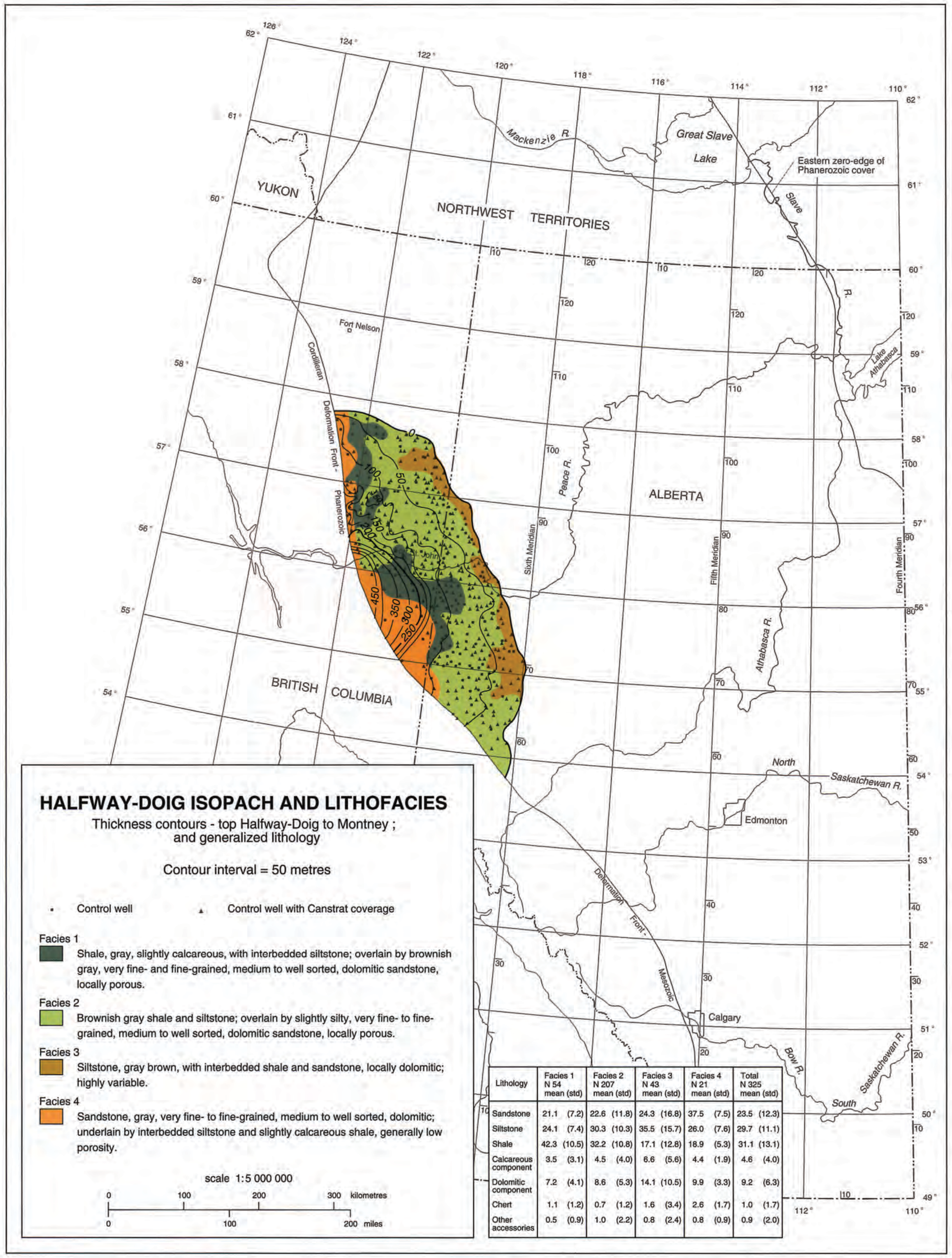


Figure 16.26 Stratigraphic dip section in the Montney Formation of the Ring-Border Field area, illustrating the sub-Cretaceous unconformity and hydrocarbon-bearing sandstones. Note the Cretaceous Gething Formation valley fill (after Sturrock and Dawson, 1990).

Halfway Formation - Doig Formation Isopach

Because of difficulty in assigning the Halfway/Doig contact in many areas, the formations are combined on the isopach map (Fig. 16.27). In the western part of the Peace River Embayment, the Halfway and Doig formations are distinct and form an overall coarsening-upward sequence (e.g., well 10-22-84-25W6, Fig. 16.13). To the north and east near the subcrop edge, the Halfway/Doig contact may be unconformable (Fig. 16.28; Barss et al., 1964; Campbell et al., 1989).

In this area, close to the subcrop edge, the Halfway Formation forms discontinuous accumulations of quartzose sandstone and dolomitic coquina that host many of the Triassic oil and gas fields in stratigraphic traps (e.g., Wembley, Weasel). Farther west, the Halfway Formation forms a thicker, continuous sandstone sheet of probable shoreface origin, and there the hydrocarbon traps are structural (e.g., Monias) or diagenetic (e.g., Flatrock) (Podruski et al., 1988).



Lithology	Facies 1 N 54 mean (std)	Facies 2 N 207 mean (std)	Facies 3 N 43 mean (std)	Facies 4 N 21 mean (std)	Total N 325 mean (std)
Sandstone	21.1 (7.2)	22.6 (11.8)	24.3 (16.8)	37.5 (7.5)	23.5 (12.3)
Siltstone	24.1 (7.4)	30.3 (10.3)	35.5 (15.7)	26.0 (7.6)	29.7 (11.1)
Shale	42.3 (10.5)	32.2 (10.8)	17.1 (12.8)	18.9 (5.3)	31.1 (13.1)
Calcareous component	3.5 (3.1)	4.5 (4.0)	6.6 (5.6)	4.4 (1.9)	4.6 (4.0)
Dolomitic component	7.2 (4.1)	8.6 (5.3)	14.1 (10.5)	9.9 (3.3)	9.2 (6.3)
Chert	1.1 (1.2)	0.7 (1.2)	1.6 (3.4)	2.6 (1.7)	1.0 (1.7)
Other accessories	0.5 (0.9)	1.0 (2.2)	0.8 (2.4)	0.8 (0.9)	0.9 (2.0)

Figure 16.27 Halfway-Doig isopach map, and generalized lithofacies distribution.

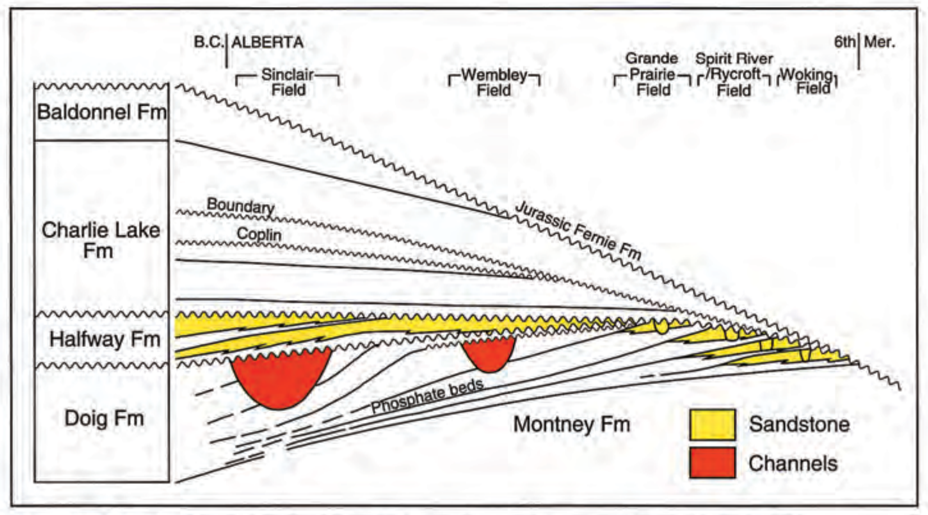


Figure 16.28 Schematic stratigraphic cross section illustrating: 1) probable unconformities between the Doig and Halfway and Charlie Lake formations; 2) blanket or continuous sandstone of the Halfway Formation; and 3) incised sandstone/coquina-filled channels in the upper Doig Formation (after Campbell et al., 1989).

The Doig Formation consists predominantly of marine shelf sandstone, siltstone and shale with the sandstone being generally finer grained than the overlying Halfway Formation. Locally, a sandstone-coquina facies occurs in the upper Doig (Fig. 16.28). Most of the facies variation shown on the Halfway–Doig Isopach (Fig. 16.27) occurs within the Doig Formation.

Sinclair Field. This field (Fig. 16.29) produces natural gas from an anomalously thick sandstone facies within the Doig Formation. The sandstone is very fine-grained, usually with high-angle stratification, and is characterized by a sharp erosional lower contact marked by a pebble lag. Both well-data isopach maps and seismic lines and isochron maps show these interpreted channel sandstone bodies to be generally sinuous in nature, trending in a predominantly north-south direction (Gibson and Edwards, 1990a,b). Recent work (Wittenburg and Moslow, 1991) interpreted these sands as infill of load-faulted features by prograding shoreline sediments. Width of the sand bodies can be up to 2 km, with a maximum sandstone thickness of 55 m. Porosity averages 9 percent with generally low (less then 50 mD) permeability.

Wembley Field. This oil field (Fig. 16.30) produces hydrocarbons from a northwest-southeast-trending barrier island shoreface succession, predominantly sandstone, with crosscutting tidal inlets filled with quartzose and/or coquinoid sandstone and dolomitic coquina (Halton, 1981; Cant, 1984, 1986; Barclay and Leckie, 1986; Brack et al., 1989). Local, thin coquina beds are present within the upper shoreface, probably representing beach lags. Both Halfway Formation and interpreted Doig Formation reservoirs occur in Wembley Field. The reservoirs have porosities of 10 to 16 percent and permeabilities up to 300 mD. Lagoonal shales and sabkha deposits of the Charlie Lake Formation form upper seals. Halfway Formation or Doig Formation offshore shales form lateral seals to the northwest and southeast.

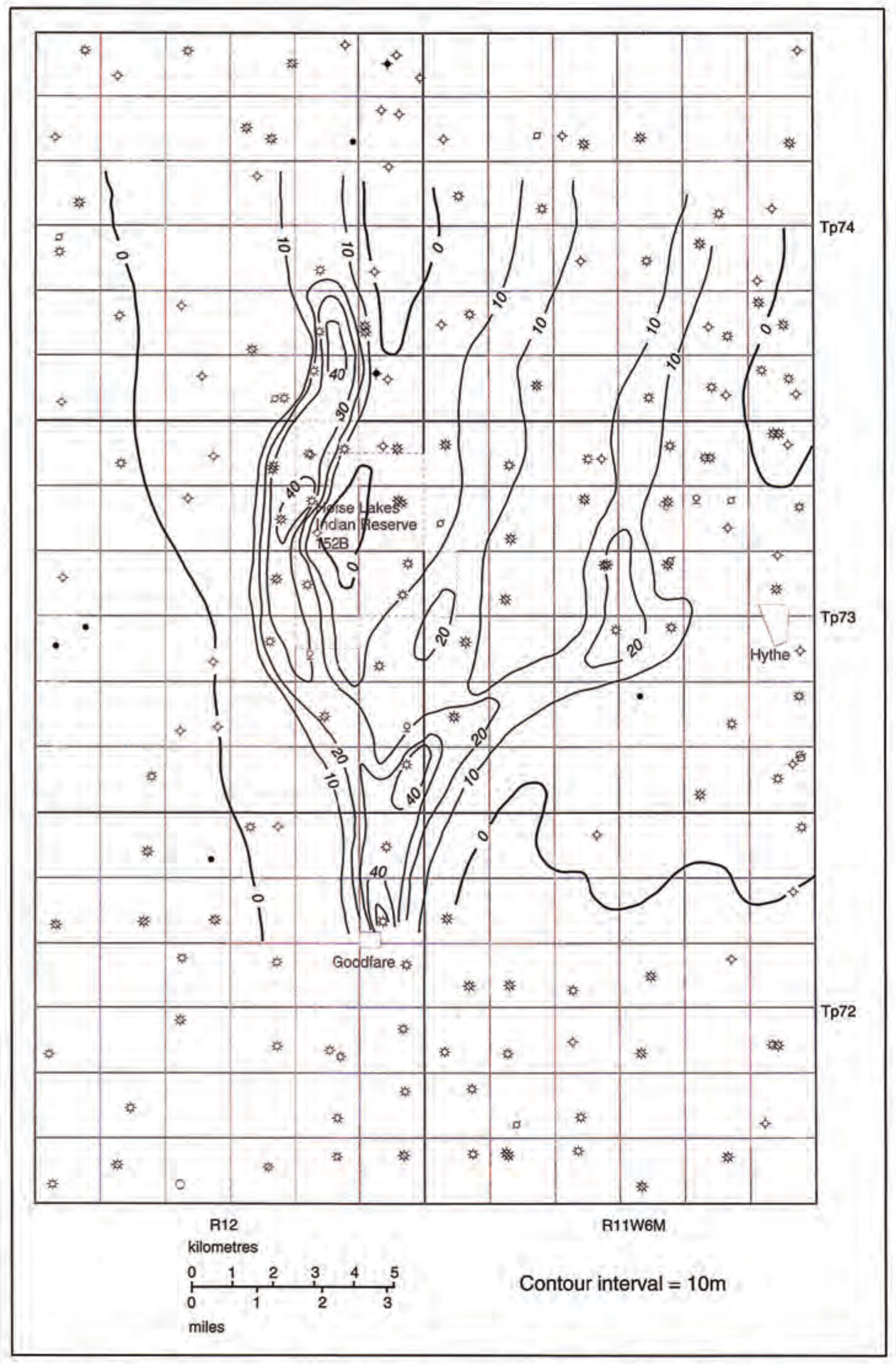


Figure 16.29 Clean or gross sandstone isopach map showing bifurcating Doig Formation "channel" facies in the Sinclair Field of west-central Alberta.

Charlie Lake Formation Isopach

In the Peace River Embayment, the Charlie Lake Formation comprises a succession of intercalated nearshore sandstone, siltstone, dolomite and anhydrite up to 500 m thick (Fig. 16.31). The depicted lithofacies are derived from summaries of the entire Charlie Lake Formation. They do not reflect individual units or cycles within the Charlie Lake.

Charlie Lake Formation deposits represent sedimentation in nearshore-marine, shoreline, tidal flat, lagoon, sabkha and aeolian environments (Fig. 16.10). The Charlie Lake Formation forms the culmination of the second major T-R cycle that began at the base of the Doig Formation (Gibson and Barclay, 1989). The Charlie Lake Formation thickens westward, grading laterally into deep-water distal shelf limestones and siltstones of the Ludington Formation (Gibson and Edwards, 1990a,b). Thinning to the east and north is caused by erosion associated with unconformities within the Charlie Lake Formation and later pre-Jurassic erosion and nondeposition (see Figs. 16.11-16.14). Hydrocarbon production is associated with coastal dunes, shallow-marine sandstones and tidal flat algal carbonates (Fig. 16.10).

Brassey Field. Hydrocarbon production (Fig. 16.32) is from the Artex member, a discontinuous coastal dune sandstone up to 5 m thick. The hydrocarbons are trapped by tight, interdune, coastal plain and playa dolomite and anhydrite (Higgs, 1990a b; Jackson, 1990). Average porosity is 16 percent and permeability is 137 mD, although there is considerable variation because of anhydrite cement in the sandstone.

Bonanza Field. The reservoir rock of this field in northwestern Alberta (Fig. 16.33) consists of Boundary Member intertidal algal carbonate, with a porosity value of 25 percent and permeabilities up to 500 mD. Boundary Member reservoirs are generally thin (less then 2 m) but have large areal distribution and are fairly homogeneous. Lateral seals are formed by shale-filled tidal channels, and the updip seals comprise impermeable sabkha shales and evaporites.

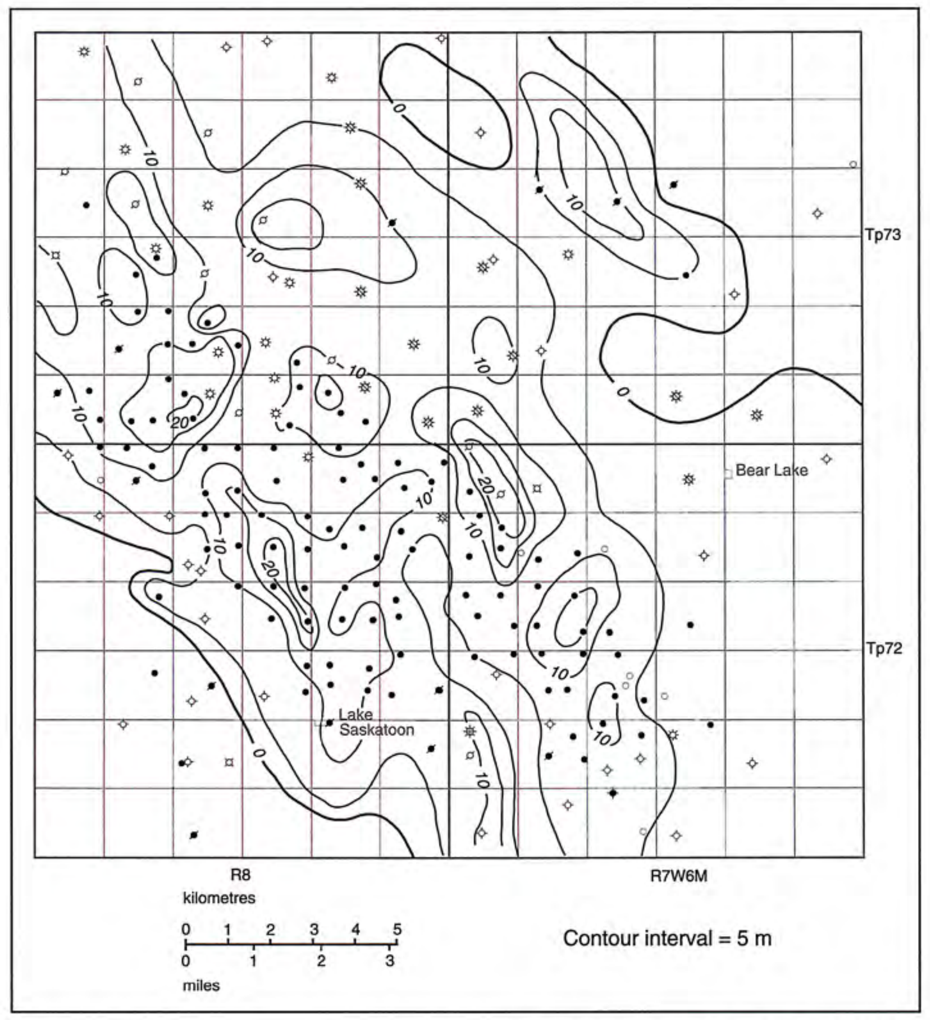


Figure 16.30 Clean or gross sandstone isopach map of the barrier island shoreface and tidal inlet facies in the Halfway Formation in the Wembley Field, Alberta.

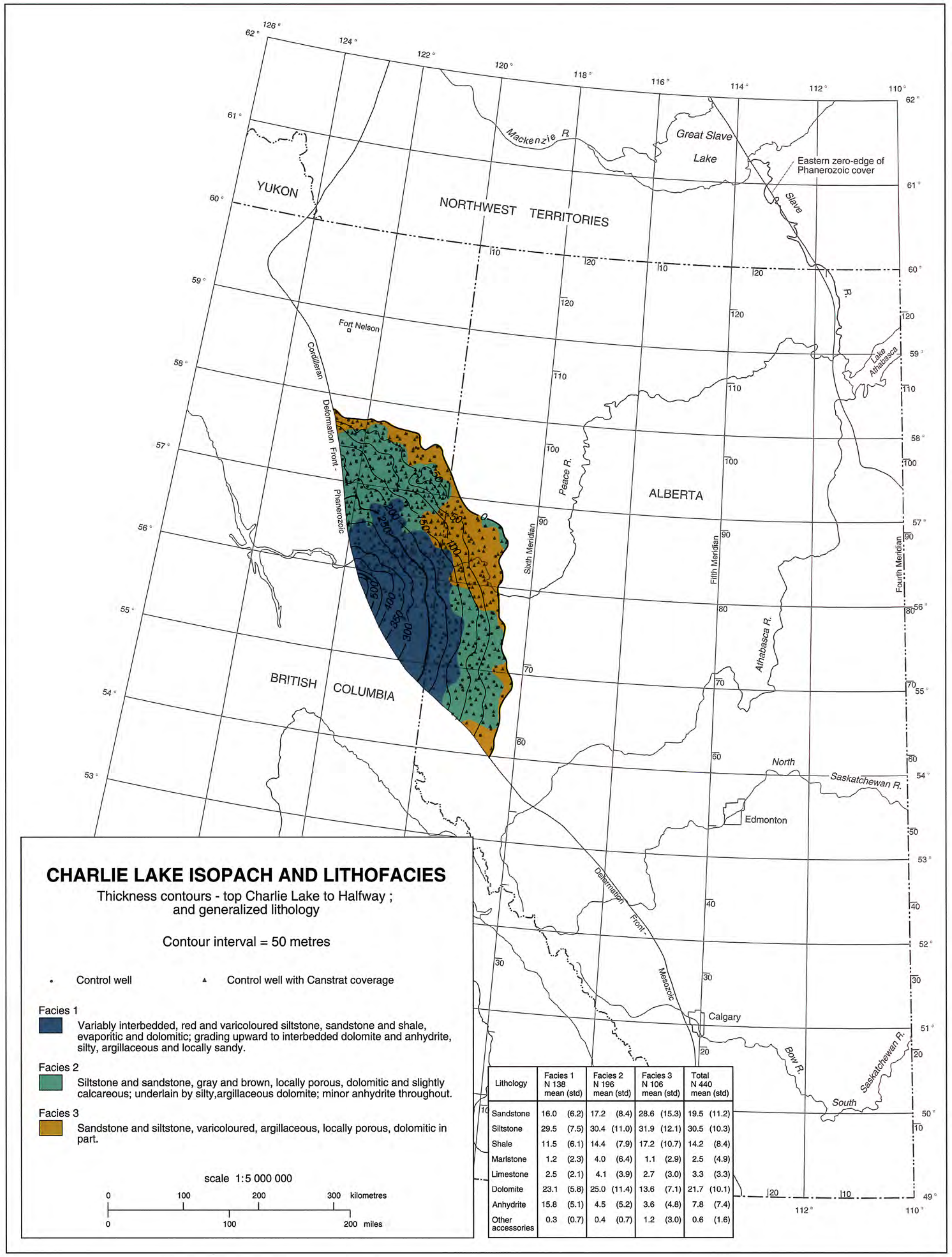
Baldonnel Formation–Pardonet Formation/Worsley Isopach

These two formations are combined for this isopach map because of their lithological similarity and because of the difficulty in separating the formations in some areas using well logs (Fig. 16.34). Both the Baldonnel and overlying Pardonet Formation thicken westward toward the foothills and outcrop belt. The Baldonnel Formation consists mainly of peloidal and bioclastic dolostones, rare limestones and rare breccias. In some areas of the subsurface and outcrop belt, the Baldonnel Formation is characterized by shallow-water, shallowing-upward cycles (Barss and Montandon, 1981; Bever and McIlreath, 1984). In many areas, the Baldonnel Formation is an excellent reservoir with porosities up to 30 percent, but apparent freshwater flushing has resulted in abundant bitumen residue.

The Pardonet Formation abruptly overlies the Baldonnel Formation, apparently conformably. The Pardonet occurs over a limited area in the basin, restricted mainly to the subsurface of the foothills and the foothills outcrop belt north of Sukunka River (Fig. 16.34; Gibson, 1975; Gibson and Edwards, 1990a,b). Much of the Pardonet Formation in the eastern foothills and plains was subjected to pre-Jurassic erosion. The Pardonet Formation in the subsurface consists mainly of dark gray dolomitic siltstone, silty limestone, shale and, locally, light gray dolostone (Barss and Montandon, 1981).

The enigmatic Worsley Member is also included on this map (Fig. 16.34) because of the way the Atlas database was set up. The Worsley comprises dolomites, shales and silty sandstones.

Laprise Creek Field. The Laprise Creek Field (Fig. 16.35) is an example of a productive reservoir in the Baldonnel Formation (Bever, 1990). It consists of dolomitized bioclastic wackestone and packstone (Armitage, 1962). Porosity in the reservoir (up to 30%) is facies controlled. The trapping mechanism is both structural, related to the Laramide folding, and stratigraphic, associated with the erosional subcrop edge.



CHARLIE LAKE ISOPACH AND LITHOFACIES

Thickness contours - top Charlie Lake to Halfway ; and generalized lithology

Contour interval = 50 metres

• Control well

▲ Control well with Canstrat coverage

Facies 1

■ Variably interbedded, red and varicoloured siltstone, sandstone and shale, evaporitic and dolomitic; grading upward to interbedded dolomite and anhydrite, silty, argillaceous and locally sandy.

Facies 2

🟩 Siltstone and sandstone, gray and brown, locally porous, dolomitic and slightly calcareous; underlain by silty,argillaceous dolomite; minor anhydrite throughout.

Facies 3

🟧 Sandstone and siltstone, varicoloured, argillaceous, locally porous, dolomitic in part.

scale 1:5 000 000

0 100 200 300 kilometres

0 100 200 miles

Lithology	Facies 1 N 138 mean (std)	Facies 2 N 196 mean (std)	Facies 3 N 106 mean (std)	Total N 440 mean (std)
Sandstone	16.0 (6.2)	17.2 (8.4)	28.6 (15.3)	19.5 (11.2)
Siltstone	29.5 (7.5)	30.4 (11.0)	31.9 (12.1)	30.5 (10.3)
Shale	11.5 (6.1)	14.4 (7.9)	17.2 (10.7)	14.2 (8.4)
Marlstone	1.2 (2.3)	4.0 (6.4)	1.1 (2.9)	2.5 (4.9)
Limestone	2.5 (2.1)	4.1 (3.9)	2.7 (3.0)	3.3 (3.3)
Dolomite	23.1 (5.8)	25.0 (11.4)	13.6 (7.1)	21.7 (10.1)
Anhydrite	15.8 (5.1)	4.5 (5.2)	3.6 (4.8)	7.8 (7.4)
Other accessories	0.3 (0.7)	0.4 (0.7)	1.2 (3.0)	0.6 (1.6)

Figure 16.31 Charlie Lake isopach map, and generalized lithofacies distribution.

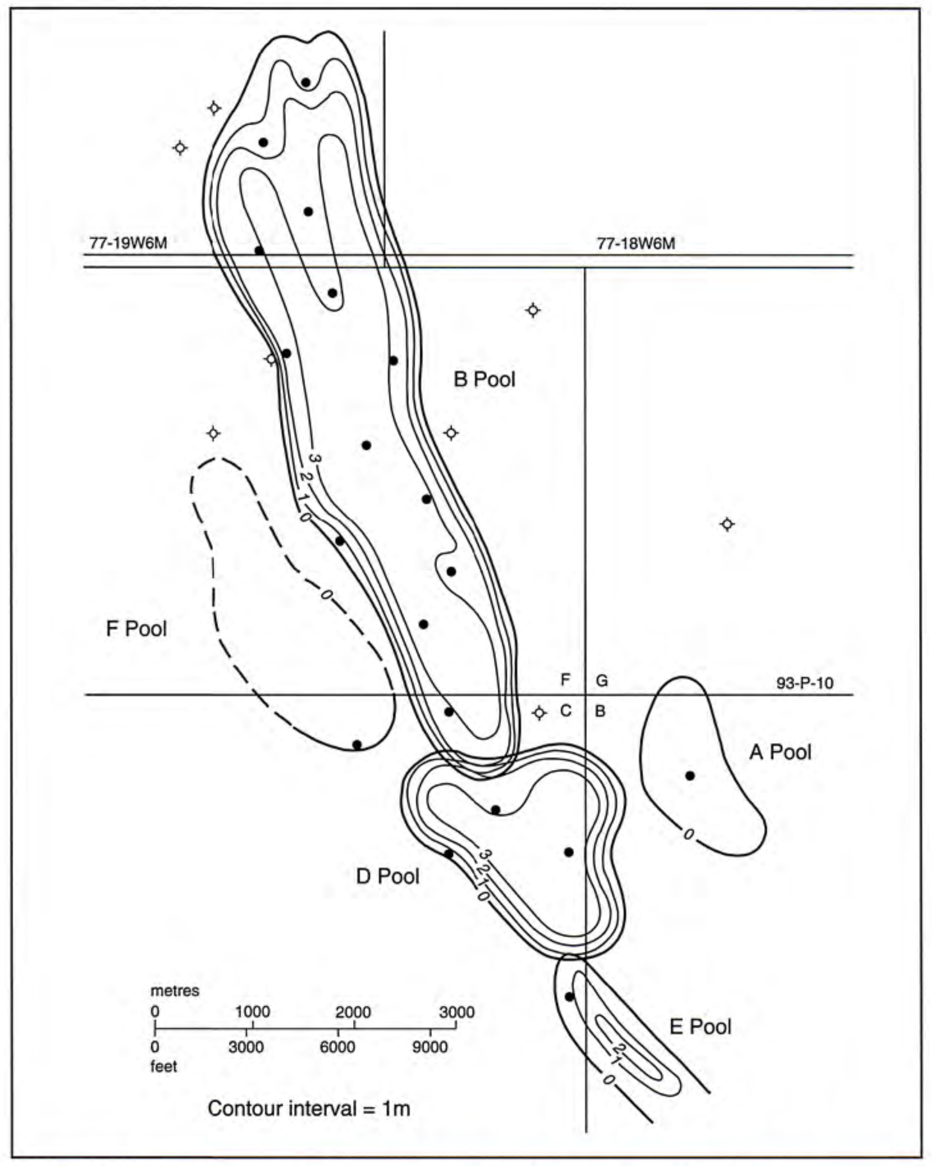


Figure 16.32 Net pay isopach map of the Artex Member, lower Charlie Lake Formation, Brassey Field area, northeastern British Columbia (after Klein and Woofter, 1989).

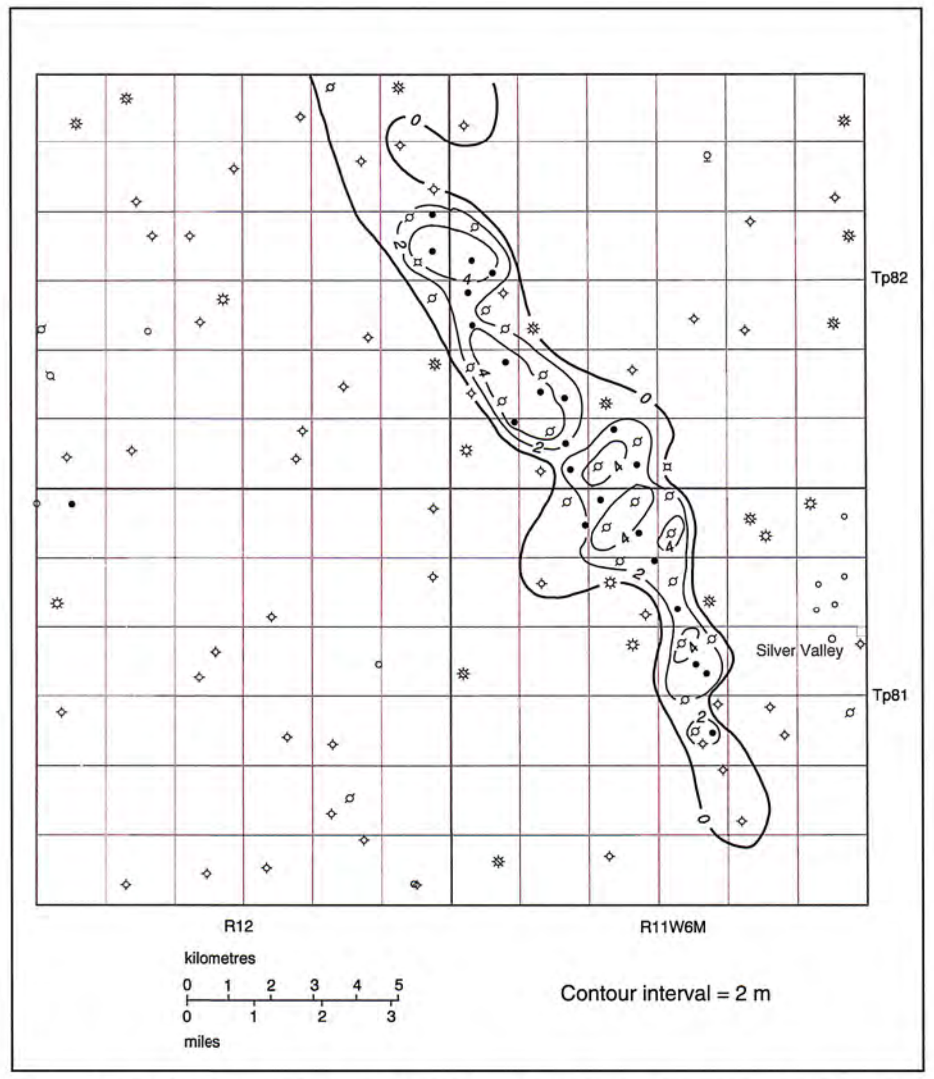
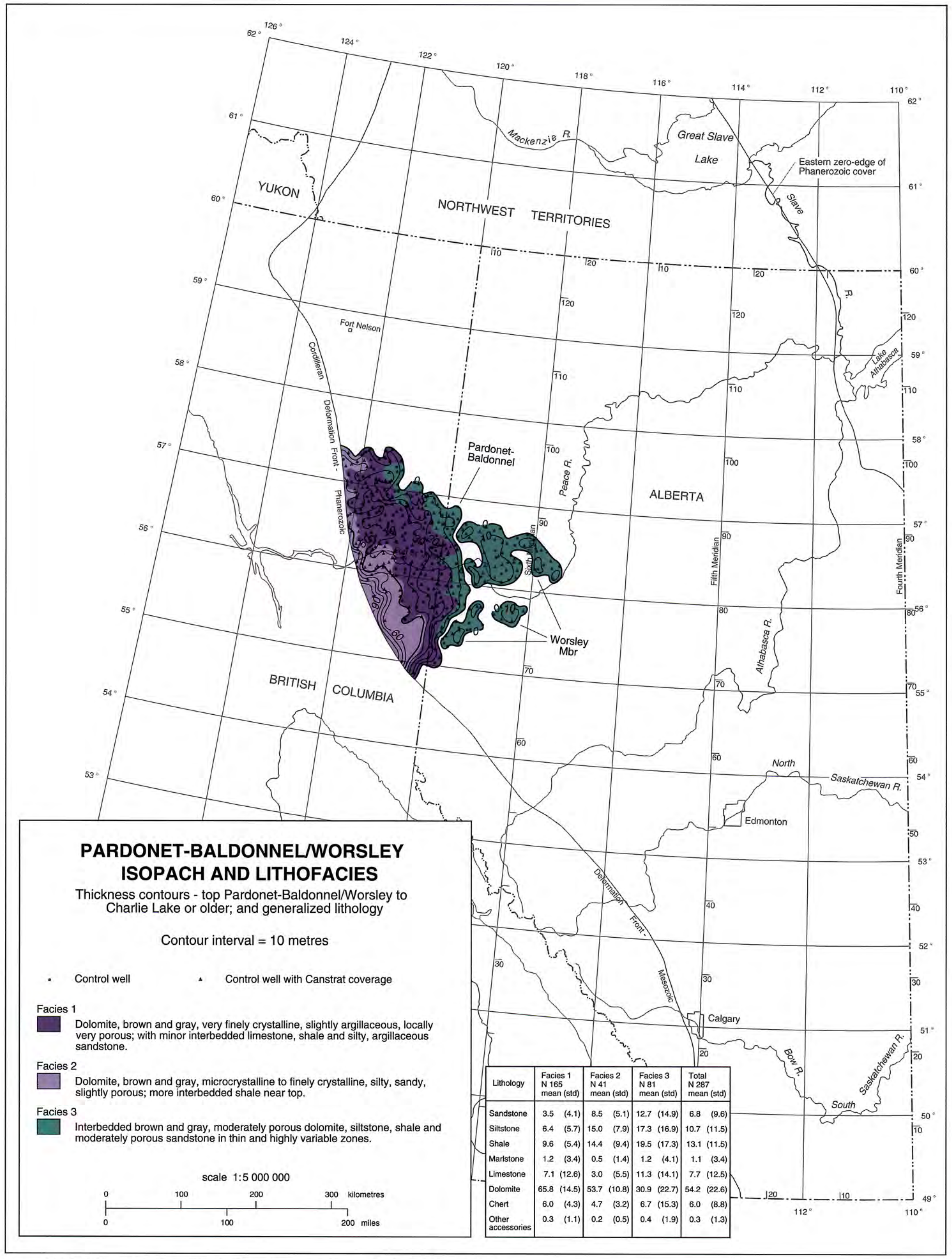


Figure 16.33 Porosity isopach map (porosity>8%), showing thickness of productive and potentially productive occurrences of tidal flat and intertidal algal carbonates of the Boundary Member, Charlie Lake Formation, in Bonanza Field, northeastern British Columbia.



PARDONET-BALDONNEL/WORSLEY ISOPACH AND LITHOFACIES

Thickness contours - top Pardonet-Baldonnel/Worsley to Charlie Lake or older; and generalized lithology

Contour interval = 10 metres

▪ Control well ▲ Control well with Canstrat coverage

Facies 1

■ Dolomite, brown and gray, very finely crystalline, slightly argillaceous, locally very porous; with minor interbedded limestone, shale and silty, argillaceous sandstone.

Facies 2

■ Dolomite, brown and gray, microcrystalline to finely crystalline, silty, sandy, slightly porous; more interbedded shale near top.

Facies 3

■ Interbedded brown and gray, moderately porous dolomite, siltstone, shale and moderately porous sandstone in thin and highly variable zones.

scale 1:5 000 000

0 100 200 300 kilometres

0 100 200 miles

Lithology	Facies 1 N 165 mean (std)	Facies 2 N 41 mean (std)	Facies 3 N 81 mean (std)	Total N 287 mean (std)
Sandstone	3.5 (4.1)	8.5 (5.1)	12.7 (14.9)	6.8 (9.6)
Siltstone	6.4 (5.7)	15.0 (7.9)	17.3 (16.9)	10.7 (11.5)
Shale	9.6 (5.4)	14.4 (9.4)	19.5 (17.3)	13.1 (11.5)
Marlstone	1.2 (3.4)	0.5 (1.4)	1.2 (4.1)	1.1 (3.4)
Limestone	7.1 (12.6)	3.0 (5.5)	11.3 (14.1)	7.7 (12.5)
Dolomite	65.8 (14.5)	53.7 (10.8)	30.9 (22.7)	54.2 (22.6)
Chert	6.0 (4.3)	4.7 (3.2)	6.7 (15.3)	6.0 (8.8)
Other accessories	0.3 (1.1)	0.2 (0.5)	0.4 (1.9)	0.3 (1.3)

Figure 16.34 Baldonnel-Pardonet/Worsley isopach map, and generalized lithofacies distribution.

Williston Basin

In the Williston Basin, strata of possible Triassic age comprise a relatively thin succession of continental to restricted-marine redbeds up to 100 m thick (Fig. 16.2). The Triassic(?) "Lower Watrous" (informal unit) is overlain unconformably by marine or non-marine Jurassic rocks in Manitoba, whereas in Saskatchewan the Lower Watrous is overlain, perhaps unconformably, by non-marine strata of the Jurassic "Upper Watrous" (informal unit) in some areas, or overlain unconformably by non-marine Cretaceous rocks elsewhere. The Lower Watrous is underlain unconformably by Devonian and Carboniferous strata in southern Saskatchewan and by Ordovician to Carboniferous strata in southwestern Manitoba (see Figs. 16.4 b, 16.5). Three oil fields have been discovered in the Williston Basin redbeds within Manitoba (Fig. 16.2), and the fields contain 3.5 x 10^6 m^3 recoverable oil reserves, which account for about 10 percent of Manitoba's oil reserves (Manitoba Energy and Mines - Petroleum Branch, *pers. comm.*, 1990).

Geological Framework

The Lower Watrous and Lower Amaranth redbed siliciclastics and anhydrites were deposited in the shallow, northwest-trending (in Canada, northeast in U.S.A.) Watrous and Amaranth sub-basins during a time when the Williston Basin was severely contracted in size (Figs. 16.1, 16.5; Christopher, 1984). Paleoclimate is interpreted as having been arid. The northwest and northeast trends presage the structural and sedimentary trends impressed by later Columbian and Laramide orogeny (Christopher, 1984). These units represent the oldest Mesozoic strata in the Williston Basin and onlap, with significant unconformity, the underlying eroded Paleozoic surface. The formations occur throughout southern Saskatchewan and southern Manitoba and extend southward into North Dakota, South Dakota and northeast Montana.

The Watrous and Amaranth sub-basins are bounded by positive elements of the Sweetgrass Arch-Shaunavon Shelf-Punnichy Arch highland system (Fig. 16.1). These arches and basins differ significantly from the roughly circular pre-Permian basin configuration and may have developed in response to the Permo-Triassic Appalachian Orogeny of eastern North America (Christopher, 1984). The continental to restricted marine redbeds also contrast depositionally with the extensive Jurassic and Paleozoic marine deposits.

Although the redbeds are normally considered as cap rocks to Mississippian subcrop-type oil fields, oil shows in sandstone lenses are known in southern Manitoba. Oil production was known from equivalent Spearfish strata at Newburg and South Westhope fields in North Dakota over thirty years ago (Stott, 1955; Francis, 1957; Barchyn, 1982).

On the Canadian side of the Williston Basin, commercial oil was not discovered until 1980 at Waskada field, southwestern Manitoba, in the Amaranth Formation (Fig. 16.2; Barchyn, 1982, 1984; Christopher, 1984). Oil was also found in Lower Amaranth basal sandstones and siltstones in 1981 at South Pierson and Coulter fields in southwestern Manitoba (Fig. 16.2; Arbez, 1990; Husain, 1990).

Stratigraphy

Stratigraphic Nomenclature

The Watrous Formation was defined by Milner and Thomas (1954) as red-orange shale and mudstone overlain by anhydrite. Silt and sand content increases downward, and local sandstone, conglomerate or a cherty anhydritic shaly breccia are contained near the base. The type section is in the Tidewater Davidson Crown No. 1 well, 16-8-27-1W3 from the nearly fully cored interval of 754.7 to 836.4 m (2476-2744 ft).

The formation is informally split into two units - a "Lower Watrous" Triassic(?) unit consisting of the argillaceous redbeds with basal sandstones and conglomerates, and an "Upper Watrous" Jurassic(?) unit consisting of the anhydrite beds (see Figs. 16.4b, 16.5; Francis, 1957; Carlson, 1968; Pocock, 1970, 1972; Christopher, 1984). These units thus carry both a lithological and an age connotation and, since no type section for the Upper and Lower Watrous units exists, should be considered as informal members of the Watrous Formation.

Our correlations hint at an unconformable Lower-Upper Watrous contact. Christopher (1984) correlated the Lower Watrous with Early Triassic upper Spearfish units, thus implying an unconformable relation with the Jurassic Upper Watrous. Stott (1955) interpreted the contact to be conformable on the basis of close physical association and because the Upper Amaranth never occurs separately. Francis (1957) suggested one or more major unconformities within the Watrous-Amaranth sequence. However, he noted a gradational relation with anhydrite stringers at the top of the Lower Watrous grading to the Upper Watrous anhydrite.

Lithological correlation northward from upper parts of the Permo-Triassic Spearfish Formation in North Dakota suggests that the Lower Watrous is Triassic, whereas the Upper Watrous is considered to be Jurassic in age (Carlson, 1968). The Lower Watrous redbeds may be correlative with thick salt deposits, such as the Pine Salt Member, Spearfish Formation, in central parts of the Williston Basin south of the Canada-U.S.A. border (Francis, 1957;

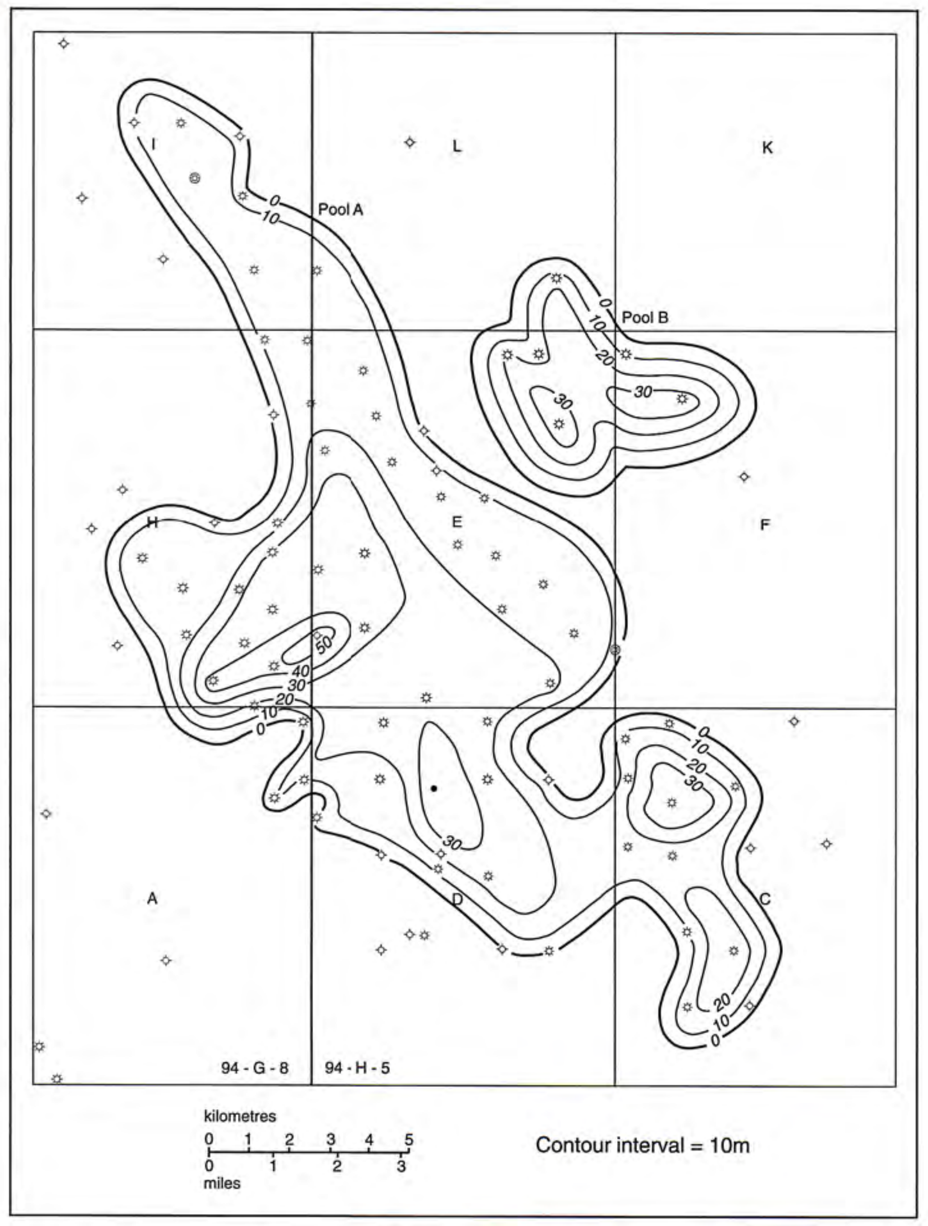


Figure 16.35 Net gas pay isopach map of the Baldonnel Formation in Laprise Creek Field, northeastern British Columbia.

Christopher, 1984). Some authors have suggested that the Lower Watrous could be as young as Middle Jurassic (see Springer et al., 1964). Lack of fossils in these redbeds hampers age designation. Physical separation prohibits correlation westward to the Triassic of the Alberta Basin. Cumming (1956, p. 169) states that "It is almost traditional that papers on the Watrous should express doubt concerning the age and correlation of that formation, and in this respect the present report is no exception". We maintain the tradition.

The Watrous Formation of Saskatchewan is considered equivalent to the Amaranth Formation of Manitoba on the basis of lithological similarity, stratigraphic position and physical continuity. The name "Amaranth" was given to the red siltstones and shales near the town of Amaranth, Manitoba by Kirk (1929) and the Amaranth Formation was formally defined by Wickenden (1945) with two type sections designated at 8-26-2-9-WPM, 359.7 to 426.7 m (1180-1400 ft) and at 9-33-14-15WPM, 228.6 to 301.8 m (750-990 ft). A suggested reference section is at 5-29-14-14WPM, 214.7 to 272.2 m (704.4-893 ft) (McCabe, 1990).

Stott (1955) divided the Amaranth Formation into two members, a lower red dolomitic shale that with increasing silt and sand grades locally to sandstone (Lower Amaranth), and an upper anhydrite with shale and dolomite interbeds (Upper Amaranth) (McCabe, 1990). A basal carbonate breccia (possibly a karstic zone and regolith developed on underlying Paleozoic carbonates, noted by Poulton (1989, p. 235) to typify the Mesozoic basal contact) occurs locally (McCabe, 1990). In the Waskada-Pierson oil field area, Barchyn (1982) informally divided the Lower Amaranth into a lower sandy unit and an upper shaly unit.

Because of lithological correlation and continuity with the Lower Watrous, it is suggested that the Lower Amaranth is Triassic in age. The Upper Amaranth is considered to be Jurassic (on that basis, we treat the Lower Watrous/Lower Amaranth in the Triassic chapter, the Upper Watrous/Upper Amaranth in the Jurassic chapter).

Stratigraphic History

The Lower Watrous-Lower Amaranth redbeds were deposited unconformably on and sourced from the eroded surface of Paleozoic carbonates that formed a tectonically stable shelf (Francis, 1957; Carlson, 1968; Christopher, 1984). The Paleozoic depositional topography consisted of a series of lows in eroded anticlinal flexures, and highs in the flanking, less eroded synclinal flexures (Christopher, 1984). Thus the lows, in former anticlines, captured Watrous sediments, while the former synclines were topographic highs, bereft of Watrous deposits. Other relief on the Paleozoic surface controlling Watrous-Amaranth deposition includes relief caused by dissolution of underlying Paleozoic salts, dewatering of Paleozoic gypsum, underlying fault relief, meteorite impact cratering and differential compaction (McCabe and Bannatyne, 1970; Barchyn, 1982; Poulton, 1989).

Lower Watrous-Lower Amaranth deposits onlapping the Paleozoic surface represent the initiation of a major transgressive event in the Williston Basin (Fig. 16.5; Barchyn, 1982) and are the precursor to extensive Jurassic marine flooding that created a much enlarged Williston Basin. The depositional environment of the redbeds during this period may represent continental mud flats and playa lakes, with eolian and fluvial deposits, which were subjected to episodic exposure as well as episodic marine incursions (Barchyn, 1984). Subaerial exposure events and transport of terra rosa sediment from basin margin carbonate source areas would be conducive to redbed deposition (Christopher, 1984).

Regional Cross Sections

The Williston Basin Triassic(?) is shown in cross sections A-A’ (southern portion) and G-G* (Figs. 16.4b, 16.5). A sharp contact with the overlying Upper Watrous anhydrite is evident on G-G* as is the contact with underlying Paleozoic carbonates. The siltstone-mudstone character of the Lower Watrous and Lower Amaranth redbeds is indicated by the high gamma-ray values. A shaling- or fining-upward is also apparent in several wells (e.g., wells 2-2-13-3W3 and 6-28-3-12W2, Figs. 16.4b, 16.5). Basal sandstones may be present on G-G* at wells 15-24-5-12W2 and 3-19-6-10W2. The Lower Watrous could be subdivided into a sandier lower unit and a shalier upper unit. The sandier unit appears to pinch out eastward and onlap the Moosomin High. The Lower Watrous can be seen infilling topographic depressions or lows on the Paleozoic unconformity on both A***-A’ and G-G*. A Devonian high, named the Birdtail-Waskada Axis by Kreis (1991a; see also Christopher, 1984; Kreis, 1991b), occurs along the Manitoba-Saskatchewan boundary, separating the Watrous and Amaranth sub-basins (Fig. 16.1, see also well 2-14-16-28W1 in Fig. 16.5).

Reference Well Logs

The Sun Imp. Coteau Lakes 11-1-1-19W2 well (Fig. 16.36) serves as a reference well log suite for the Lower Watrous unit.

The siltstones of the Lower Watrous exhibit high and relatively uniform gamma-ray character and low resistivity reflecting the conductivity of clay particles. This contrasts with the low and serrated gamma-ray character and higher resistivity common to Upper Watrous anhydrites. The sonic response of the Lower Watrous has a similar value but a less serrated character than the Upper Watrous. SP values are similar, reflecting the low permeabilities of both units.

The red shaly sandstones of the Carboniferous Kibbey Formation, underlying the Lower Watrous in this area, are fairly similar in lithology and log response to the Lower Watrous. The interbedded carbonates in the Kibbey, however, have lower gamma-ray and sonic responses, which aid in separating the Watrous and Kibbey.

Structure

The overall pattern of the top-Lower Watrous and Lower Amaranth units structure is simple. Structure contours display an arcuate shape deepening toward the centre of the Williston Basin in southeasternmost Saskatchewan (Fig. 16.3). Structural elements visible on the isopach map of these units are not apparent on the top of the unit. The smooth surface can be interpreted as indicating a filling of those basin elements by the Lower Watrous and Lower Amaranth units.

Contours are roughly east-west in the centre of the Canadian Williston Basin and curve to a north-south orientation on the west basin flank and to a northwest-southeast orientation on the east flank. On the west basin flank, the bend to north-south contours reflects the eastern margin of the Sweetgrass-Punnichy Arch system. The northwest-southeast contours on the east flank of the basin outline a gradual rise toward the Canadian Shield. Some of the finer irregularities on the surface may be the result of salt dissolution in underlying Devonian strata.

Thickness, Lithology, and Petroleum Fields

The Lower Watrous and Lower Amaranth units occupy two northwest-trending sub-basins and thicken from their zero-edges to a maximum of 100 m in south-central Saskatchewan near the U.S.A. border (Figs. 16.1, 16.2). Lower Watrous and Lower Amaranth deposits consist of red-orange shale, siltstone and sandstone that are widespread and persistent throughout the Williston Basin (Springer et al., 1964).

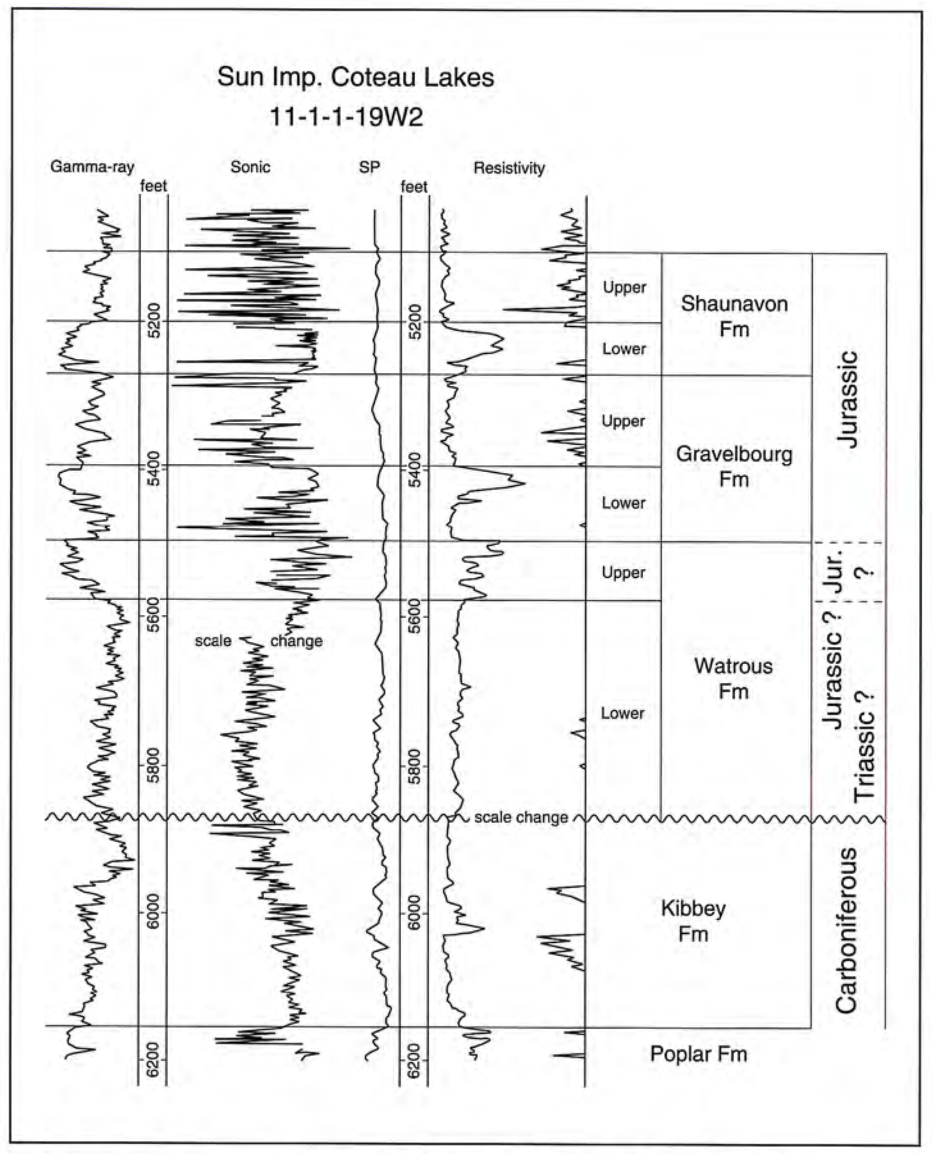


Figure 16.36 Reference well logs for the Lower Watrous of south-central Saskatchewan. Vertical scale is 1:3000.

The clastics fine upward, are dolomitic, slightly anhydritic and contain rounded and frosted sand grains. Klingspor (1958) reported sandblasted pebbles (dreikanters). Barchyn (1982) noted desiccation cracks in some shales. Anhydrite occurs as pore-filling cements and as nodules and lenses (Barchyn, 1982). Sandstones are more common toward the east and southeast, particularly in the Amaranth sub-basin (Christopher, 1984), such sandstones forming the reservoir at Waskada, South Coulter and Pierson oil fields (Barchyn, 1982, 1984; Arbez, 1990; Husain, 1990).

Waskada Field. Oil in the Amaranth Formation was discovered at Waskada Field (Fig. 16.2) during recompletion of a former Carboniferous oil well (Barchyn, 1982). Here, the oil is trapped stratigraphically in an updip porosity pinch-out of gray, permeable, quartz and feldspathic arenites and siltstones enclosed within impermeable redbed mudstones and siltstones (Barchyn, 1982, 1984). Oil appears to have migrated from underlying, poorly sealed Mississippian accumulations (Barchyn, 1982). The field also occurs on a structural high suggesting some structural trapping control (see Rodgers, 1986).

South Pierson and Coulter fields. Oil was found in Lower Amaranth basal sandstones and siltstones in 1981 at South Pierson and Coulter fields in southwestern Manitoba (Fig. 16.2; Arbez, 1990; Husain, 1990). These fields may also be stratigraphic traps, as at Waskada field, with a northern updip pinch-out and southern downdip water leg.

Summary

During Triassic time, tectonic activity, presumably related to the breakup of Pangea, decreased markedly. Worldwide conditions were arid and relatively mild (Habicht, 1979). Within this global framework, the Western Canada Sedimentary Basin occupied a west-facing shoreline, with the Peace River Embayment situated at approximately 30° N (Fig. 16.1). Sediments of the Embayment were derived from a low-relief, sediment-covered cratonic platform to the east and were deposited on a westward-deepening continental shelf margin.

The Williston Basin in southeastern Saskatchewan and southwestern Manitoba was severely contracted in size compared to its Paleozoic outlines. The basin was cut off from most normal-marine influence and was dominated by the deposition of continental to possibly restricted-marine redbeds.

Sedimentation in the western part of the foothills and Rocky Mountain Front Ranges was apparently essentially continuous throughout Triassic time and was dominated by shelf-slope shale and silt deposits. Eastward in the Peace River Embayment, the effects of several major and minor unconformities can be seen (e.g., Fig. 16.13). All areas of the Alberta Basin were subjected to three major (Figs. 16.6, 16.8; Podruski et al., 1988; Gibson and Barclay, 1989) and numerous, minor, transgressive-regressive ("T-R") cycles, resulting in many hiatal and parasequence boundaries.

Strata of the Lower Triassic Montney, lower Toad and lower Sulphur Mountain formations were deposited mainly in a deep-water inner to distal shelf environment (Figs. 16.7, 16.8). These strata formed part of the first major T-R cycle, during which time the northeastern part of the basin was subjected to several minor or secondary T-R cycles. In the eastern part of the basin, the Lower Triassic succession is characterized by relatively thick, shallow-water deltaic and/or inner shelf or shoreline sandstones deposited near or at the present-day Triassic subcrop edge. Also in this eastern area, presumed synsedimentary faulting occurred (Wittenburg and Moslow, 1991). Tempestites and possible turbidites occur in the deeper part of the basin.

The Middle Triassic Doig, Halfway, upper Toad, Liard and upper Sulphur Mountain formations formed part of the second major T-R cycle (Figs. 16.6, 16.8). Again, the cycle was interrupted in many areas of the basin by several secondary transgressions and regressions. The regressive pulses appear to have been most dominant. In the subsurface eastern foothills and plains, during the major regressive phase of the cycle, a discontinuous barrier island shoreline system in the Halfway Formation (Fig. 16.10) developed in the east, whereas a continuous "sheet" sandstone developed in the west. In the outcrop belt of the foothills and Rocky Mountain Front Ranges, the Middle Triassic succession was deposited in a deeper water inner to probable mid-shelf environment (Fig. 16.7). The Upper Triassic Charlie Lake and lower Whitehorse formations also were deposited within the second T-R cycle, and like the underlying formations were subjected to secondary or minor T-R cycles. Restricted marine/sabkha sedimentation dominated, associated with migrating dune fields and playas and the deposition of thin and thick units of anhydrite and, locally, halite. Numerous minor unconformities, as well as at least three major unconformities, occur within the subsurface extent of the Charlie Lake Formation (Fig. 16.13). One of these, the Coplin, is traceable over the entire Peace River Embayment in the subsurface, but has not been recognized westward in outcrop in the Charlie Lake or lower Whitehorse Formation of the foothills and Rocky Mountain Front Ranges. In the extreme western foothills outcrop belt, Charlie Lake Formation-equivalent, deep-water, distal shelf/slope strata of the Ludington Formation were deposited (Fig. 16.7).

The last, third major T-R cycle resulted in the deposition of the Baldonnel, Pardonet and upper Whitehorse formations (Figs. 16.6, 16.8). Preserved strata in the northern half of the basin appear to be mainly transgressive, whereas in the Smoky River-United States border area, the uppermost Triassic Whitehorse Formation appears to be regressive. Within this major cycle, a series of repeated progradational events resulted in the deposition of shallowing-upward cycles consisting of shallow-water shelf and tidal-flat carbonates. The carbonates have since been influenced by karsting, brecciation and freshwater flushing. The predominant deposition of carbonates during this cycle differs from the underlying clastics of the Charlie Lake, Halfway, Doig and Montney formations. Such deposition may indicate a warming climatic trend and/or a lessening of clastic influx because of a lowering of relief of the continental interior near the end of the Triassic period.

The series of transgressions and regressions that took place during Triassic time within the Western Canada Sedimentary Basin resulted in the deposition of strata that form prolific oil and gas reservoirs in the Peace River Embayment. Hydrocarbons were sourced internally from the lower Doig Formation and Whistler Member of the Sulphur Mountain Formation as well as from the overlying Jurassic Nordegg Member of the Fernie Formation (Riediger, 1991). Reservoirs occur within Montney, lower Sulphur Mountain Formation, Doig and Halfway shoreline clastics and coquinas, Charlie Lake algal mats and dunes, and Baldonnel and Pardonet shallow-water carbonates. While most of the traps are stratigraphic in nature, the Laramide Orogeny produced a number of fold and thrust fault anticlinal structural traps in northeastern British Columbia.

The dynamics of the basin in the Peace River Embayment during the Triassic resulted in a wedge shaped sedimentary profile that has been modified by early Jurassic and, in some cases, pre-Cretaceous erosion, which increases to the north and east.

In the Williston Basin "depression", continental to restricted-marine Triassic strata unconformably overlie Paleozoic strata and are truncated toward the edge of the basin by nondeposition and pre-Jurassic erosion.

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Frontispiece 17.0 Foreland basin sediments. Maastrichtian to Paleocene strata of the Willow Creek Formation (middle distance) overlain by Porcupine Hills Formation beds in the background, at Cowley, Alberta, near Pincher Creek. Continental strata of this type are prevalent throughout the Jurassic to Paleocene foreland basin, the sediments supplied by the rising Cordillera to the west (left). Porcupine Hills in the distance. Photograph by T. Jerzykiewcz.