Pseudospira 11.9 Devonian platform carbonates. Ordovician-Devonian section on the west side of Glacier Pass, Jasper National Park, Alberta. At this locality, Devonian Bearpaw/Lake Athabaska (upper left) directly overlie Ordovician rocks (lower right) along the sub-Devonian unconformity, which stretches from the base of the foreground snow patch to the oil on the horizon. Photograph by R. Warkentin.
Chapter 11 – Devonian Beaverhill Lake Group of the Western Canada Sedimentary Basin

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Introduction

The Upper Givetian to Lower Frasnian Beaverhill Lake Group (Fig. 11.1 and 11.2) covers a major part of the Western Canada Sedimentary Basin, attaining a maximum thickness of approximately 240 m (Fig. 11.3). This stratigraphic interval is bounded below by the post-Elk Point unconformity (Fig. 11.2) and above, conformably to discontinuously, by the Wood bend Group. The succession can be subdivided into two stratigraphic phases: a transgressive “reelfoot” phase (Fig. 11.4), dominated by restricted to open-marine carbonates of the Slave Point and Swan Hills formations (Fig. 11.2), and a regressive “basin-fill” phase (Fig. 11.5), dominated by shales and argillaceous carbonates of the Waterways Formation (Fig. 11.2). Selected reference wells (Fig. 11.6) illustrate the regional stratigraphic and lithologic character of the strata that comprise the Beaverhill Lake Group and its Manitoba Group correlates in Saskatchewan and Manitoba.

The banks and reefs of the transgressive phase are host to significant hydrocarbon reserves, and remain a focus of exploration activity, with recent discoveries at the Caroline Field (Ty 34, R 4 W6M) in southern Alberta and at Hambur (Ty 96, R 11 W6M) in northern Alberta (Fig. 11.3).

Previous Work

The previous atlas (Committee on the Slave Point and Beaverhill Lake formations, 1964) set out the regional distribution of Beaverhill Lake and equivalent strata. The subsurface stratigraphy has since become much better known because of the increased drilling activity associated with this economically important depositional sequence.


Geological Framework and Synthesis

The post-Elk Point relative sea-level rise allowed sea to return to the intracratonic Elk Point Basin, transgressing the older basin margins. The marine incursion deposited open-marine carbonates that formed an extensive carbonate platform. Continued relative sea-level rise segregated the interior basin into several bank complexes and intraplatform “basins” (Fig. 11.1). A carbonate bank, the Hay River Bank, developed in the northern part of the basin with the seaward margin roughly coincident with the underlying Elk Point barrier, forming a continuous “barrier reef” known as the Presqu’ile Barrier. Along the western margin of the basin a fringing reef complex developed flanking the Peace River Arch, and the Swan Hills Complex developed marginal to the west Alberta Ridge (Fig. 11.3). Following the transgressive phase, westward- and northward-prograding shelf-carbonate clinoform cycles of the regressive phase infilled the Watersways Basin and downwaded the reef complexes. These clinoforms correlate with shallowing-upward carbonate-evaporite cycles that were stacked aggradationally in the Souris River Shale (Fig. 11.1).

The basin is presumed to have extended farther eastward but is not preserved because of post-Devonian tectonics and erosion. The basin also extended farther south into Montana and North and South Dakota.

Tectonic History

The Peace River Arch and West Alberta Ridge (Fig. 11.1) were palaeotopographic high features that strongly influenced the Beaverhill Lake stratigraphy and depositional facies pattern. Their origin predates the Middle Devonian (O'Connell et al., 1908) and, except for minor tectonic activity associated with the Peace River Arch, they remained relatively inactive during Late Givetian-Early Frasnian time.

Normal block faulting (post-Elk Point, pre-Beaverhill Lake) was a result of possible readjustment of the Peace River Arch. The evidence includes local erosion of the Elk Point surface (Ukikuma area, Ty 82, R 10 W6M), local dissolution of Elk Point salts (Kidney area, Ty 91, R 6 W6M) and the presence of course, arctic clastic sediment. Arkoisic clastic debris was shed off the arch during the post-Elk Point hiatus, as a result of tectonic uplift and erosion. The sediment was reworked and deposited as a fluvial-deltaic complex (Gillwood Member; Fig. 11.2) during the ensuing relative sea-level rise. Arkoisic clastic sediment is also present within the Watersways Formation in the Circleville area (Ty 78, R 21 W6M) along the southern flank of the arch, indicating a later tectonic pulse.

Givetian-Franchian tectonic activity associated with the West Alberta Ridge and Tahlibna High (an Elk Point palaeotopographic feature in southern N.W.T.) is not documented or strongly exhibited, but may exist, as the tectonic history of these two features is thought to be similar to that of the Peace River Arch.

Figure 11.1. Index and regional paleogeography map, identifying six paleogeographic areas, the location of the master and disjunctive cross sections and the reference wells.

Figure 11.2. Table of formations for each of the six defined paleogeographic areas, presented in a northwest to southeast orientation. The biostratigraphic zonation of Braun et al. (1989) is illustrated.
Figure 11.3 Beaverhill Lake isopach map. The isopach interval does not include the Wapiti Mountain Formation because of database limitations; however, the Wapiti Mountain is less than 0.1 m thick and does not significantly affect this map. Neither does it include the Dunvegan Sandstone, which is mapped separately (Fig. 11.14). The Beaverhill Lake Group attains a maximum thickness of 300 m in south-central and northeastern Alberta, within the Wabamun Basin, an intra-platform basin. The strata thin eastward as a result of erosion. The group also thins westward as it encroaches the emergent Peace River Arch and West Alberta Ridge. The bank margin of the transgressive sequence is outlined. A depositional thickening, the Hatzic Lake Embayment, separates the Peace River Arch Fringing Reef Complex from the Hay River Bank. Isopach thickening within the depositional area west of the Hay River Bank margin, and within the Contwoyto Embayment, occurs as a result of an inability to differentiate between Beaverhill Lake and older basin strata. Hydrocarbon accumulations occur along the bank margins and within the bank complexes.
Figure 11.4 Transgressive phase isopach map. The transgressive phase exhibits general southeastward thinning from the bank margin of the Hay River Arch. Shallow-marine carbonates unroofed the emergent Peace River Arch. In the Swan Hills, Conklin the bank developed initially and thickened to over 100 m. In southern Saskatchewan the transgressive phase thins to less than 30 m and forms the lower portion of the Souris River Formation (not shown). The Dawson Bay Formation and its equivalent, the Wat Mountain Formation, are not included because of database limitations in differentiating the Wat Mountain Formation (see also Figure 11.14).

Several stages of post-Beaverhill Lake salt solution in southern Saskatchewan overprinted earlier dissolution events, creating complex stratigraphic and structural relations. The isopach map (Fig. 11.3) depicts the solution-influenced geometries in only a very generalized way. Post-Beaverhill Lake solution removal of Elk Point evaporites along the subcrop edge near the Alberta-Saskatchewan border is best reflected in the Beaverhill Lake structure map (Fig. 11.7).

Stratigraphy

Stratigraphic Nomenclature

The Geological Staff of Imperial Oil Ltd. (1950) originally defined the Beaverhill Lake Formation in the Edmonton area, in the Alberta-Canadian Beaverhill Lake No. 2, 11-15, 54-15, 74-15 well. It was later equated to the Waterways Formation as defined by Cracknay (1957) in northeastern Alberta. Leavitt and Fischbuch (1988) raised the Beaverhill Lake to group status and defined the group to include the Fort Vermilion, Swan Hills and Waterways formations in the Swan Hills area of central Alberta (Fig. 11.3). The lower stratigraphic range of the Beaverhill Lake Formation is in the Nisku Group, on the basis of correlation between the Fort Vermilion and Swan Hills formations in the Peace River area. The Waterways Formation in the northern part of the basin is subdivided into five lithostratigraphic members (Cracknay, 1957); Mildred, Mobley, Christina, Calnutt (Calnutt) and Frying, (e.g., Fig. 11.6). Waterways stratigraphy is discussed in the Swan Hills area by Sheasby (1971) and central Alberta by Keith (1990). The Beaverhill Lake Group is known as the Manitoba Group in Saskatchewan and Manitoba and consists of the Dawson Bay and Souris River formations (Figs. 11.2 and 11.6).

Reefal carbonate complexes in the Swan Hills area are known as the Swan Hills Formation or as the Slave Point Formation forming the Peace River Arch (Fig. 11.2). In northeastern British Columbia and southern Northwest Territories the Slave Point Formation comprises open-marine shell carbonates that make up the upper portion of an extensive carbonate bank complex (Williams, 1981; Griffin, 1967; Norris, 1965). Fort Vermilion age-equivalent strata are those included within the Slave Point Formation. The Otter Park Member of the Horn River Formation in northeastern British Columbia (Griffin, 1967) and the Horn River Formation in southern Northwest Territories (Norris, 1965) consist of dark shales that are in part equivalent to the Fort Vermilion Formation (Fig. 11.2). In the Normann Wells area of the Northwest Territories, Cretaceous platform carbonates are known as the Kaskar Reefal of the Ramparts Formation and are the equivalent of the Slave Point Formation (Braun et al., 1988). The Flame Formation of the southern Canadian Rockies is considered equivalent to the upper part of the Swan Hills Formation.

The Waterways Formation in the northern part of the basin is subdivided into five lithostratigraphic members (Cracknay, 1957): Mildred, Mobley, Christina, Calnutt (Calnutt) and Frying, (e.g., Fig. 11.6). Waterways stratigraphy is discussed in the Swan Hills area by Sheasby (1971) and central Alberta by Keith (1990). The Beaverhill Lake Group is known as the Manitoba Group in Saskatchewan and Manitoba and consists of the Dawson Bay and Souris River formations (Figs. 11.2 and 11.6).
Figure 11.6: Subsurface reference wells. Vertical scale is Altas standard 1:3000. a. B.A. Shell K-4a-6-9F-12-J-9 is the reference well for the Hay River Bank area. It is a tie well for master cross sections A-A' (Fig. 11.6a) and B-B' (Fig. 11.6b) and is included in Figure 11.18. b. The Peace River Arch Fringing Reef Complex is represented by the Chervon Sup. c. Swan Hills Complex. 4. Craig (1987) proposed the Imperial Bayly Settlement Refractile 1-27-60-29W5M as well as the subsurface type section for the Waterways Formation. The well occurs within and is representative of the stratigraphy of the Waterways Basin. d. The Souris River Shell 1-14-28-29W5M well represents the stratigraphy of the Souris River Shell. Lane (1964) proposed this well as the subsurface type section for the Souris River Formation. Dunn's (1983b) member subdivision for the Dawson Bay Formation is illustrated.
Figure 11.7. Regional structure map on the top surfaces of the Beaverhill Lake and Mannitea groups. Within Alberta, the surface has a monocline dip that increases in a westerly direction. The Horn River Basin in northeast British Columbia is depicted by a structural low. A structural ridge is evident in southeastern Alberta, reflecting post-Devonian tectonics associated with the Sweetgrass Arch. Post-Devonian tectonics are also reflected in southeastern Saskatchewan by the development of the Wiliston Basin during the late Paleozoic. Local anomalies reflect differential bevelling of the Beaverhill Lake Group along the subcrop edge, and post-Frasnian ast dissection in southern Saskatchewan.
Regional Cross Sections:

Regional stratigraphic relations are illustrated in the Atlas cross sections shown in Figures 11.8 (A-A'), 11.9 (B-B'), 11.10 (C-C'), 11.11 (D-D'), 11-12 (E-E') and 11.13 (G-G'). For most of Alberta, the top of the Wat Mountain serves as the stratigraphic datum for the cross sections; it is regionally extensive, distinctive on logs, and is chronostratigraphically significant. It is interpreted as representing the base of a relative sea-level rise that caused marine conditions to develop over most of the basin. The top of the First Red Bed Member is used as datum in Saskatchewan and Manitoba (Figs. 11.8b, 11.12 and 11.13). This does not extend to imply that the Wat Mountain Formation and the First Red Bed are stratigraphically equivalent. The regional cross sections were constructed without any preconceived stratigraphic relations.

The Wat Mountain Formation is absent or difficult to distinguish in the north, so the top of the Chinchaga Formation (Elk Point Group) is used as a datum. This datum facilitates illustration of the underlying Elk Point stratigraphy, which influenced Beaverhill Lake deposition. As a result of the interrelationship of these two groups, both the Elk Point and Beaverhill Lake groups are illustrated on cross sections in the northern area (Figs. 11.9 and 11.10).

Extended captions for each of the cross sections set out details of the stratigraphic relations.

Stratigraphic Problems:

Several stratigraphic problems are manifest in the Beaverhill Lake Group:
- The equivalence relations of the Dawson Bay Formation; the equivalence relations of the Dawson Bay Formation; and the transgressive phase of the Dawson Bay Formation.
- The transgressive phase of the Dawson Bay Formation; and the transgressive phase of the Dawson Bay Formation.
- The transgressive phase of the Dawson Bay Formation; and the transgressive phase of the Dawson Bay Formation.
- The transgressive phase of the Dawson Bay Formation; and the transgressive phase of the Dawson Bay Formation.
- The transgressive phase of the Dawson Bay Formation; and the transgressive phase of the Dawson Bay Formation.

With overlying strata, regional stratigraphic correlations, biostratigraphic constraints, and palynographic and depositional facies interpretations.

The stratigraphic relation between the transgressive phase (Dawson Bay and Wat Mountain formations) and the regressive phase (Waterways Formation) remains controversial. Most recent work, including this paper, suggests that the two phases are distinct, non-contemporaneous sedimentary events.

In summary, the authors believe that the transgressive and regressive phases are not contemporaneous and that their relation is one of onlap/downdip, based on the following criteria: 1) the distinct change in depositional style; 2) the presence of submarine, highstand surfaces; 3) the distinctive facies assemblage of one phase; and 4) the widely demonstrable onlap/downdip geometry, as illustrated in regional cross sections (Figs. 11.8 - 11.11) and other related diagrams (Figs. 11.19 and 11.23).
The top of the Beaverhill Lake Group (Waterways Formation) and the top of the Manitoba Group (Sours River Formation), as formally defined, do not occur at the same stratigraphic level (Figs. 11.8b). The top of the Manitoba Group occurs one stratigraphic cycle lower, within the regressive phase. This appears to have resulted from the fact that the top of the Beaverhill Lake Group was originally defined as being the base of the Cooking Lake Formation, which is not recognized in Saskatchewan. The division between the Manitoba and Saskatchewan groups was independently defined within this conformable succession.

**Atlas Mapping**

The top of the Beaverhill Lake Group is well documented in the Atlas database, as is the top of the Manitoba Group (Sours River Formation). The stratigraphic gap between the two, discussed above, is perpetuated in the Atlas isochoc and structure maps (Figs. 11.3 and 11.7), however the difference (less than 10 percent of the contour interval) is not considered to significantly alter the overall contour pattern.

At the base of the subject succession, mapping difficulties are also manifested. In Alberta, the Watt Mountain Formation (despite the above cited stratigraphic arguments to the contrary) is included in the Elk Point Group (as per formal definition) and is excluded in the isochoc maps in this chapter (Figs. 11.3 and 11.4). The principal reason for mapping the Watt Mountain top rather than its base, is that the top picks are generally much more reliable than picks on the underlying evaporites.

Similarly, in Saskatchewan and Manitoba, the isochoc base of the subject succession is taken at the top of the Dawson Bay Formation, (Figs. 11.3 and 11.4) not the base, where the picks on the Prairie Evaporite salts (commonly collapsed through dissolution) are less reliable. The Figure 11.14 isochoc of the Dawson Bay Formation depicts the geometry of the Dawson Bay salt as, on stratigraphic grounds, is covered in this chapter, but in terms of Atlas mapping is best covered in the Elk Point Chapter (Mooring, 1983, this volume, Chapter 10, Figs. 10.3 and 10.8).

**Stratigraphic Framework**

Two second-order depositional phases are recognized within the strata (Fig. 11.15): a transgressive "reefal" phase (a term introduced by Stokes, 1980) and a regressive "basin-fill" phase. Each phase exhibits a distinctive style of deposition and consists of genetically related depositional cycles (parasequences). The phases are bounded by an unconformity or a surface of nondeposition (disconformity) and can be equated to a depositional "sequence" utilizing the sequence stratigraphic concept. Each cycle reflects a third-order depositional sequence.

The transgressive phase was deposited during a period of increasing rate of relative sea-level rise. This phase (isochoc in Fig. 11.4) is prevalent in the western and northern parts of the basin, and comprises restricted to shallow-water carbonates of the Watt Mountain, Fort Vermilion, Slave Point and Swan Hills formations (Fig. 11.15) that form an extensive carbonate bank complex. (The Watt Mountain and Dawson Bay Formation intervals are isochochic separately in Fig. 11.14 because of data base limitations). The bank complexes comprise several shallowing-upward "reefal" cycles that are a response to episodic pulses of relative sea-level rise. The banks developed in a transgressive or aggradational depositional style.

The regressive phase refers to deposition during a relative sea-level fall or decreasing rate of relative sea-level rise. This phase (isochoc in Fig. 11.5) dominates the southern and eastern part of the basin and comprises shales and argillaceous carbonates of the Waterways Formation and shallow-marine carbonates and evaporites of the Sours River Formation (Fig. 11.15). These sediments form numerous basinal to ramp depositional cycles. Each cycle, and the entire sequence, exhibits a basinward progradation of the platform margin facies. This indicates that the rate of sediment accumulation was greater than the accommodation space, producing a relative sea-level fall. As a result, the sequence is referred to as the "regressive phase". The basal slope portion of this phase infills the intraplatform basin and overprints the bank complex of the transgressive phase.

**Stratigraphic History**

The initial transgression of the seas into the Elk Point Basin during the Late Givetian deposited a thin detrital to marginal-marine unit unconformably overlying the restricted-marine deposits of the Elk Point Group (Fig. 11.16a). This initial deposit consists of green
Relative sea level continued to rise and open-marine carbonates of the Slave Point Formation were deposited over the entire basin (Fig. 11.16c). A carbonate bank (the Hay River Bank) developed in the northern part of the basin with its reefal margin generally coincident with the underlying Elk Point barrier reef. Southward, the Slave Point Formation formed the platforms for subsequent reef growth of the Swan Hills Complex (Swan Hills Formation) and the Peace River Arch Fringing Reef Complex (the Slave Point Formation or, locally, the Swan Hills Formation). In southern Saskatchewan and Manitoba, and southeastern Alberta, the Slave Point Formation is correlated to the broad shallowing-upward cycle of the Sours River Formation (Fig. 11.15).

The regressive phase is represented by the Waterways Formation and its Sours River equivalent (Fig. 11.16d). Numerous clinoformal shore and argillaceous carbonate cycles infilled the Waterways Basin in a westerly and northerly direction. The shallowing-upward clinoforms “shingle” and thin in a westward and northerly direction as they downlap the reefal carbonates of the transgressive phase. Southward, the clinoforms grade laterally to shallowing-upward carbonate-evaporite sequences (Moore, 1990) of the Sours River Shale (Figs. 11.11 and 11.15).

Regional Facies Development

Six paleogeographic areas are recognized for the Beaverhill Lake Group (Fig. 11.11):

1. Horn River Basin
2. Hay River Bank
3. Peace River Arch Fringing Reef Complex
4. Swan Hills Complex
5. Waterways Basin
6. Sours River Shale

Each area is discussed independently because of its unique stratigraphic relations. The boundaries between the areas are transitional, particularly where Waterways basin-fill sediments onlap the bank complexes of the transgressive phase.

Horn River Basin

The Horn River Basin of northeastern British Columbia, southern Yukon and Northwest Territories is situated seaward of the “barrier reef” complex (Fig. 11.3). The Horn River Formation consists of Givetian-Francian basininal shales stratigraphically equivalent to reefal carbonates of the Elk Point and Beaverhill Lake groups (Fig. 11.17). Numerous reef complexes (Fvie, Roger, Yoyo and Sierra in northeastern B.C. and Horn Plateau Reefs and Deep Bay Bank in southern N.W.T.) developed during the Givetian within the Horn River Basin (Fig. 11.18).

What effect did post-Elk Point regression and subsequent relative sea-level rise have on these reef complexes? Three scenarios exist: reef growth was terminated; the reef complexes were subaerially exposed but reef growth was reestablished during the upper Givetian; or reef development continued during the Givetian without any significant hiatus. Lack of faunal evidence and the absence of a lithologically distinct Watt Mountain shale create a stratigraphic correlation problem.

The recognition of a Watt Mountain “shale” equivalent in the region would provide valuable evidence of a stratigraphic “event”; however, two problems limit its credibility. Firstly, the source of the “shale”, the Peace River Arch, is far distant from the Horn River Basin. Williams (1983) shows the recognizable limit of the Watt Mountain Formation occurring east of the Hay River Bank margin. Secondly, Meijer Drees (1988) suggests that the Watt...
Mountain "shale" represents a palaeokarst along the margin of the Hay River Bank. Therefore, its stratigraphic significance is limited because it could occur at the top of or within underlying Elk Point carbonates.

In northeastern British Columbia the Watt Mountain "shale" is generally absent or poorly developed in these basinal reef complexes. The Evie reef complex is illustrated in Figure 11.8a by B-82-N, 94-41. The top of the reef-to-churchilla interval is considerably thinner than in a barrier reef well (B-49-R, 94-59), but a shaly unit occurs at approximately the Watt Mountain stratigraphic level, suggesting that possibly the upper portion of the Evie reef may be upper Givetian in age. In the southern Northwest Territories the Watt Mountain "shale" is absent in the Horn Plateau reefs (Williams, 1980) and poorly developed in the Deep Bay Bank (Meijer Drees, 1990). The Deep Bay Bank, illustrated in Figure 11.9 by well B-0-1, appears as a stratigraphic anomaly as a result of depositional thinning of the Elk Point sequence in the vicinity of the Tathlina High. Skall (1975) suggests that marine carbonate sedimentation occurred within the basin during post-Elk Point regression.

The lack of a distinctive Watt Mountain shale, the presence of carbonates at approximately the same stratigraphic position, and the documentation of marine carbonate deposition equivalent to the Watt Mountain Formation suggest that the Horn River Basin reef complexes continued to develop throughout Givetian time without being significantly affected by the post-Elk Point regression and hiatus.

Hay River Bank

The paleogeography of the underlying Elk Point (Pesquille) barrier reef complex influenced Beaverhill Lake deposition. The post-Elk Point transgression led to development of an extensive carbonate bank complex with its barrier margin roughly coincident with the underlying Elk Point barrier reef margin (Fig. 11.16). An erosional and/or transgressive event represented by a thin green shale bed, the Watt Mountain Formation, (Meijer Drees, 1985; Williams, 1984) separates the two stages of barrier reef growth. The Watt Mountain "shale" is absent or poorly developed along the barrier margin (Figs. 11.8a, 11.9, and 11.17), suggesting continuous "reefal" sedimentation (similar line of reasoning to that discussed for the Horn River Basin reef complexes). The Late Givetian-Early Frasian barrier margin grew aggradationally and prograded seaward (westward) from the underlying barrier, commonly by several kilometres, and up to 30 km in the Clarke Lake area (Fig. 11.17). The Slave Point reefal carbonates thin depositionally within the Khio embayment (d-95-B, 94-3-15; Fig. 11.8a) and grade abruptly to basinal shales of the Horn River Formation (Otter Park Member) within the Cordova embayment (Fig. 11.9, represented by d-20-I, 94-10).

The bank complex developed aggradationally as a cyclic succession of shallowing-upward reefal cycles. Primary facies have been completely destroyed as a result of pervasive "Pesquille" style dolomitization along the barrier trend. Eastward from the barrier, the bank is undolomitized and consists of several shallowing-upward carbonate sequences. A localized intraplatform sub-basin (or possible embayment), known as the Hotchkiss embayment, separates the Hay River Bank from the Peace River Arch Fringing Reef Complex (Fig. 11.17). Reefal buildups such as Hamburg and Cranberry developed within this basin and along the northern margin of the Peace River Arch Fringing Reef Complex.

The regressive phase (the Waterways Formation) thins westward and is absent along the barrier reef trend (Fig. 11.18). The basinal cliniforms depositionally downlap the barrier reef trend. The Waterways Formation thickens locally within the Khio and Hotchkiss embayments (Figs. 11.8a and 11.17).
**Peace River Arch Fringing Reef Complex**

An extensive bank complex that fringed the emergent Peace River Arch developed during the transgressive phase. Palaeotopography of the arch greatly influenced sedimentation during that time. The carbonate bank complex is composed of several shallowing-upward "reefal" cycles that formed in response to episodic rises in relative sea level. The cycles were stacked aggradationally and in a backstepping manner as the sea transgressed the Peace River Arch (Fig. 11.19). Laminations of the regressive phase downlap onto the bank complex and the arch.

Initial deposition consisted dominantly of aragonite sandstones (Gilwood Member, Waterton Formation), which were deposited as a fluvial-deltaic complex that radiated from the Peace River Arch (Fig. 11.16a). Along the southern flank of the arch, the deltaic system was extensive, with development of several braided delta-levee island systems (Jansa and Fischbuch, 1974). Palaeotopography along the north side of the arch was steeper (O'Connell et al., 1990) and Gilwood sands (Manning sand, now obsolete) were deposited as a series of thick, laterally discontinuous fluvial channels (Rottensten and Oliver, 1979). Isolated fluvial-deltaic deposits occur along the eastern flank of the arch in the Evi (Ty 87, R 12 WSM) and Utikuma-Mapisi (Ty 78-83, R 8 and 9 WSM) areas. Relative sea level continued to rise and restricted carbonateal evaporites of the Fort Vermilion Formation (Fig. 11.16b) were deposited in a hypersaline shelf depositional environment (Craig, 1987). The transgressive sequence was capped by open-marine carbonates (Slade Point Formation) that formed an extensive carbonate platform flanking the Peace River Arch (Fig. 11.16c). A high-energy shoal-reef environment (transgressive shoal-flat to outer-platform) developed in the platform (Tooth and Davies, 1989; Gosselin et al., 1989). This high-energy facies became localized and provided a suitable substrate for subsequent bank development.

A shallow-water carbonate ramp depositional model with reef rimmed platforms or banks has been proposed by Craig (1967) for this area. Palaeoenvironmental interpretations illustrate distinct lateral facies variations across the bank complex (Fig. 11.19), which is composed of several shallowing upward "reefal" cycles, each 10 to 15 m thick. A relative rise of sea level initiated each cycle, which shallowed upward as the relative sea level rise decreased. Individual cycles can be separated by a basinward shift in facies within a vertical sequence.

A high-energy reef margin (cycle 1) developed along the seaward margin of the bank complex, largely coincident with the underlying platform shoal-reef facies (Fig. 11.20). It is referred to as the Saw-Point trend. The sedimentology and stratigraphy of the reef pool (Ty 78, R 10 WSM), situated along this trend, is discussed by Tooth and Davies (1989). Reefal buildups like Red Earth (Ty 88, R 8 WSM; Fig. 11.20) occur basinward (east) of the bank margin. A stratigraphically younger reef margin (cycle 2) known as the Slave-Stool trend, developed farther landward (Fig. 11.20) in response to relative sea-level rise. Paleokarst were localised and influenced reef growth along this trend (e.g., Slave, Ty 84, R 14 WSM; Dumbbarn et al., 1983). Local areas on the cycle 1 bank were able to keep up with the rise in relative sea-level and a second "reefal" cycle developed aggradationally (e.g., Evi, Ty 87, R 12 WSM; Gosselin et al., 1989). Younger "reefal" buildups (i.e., Springfield Member) are present farther landward, representing another backstepping reef margin (cycle 3, Fig. 11.19).

The shoal-argillaceous carbonate clyloths of the regressive phase (Waterways Formation) thin in a shingling pattern as they downdrop and depositories pinch out against the reef complex and the Peace River Arch (Figs. 11.10 and 11.19). A hardground surface (Tooth and Davies, 1989; Gosselin et al., 1989) generally occurs at the top of the Slave Point carbonates, separating the depositional units distinct sequences.
Figure 11.16 Beaverhill Lake Group paleogeography and facies maps, illustrating the development through time of the Beaverhill Lake sequence. The transgressive sequence is depicted in a to d and the regressive sequence in d. The initial transgression (a) deposited a marginal-marine unit (Watt Mountain Formation). Anoxic sandstones (Glewwood Member) were deposited as a fluviolacustrine system that prograded into the marginal-marine body of water flanking the Peace River Arch. The Dawson Bay Basin was infilled by a deepening-upward transgressive sequence (Dawson Bay Formation). An incursion of open-marine waters from the sea is postulated because of the presence of normal-marine faunas in the Dawson Bay Formation. In the northern part of the basin open-marine carbonate sediments continued with minimal influence of the post-Ek Point facies, particularly along the basin margin. Relative sea level continued to rise, resulting in restricted-marine conditions over the majority of the basin (b). The facies change from open-marine to restricted-marine to continental sedimentation is a southwardly direction indicates a southward-advancing sequence. A tidal flat to continental facies flanked the Peace River Arch and baseline conditions existed in the Horn River Basin. By the time of Slave Point deposition, marine conditions developed over most of the Ek Point Basin (c). The development of a shallow-marine carbonate platform provided a substrate for subsequent reef growth. Carbonate bank complexes overlain by the Ek Point bank complex developed in the northern part of the basin (Horn River Bank) and flanking the Peace River Arch and West Alberts Ridge. The bank complexes consist of a number of shallowing-upward (real) cycles that formed in response to episodic cycles of relative sea-level rise. The intra-platform basin (Watersways Basin) was a site of basinal off-reef sedimentation during this time. Residual marine carbonates equivalent to the Slave Point platform were deposited in the southern part of the basin. The intra-platform basin became infilled by the regressive sequence (d). A shelf complex developed in southern Saskatchewan (Sours River Shelf) consisting of a series of shallowing-upward carbonate-evaporite cycles (Sours River Formation). These cycles grade laterally northward to shallowing-upward shale-carbonate-dolomitic cycles that were deposited in a basin to slope depositional setting. The contrasting cycles deposionally overlie the transgressive reef complexes. Basinal conditions existed within the Horn River Basin.
Swan Hills Complex

The bank complex (Swan Hills Complex, Fig. 11.21) that flanked the West Alberta Ridge along the western margin of the basin (Fig. 11.11) developed during the transgressive phase. South of the Peace River Arch, the Gilwood Member formed a fluvial-deltaic complex (Jansa and Fischbach, 1974) that prograded into a lacustrine to marginal-marine body of water during post-Elk Point relative sea-level rise (Fig. 11.16a). The Gilwood Member thins in an eastward and southward direction and the Wask Mountain Formation consists of green waxy shales with thinly interbedded limestones. Continued relative sea-level rise resulted in drowning the basin. Deposits, and evaporites and argillaceous dolomites of the Fort Vermilion Formation were deposited (Fig. 11.16c). The evaporites thin in a southeasterly direction and are stratigraphically equivalent to the First Red Bed Member, a continental facies. Open-marine carbonates of the Slave Point Formation cap the transgressive sequence (Fig. 11.11c). The Slave Point Formation formed a platform facies that acted as a substrate for subsequent reef growth of the Swan Hills Formation.

The bank complex developed as a series of shallowing-upward reefal cycles, each 10 to 15 m thick (Fig. 11.22). A relative rise of sea level initiated each cycle and drowned the previous reefal cycle (Wendt and Stoakes, 1982). As a result the cycle boundaries are identified by a basinward shift in facies within a vertical sequence. The rate of relative sea-level rise subsequently decreased, producing a shallowing-upward sequence. Each cycle developed a windward, high-energy reefal margin (eastward facing) that developed either aggradationally or progradationally (Wendt and Stoakes, 1982). The reef margin separated the low-energy reef interior from the open-marine basin. Wendt and Stoakes (1982) provide a detailed discussion of the various depositional environments and their lateral and vertical facies variation, and present a paleobathymetric profile.

Figure 11.18 Palaeogeographic map of the Horn River Basin and Hay River Basin. The reef margin of the transgressive phase (Slave Point), the basinal reefs, and the depositional limit of the regressive phase (Wadeaway Formation) are illustrated. Where the underlying Elk Point barrier margin is not coincident with the Slave Point reef margin it is illustrated separately.

The cycle 1 reef margin developed coincident with a high-energy reefal-shale facies of the platform. This reef margin was probably influenced by paleo-topography on the platform. Jansa and Fischbach (1974) suggest that paleo-topography of the underlying Gilwood deltaic complex and resulting differential compaction was the major influence on paleo-topography. The cycle 2 reef margin developed farther landward (westward) as a result of the relative sea-level rise that drowned the cycle 1 reef. Basinward of the cycle 2 reef margin, deposition in localized areas on the cycle 1 bank was able to keep up with the rise of sea-level and cycle 2 reefs developed (i.e., Jady Creek, Swan Hills South, etc.). Subsequent pulses of relative sea-level rise developed shallowing-upward reefal cycles aggradationally on cycle 2 banks (Jady Creek, Wendt and Stoakes, 1982) or backstepped the complex farther landward. As a result the Swan Hills complex evolved as a series of backstepping, reef rimmed banks and isolated reef complexes.

The bank complex continues southward along the west Alberta Ridge into southern Alberta. The Caroline Field (Fig. 11.19) is situated along the reefal margin of the complex. As illustrated in Figure 11.23, the bank consists of several shallowing-upward reefal cycles that backstepped in a westward direction as a result of episodic pulses of relative sea-level rise. Farther westward the bank complex is overlain by Frasnian carbonates, forming a continuous carbonate succession.

Porosity development in the Swan Hills area is associated with the high-energy reef margin facies of each shallowing-upward cycle (Wendt and Stoakes, 1982). Dolomitization occurs in some banks or reefs (Kaybob South, Rosevear, etc.) and is commonly associated with the bank-margin facies, suggesting a facies relationship. Porosity development in the Caroline Field is a function of facies and dolomitization along the bank margin.

Figure 11.19 Stratigraphic cross section H-H'. Illustrating Beaverhill Lake and Elk Point stratigraphy from the barrier margin of the Hay River Bank southward, as the whole succession onlaps the Peace River Arch. The Elk Point stratigraphy is illustrated because of the interrelationships of the two groups in the area. Shallow-marine carbonates of the transgressive sequence (Slave Point Formation) on the southeast as they onlap the Peace River Arch. (Hamburg 5-32-6-11 W6M) and Cranberry (not illustrated) are significant gas pools within the Slave Point Formation (Fig. 11.11) that developed as reef complexes within the Holohka Embayment, or along the northern bank margin of the Peace River Arch Fringing Reef Complex. The Slave Point Formation is pervasively dolomitized along the bank margin of the Hay River Bank and margins to embayments within the underlying Elk Point Bank complex (i.e., Kua Embayment, represented by 0-16 to 0-34 to 0-3). The upper part of the bank complex (Slave Point Formation) progressed further basinward over the underlying Elk Point bank margin. The regressive phase (Wadeaway Formation) onlapped the Hay River Bank margin to the north and the Peace River Arch to the south. It filled the local paleotopography of the underlying bank complex (i.e., Holohka Embayment). Note that the vertical scale (1:6000) is slightly contracted from the Atlas standard (1:6000) and the horizontal scale expanded. Line of section H-H' is shown in Figure 11.18.

Figure 11.20 Peace River Arch Fringing Reef Complex palaeogeographic map illustrating the bank margins, depositional edges and topsets of the transgressive phase. The locations of sections J-J' (Fig. 11.18) and C-C' (Fig. 11.16) and major Slave Point oil pools are indicated.
The clinofolds of the regressive phase (Waterways Formation) depositionally overlie the bank complex (Fig. 11.23) and infill interbank areas. These interbedded carbonates provide top and lateral seals for hydrocarbon accumulations associated with the bank complexes. Shuab (1972) indicates that deep-water sediments of this phase were derived from the east and are significantly younger than the shallow-marine carbonates of the bank complex. Numerous workers report the presence of a hardground surface at the top of the Swan Hills Formation. It is thought that the hardground represents a submarine hardground (Wendle and Shoakes, 1982), marking a transition period between the depositional sequences. Biostratigraphic evidence indicates a distinct faunal change between the two successions, suggesting non-contemporaneous deposition (Franco et al., 1988).

The Swan Hills Complex is separated from the Peace River Arch Fringing Reef Complex by the vicinity of latitude 55°N (Fig. 11.1). The platform (Slave Point Formation) changes from a shallow-marine facies within the bank complexes to an open-marine facies in the interbank areas. During subsequent periods of reef development the area remained a site of baiusal sedimentation and later became infilled with clinofolds of the regressive sequence.

The evolution of the two bank complexes is very similar (Fig. 11.24). Both complexes have a platform composed of shallow-marine facies, and high-energy reef-shelf facies formed the base for subsequent reef growth (Jansa and Flischtuch, 1974; Tooth and Davies, 1989; Gosselin et al., 1989). Periodic pulses of relative sea-level rise formed shallowing-upward "meatal" cycles 80 to 15 m thick that are stacked aggradationally or in a backstepping manner. The Swan Hills Complex developed more aggradationally and formed a thicker transgressive reef sequence than the Peace River Arch Fringing Reef Complex, which formed as a series of backstepping banks. This was probably the result of greater basin subsidence (accommodation space) in the Swan Hills area than in the area flanking the Peace River Arch.

Waterways Basin

The regressive phase (Waterways Formation) of the Beaverhill Lake Group dominates the intra-platform basin (Fig. 11.1). The basin is infilled by shale-carbonate clinofold cycles that extend westward and northward and downlap onto the bank complexes.

Figure 11.21 Swan Hills Complex paleogeographic map illustrating the cycle 1 and 2 bank margins of the transgressive phase. Younger "meatal" cycles developed aggradationally on the cycle 1 and 2 banks, but are not illustrated in detail (refer to Jansa and Flischtuch, 1974). The bank margins are modified from previous workers, namely, Jansa and Flischtuch (1974).

Figure 11.22 Stratigraphic cross section K-K', portraying the stratigraphy of the transgressive sequence across the Swan Hills Complex. The cross section is taken from Jansa and Flischtuch (1974) with the depositional facies simplified. Line of section K-K' is shown on Figure 11.21.

Figure 11.23 Caroline area stratigraphic cross section L-L'. The Swan Hills Complex margins to the West Alberta Ridge in the Caroline area developed as a series of westward backstepping, shallowing-upward "meatal" cycles. A high-energy reef facies developed along the bank margin of each cycle. Westward, the Swan Hills reef complex narrows and becomes difficult to distinguish from overlying carbonates of the Woodbend Group. The regressive sequence (Waterways Formation) developed the transgressive reef complex in a westward direction.

Figure 11.24 Peace River Arch Fringing Reef Complex - Swan Hills Complex correlation panel. Correlation of the transgressive reef cycles from the Peace River Arch Fringing Reef Complex and the Swan Hills Complex represents the sector author's interpretation. A relative sea-level curve is presented for the transgressive sequence. Each cycle was initiated by a relative sea-level rise. As the rate decreased the bank grew to sea level, forming the characteristic shallowing-upward "meatal" cycle.
The transgressive phase consists of the Watt Mountain, Fort Vermilion, and Slave Point formations (Fig. 11.16). Post-Ek Point transgression deposited green, waxy shales with thinly interbedded limestones (Watt Mountain Formation) that grade vertically to evaporites with interbedded dolomites and shales (Fort Vermilion Formation). This deepening-upward succession is capped by open-marine limestones (Slave Point Formation) that were deposited in an off-shelf to basinal depositional environment (Fig. 11.16a, b, c). The lack of platform facies development precluded subsequent reef growth.

The transgressive phase (Fig. 11.16d) averages about 20 m in thickness within the basin area (Fig. 11.4). The Slave Point Formation is only 5 to 6 m thick within the basin, but thickens westward as it develops into a shelf-platform and bank complex. The Fort Vermilion is typically thin in a southerly direction and becomes stratigraphically equivalent to the First Red Bed Member. The Watt Mountain Formation remains relatively constant in thickness until it becomes stratigraphically equivalent to the Dawson Bay Formation in the southern portion of the basin (Fig. 11.14).

The regressive phase (Waterways Formation) is composed of numerous shallow-upward shelf-carbonate clinoforms that filled the basin (Fig. 11.11). The Waterways Formation was originally subdivided into five lithostratigraphic members (Crickmay, 1997), but the shelf-carbonate clinoform cycles do not correspond to this lithostratigraphic subdivision. Each cycle is composed of a shelf base that grades vertically to argillaceous carbonate, representing a basin to slope depositional environment. The shelf depositional environment is represented by the carbonates of the Sours River Formation in the southern part of the basin (Figs. 11.8b and 11.11). The transition between the clinoform cycles of the Waterways Basin and the shallowing-upward cycles of the Sours River Shelf are illustrated as abrupt (Figs. 11.8b and 11.11); however, the relation is in fact progradational and very transitional, as illustrated schematically in Figure 11.13.

Southern Bank
In the region of the Sours River Shelf, the transgressive phase is represented by the Dawson Bay Formation, the First Red Bed Member and the basal shallowing-upward cycle of the Sours River Formation (Fig. 11.16). The Dawson Bay Formation represents a deepening-upward transgressive sequence, unconformably bounded, deposited within the Dawson Bay Basin (Fig. 11.16a). The Second Red Bed Member, a dolomitic mudstone, represents initial deposition following exposure and erosion of the Elk Point surface (Fig. 11.16b). As relative sea level continued to rise, restricted-marine carbonates of the Bunny Member (Dunn, 1982a, b) were deposited (Fig. 11.6e). Dunn (1982a) documented the presence of numerous hardgrounds that are interpreted as representing periods of mnerdeposition or subaerial exposure within the Dawson Bay Basin. The Bunny Member is overlain by open-marine carbonates of the Noely Member (Fig. 11.6c), indicating continued relative sea-level rise. Carbonates of the Noely Member contain "reef" beds consisting of normal-marine fauna, corals and stromatoporoids. The sequence is capped by restricted-marine carbonates and anhydrites and, locally, by the Hubbard Evaporite, a halite unit, indicating a fall in relative sea level. These sediments were deposited in a sabkha environment (Dunn, 1982b).

The Dawson Bay Formation is illustrated in Figure 11.8b to be stratigraphically equivalent to the Watt Mountain Formation in northern Alberta. Dunn (1982) stated that the Dawson Bay Formation is equivalent to the Watt Mountain Formation, but also included the First Red Bed Member within the stratigraphic section. This interpretation does not conflict with the biostratigraphic data (Braun and Mathison, 1986) but does pose two questions: what was the origin of the sub-basin, and what was the direction of the marine incursion?

During the exposure of the Elk Point Group, solutioning of the underlying salts may have created a local depression. The deposition of Dawson Bay carbonates within such a topographic low could have caused continued subsidence and created an essentially extensive sub-basin. Carbonate sedimentation changed to evaporitic sedimentation as relative sea-level fell (rate of sedimentation greater than accommodation space) and the beds eventually became subaerially exposed by the end of Dawson Bay deposition.

Braun and Mathison (1986) and Dunn (1982b) identified an olistood within the Bunny Member that is typical of the Michigan area, suggesting an incursion of a seaway from the southwest. However, olistostromes found in the normal-marine Noeily Member exhibit a western affinity (Braun and Mathison, 1986). This suggests an initial southwesterly marine influence followed by a northerly influence during deposition of the Dawson Bay sequence. The northern part of the basin was periodically subaerially exposed during deposition of the Bunny and Second Red Bed members. Multiple exposure surfaces within the Bunny Member (Dunn, 1982b) may reflect tectonic pulses associated with the Peace River Arch, as suggested by Braun and Mathison (1986). This palo-landmass divided the basin into two local sub-basins during early Dawson Bay deposition. Within the upper portion of the Watt Mountain Formation in northern Alberta, limestone beds are present, indicating a marine influence from the north. This marine incursion may have extended farther southward along the eastern side of the interior basin into the Dawson Bay Basin, providing the western faunus influence during Neoeily Member time. The marine influence was terminated as the Dawson Bay sequence was capped by restricted-marine carbonates, evaporites and halite. In Alberta, continental to marginal-marine deposits of the Watt Mountain Formation gave way to restricted-marine conditions as the sea advanced further southward. The Fort Vermilion Formation exhibits a facies change (Fig. 11.16b) in a southerly direction and is thought to be correlative with the First Red Bed Member of the Sours River Formation. The open-marine Slave Point Formation exhibits an assemblage of restricted facies to a restricted facies in a southerly direction (Fig. 11.16c) and is thought to be equivalent to the lower cycle of the Dawson Member of the Sours River Formation.

The remainder of the Sours River Formation was deposited during the regressive depositional phase. The Sours River Formation is made up of numerous shallow-upward carbonate-evaporite cycles (Figs. 11.12, 11.13) that form the Sours River Shelf (a carbonate platform). These carbonate-evaporite cycles prograde basinward (northwest) to shelf-carbonate clinoforms that constitute the Waterways Formation in Alberta. These carbonate-evaporite sequences continue into the Woodbend succession (Dupiter Formation) without any significant hiatus (Switzer et al., this volume, chapter 12).

Summary
The Late Eocene to Early Eocene aged Beaverhill Lake Group is composed of two distinct depositional phases: a transgressive "beach" phase and a regressive "estuarine" phase. During the transgressive phase, the intra-rift basin became segregated into bank complexes and basinal areas. The regressive phase infilled the interbank and basinal areas and enveloped the bank complexes of the transgressive phase.

The transgressive phase was deposited during a period of relative sea-level rise. A shallowing-upward depositional sequence was deposited above exposed and eroded evaporite sediments of the underlying Elk Point Formation. Continental to marginal-marine sediments of the Watt Mountain Formation, evaporites and restricted marine carbonates of the Fort Vermilion Formation and open-marine carbonates of the Slave Point Formation constitute this transgressive sequence. A fluvial-deltaic system developed flanking the Peace River Arch and a marine sub-basin developed in southern Saskatchewan during Watt Mountain/Dawson Bay deposition. The southward-advancing sea produced open-marine conditions over the majority of the basin by the end of the Slave Point (lower Slave Point in the northern basin). The (lower) Slave Point formed a platform for subsequent reef and bank development. The bank complexes are composed of cyclic shallow-upward reefal sequences (Swain Hills or upper Slave Point formations) which formed as a result of episodic fluctuations of relative sea-level rise. The response of the bank complexes to the relative sea-level rise ranges from vertical aggradation (Lay Bay Bank) to transgressive backstepping (Peace River Arch Fringing Reef Complex), or a combination of both (Swain Hills Complex).

The regressive phase was deposited during a period of relative sea level fall or decreased rate of relative sea-level rise. The Sours River Shelf, composed of cyclic shallow-upward sequences (Steven River Formation), developed in the southern portion of the basin. The lack of basin accommodation and/or sea-level fall gave rise to a progradational depositional style. The shelf sequences prograded northward to basin-slope clinoforms (Waterways Formation) without any significant hiatus (Switzer et al., this volume, chapter 12).
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References