Athabasca oil sands: Megatrap restoration and charge timing

Richard S. J. Tozer, Albert P. Choi, Jeffrey T. Pietras, and Donald J. Tanasichuk

ABSTRACT

The petroleum trap for the Athabasca oil sands has remained elusive because it was destroyed by flexural loading of the Western Canada Sedimentary Basin during the Late Cretaceous and Paleocene. The original trap extent is preserved because the oil was biodegraded to immobile bitumen as the trap was being charged during the Late Cretaceous. Using well and outcrop data, it is possible to reconstruct the Cretaceous overburden horizons beyond the limit of present-day erosion. Sequential restoration of the reconstructed horizons reveals a megatrap at the top of the Wabiskaw-McMurray reservoir in the Athabasca area at 84 Ma (late Santonian). The megatrap is a four-way anticline with dimensions 285 × 125 km (177 × 78 mi) and maximum amplitude of 60 m (197 ft). The southeastern margin of the anticline shows good conformance to the bitumen edge for 140 km (87 mi). To the northeast of the anticline, bitumen is present in a shallower trap domain in what is interpreted to be an onlap trap onto the Canadian Shield; leakage along the onlap edge is indicated by tarry bitumen outliers preserved in basement rocks farther to the northeast. Peripheral trap domains that lie below the paleo-spillpoint, in northern, southern, and southwestern Athabasca, and Wabasca, are interpreted to represent a late charge of oil that was trapped by bitumen already emplaced in the anticline and the northeastern onlap trap. This is consistent with kimberlite intrusions containing live bitumen, which indicate that the northern trap domain was charged not before 78 Ma. The trap restoration has been tested using bitumen-water contact well picks. The restored picks fall into groups that are

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consistent both with the trap domains determined from the top reservoir restoration and the conceptual charge model in which the four-way anticline was filled first, followed by the northeastern onlap trap, and then the peripheral trap domains.

INTRODUCTION

The heavy-oil or bitumen reservoirs of northeast Alberta contain 1.8 trillion bbl of resources. Of this, almost 1 trillion bbl are contained in the Lower Cretaceous Wabiskaw and McMurray reservoirs of the Athabasca oil sands (Crowfoot et al., 2012). The Athabasca oil sands lie close to the eastern edge of the Western Canada Sedimentary Basin (Figure 1) at outcrop or a shallow depth of burial, and therefore, their location has been known from direct observation even prior to the first descriptions by the Geological Survey of Canada (1875, 1883). However, the geometry and timing of development of the petroleum trap have remained elusive because the original trap was destroyed by continued flexural loading of the basin and subsequent uplift and erosion (Ranger, 1994). The objective of this study is to model the original trap to understand the trap geometry and charge timing.

BACKGROUND

Basin Subsidence History, Megasequences, and Play Elements

The Western Canada Sedimentary Basin comprises the Alberta Foreland Basin in the west and the Williston Intracratonic Basin in the southeast (Beaumont, 1981; Wright et al., 1994) (Figure 1). The Western Canada Sedimentary Basin developed following a period of rifting in the Precambrian, which was followed by thermal subsidence along the passive margin of western North America during the Paleozoic (Bond and Kominz, 1984; Klein and Hsui, 1987). The sedimentary fill of the basin can be divided into several megasequences, each with a common subsidence mechanism and similar lithological characteristics. In the area of this study, the passive-margin megasequence (Figure 2) that was deposited during Paleozoic thermal subsidence is incomplete because of the presence of the Peace River arch (O'Connell, 1994), an important, long-lived, dynamic structure in the basin. Therefore, stratigraphy of Cambrian to Silurian age is not represented, and thermal subsidence is recorded by stratigraphy of Middle

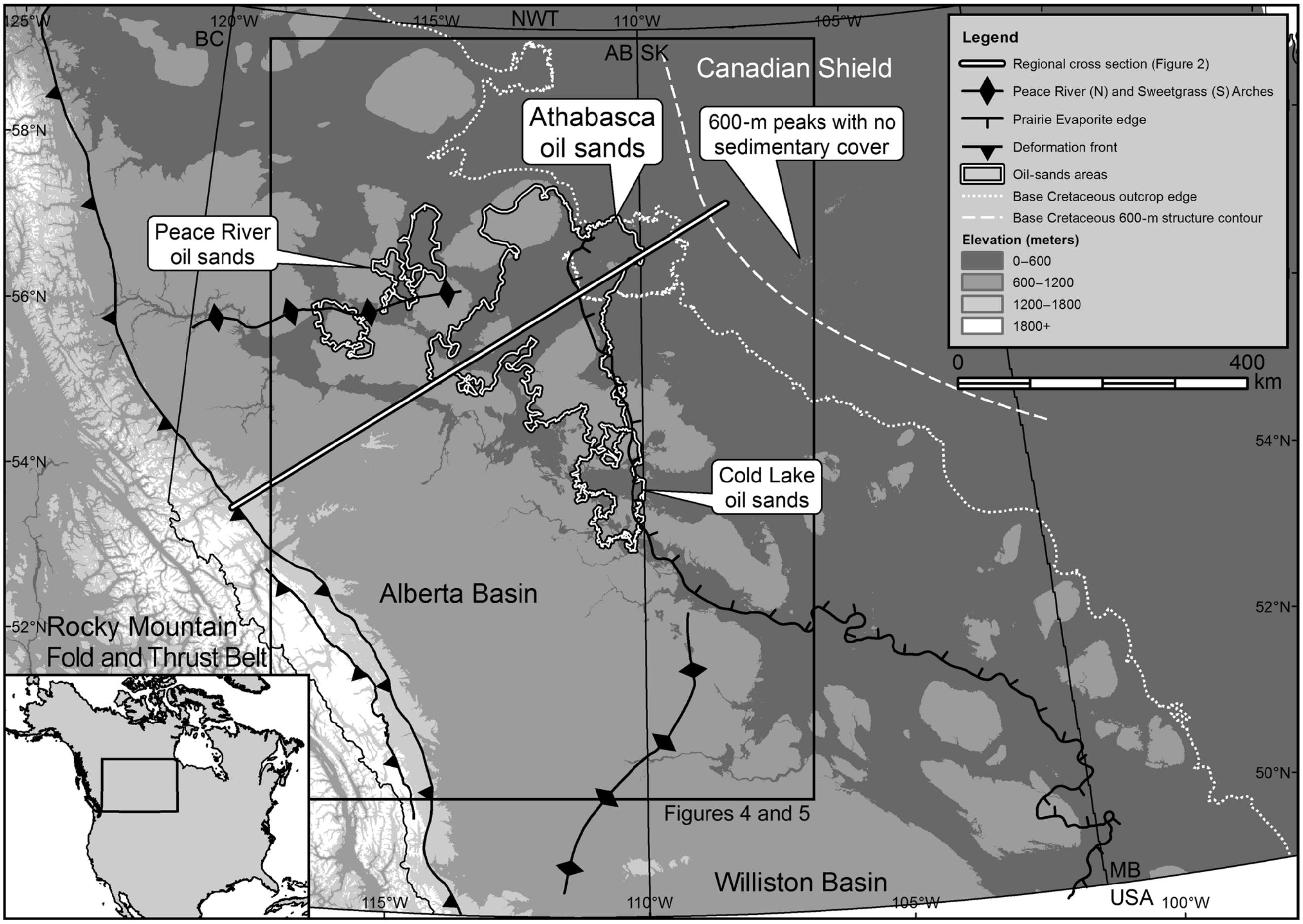

Figure 1. Regional map showing the location of the Athabasca oil sands and key tectonic elements. Position of the Peace River arch and Sweetgrass arch is from Wright et al. (1994); oil sands outlines are from Crowfoot et al. (2012).

Devonian (which rests unconformably on Precambrian basement) to Mississippian age (Kent, 1994). The sediments deposited during this time are a mixed succession of carbonates, evaporates, and shales, including at least one significant source rock, the Upper Devonian Exshaw Formation (Creaney et al., 1994). A period of relatively subdued subsidence (transitional megasequence; Figure 2) from the Late Mississippian to Late Jurassic was characterized by deposition of a siliciclastic-dominated succession, which also includes at least one major source rock, the Lower Jurassic Gordondale (formerly Nordegg) Member of the Fernie Group (Creaney et al., 1994).

A shift in sediment provenance from east to west during the Late Jurassic (Kimmeridgian) marks the change to flexural subsidence as a result of development of the Rocky Mountain fold and thrust belt (Beaumont, 1981; Price, 1981, 1994; Miall, 2009) (Figure 1). The stratigraphy of the associated foreland basin megasequence (Figure 2) is siliciclastic dominated and includes the siliciclastic reservoirs of the Mannville Group (latest Barremian to early Albian; Stott et al., 1993) (Figure 3). The Mannville Group was deposited in three main axial trends along the foreland basin, separated by ridges of Paleozoic carbonates that were resistant to erosion (Stott et al., 1993; Hayes et al., 1994). Along the eastern axial trend, in the Athabasca area, accommodation space for the Mannville Group was produced both by dissolution of the Devonian Prairie Evaporite and erosion of the Devonian stratigraphy (Vigrass, 1968; Stott et al., 1993). Deposition of the Mannville Group began with fluvial-estuarine sands of the McMurray Formation and marine sands of the Wabiskaw Member (Clearwater

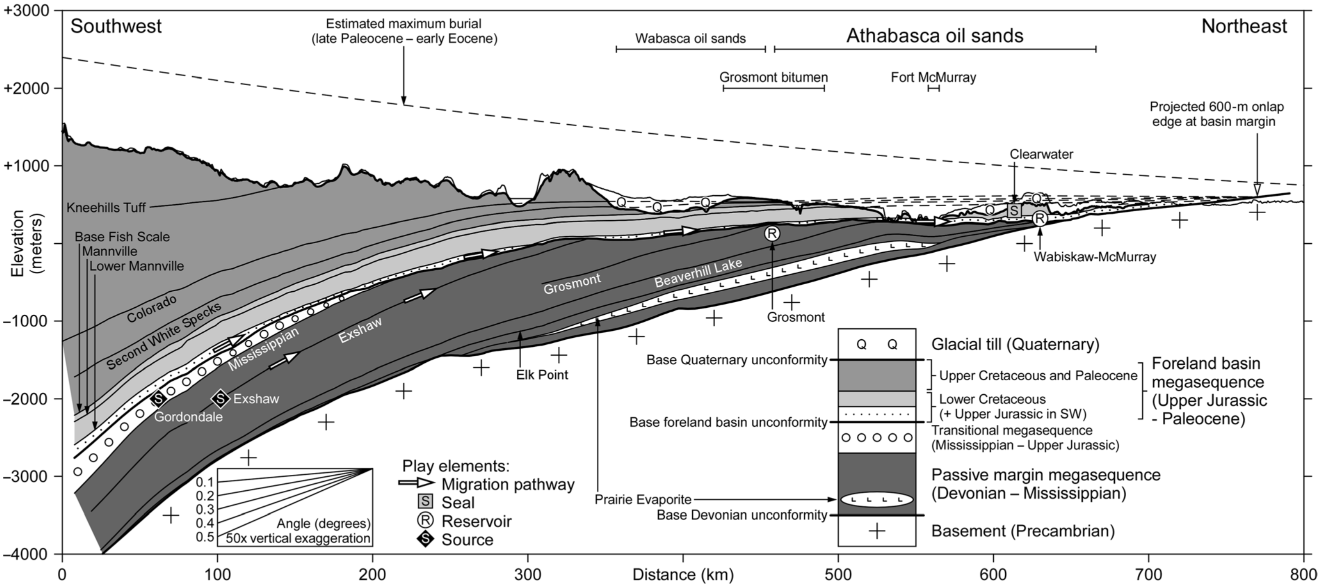

Figure 2. Regional cross section showing the present-day geometry of the basin, the megasequences, and key play elements. The line showing estimated maximum burial at the top of the section is derived from vitrinite reflectance data compiled by Stasiuk et al. (2002). Refer to Figure 1 for location.

Formation); these were subsequently sealed by the shale member of the Clearwater Formation during a major marine transgression in the early Albian (Stott et al., 1993) (Figure 3). In the Athabasca area, the overburden stratigraphy is represented by marine sediments of the Colorado Group (Stott et al., 1993) (Figure 3). Flexural subsidence continued until the early Eocene, when a change from active compression to uplift and erosion is thought to have resulted from an episode of crustal extension in the central part of the fold and thrust belt (Price, 1994).

Petroleum Systems and Trap Timing: Previous Studies

The source rock for the oil sands of northeast Alberta remains controversial, with different emphasis placed on the contribution from the Upper Devonian Exshaw Formation and the Lower Jurassic Gordondale (formerly Nordegg) Member (Figure 2). Based on geological and geochemical data, Riediger (1994) argued that the Gordondale could not have been a major source for the oil sands, which are instead dominated by contribution from the Exshaw (Adams et al., 2013), except locally in the Peace River oil sands where charge from the Gordondale can be recognized. In contrast, four-dimensional basin modeling and inorganic petroleum fingerprinting suggest that the dominant source rock is the Gordondale (Higley et al., 2009; Berbesi et al., 2012; Finlay et al., 2012). Other authors suggest that a combination of these and additional source rocks is responsible (Creaney and Allan, 1990).

Regardless of this controversy, in northeast Alberta, these source rocks were either eroded (Exshaw) or never deposited (Gordondale) during flexural loading of the Western Canada Sedimentary Basin. Petroleum systems modeling shows that source maturity was achieved during the Late Cretaceous, with peak generation in the source kitchen, where flexural loading resulted in maximum burial in the basin, during the latest Cretaceous and Paleocene (e.g., Creaney and Allan, 1990; Higley et al., 2009; Berbesi et al., 2012; see Adams et al., 2013, for a review); much of the petroleum then migrated hundreds of kilometers across the basin from west to east (Higley et al., 2009; Adams et al., 2013) (Figure 2). The Cretaceous Mannville Group siliciclastic reservoirs and Devonian Grosmont Formation carbonate reservoir in northeast Alberta acted as the ultimate gathering point for the underlying source-carrier systems (Piggott and Lines, 1991).

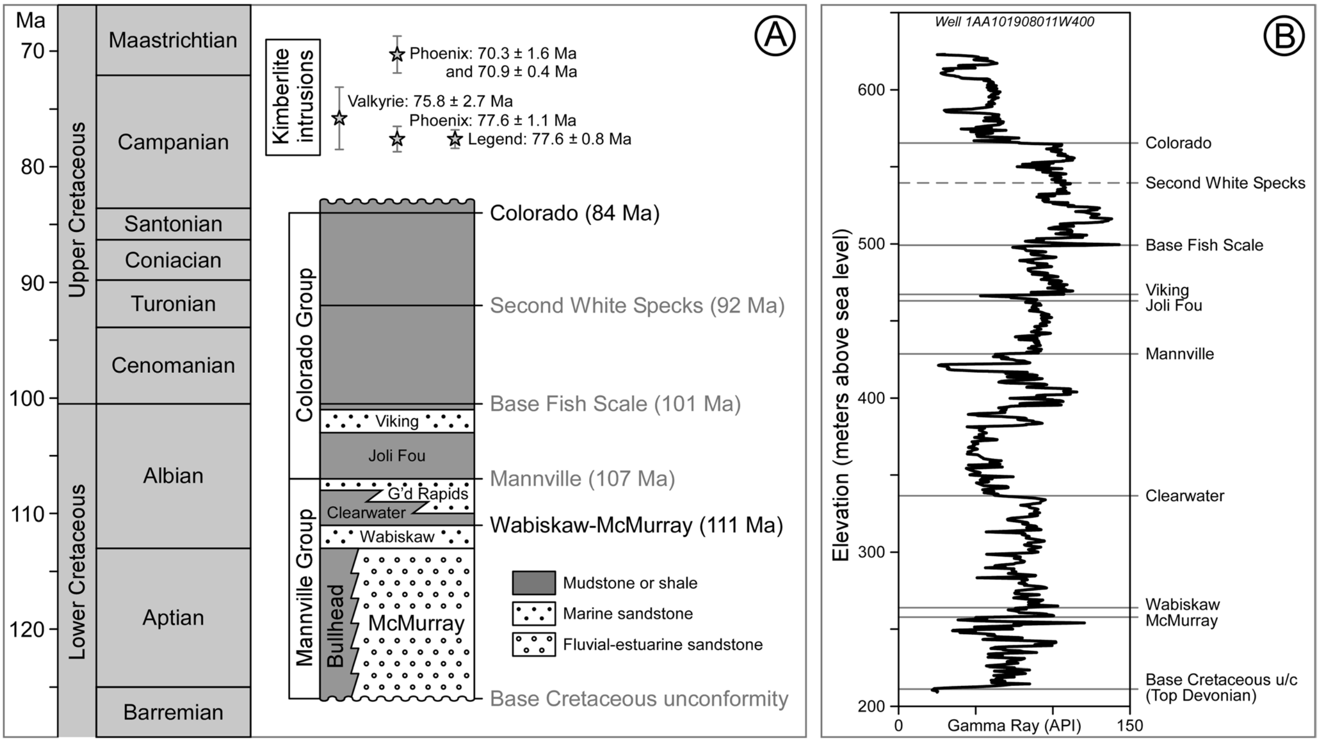

Figure 3. (A) Simplified Cretaceous stratigraphy of the Athabasca area showing the horizons used in this study. Stage assignments are from Stott et al. (1993), correlated to absolute ages from Cohen et al. (2012); data for kimberlites are from Aravanis (1999) and Eccles (2011). (B) Example well log from central Athabasca showing the well picks used in this study (well picks in this example are from IHS Energy Canada Ltd., 2011).

Because of the position of the Athabasca area at the edge of the basin, these reservoirs were never buried deeply enough to be pasteurized (Head et al., 2003; Adams et al., 2006; Larter et al., 2006), and therefore, the oil has been biodegraded to bitumen. Insight into the timing of biodegradation is provided by Adams et al. (2006, 2013); using a model of gradual charge and coeval biodegradation from 100 Ma until the time of maximum burial, these authors were able to model successfully the observed range of API gravity in the oil sands (13°–9° API in Peace River, ≤10° API in Athabasca). This model of coeval charge and biodegradation is consistent with subsurface biodegradation flux estimates from Larter et al. (2003, 2006), which suggest that approximately 20–35 m.y. of biodegradation would be required to convert the Athabasca oil into bitumen before tilting (Adams et al., 2013). Despite the long residence time of the oil in the reservoir (>60 m.y.), further biodegradation was hindered by the combined effects of the displacement of bottom water (the site of active biodegradation) in areas filled to an impermeable underseal, increasing resistance of the degraded oil to further biodegradation, and a "refrigerator" effect during uplift and erosion (Larter et al., 2006).

A major issue for existing work on the heavy-oil petroleum system of western Canada is the absence of a trap in the Athabasca area at the time of charge. For example, Higley et al. (2009, p. 222) noted that in their model, "most generated petroleum was not trapped in the Mannville Group… but is instead residual oil in reservoir and carrier bed pores or migrated to the east and northeast." Berbesi et al. (2012) improved the same model by adding impermeable lateral stratigraphic seals, because without these barriers, the petroleum would have leaked updip as described by Higley et al. (2009). The problem is that the original petroleum trap was destroyed by continued flexural loading of the basin during the Late Cretaceous and Paleocene and subsequent uplift and erosion (Ranger, 1994). Therefore, only a minor area of bitumen lies within structural closure today (Vigrass, 1968). Previous modeling of the trap geometry is limited to the study by Ranger (1994); in that study, the assumption was that the bitumen-water contact (BWC) was originally horizontal, and has been tilted by flexural loading of the basin after the oil was biodegraded to immobile bitumen. Therefore, by correcting the structure of the top of the reservoir so that the BWC is flattened, the geometry of the trap at the time of oil accumulation can be reconstructed. Although the analysis is limited to the area where the BWC can be picked and, therefore, closure of the trap is not demonstrated, the trap restoration of Ranger (1994) shows a gently south-plunging arch with a width of 150 km (93 mi) and maximum relief of 60 m (197 ft).

ATHABASCA TRAP MODELING

Hypothesis and Method

The hypothesis for this study is that the trap could be reconstructed using a megaregional, basin-scale view. Basin-scale horizon structure grids (hereafter called 'horizon[s]') were first constructed to honor the present-day geometry of the Cretaceous stratigraphy, including areas where erosion has occurred (this process is fully described in the section titled Data and Grid Modeling Methodology). The horizon corresponding to the boundary at the top of the Wabiskaw-McMurray reservoir and the base of the overlying of the Clearwater Formation (shale member) seal was then sequentially restored by flattening each overburden horizon to a sea level datum; this yields an approximate paleostructure grid (the method is similar to the isopach method described by Vigrass, 1968, p. 1991). Each top reservoir restoration was checked for structural closure and/or conformance of bitumen to structure using the published bitumen outline (Crowfoot et al., 2012, their figure AE.4). Finally, the best trap restoration was tested by restoring well picks of the BWC using the same overburden horizon. The restored BWC picks were assessed to see if they fell into areal groups of similar elevation that are consistent with the trap restoration.

Two key advantages of this method are present over the existing analysis by Ranger (1994). First, the trap restoration is not limited to the area covered by the BWC, and second, the horizon that restores the trap geometry and BWC provides the precise trap timing.

We have deliberately chosen not to use decompaction in our modeling to present the simplest reconstruction possible. Defining the method and parameters for decompaction and reconstructing the maximum burial datum are beyond the scope of this article. However, reconnaissance modeling using a standard method and parameters for decompaction (Allen and Allen, 2005), combined with a maximum burial datum extrapolated from Mannville vitrinite reflectance data (Stasiuk et al., 2002), indicates that our conclusions would remain the same.

Data and Grid Modeling Methodology

The horizons used in the trap model and their constituent well and outcrop data are summarized in Figure 3 and Table 1. Restorations of the Wabiskaw-McMurray horizon using the Mannville, base Fish Scale Sandstone, and Second White Specks Sandstone overburden horizons did not provide significant insight into the trap geometry or timing, and therefore, the details of modeling for these three horizons are omitted. The well picks for the Wabiskaw-McMurray horizon are from Paterson et al. (1978), Mossop and Shetsen (1994), Ranger (1994), Christopher (2003), IHS Energy Canada Ltd. (2011) and proprietary sources; those for the Colorado horizon, which represents the top of the Colorado Group (Figure 3; Table 1), are from IHS Energy Canada Ltd. (2011) and a proprietary source only. The well-pick editing and horizon structure grid modeling for this study were done in EarthVision® (EarthVision is a registered trademark of Dynamic Graphics, Inc.).

The outcrop data points used in this study come from the most recent compilation of the geology in the area by Okulitch and Fallas (2007). For the Wabiskaw-McMurray horizon, only three outcrop data points were included. These correspond to the eastern tip of the outcrop at the top of

Table 1. Data Used to Build the Cretaceous Horizon Structure Grids for This Study*

Well Top Pick and Horizon Name	Stage	Horizon Age (Ma)	No. Well Picks after Editing	No. Outcrop Picks
Colorado	late Santonian	84	9143	14
Second White Specks	middle Turonian	92	11,314	14
Base Fish Scale	Albian–Cenomanian	101	13,690	n/a
Mannville	middle Albian	107	18,645	n/a
Wabiskaw-McMurray	early Albian	111	26,037	3
McMurray BWC	n/a	n/a	1689	1 (Christina River)

*Stage assignments from Stott et al. (1993), absolute ages from Cohen et al. (2012). BWC = bitumen-water contact.

the shale member of the Bullhead Group in northern Alberta and two points where the Wabiskaw-McMurray unit onlaps the Devonian in western Saskatchewan and northern Alberta (Figure 4). In the case of the Colorado horizon, the outcrop data come from northern Alberta only; the outcrops that were included correspond to the almost time-equivalent boundary at the top Smoky Group–base Wapiti Formation (Stott et al., 1993) (Figure 4). The elevation values for all outliers were taken from a regional digital elevation model covering the Western Canada Sedimentary Basin;

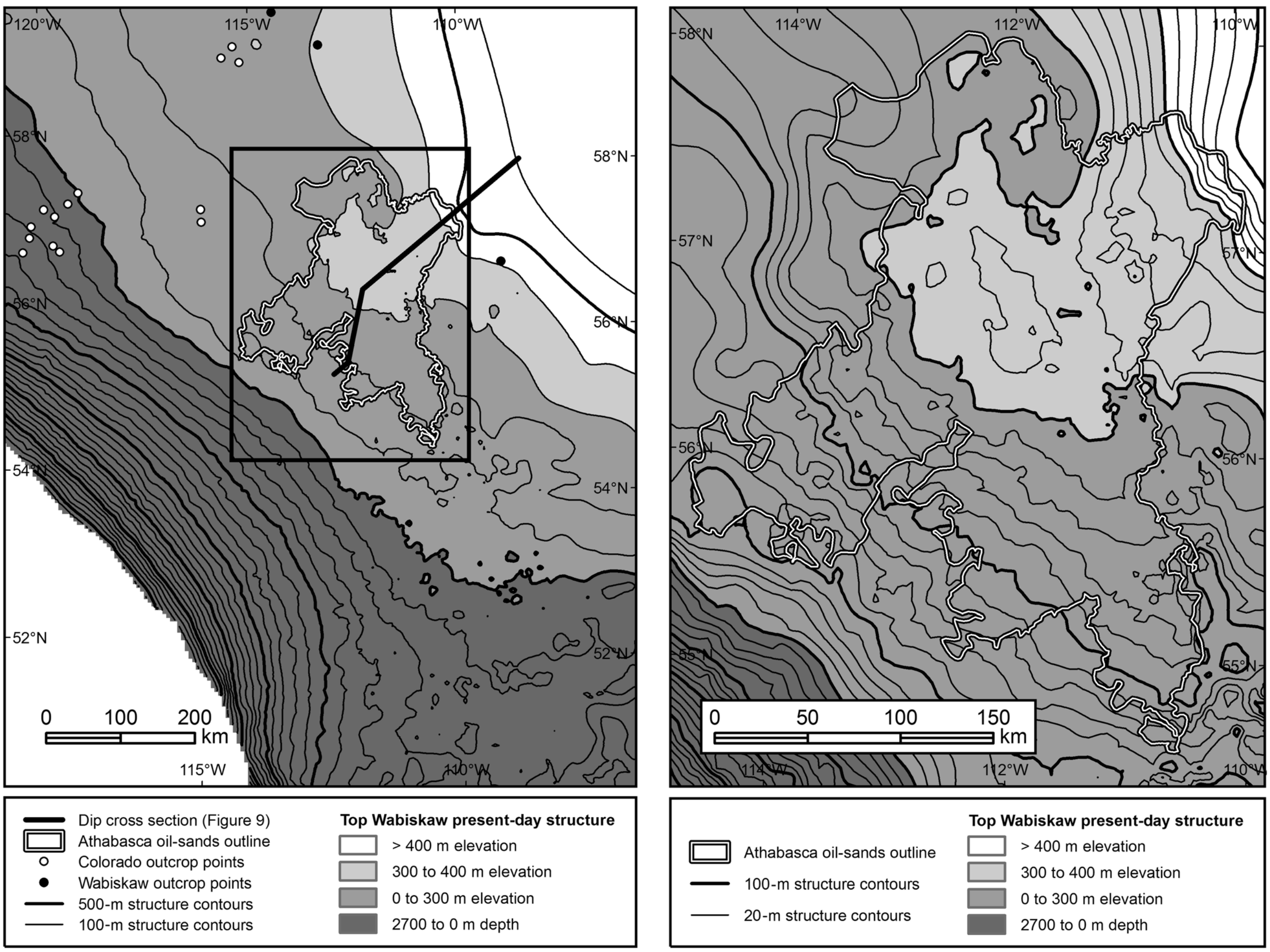

Figure 4. Wabiskaw-McMurray present-day structure: regional (left), subregional (right). Oil sands outline is from Crowfoot et al. (2012). Refer to Figure 1 for location.

in areas where a significant thickness of Quaternary till is present, this was also considered (modified after Christopher, 2003; Atkinson and Lyster, 2010). Having determined the coordinates and elevation of the outliers, these points were then gridded together with the well picks.

To define correctly the present-day horizon geometry without the effects of recent erosion, two steps were required during initial data editing. First, where the formation tops have been eroded and, therefore, no longer represent the original stratigraphic thickness, they were deleted. In the case of the Wabiskaw-McMurray, this was done by making a polygon from the outcrop edge corresponding to the top of the McMurray Formation (Okulitch and Fallas, 2007); Wabiskaw-McMurray well picks within this polygon were then deleted. In the case of the Colorado, well picks that lie beyond the present-day subcrop edge are observed to be anomalously deep and were deleted by hand; note that in the Athabasca area, the full thickness of the Colorado Group is preserved in local bedrock highs beneath Quaternary till. Second, a series of points was added to each horizon to represent the estimated onlap edge of the basin onto the Canadian Shield. The position of this onlap edge can be estimated because a group of peaks exists in northern Saskatchewan at 600 m (1968 ft) elevation that are composed of basement rocks of the Canadian Shield without sedimentary cover (Figure 1). Therefore, the base Cretaceous unconformity horizon projects above these peaks, and the 600-m (1968-ft) structure contour on this horizon must lie in a narrow zone between these peaks and outcrops to the southwest where the base Cretaceous unconformity is exposed at elevations of 500 m (1640 ft) and less (Okulitch and Fallas, 2007) (Figure 1). This 600-m (1968-ft) structure contour was added as a series of points to the well picks for the overlying horizons; the onlap edge estimated using this method is shown in cross section in Figure 2.

Having removed the eroded well picks and added the estimated onlap edge, a raw horizon structure grid was generated. The grid elevation value at each well pick was then determined by back-interpolation to the horizon, and picks beyond a ±20-m (±66-ft) buffer were deleted. Because of the number of data involved, this step is a quick and objective way of removing a large number of outlying picks; these are thought to be caused by basic errors in pick elevation, log-depth calibration, or the well survey. The data were then regridded, and any remaining outlying picks were removed by hand editing during three-dimensional visualization. An additional quality control step was also conducted by creating isochore grids for the interval above and below the horizon of interest and then hand editing the picks to remove any isochore anomalies. The resultant edited picks were then used to create the final horizon structure grid.

The BWC well picks are from proprietary sources only, supplemented by a single outcrop point from the Christina River. The picks were restored directly using the Colorado horizon to test the trap restoration.

ATHABASCA TRAP: RESULTS AND INTERPRETATION

Wabiskaw-McMurray Present-Day Structure

The present-day structure of the Wabiskaw-McMurray (Figure 4) shows limited areal and vertical closure (330–300 m [1082–984 ft] elevation, dimensions 170 × 95 km [106 × 59 mi]), mainly confined to the northern Athabasca area; a similar feature was recognized by Vigrass (1968). Although poor agreement of this closure exists with the published bitumen outline (Crowfoot et al., 2012), moderate conformance of the southeast bitumen edge is found at 200 m (656 ft) elevation for a distance of 85 km (53 mi). The west and east margins of this closure are coincident with the Grosmont escarpment and the edge of the Prairie Evaporite, respectively. A major east–west-trending structural high can be traced through the Athabasca area to the limit of well data and up to the outcrop edge (where Cretaceous sediments rest directly on basement rocks of the Canadian Shield; Okulitch and Fallas, 2007) in western Saskatchewan; this structural high represents the present-day expression of the Athabasca arch (Okulitch and Fallas, 2007).

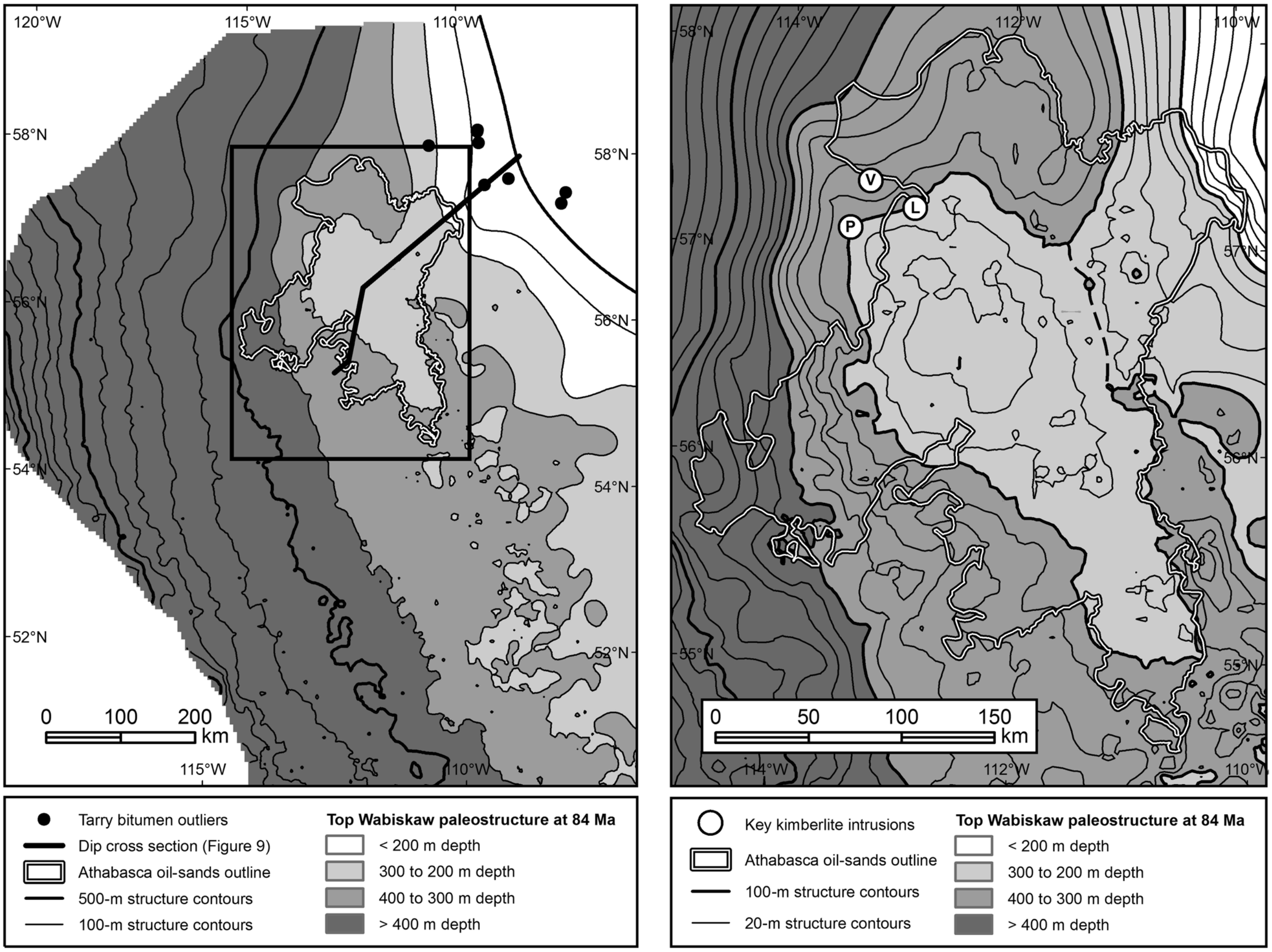

Figure 5. Wabiskaw-McMurray paleostructure, restored using the 84-Ma (late Santonian) Colorado horizon: regional (left), subregional (right). Note the presence of a major four-way anticline in the Athabasca area with structural closure at 300 m (984 ft) depth. P, V, L = Phoenix, Valkyrie, and Legend kimberlite intrusions, respectively. Oil sands outline is from Crowfoot et al. (2012). Refer to Figure 1 for location.

Although the original trap is no longer present in the Athabasca area, the bitumen is, of course, immobile and therefore remains in place.

Wabiskaw-McMurray Paleostructure at 107, 101, and 92 Ma

The paleostructure of the Wabiskaw-McMurray shows poor conformance with the published bitumen outline when restored with the Mannville (middle Albian, 107 Ma) and base Fish Scale (Albian–Cenomanian, 101 Ma) horizons (stage assignments from Stott et al., 1993; absolute ages from Cohen et al., 2012). The paleostructure shows only moderate conformance with the bitumen outline when restored with the Second White Specks (middle Turonian, 92 Ma) horizon. In all three restorations, the Wabiskaw-McMurray paleostructure shows only isolated areas within structural closure. These paleostructure maps are therefore not presented.

Wabiskaw-McMurray Paleostructure at 84 Ma

The paleostructure grid of the Wabiskaw-McMurray horizon restored at 84 Ma using the Colorado horizon (late Santonian; stage assignment from Stott et al., 1993; absolute age from Cohen et al., 2012) shows the presence of a major four-way anticline in the central Athabasca area (Figure 5). The deepest closing contour is at a depth of 300 m (984 ft), although this contour must be closed by hand through the saddle area to the east of the anticline crest. The anticline has good conformance at 300 m (984 ft) depth along the southeast of the published bitumen outline (Crowfoot et al., 2012) for a distance of 140 km (87 mi). The dimensions of the anticline are 285 km (177 mi) (northwest to southeast) by 50 km (31 mi) width in the south and 125 km (78 mi) width in the north; the maximum amplitude of the anticline is 60 m (197 ft), from 240 to 300 m (787 to 984 ft) restored depth (approximately 300 to 360 m [984 to 1181 ft] restored depth with decompaction and erosion considered).

This four-way anticline is interpreted to represent the primary structural trap in the Athabasca area, and it explains why the bitumen is found concentrated in one area on the basin margin. The geometry of the anticline is interpreted to have been generated by two major trap-forming elements; the arch on the west side of the Prairie Evaporite edge (the north–south-trending trap element) and the Athabasca arch (the east–west-trending trap element). Dissolution of the Prairie Evaporite and the consequent dip reversal of the overlying Cretaceous stratigraphy have long been recognized as an important trap element (Vigrass, 1968). However, we also emphasize the role of the east–west-trending Athabasca arch (Okulitch and Fallas, 2007), which is contiguous with the Peace River arch, an important, long-lived, dynamic structure in the basin (see O'Connell, 1994, and references therein). The maps indicate that the Athabasca arch was active as a subtle positive feature during the Late Cretaceous (Figure 5) and remains so today (Figure 4). In addition to its function in creating the trap, it would also have acted to focus the petroleum charge toward the Athabasca area.

The extremely shallow depth of burial in the Athabasca area that is shown by the paleostructure map at 84 Ma (Figure 5) is notable. Petroleum systems modeling indicates that the reservoir temperature in the Athabasca area never exceeded 45°C (Adams et al., 2006; Larter et al., 2006), which is significantly below the 80°C lower limit for pasteurization (e.g., Head et al., 2003; Adams et al., 2006, and references therein). Therefore, we interpret that charge and biodegradation of petroleum in Athabasca were coeval; this is supported by petroleum systems modeling (Adams et al., 2006, 2013). However, in addition to this important process of coeval charge and biodegradation, the trap restoration suggests that the distribution of bitumen was strongly controlled by structural and stratigraphic trap elements. These are described in the following section.

Athabasca Trap Domains

Using the structural restoration, it is possible to divide the Athabasca oil sands into six different trap domains; these are summarized in Figure 6

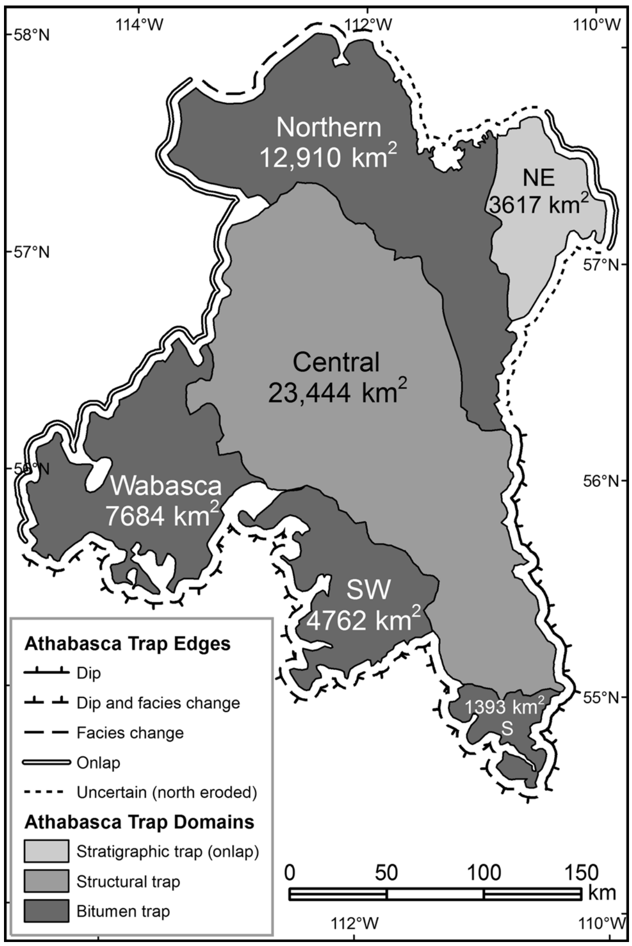

Figure 6. The Athabasca oil sands can be divided into six trap domains using the 300- and 270-m (984- and 886-ft) paleostructure (84 Ma) depth contours and the published bitumen outline (Crowfoot et al., 2012).

Table 2. Trap Domain Areas

Trap Domain	Trap Type	Area (km^2)	% of Total Area
Central Athabasca	Structural trap (four-way anticline)	23,444	43.6
Northeastern Athabasca	Stratigraphic (onlap) trap	3617	6.7
Northern Athabasca	Bitumen trap	12,910	24.0
Southern Athabasca	Bitumen trap	1393	2.6
Southwestern Athabasca	Bitumen trap	4762	8.8
Wabasca	Bitumen trap	7684	14.3
Total		53,810	

and Table 2. The giant paleostructure anticline with closure at 300 m (984 ft) restored depth is interpreted as the primary trap in the Athabasca area. As discussed, this structure is interpreted to have developed because of interaction of the north–south-trending arch on the west side of the Prairie Evaporite edge and the east–west-trending Athabasca arch. Note that the anticline accounts for 44% of the Athabasca oil sands by area. We interpret that the anticline was being charged by oil even as it developed at 84 Ma, and that this oil was rapidly biodegraded to immobile bitumen. This interpretation is consistent with petroleum systems modeling showing, first, the onset of peak oil generation in the Late Cretaceous (Creaney and Allan, 1990; Higley et al., 2009; Berbesi et al., 2012; see Adams et al., 2013, for a review), and second, coeval charge and biodegradation (Adams et al., 2006, 2013). The initial bitumen that collected in the central four-way anticline would have blocked the porosity and permeability, and this would explain why a regional paleogas cap is absent in this area.

The shallowest trap edge (both present and restored) is found in the northeastern trap domain, where the paleostructure reaches depths of 200 m (656 ft) and less. The lower limit of the northeastern trap domain is placed at the 270-m (886-ft) paleostructure depth contour on the basis of a shallow population of BWC picks that lie to the east of this line. We interpret this trap domain to be a stratigraphic trap where the reservoir interval onlaps the Canadian Shield (see Ranger, 1994, for a similar interpretation). This is supported by the presence of tarry bitumen outliers that are found in basement rocks farther to the northeast (Wilson et al., 2007), along trend with the Athabasca arch. The bitumen outliers are interpreted to represent leakage along the stratigraphic pinch-out at the edge of the trap (Ranger, 1994; Adams et al., 2013). Additional outliers of tarry bitumen to the north of this trap domain (Wilson et al., 2007) are interpreted to indicate the original reservoir footprint prior to Cenozoic erosion. The observation that the shallowest trap domain is located in northeast Athabasca agrees with the description of Ranger (1994) that the thickest zones of lean bitumen and water are found at the top of the reservoir interval in this area. These are thought to represent a paleogas cap that accumulated in this area, leaked off during uplift and erosion, and was subsequently filled by meteoric water. Fustic et al. (2012) argue that the gas was more likely to have been of biogenic origin.

The bitumen in the northern trap domain lies below the 270-m (886-ft) paleostructure depth contour. This trap domain includes the saddle area between the central four-way anticline and northeastern onlap trap and is interpreted to represent a late charge of oil that was trapped below these trap domains by bitumen already emplaced. On the north flank of the saddle, a strong stratigraphic component almost certainly exists to the west (onlap onto the Grosmont ridge) and north (facies change to the shale member of the Bullhead Group) edges of this trap domain.

The final three trap domains are located in southern and southwestern Athabasca and Wabasca. These trap domains lie below the 300-m (984-ft) paleostructure spillpoint and are also interpreted to represent a late charge of oil that was trapped by bitumen already emplaced in the central four-way anticline. The ragged southwest margins of all three trap domains are thought to have a strong stratigraphic (facies change) component, which would also have been enhanced by the regional dip of the reservoir into the basin. The north edge of the Wabasca trap domain is interpreted as onlap onto the Devonian subcrop (Figure 6).

Bitumen-Water Contact Restoration

A key component of the new trap hypothesis is that the paleotrap model can be tested using the BWC. Assuming this was originally a subhorizontal oil–water contact, the overburden horizon that restores the trap should also return the BWC to its original orientation.

When the BWC data are viewed in three dimensions, significant local variation in the BWC is apparent. Ranger (1994) suggested three reasons for this. First, structural events (e.g., faulting, karst collapse, salt collapse) that occurred after biodegradation would have lowered the BWC elevation in affected areas. Second, many wells have a significant transition zone between the bitumen and underlying aquifer, instead of an abrupt BWC; the elevation where the BWC is picked in the transition zone is therefore subjective. Third, basic errors in pick elevation, log-depth calibration, or well survey may also be a source of the observed variation.

An additional two factors may also be significant. First, in view of the scale of the oil sands, a significant variation in the oil–water contact caused by original structural, stratigraphic, or other factors might be expected (for examples of these factors, see Jolley et al., 2010). In the Athabasca area, examples of lateral reservoir compartmentalization caused by local stratigraphic complexity are documented by Fustic et al. (2012), and primary variation of the BWC is shown by an outcrop of the McMurray Formation exposed at the Christina River (east of Fort McMurray), where the BWC is an irregular surface that varies in elevation by 2 m (6.6 ft) over approximately 8 m (26 ft) of distance (Ranger, 1994). Second, local variations in the resistivity of the pore water are known to be present along the edge of the Prairie Evaporite; consequently, where the BWC has been picked from resistivity alone, without the use of core, it may be incorrect.

Our hypothesis is that the different trap domains originally had different BWCs. This was tested by first determining the elevation of the Colorado horizon structure grid at each BWC pick by back-interpolation. The difference between the Colorado elevation and the BWC elevation represents the restored depth of the BWC point at 84 Ma. The points were then divided into different populations corresponding to the central, northeastern,

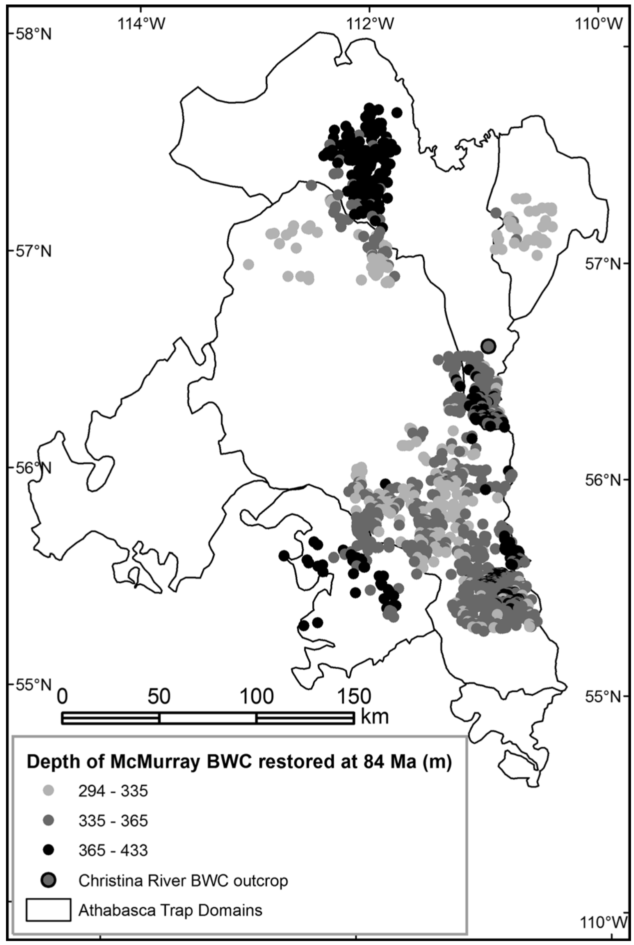

Figure 7. McMurray bitumen-water contact (BWC) picks restored using the 84-Ma Colorado horizon. Note the increase in depth of the restored BWC between the central four-way anticline and the peripheral trap domains (northern and southwestern), and the shallower depth of the restored BWC in the northeastern onlap trap.

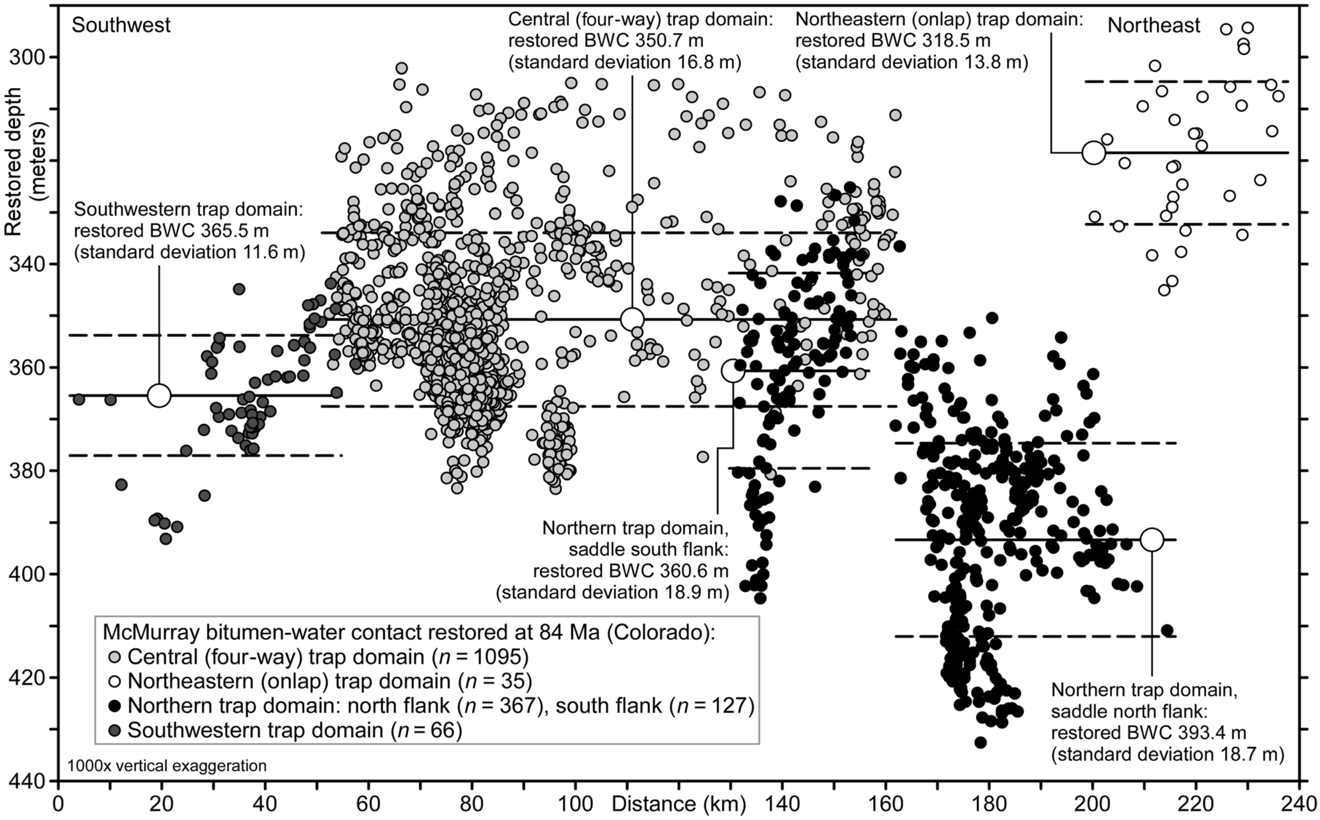

Figure 8. Paleostructure cross section showing distance versus depth of the McMurray bitumen-water contact (BWC) after restoration using the 84-Ma Colorado horizon; note the different restored BWC elevations in the different trap domains. The points have been projected to a common plane oriented southwest–northeast.

northern, and southwestern trap domains. In each of these areas, the mean present-day elevation and restored depth of the BWC was then determined. The results of this are shown in Figures 7 and 8 and Table 3.

The restored picks fall into groups that are consistent with the trap domains determined from the top Wabiskaw-McMurray reservoir restoration. The northeastern (onlap) trap domain has the shallowest restored BWC at 319 m (1046 ft) depth, followed by the central (four-way anticline) trap domain at 351 m (1151 ft), the southwestern trap domain at 366 m (1200 ft), and the northern trap domain at 361 and 394 m (1184 and 1292 ft), respectively, on the south and north flanks of the saddle between the central and northeastern trap

Table 3. Results of McMurray Bitumen-Water Contact Modeling*

Trap Domain	Number of BWC Picks	Mean BWC Elevation Present Day (m)	Standard Deviation Present Day (m)	Mean BWC Depth after Restoration at 84 Ma (m)	Standard Deviation after Restoration (m)
Central	1095	204.1	28.1	350.7	16.8
Northeastern	35	296.9	13.8	318.5	13.8
Northern: saddle north flank	367	230.9	20.2	393.4	18.7
Northern: saddle south flank	127	237.0	20.0	360.6	18.9
Southwestern	66	174.3	13.1	365.5	11.6
Total	1690				

*BWC = bitumen-water contact.

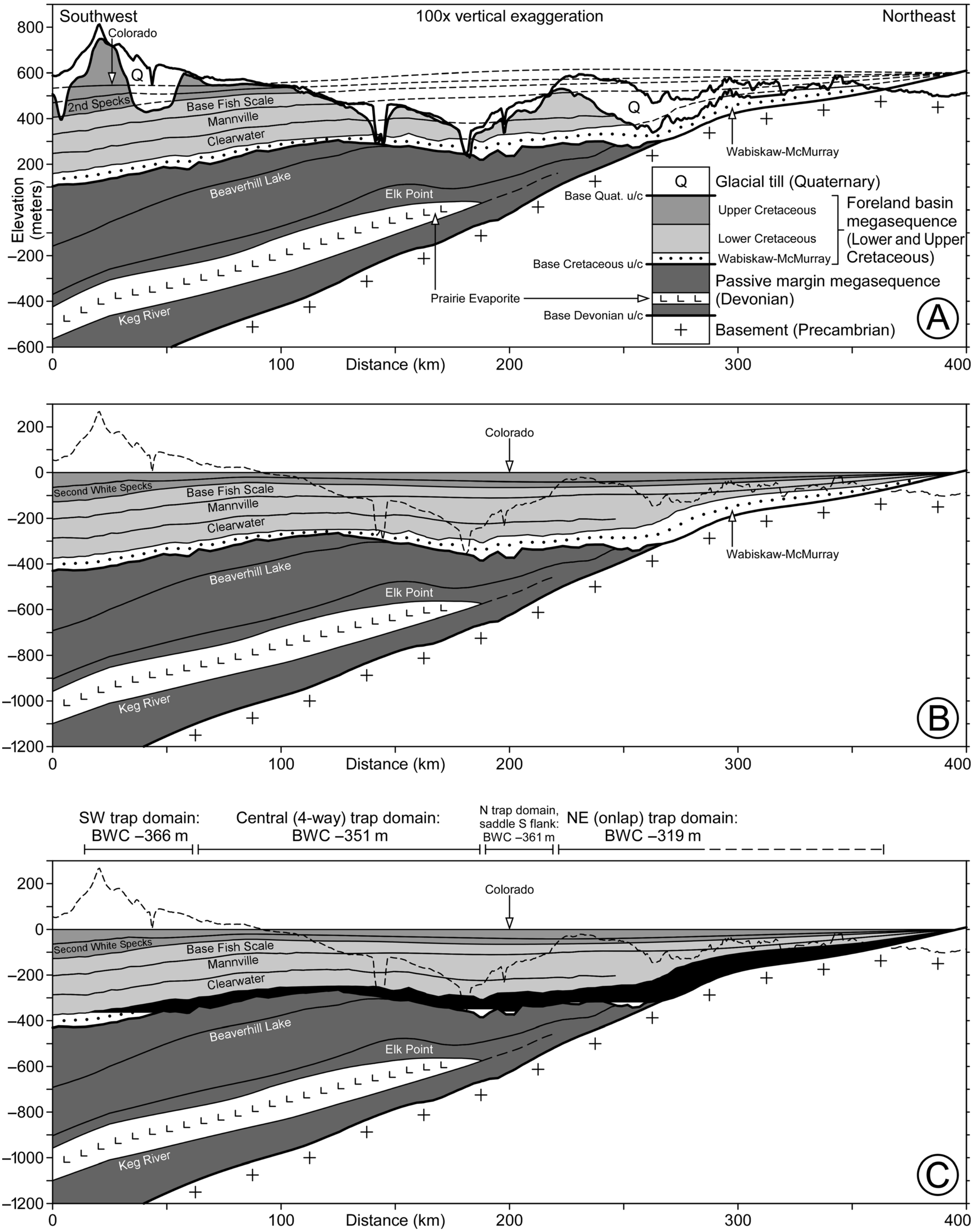

Figure 9. Dip cross section through the southwestern, central, and northeastern trap domains. (a) Present day, (b) restored using the 84-Ma Colorado horizon, (c) restored section with bitumen fill showing the bitumen-water contact (BWC) depths in the different trap domains. See Figures 4 and 5 for location.

Table 4. Data for Key Kimberlite Intrusions in Northwest Athabasca (Northern Trap Domain)*

Kimberlite	Drill Hole	Coordinates (m; NAD27 UTM12N)	Radiometric Age (Ma)
Phoenix	98DH-PH01	351500 E; 6330580 N	77.6 ± 1.1 (U-Pb perovskite) 70.9 ± 0.4 (Rb-Sr phlogopite) 70.3 ± 1.6 (U-Pb perovskite)
Valkyrie	98DH-VA02	362350 E; 6355490 N	75.8 ± 2.7 (U-Pb perovskite)
Legend	98DH-LE01	386200 E; 6340600 N	77.6 ± 0.8 (Rb-Sr phlogopite)

*Compiled from Aravanis (1999) and Eccles (2011).

domains (Figure 8). The difference in these elevations is consistent with the interpretation that the central four-way anticline was filled first, followed by the shallower northeastern onlap trap, and then the deeper peripheral trap domains, which would have been sealed by immobile bitumen farther updip. The trap geometry and restored BWCs are illustrated by the cross sections in Figure 9.

Note that the standard deviation of the BWC picks in the central four-way anticline improves significantly from 28 m (92 ft) today to 17 m (56 ft) when restored (Table 3); this trap domain has the broadest spatial extent, and therefore, this improvement supports the structural restoration of the paleotrap. The standard deviation of the restored BWC picks in the other trap domains also shows moderate improvement, with the exception of the northeastern onlap trap, which remains the same because of its limited spatial extent.

We speculate that the discrepancy between the restored BWCs for the central and northeastern trap domains (at 351 and 319 m [1151 and 1046 ft], respectively) and the paleostructure contours used to define the lower limit of these trap domains (at 300 and 270 m [984 and 886 ft], respectively) is meaningful. In both areas, the difference is 50 m (164 ft) and would equate approximately to the boundary between the middle and upper McMurray; above this boundary, change to more laterally extensive marine shales of the upper McMurray is evident (Ranger, 1994). We interpret this boundary to represent an important baffle that controlled vertical petroleum migration in the Athabasca oil sands; therefore, the spillpoint of this boundary can still be recognized in the restored BWC.

Kimberlites and Charge Timing

A period of diamond exploration from 1990 to 2010 revealed the presence of numerous kimberlite pipes of Late Cretaceous and Paleocene age in northern Alberta (Eccles, 2011). Fifty-one kimberlite pipes have been discovered to date in three distinct clusters: Mountain Lake (2), Buffalo Head Hills (41), and Birch Mountains (8); the Birch Mountains kimberlite cluster lies on the northwestern margin of the Athabasca oil sands (Eccles, 2011).

Radiometric age dates have been determined for the kimberlites (Aravanis, 1999; Eccles, 2011), and therefore, their spatial and temporal relationship to the bitumen (coked vs. unaltered; S. R. Larter, 2012, personal communication) provides an independent test for our model of trap and charge timing. The kimberlites are a blind test because the trap restoration was completed before we were aware of this information. The original geological descriptions for the 19 kimberlite exploration drill holes (Aravanis, 1999) were reviewed to check their relationship to the bitumen. Bitumen is described for only three of the exploration drill holes, the Phoenix, Valkyrie, and Legend kimberlites; in all three cases, the descriptions suggest that the bitumen in the kimberlites is live and has not suffered thermal alteration. For example, core from the Valkyrie kimberlite is described as “black medium grained fragmental, competent bitumen-rich kimberlite… the nature of this unit [is] that it is “soaked” in bitumen (bitumen is oozing from the core causing both black and faint yellow staining)” (Aravanis, 1999, p. 276). Similar descriptions for the other two drill holes strongly suggest that petroleum charge occurred after intrusion of the kimberlites.

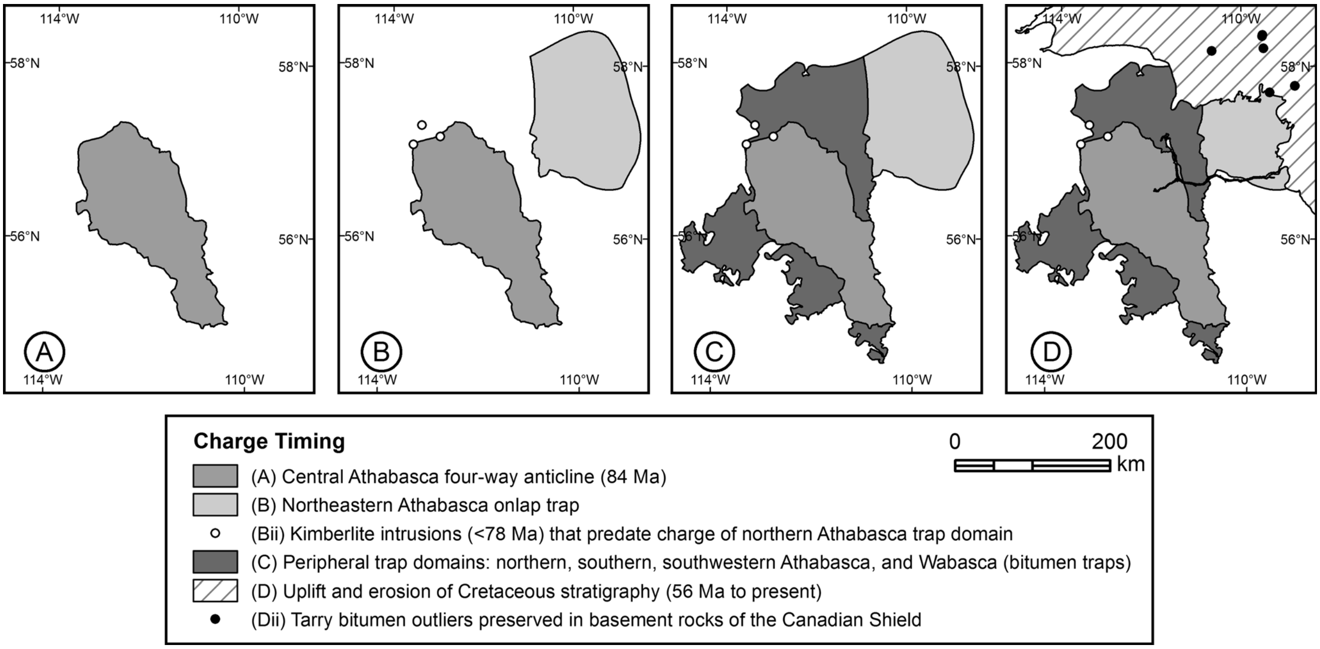

Figure 10. Conceptual charge model for the Athabasca oil sands. (A) Initial charge of the central four-way anticline around 84 Ma. (B) Charge of the northeastern onlap trap domain down to 270 m (886 ft) depth. (C) Charge of the peripheral trap domains below the 300-m (984-ft) spillpoint; charge of the northern trap domain not before 78-Ma kimberlites (data for kimberlites from Aravanis, 1999; Okulitch and Fallas, 2007; Eccles, 2011). (D) Uplift and erosion from Eocene to present; the original trap footprint and onlap edge are indicated by outliers of tarry bitumen in basement rocks of the Canadian Shield (Wilson et al., 2007).

The radiometric age dates for the kimberlites (Figure 3; Table 4) indicate that all three intrusions are middle Campanian to early Maastrichtian in age (the spread of dates is 78 to 70 Ma). Relative to the top reservoir paleostructure at 84 Ma, the Phoenix and Legend kimberlites lie almost exactly on the 300-m (984-ft) closing contour, whereas the Valkyrie kimberlite lies farther downdip in the northern trap domain at 334 m (1095 ft) paleodepth (Figure 5). Therefore, the data for the kimberlites are consistent with the interpretation that the central four-way anticline was filled first, around 84 Ma, whereas the northern trap domain experienced later oil charge, not before 78 Ma. If further kimberlites are discovered in the other paleotrap domains, these would allow the sequence of charge timing to be understood further.

The trap restoration and data for the kimberlites are inconsistent with the 111.6 ± 5.3 Ma rhenium-osmium (Re-Os) isochron age of bitumen from the Alberta oil sands (Selby and Creaser, 2005). Not only does this predate deposition of the Clearwater seal, but we also note that a critical assumption of the Re-Os technique is that the petroleum is derived from a single source rock, whereas there is agreement that multiple source rocks exist for the oil sands (e.g., Finlay et al., 2012, and references therein). Additional issues with the Re-Os technique are described by Larter et al. (2012). These problems may explain why the 112-Ma date is inconsistent with our geological model of trap timing (84 Ma), the charge timing indicated by the kimberlites (<78 Ma; Aravanis 1999; Eccles 2011), and existing petroleum systems models that indicate that source maturity was achieved during the Late Cretaceous, with peak generation during the latest Cretaceous and Paleocene (Creaney and Allan, 1990; Higley et al., 2009; Berbesi et al., 2012; see Adams et al., 2013, for a review).

In summary, the conceptual charge model for the Athabasca oil sands is illustrated in Figure 10 and is described as follows:

a. Initial fill of the central Athabasca four-way anticline during the late Santonian (Colorado horizon, 84 Ma). Our interpretation that the early oil-rich charge in this area was subjected to coeval biodegradation is consistent with petroleum systems modeling (Adams et al., 2006, 2013). The resultant bitumen would have blocked the porosity and permeability in this trap domain, and this would explain why a regional paleogas cap is absent in this area.

b. Subsequent fill of the northeastern onlap trap. This is the shallowest trap domain and would have filled immediately after the spillpoint of the anticline (at 300 m [984 ft] paleodepth) had been reached. Because of the shallow depth of this trap domain, it was a site of gas accumulation; the origin of this gas is thought to be biogenic (Fustic et al., 2012).
c. Final fill of the peripheral trap domains (northern, southern, and southwestern Athabasca and Wabasca) against an updip bitumen seal. Charge timing in the northern trap domain was not before 78 Ma, as indicated by kimberlite intrusions containing live bitumen (Aravanis, 1999; Eccles, 2011).
d. Uplift and erosion from Eocene to present. The original trap extent is preserved because the oil was biodegraded to immobile bitumen before the trap was destroyed. Where the oil sands reservoir has been eroded, the original trap footprint and leaky onlap edge are indicated by outliers of tarry bitumen in basement rocks of the Canadian Shield (Wilson et al., 2007).

CONCLUSIONS

The original extent of the trap for the Athabasca oils sands is preserved despite flexural loading of the basin during the Late Cretaceous and Paleocene and subsequent uplift and erosion. This is because the petroleum charge was rapidly biodegraded to immobile bitumen; this interpretation of coeval charge and biodegradation is supported by petroleum systems modeling (Adams et al., 2006, 2013). The original trap extent is revealed by restoration of the top Wabiskaw-McMurray reservoir using the overlying 84-Ma Colorado horizon (late Santonian); both horizons have been reconstructed using well and outcrop data. The principal trap domain after restoration is a central four-way anticline with dimensions 285 × 125 km (177 × 78 mi) and maximum amplitude of 60 m (197 ft). The southeast margin of the anticline shows good conformance to the bitumen edge along a distance of 140 km (87 mi) at a paleodepth of 300 m (984 ft).

Using the structural restoration, it is possible to divide the Athabasca oil sands into five additional trap domains. To the northeast of the restored anticline, the northeastern trap domain is located in a more elevated position above the paleospillpoint of the anticline. A stratigraphic (onlap) trap onto the Canadian Shield is interpreted to explain this arrangement; this is supported by the presence of outliers of tarry bitumen preserved within basement rocks farther to the northeast (Ranger, 1994; Wilson et al., 2007). Below the northeastern onlap trap, the northern trap domain is interpreted to represent a late charge of oil that was trapped by bitumen already emplaced in central and northeastern Athabasca. This is consistent with kimberlite intrusions containing live bitumen; radiometric age dates for these intrusions indicate that the northern trap domain was charged not before 78 Ma (Aravanis, 1999; Eccles, 2011). The southern and southwestern Athabasca trap domains and the Wabsaca trap domain lie below the 300-m (984-ft) paleospillpoint and are also interpreted to represent late charge that was trapped by updip bitumen.

The trap restoration has been tested by restoring the McMurray BWC using the overlying 84-Ma Colorado horizon (late Santonian). The restored BWC picks fall into groups that are consistent with the trap domains determined from the top Wabiskaw-McMurray reservoir restoration. The northeastern onlap trap has the shallowest restored BWC at 319 m (1046 ft) depth, followed by the central four-way anticline at 351 m (1151 ft), the southwestern trap domain at 366 m (1200 ft), and the northern trap domain at 393 m (1289 ft). The difference in these elevations is consistent with the conceptual charge model in which the central four-way anticline was filled first, followed by the northeastern onlap trap and then the peripheral trap domains that would have been sealed by immobile bitumen farther updip.

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