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Three-Dimensional Geometry of Fluvial-Estuarine Oil Sand Deposits of the Clarke Creek Area (NTS 74D), Northeastern Alberta

Alberta Energy and Utilities Board
Alberta Geological Survey

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C.W. Langenberg, F.J. Hein and H. Berhane

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Fax: (780) 422-1918

Website: www.ags.gov.ab.ca

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Acknowledgments

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Abstract

Most of the bitumen resources in the Athabasca oil sand area are contained in fluvial and estuarine channel deposits of the Lower Cretaceous McMurray Formation. The subsurface of the Clarke Creek area is characterized by data from about 60 wells and 4 high-quality seismic lines. Integration of subsurface data shows that seismic surveys give an accurate three-dimensional picture of the various structures in the subsurface. Identification of bounding surfaces of specific strata and lithofacies associations have identified channel complexes. A channel complex is a lithofacies package defined by major bounding surfaces, with genetically related facies and consistent paleoflow patterns.

Two channel complexes can be recognized in the Upper McMurray Formation at Clarke Creek, both interpreted as estuarine meandering-channel–point-bar complexes. The older channel complex was oriented to the northwest, with prominent low-angle cross-bedding (seen in core and interpreted on dipmeter logs and seismic sections) striking parallel to the main channel axis and dipping variably at 90° to the channel-axis trend. This cross-bedding is interpreted as being due to the lateral migration of point bars within the estuarine complex. A younger channel complex removed much of the older estuarine meandering-channel–point-bar complex. The younger channel complex trends to the north, and has similarly associated lateral-accretion surfaces, due to point bars bordering along the axial trend of the main channel. The lower part of each channel complex is characterized by medium- to large-scale trough-cross-bedded sand units, with high porosity and permeability, representing main channel deposits and containing the highest bitumen grades. Tops of channel complexes are outlined by dipping surfaces of lateral-accretion cross-bedding (sandy or muddy, inclined, heterolithic stratification) of estuarine point-bar successions, with reduced permeabilities and containing lower bitumen grades. These channel complexes may represent hydraulically equivalent zones of similar porosity and permeability.

A large percentage of the oil sands are contained in the central, younger channel complex. Results from the present study indicate that channel complexes can be realistically imaged by seismic methods. Recognition of channel complexes could help define thick bitumen deposits in other oil sand areas.

1 Introduction

The oil sands of northeastern Alberta are located in three main areas: Cold Lake, to the south; Peace River, to the west; and Athabasca, to the north (*see* inset of Figure 1). Of these deposits, the largest is the Athabasca, which has an area exceeding 42 000 km^2 and total bitumen reserves estimated in excess of 1 trillion barrels, of which only about 30 billion barrels are in reservoirs shallow enough to recover by surface mining. The bulk of the bitumen reserves in the Athabasca deposit will have to be extracted by in situ thermal-recovery processes, Steam-Assisted Gravity Drainage (SAGD) being the most commonly used process in pilot plants (cf. Lee et al., 2000). The recent surge in heavy-oil, oil sand and bitumen activity by industry in Alberta is expected to continue over the next decade or so. This, of course, was sparked by the decline in production and reserves of conventional heavy and light fuels. In 1998, it was predicted that about half of Canadian crude-oil production (both bitumen and synthetic crude-oil products) would be from the oil sands by the year 2005 (Oil Sands Developers of Alberta, 1998). As of December 2000, there were 20 announced projects by industry in the oil sands of northeastern Alberta, the bulk of which (9) are in the Athabasca deposit (Stringham, 2000). Since 1998, industry has invested $9 billion (Canadian dollars) in the oil sands of northeastern Alberta, with another $34 billion announced in new or expanded oil sand projects (Williamson and Lee, 2000). Of these, expenditures for in situ bitumen-recovery projects proposed or under consideration exceed $4.5 billion (Brunka, 2000).

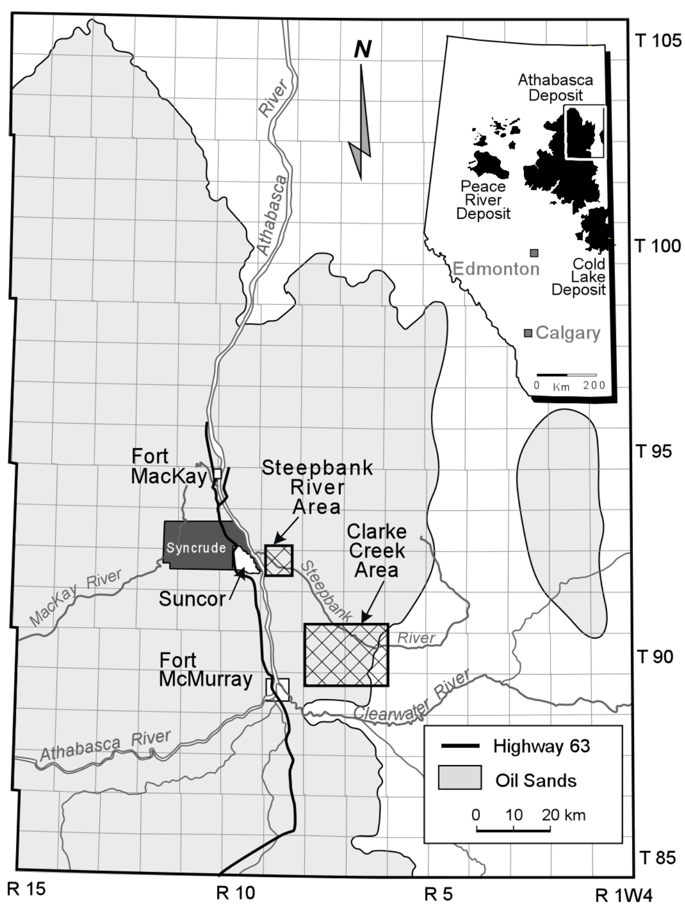

Figure 1. Athabasca oil sand deposit in the Fort McMurray area, showing location of Clarke Creek study area; inset shows the oil sands of northeastern Alberta, highlighting the Athabasca North area (white outline).

Since 1978, bitumen rights have been separated from other mineral rights, such as shallow gas in overlying reservoirs, and there have been disputes between the bitumen-rights owners and the gas producers in the same development-lease area. On average, there are about 35 hearings held each year by the Alberta Energy and Utilities Board (EUB) to resolve disputes. Most recently, an inquiry and hearings by the EUB have addressed coproduction conflicts between gas producers/leasers and in situ thermal-plant operators/leasers in the Athabasca oil sand area (Alberta Energy and Utilities Board, 1998, 1999, 2000, 2001; Theriault, 2001; Block, 2000; Lee et al., 2000; Williamson and Lee, 2000). Technical submissions focused on possible influences of interbedded mudstone (as lateral accretion crossbeds, intraclast breccia units or mud-plug, vertical accretion abandonment fills) on SAGD processes. In a recent decision dealing with shut-in of gas in the Surmont area (Alberta Energy and Utilities Board, 2000), part of the Board's assessment relied upon submitted confidential seismic results (Alberta

Energy and Utilities Board, 1999). However, in the public domain, there are not many seismic sections of the Athabasca oil sands that can be tied directly to observed sedimentary features in core or outcrop.

Reservoir simulation/modelling techniques are often used where there may be little well control, and the input of inappropriate data may result in the incorrect placement of future wells, and spurious estimates of future reservoir production history. Recent numerical simulations, stochastic modelling and object modelling of subsurface reservoirs, show the need for increasingly more sophisticated descriptions of basic geological features and their three-dimensional orientations in space (cf. Tyler et al., 1995; MacDonald et al., 1998; Parks et al., 2000). Current research on modern and ancient examples is using ground-penetrating radar and amplitude analysis of two-dimensional, three-dimensional (or, less commonly, four-dimensional) seismic data to model fluvial and estuarine channel patterns (e.g., Weber, 1993; Hardage et al., 1994, 1996; Burnett, 1996); however, the applicability and reliability of such approaches depend upon the scales of resolution of seismic or ground-penetrating radar data and the direct calibration of these surveys to wireline logs and cores in the study area. In particular, it is very difficult to resolve thinly interbedded sandstone-mudstone successions, either in the modern or ancient environment, with any degree of confidence using indirect subsurface methods, such as log analysis, seismic or ground-penetrating radar.

The geometry of fluvial-estuarine channel complexes in the Clarke Creek area (Figure 1) presented here, is an example of how seismic surveys, log analysis and dipmeter analysis can aid in the accurate three-dimensional (3-D) definition of this type of oil sand deposit.

2 Geological Setting of the McMurray Formation

Since Allan's (1921) first publication dealing with extraction of bitumen from the oil sands in the Athabasca area, there has been a long history of geological work on the oil sands of northeastern Alberta. This earlier work was summarized by Carrigy (1965); an updated historical overview was given by Hein (2000). Overviews of heavy crude and oil sands of western Canada can be found in McPhee and Ranger (1998). The oil sands of the Athabasca area are contained in the lower part of the Mannville Group. A regional description of the internal stratigraphy of the Lower Mannville Group can be found in Cant and Abrahamson (1996). Two compilation volumes of the Mannville Group were completed, the first being a CSPG Mannville Core Conference (Pemberton et al., 1994), followed by an edited volume by Pemberton and James (1997).

The McMurray Formation is the lowest part of the Mannville Group preserved in northeastern Alberta, where it unconformably overlies Paleozoic successions and, in turn, is unconformably overlain by incised valley fills and other transgressive deposits of the Wabiskaw Member of the Clearwater Formation (Figure 2). Most of the bitumen resources in the Athabasca oil sand area are contained within fluvial and estuarine channel–point-bar deposits of the Lower Cretaceous McMurray Formation, as indicated by the lithofacies work of Flach, Mossop and Wightman (Flach, 1977, 1984; Flach and Mossop, 1985; Mossop, 1980a, b; Mossop et al., 1982; Mossop and Flach, 1983). Trace fossils clearly indicate a brackish estuarine depositional setting for these rocks (Pemberton et al., 1982; Ranger and Pemberton, 1992; Wightman et al., 1992; Bechtel et al., 1994). Other detailed sedimentological, ichnological and paleontological studies on these rocks include the work by Fox (1988) and Mattison and Pemberton (1988) at the Syncrude Oil Sands Lease 17; the overview by Wightman and Pemberton (1993) of the surface mineable area; and the subsurface study of James (1977) and James and Oliver (1978) to the east.

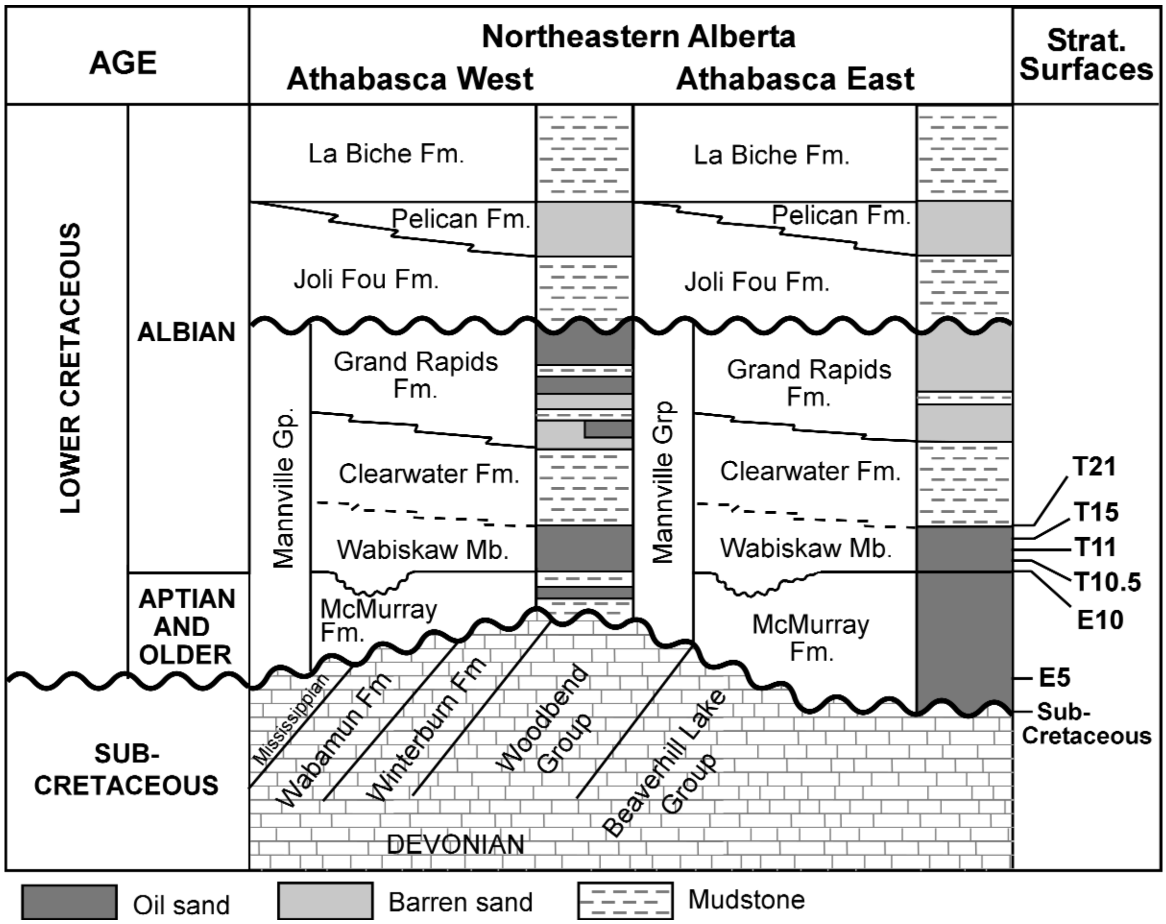

Figure 2. Stratigraphic nomenclature for Lower Cretaceous and older strata in the Athabasca deposit of northeastern Alberta; stratigraphic (strat.) surfaces show prominent geophysical log and stratigraphic 'picks' used in the Athabasca Oil Sands Database by the Alberta Geological Survey (Wynne et al., 1994; see also Appendix 1).

An older, pre-McMurray Formation, quartz-cemented sandstone of pre-Aptian (Valanginian or Hauterivian) age, reported by Burden (1984) from the Steepbank area, was sampled from the northern end of the Steepbank Outcrop #4, located in LSD 15, sec. 30, twp 92, rge 9, W 4th mer (15-30-092-09W4). Palynological analysis of samples from nearby wells AB/10-29-092-09W4 and AE/01-29-092-09W4 has recovered dinocysts, but they do not range below the Aptian (Middle Barremian). Consequently, the pre-Aptian date reported by Burden (1984) could not be confirmed (Hein et al., 2000, Appendix 4). A quartz-cemented sandstone was also sampled in outcrop in the Fort MacKay area; here, the oldest pollen appears to be Aptian–Cenomanian in age (Hein et al., 2000, Appendix 4). Additionally, Brideaux (1995) stated that for the base of the Mannville Group, there was no evidence for an age older than Aptian . If the date by Burden (1984) is correct, then very old, pre-McMurray remnants may be locally preserved.

Typically, in the past, the McMurray succession has been subdivided into three informal members: the 'Lower McMurray', interpreted as fluvial; the 'Middle McMurray', interpreted as estuarine channel and point bar; and the 'Upper McMurray', interpreted as coastal plain (Carrigy, 1959). Current lithostratigraphic and biostratigraphic frameworks show that distinctions between the 'Middle' and 'Upper' McMurray are not possible on a regional scale (Hein et al., 2000; Hein and Dolby, 2001). Locally, however, such lithostratigraphic designations may be useful within single lease areas, such as

- the Dover River Project (Alberta Oil Sands Technology and Research Authority [AOSTRA] Underground Test Facility) in twp 93, rge, 12, W 4th mer (Strobl et al., 1997a, b);
- the Deer Creek Energy Joslyn thermal recovery pilot (near the confluence of Joslyn Creek and the Ells River) in twp 96, rge 11, W 4th mer (Flach and Hein, 2001); and
- the proposed Pan Canadian Christina Lake thermal-recovery pilot near Chard, south of Fort McMurray in twp 77, rge 7, W 4th mer (Cody, 2001).

Although regional facies tracts such as fluvial, estuarine and coastal plain can be mapped in these different lease areas and designated as 'Lower', 'Middle' and 'Upper' McMurray, it is not clear, either through regional lithostratigraphic mapping/correlation or biostratigraphic dating, that these represent the same time slices of the McMurray Formation in these different areas. In this study, we follow the convention adopted by Hein et al. (2000, 2001), where the McMurray Formation is divided into a lower fluvial member and an upper estuarine–coastal-plain member.

McMurray Formation rocks were deposited in a ridge-and-valley system developed on the regional sub-Cretaceous unconformity. Deposits of the Lower McMurray represent a fluvial low stand systems tract of braided-fluvial continental sedimentation that infilled paleotopographic lows on the sub-Cretaceous unconformity surface (Hein et al., 2000, 2001; Flach and Hein, 2001). In outcrop and core, there are indications of a disconformity or unconformity separating the Lower and Upper (including the 'Middle') McMurray (Appendix 1, Surface E5). Regionally, coal or mudstone is preserved below the unconformity at the top of the Lower McMurray. These coal and mudstone units are interpreted as representing widespread flooding events prior to emplacement of the overlying transgressive and high-stand systems tracts of the Upper McMurray units (Flach and Hein, 2001). The interplay between rising sea level and northward-flowing fluvial-estuarine systems resulted in deposition of the main bitumen-bearing reservoirs of the Upper McMurray Formation.

For much of the Athabasca area, the Lower McMurray fluvial succession has a basal water leg (in lows along the sub-Cretaceous unconformity) overlain by bitumen of moderate to high grade; the lower part of the Upper McMurray ('Middle') has high bitumen content; and the upper part of the Upper McMurray is a weaker bitumen-bearing zone (e.g., Mossop, 1980a, b; Hein et al., 2000, 2001). Most characteristic of the McMurray Formation is the high degree of reservoir heterogeneity, which presents an enormous challenge for economic development of the oil sands (cf. McPhee and Ranger, 1998; Lee et al., 2000; Hein et al., 2001). A variety of units occur within the McMurray Formation, from fluvial-dominated to fluvial-estuarine channel and point bars, tidal flat-channel, brackish bay, open estuarine and various overbank settings, including peat swamps. The depositional settings and types of deposits are controlled, in part, by the pre-Cretaceous topography (Hein et al., 2000). Other paleotopographic controls on bitumen reservoirs reflect syndepositional solution collapse of underlying evaporites, which created a regional salt-dissolution front trending to the north, slightly oblique to the present-day main valley of the Athabasca River (Figure 3). To the north, in twp 93–97, rge 7–12, W 4th mer, a large depression (called the Bitumount Basin) formed largely in response to regional salt withdrawl and collapse, which resulted in increased accommodation space prior to and during McMurray sedimentation. Here, more open estuarine or bay-fill sand and mudstone are better developed, in response to a deeper seaward position and as a consequence of sedimentation rates matching relative sea-level rise associated with the ensuing transgressions (Hein et al., 2000; Cotterill et al., 2000). In the Clarke Creek and Steepbank River areas, fluvial and estuarine point-bar successions generally dominate, indicating a paleotopographically higher and more landward position, with less accommodation space and, by inference, less influence of salt-withdrawal tectonics during sedimentation. Further to the south (e.g., in twp 84–85, rge 5, W 4th mer), other salt-withdrawal collapse features influenced McMurray sedimentation in the Surmont

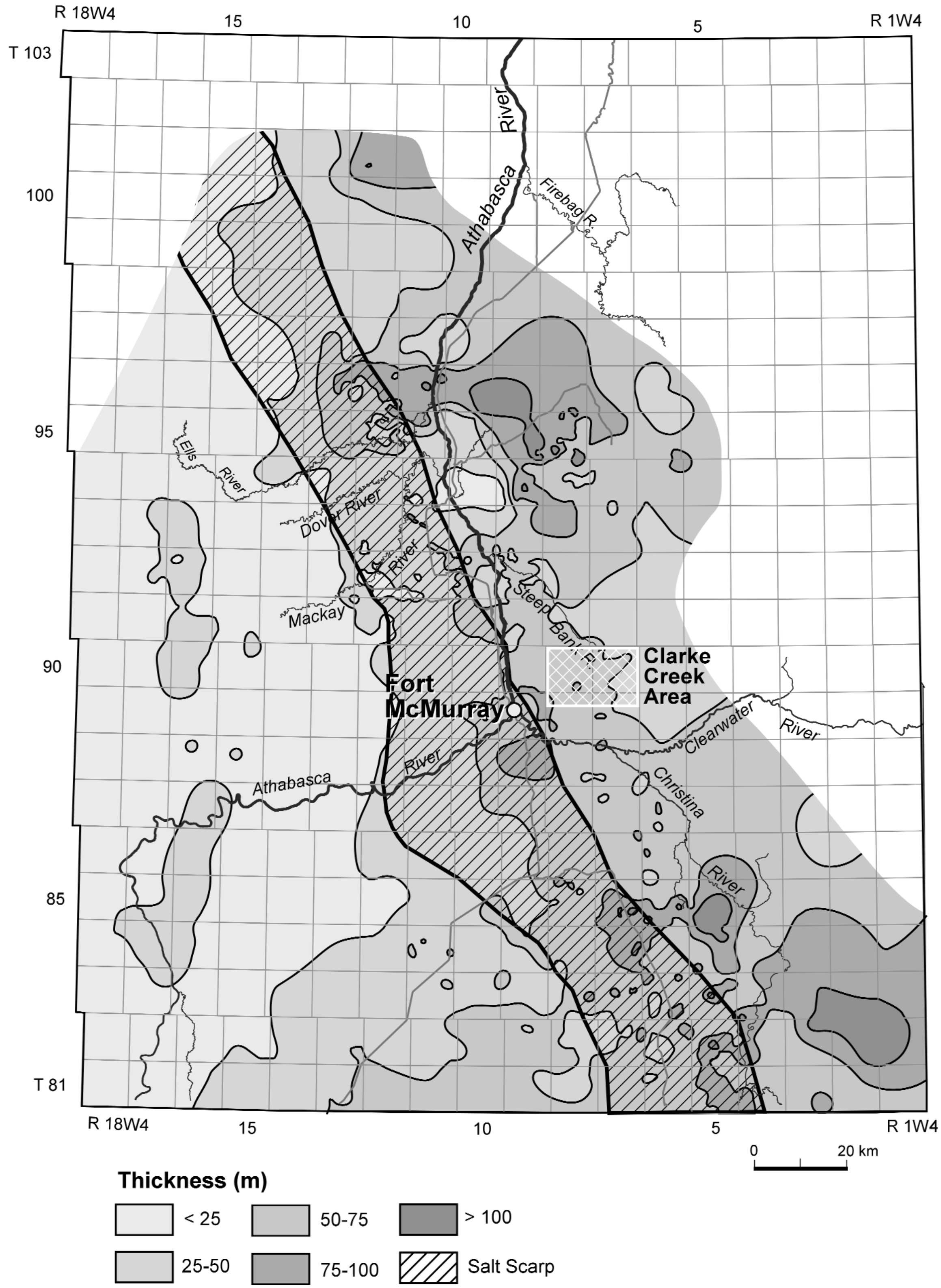

Figure 3. Isopach map of the McMurray Formation; regional salt-dissolution front shown by hachured pattern; Bitumount Basin underlies twp 95–97, rge 7–13, W 4th mer; Surmont area located in twp 84–86, rge 4–7, W 4th meridian.

area (Figure 3).

In the Clarke Creek area, the pre-Cretaceous unconformity (Figure 4) shows the regional dip to the southwest with minor undulations, resulting from limited karstification. A prominent low in the southwest results from more extensive karst and salt collapse. The top of the Lower McMurray Formation (Figure 5) shows highs and lows resulting from differential erosion by Upper McMurray estuarine channels. In contrast, the top of the Upper McMurray Formation is fairly flat along the regional dip, with a high in the central part of the area (Figure 6).

The present work is part of a larger, 3.5 year study by the Alberta Geological Survey dealing with regional lithofacies classification and reservoir characterization of the oil sands in the entire Athabasca deposit. The other results are published as a series of reports, including a lithofacies atlas and comprehensive field guide to the area (Hein et al., 2000, 2001).

3 Methodology

3.1 Subsurface Mapping

Since 1986, the Alberta Geological Survey has been conducting a program of regional mapping of the McMurray Formation and overlying Wabiskaw Member in the Athabasca oil sand deposit. This program has resulted in an Athabasca Oil Sands Database (Wynne et al., 1994). A relational database is used to manage the stratigraphic picks, to handle queries and to conduct regional mapping for resource characterization. Since its beginning, the database has ensured data consistency, and database management and reports are based on Structured Query Language (SQL) statements. To date, picks from more than 6000 well logs have been entered into this database (*see* Appendix 1 for a description of the picks and their reliability). Basically, two types of regionally correlative surfaces are picked: major erosional surfaces (E surfaces) with significant relief, and transgressive surfaces of erosion (T surfaces) with relatively minor or low relief. Included in these picks are the basal sub-Cretaceous unconformity (Pz), the unconformity between the Wabiskaw Member and the McMurray Formation (E10), and other regionally correlative markers, such as the top of the 'Wabiskaw D' (T10.5), the top of the 'Wabiskaw C' (T11), the 'Wabiskaw Marker' (T21) and so on (Figure 2).

For the Clarke Creek study area, a subset of the Athabasca Oil Sands Database consisting of about 60 wells was loaded into a Landmark Graphics Corporation GeoGraphix™ workstation for mapping, and logs were analyzed using the PRIZM™ module of GeoGraphix™, with the log-analysis program customized for the present oil sand project. Resource maps included regional structure on the base and top of the McMurray Formation and a McMurray Formation isopach, as well as detailed isopachs of sand, shale, gas and 6% tar-mass for the Steepbank River area. A major constraint on the distribution of wells for resource mapping was the availability of geophysical logs.

3.2 Dipmeter data

Interpreted dipmeter plots (tadpole plots) for 34 wells in the area were obtained from Mobil Canada (now ExxonMobil Corporation) and digitized for import into GaiaBASE™ (Gaia Software Inc.). A GaiaBASE™ data set was built that consists of picks and dipmeter data. These picks include the various lower Cretaceous picks and the base of the Quaternary deposits. The dipmeter data were recorded as good (solid tadpoles) or not so good (open tadpoles), according to the classification by the logging company. Only the good orientations were used in the analysis. The orientation data of dipping beds were analyzed by constructing dip profiles and by calculating the mean orientations for various intervals. The mean bedding orientations enable correlation of lateral-accretion bedding between wells that are spaced 400 m apart.

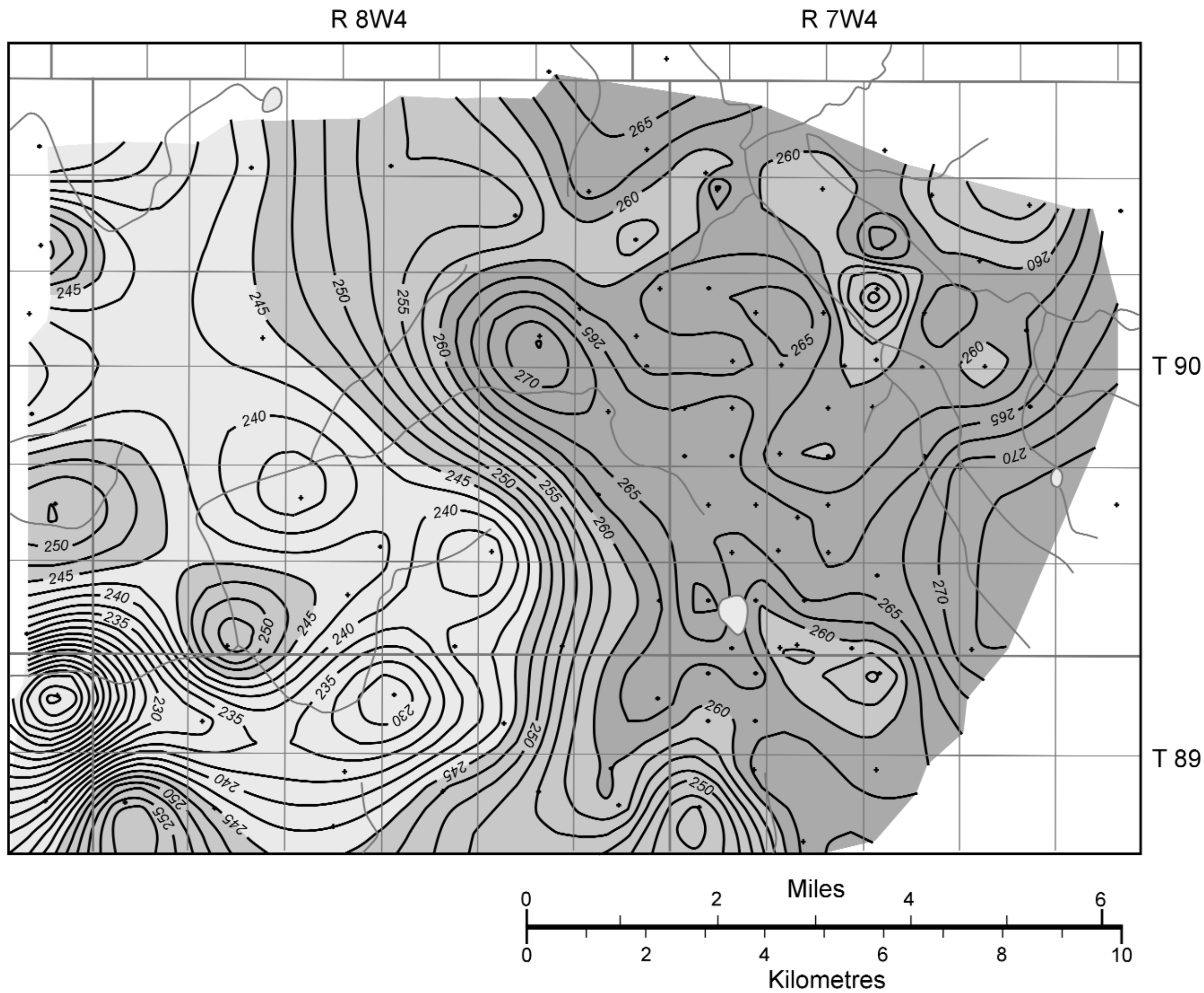

Figure 4. Structure on the pre-Cretaceous unconformity, Clarke Creek area; contour interval 2.5 m.

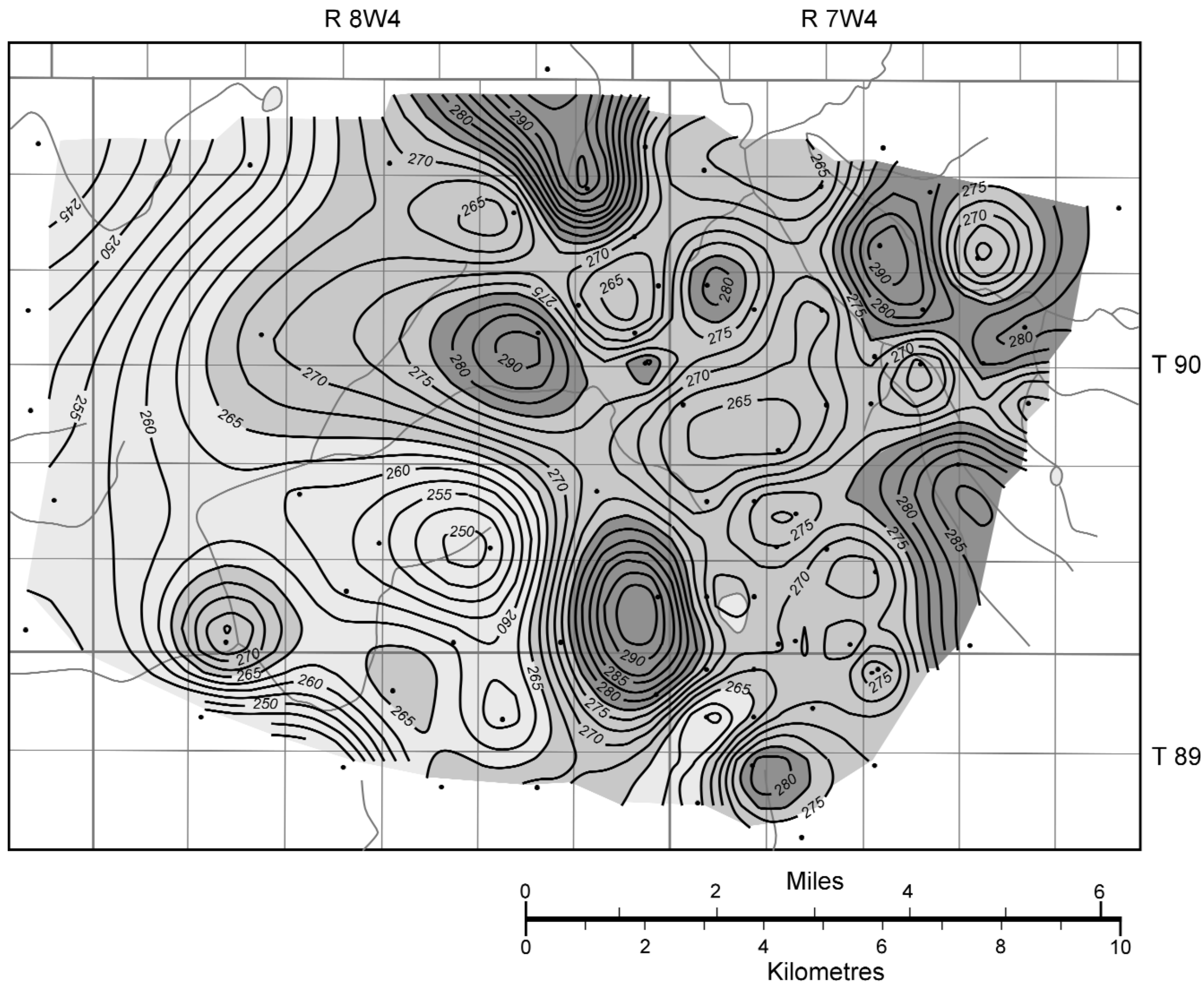

Figure 5. Structure on the top of the Lower McMurray Formation, Clarke Creek area; contour interval 2.5 m.

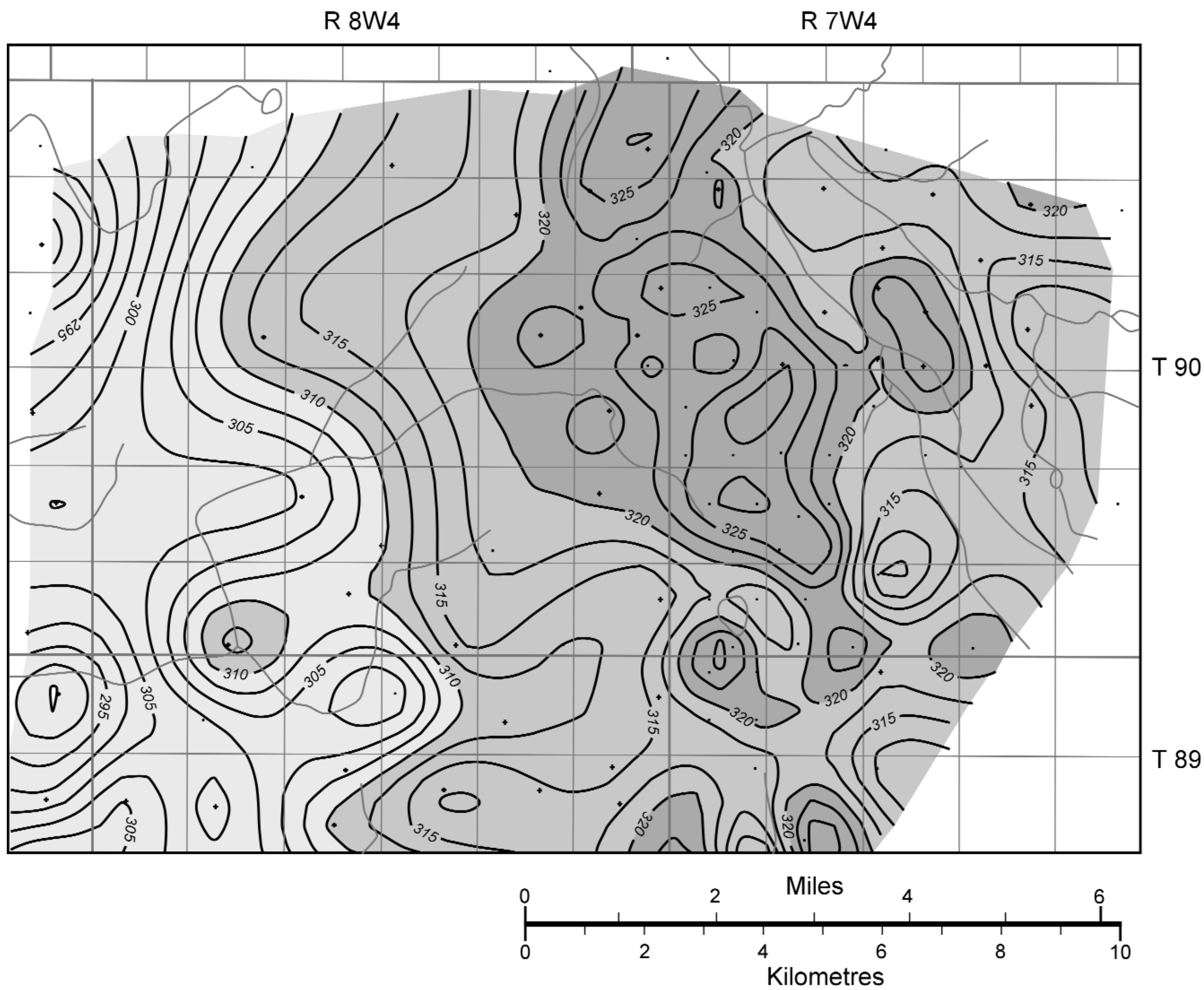

Figure 6. Structure on the top of the McMurray Formation (surface E10), Clarke Creek area; contour interval 2.5 m.

Industry terminology was used in the interpretation of dipmeter logs (Schlumberger, 1986). Industry has settled on a standard, whereby green lines connect dips of constant magnitude (green pattern), red lines connect dips that increase in magnitude with increasing depth (red pattern), and blue lines connect dips that decrease in magnitude with increasing depth (blue pattern). In this report, the coloured lines are not drawn on the figures, but the patterns are clear in the plots of true dip against depth.

The distinction of channel versus point bar was based on the following criteria. Within a single well bore, trough- and ripple-cross-bedded channel fills show a less organized and random orientation of dipmeter (tadpole) plots. In contrast, the consistent angles of dip and dip directions within lateral-accretion cross-beds result in strikingly uniform dipmeter (tadpole) plots. On average, the dips of the channel cross-beds tend to be at a higher angle (15–25°) compared with lower dips on inclined heterolithic stratification (10–15°). Finally, the dips of lateral-accretion cross-beds decrease downsection (blue pattern), whereas dips of vertical-accretion deposits (either point-bar top deposits or the fill of abandoned channels) increase downsection (red pattern). Using these patterns, the dipmeter data were used, in conjunction with subsurface cores and logs, to map the bases and edges of channels versus the extent of inclined heterolithic stratification, interpreted as point-bar deposits. By separating uniform versus nonuniform patterns, divergent trends, and upward decreasing or increasing dips during this mapping, one can separate individual point-bar sets and multistory channel fills from one another.

3.3 Seismic Lines

Four seismic lines, shot by Mobil Corporation (now ExxonMobil Corporation), were made available to the Alberta Geological Survey (AGS) as part of a research agreement between the two parties. The seismic data were acquired using vibroseis techniques, where frequencies between 8 and 250 Hz were collected, resulting in a high resolution of the geology. Beds with a spacing of about 2 m could be resolved on the seismic cross sections. Synthetic one-dimensional (1-D) seismograms of wells with sonic (and/or density) logs tied specific geological picks to the seismic data. Interpretations could then be drawn on the seismic lines, which were transferred to structural cross sections.

The orientation of the dipping beds at the intersection of the seismic lines can be calculated from two apparent dips on the intersecting planes.

3.4 Channel Complexes

In order to properly construct the lithostratigraphic framework needed for seismic interpretation, core and logs of wells were examined along cross sections. The unified lithofacies classification scheme developed by Hein et al. (2000) for the oil sands was used for bed-by-bed description. Major bounding surfaces could be defined in these wells, which were correlated along the cross sections. Vertical and lateral facies changes were described within different lithofacies packages separated by major bounding surfaces. Individual sediment bodies, called channel complexes, could be recognized. These channel complexes are generally bounded at the base by major scour features, and at the top by lateral-accretion cross-bedding. Channel complexes have consistent paleoflow patterns within them, and can be interpreted as 'genetically linked' facies associations that were deposited by a single episode of valley cut-and-fill. Similar units have been mapped in outcrop within the heterolithic valley-fill units of the Upper McMurray Formation along the Steepbank River (Langenberg et al., 2002).

3.5 Structural Cross-Sections

The GaiaBASE™ software was used to construct structural cross sections (with six times vertical exaggeration) with apparent dips of the dipping strata (measured by the dipmeter in the wells), together with picks in wells along the seismic lines. These cross sections form the framework for the interpretation of the subsurface, whereby interpretations from the seismic lines, tied by the synthetic 1-D seismograms of the wells, are drawn on the cross sections. These structural cross sections define the subsurface geology of the area.

4 Cored Intervals and Wireline Logs

Core from ten drillholes available at the EUB Core Research Centre (see Figure 7) allows the wireline log response to be tied to specific rock types and facies. Of these, two will be described below. An additional three wells drilled by Mobil Canada (now ExxonMobil Corporation) that have core were studied. The core from these three wells has not become part of the EUB core inventory (it is presently stored at Mineral Core Research Facility (MCRF), the AGS core-storage facility in Edmonton).

The AA/11-7-90-7W4 core (Figure 8) intersects the Wabiskaw D sand, Upper McMurray, Lower McMurray and Devonian successions. The Lower McMurray succession is about 2 m thick and consists of medium to fine sand. Abruptly overlying the Lower McMurray (from 185 to 173 m) is a thick succession of massive and parallel laminated sand beds with mudstone intraclasts that gradually fines upward, which is in turn overlain by sandy and muddy, inclined, heterolithic stratification that becomes muddier up-section. This package represents a lower estuarine channel, for which the dipmeter indicates westerly dips on the point bars (*see* 'Dipmeter Analysis' section). This is overlain, from 173 to 152 m, by another estuarine channel with westerly dipping point bars. Both channels have high bitumen content, as indicated by the staining. The upper part of the Upper McMurray is composed of amalgamated channels, topped by muddy embayment deposits. The McMurray succession is interpreted as fluvial for the Lower Member, followed by estuarine channel, estuarine point-bar and embayment deposits in the Upper Member.

The AA/16-24-90-8W4 core (Figure 9) intersects the Clearwater regional marine shale, with Wabiskaw C and D, Upper and Lower McMurray, and Devonian successions. Marl occurs just above the sub-Cretaceous unconformity. The underlying Devonian limestone shows karstic features. On wireline logs, the marly unit occurs as a low on the gamma-ray and resistivity curves. Overlying sand units of the Lower McMurray are pebbly, with planar tabular, trough and chaotic bedding. Abruptly overlying these are stacked complexes of tidal and estuarine channels, point bars and vertical-accretion abandonment fills that become muddier up section. Mudstone-intraclast breccia beds are common, along with trough and ripple cross-bedding, and inclined heterolithic stratification. Bitumen content is considerable, as indicated by black staining of the core.

Figure 10 shows core of massive oil sand and mudstone-clast breccia in the Lower McMurray of well Mobil AA/6-8-90-7W4. The photographed portion of the cored section is at the top of a coarsening- to fining-upward succession, interpreted as stacked channel-fill sand. Where the mudstone-clast breccia is the predominant facies, there is a response on the geophysical logs that could be interpreted as alternation of inclined heterolithic stratification but, upon examination of the core, consists of mudstone clasts within an oil sand unit. Additional massive oil sands are present in overlying channels of the Upper McMurray. The Lower McMurray has easterly dipping point bars and the Upper McMurray has westerly dipping point bars (*see* 'Dipmeter Analysis' section).

Core of well Mobil AA/8-31-89-7W4 (Figure 11) shows rippled sand at the base, overlain by low-angle inclined mudstone interbeds and mudstone-clast breccia alternating with massive oil sand. This portion of the core in the photograph is near the top of an upward-fining succession of the Upper McMurray Formation, interpreted as a channel to point-bar transition.

Figure 12 shows fine-grained overbank deposits within the Upper McMurray Formation in the core of well Mobil AA/10-20-090-07W4. Within the cored portion is thinly laminated and interbedded, silty

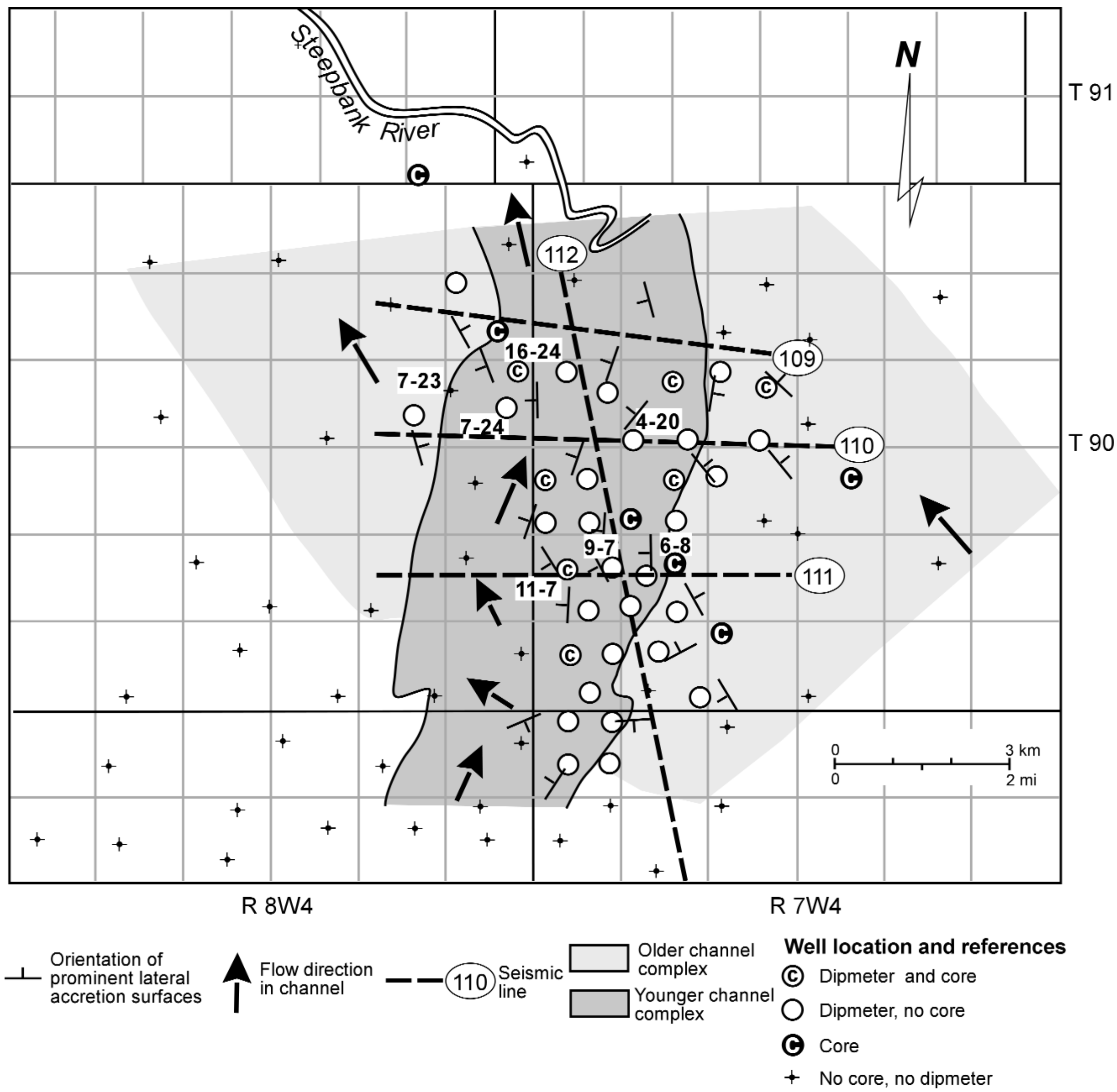

Figure 7. Clarke Creek area, showing seismic lines, interpreted distribution of Upper McMurray Formation (older and younger channel complexes), inferred paleoflow patterns and orientation of interpreted, prominent, lateral-accretion surfaces.

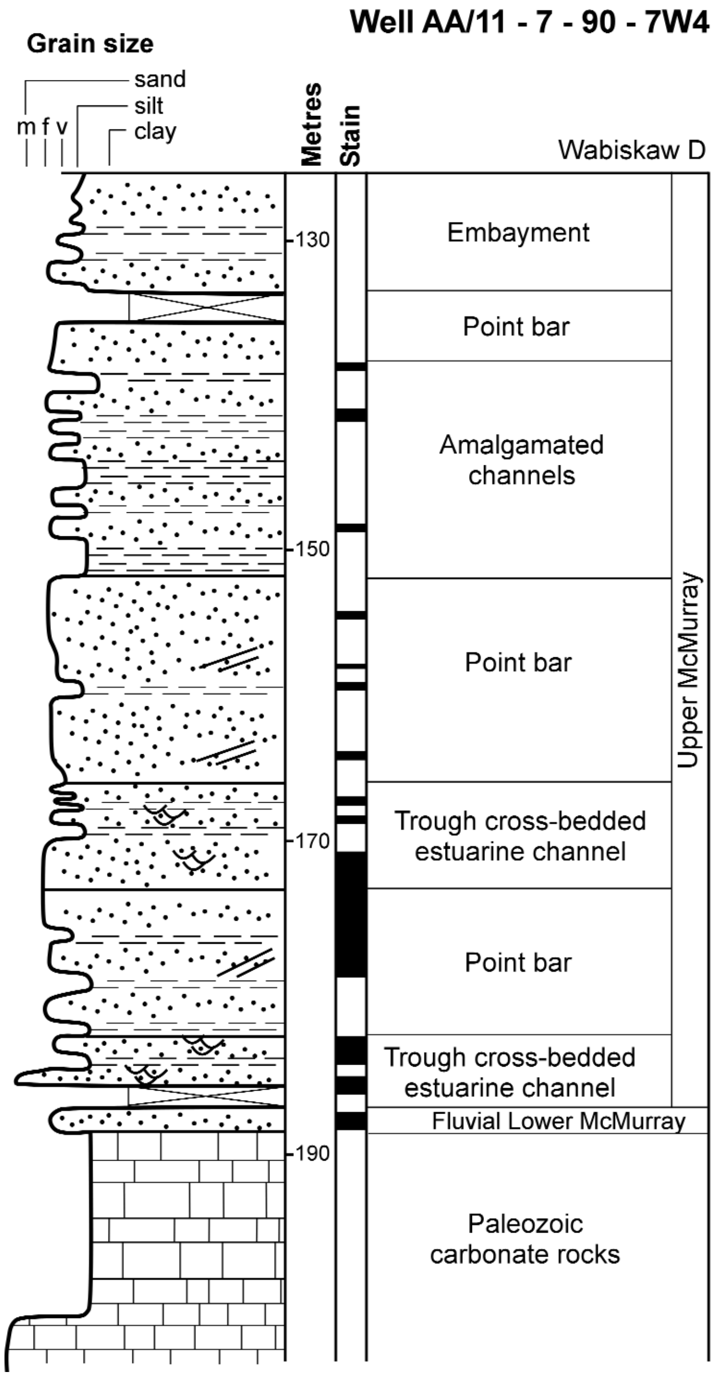

Figure 8. Measured stratigraphic-sedimentological log of core from the AA/11-7-90-7W4 well, located along seismic line 111 (see Figure 7 for location).

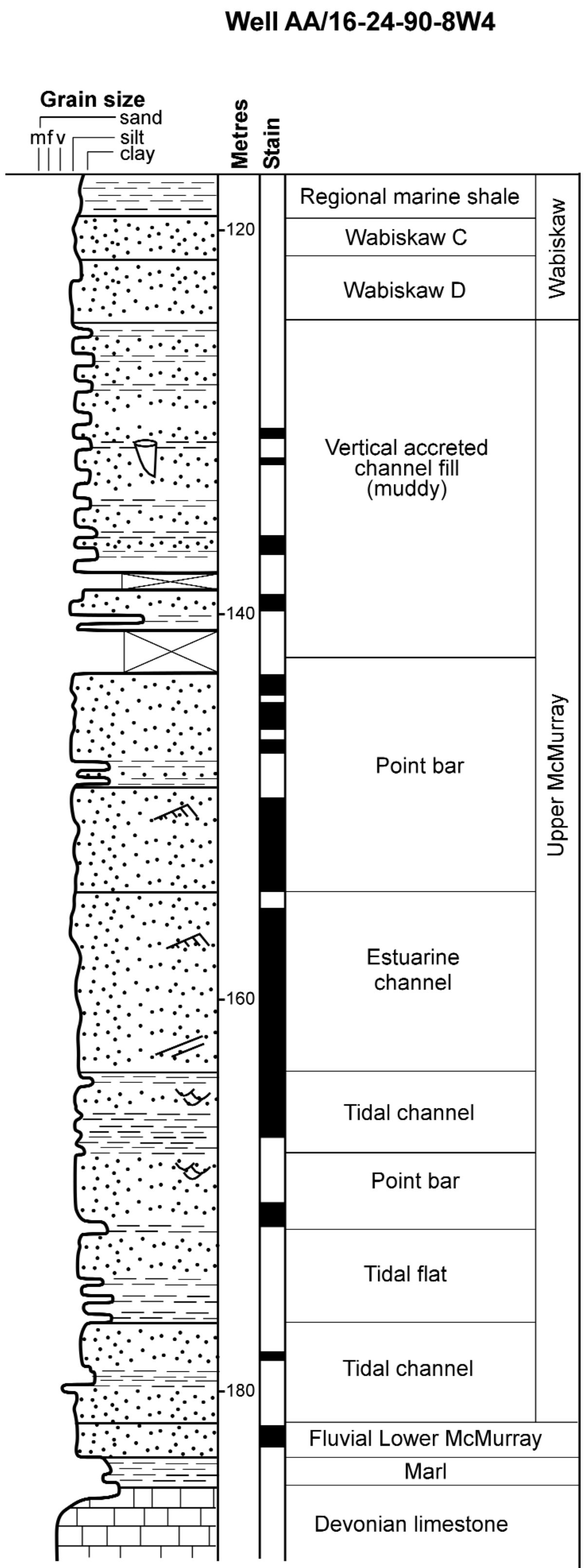

Figure 9. Measured stratigraphic-sedimentological log of core from the AA/16-24-90-8W4 well, located between seismic lines 109 and 110 (see Figure 7 for location).

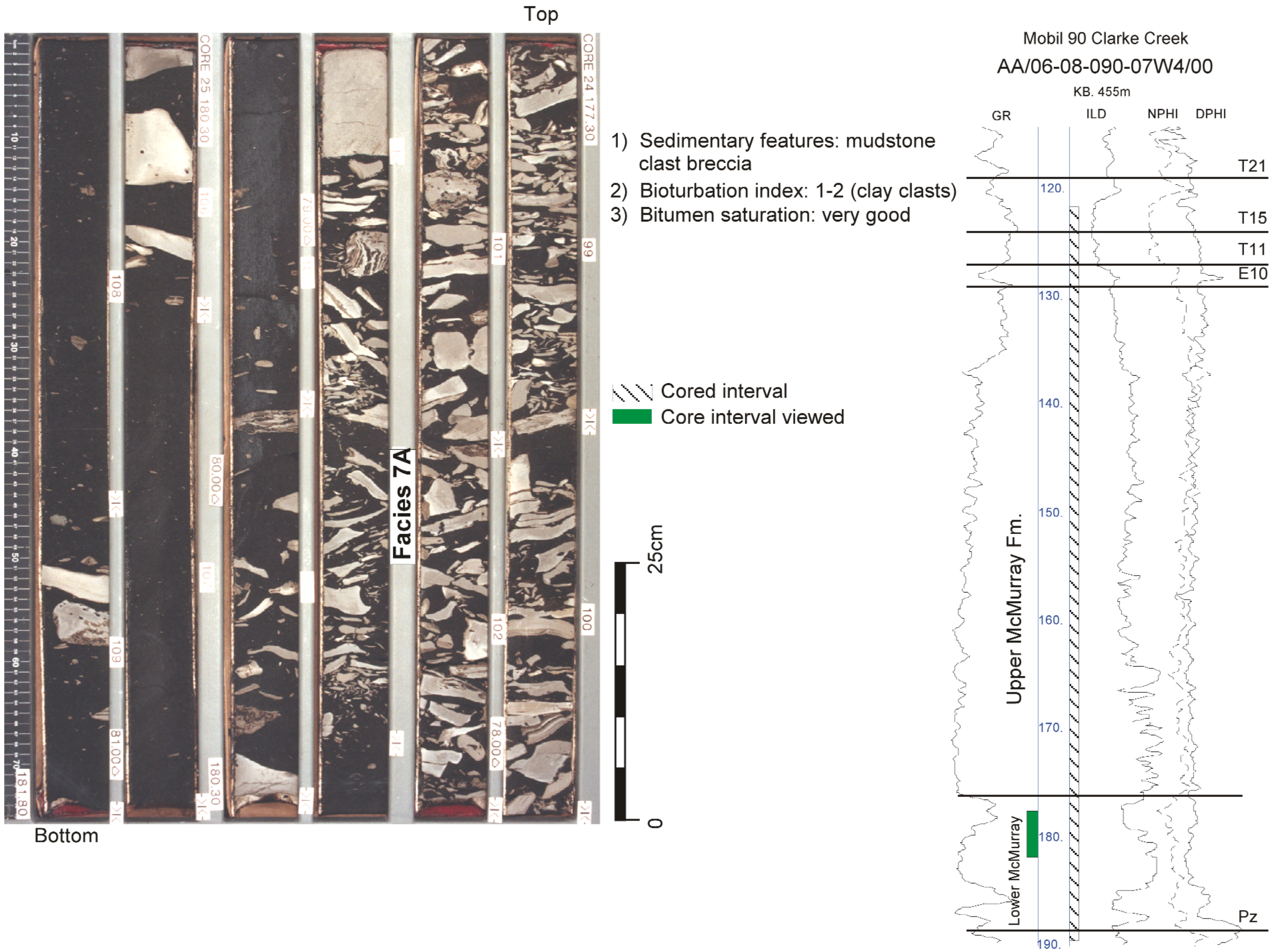

Figure 10. Heavily bitumen-stained, matrix-supported mudstone breccia, interbedded with massive sand at the base, Lower McMurray Formation in well AA/6-8-90-7W4 along seismic line 111 (see Figure 7 for location).

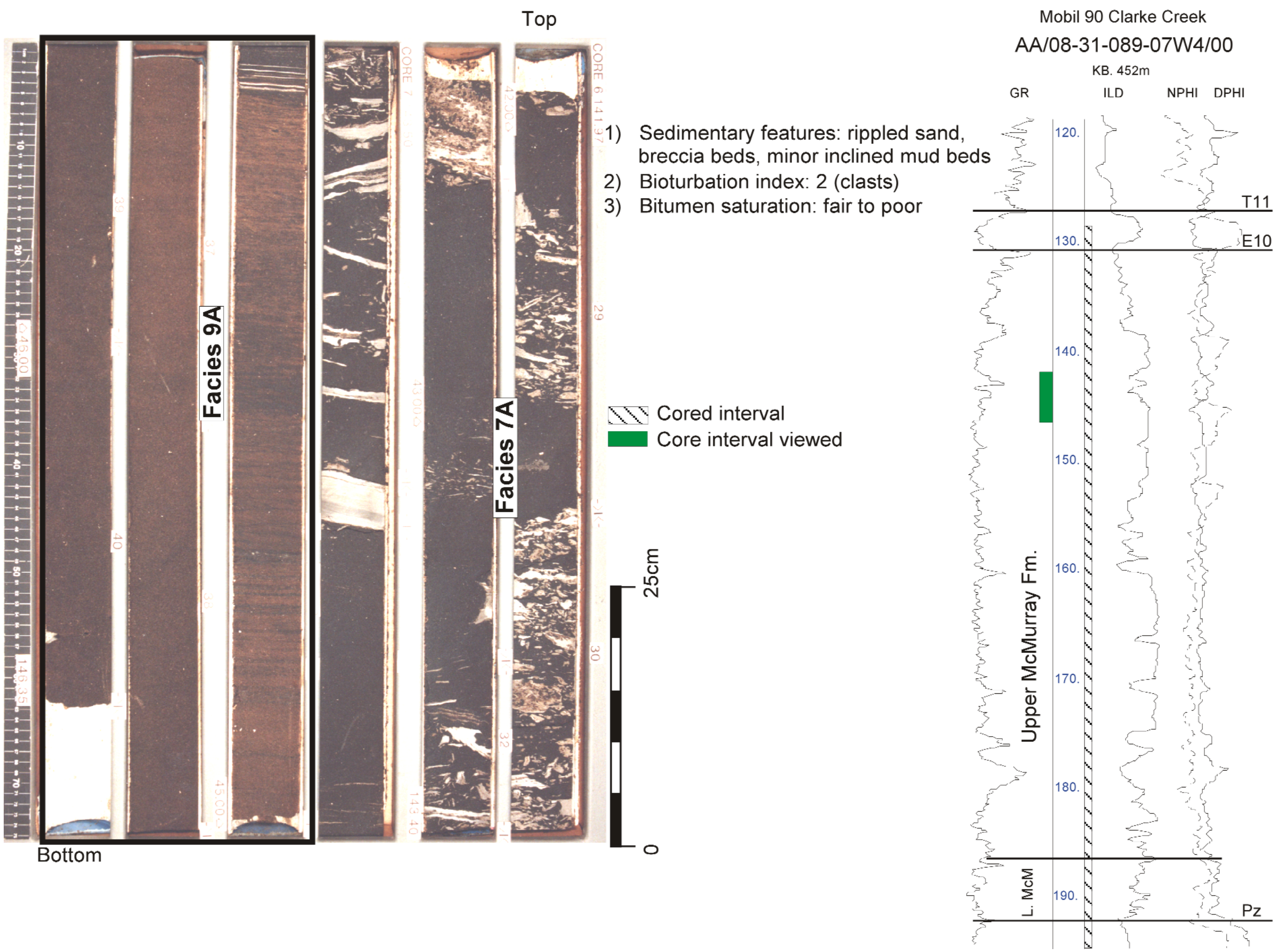

Figure 11. Rippled sand, overlain by mudstone-clast breccia beds with inclined mud beds (point bars) in well AA/8-31-89-7W4.

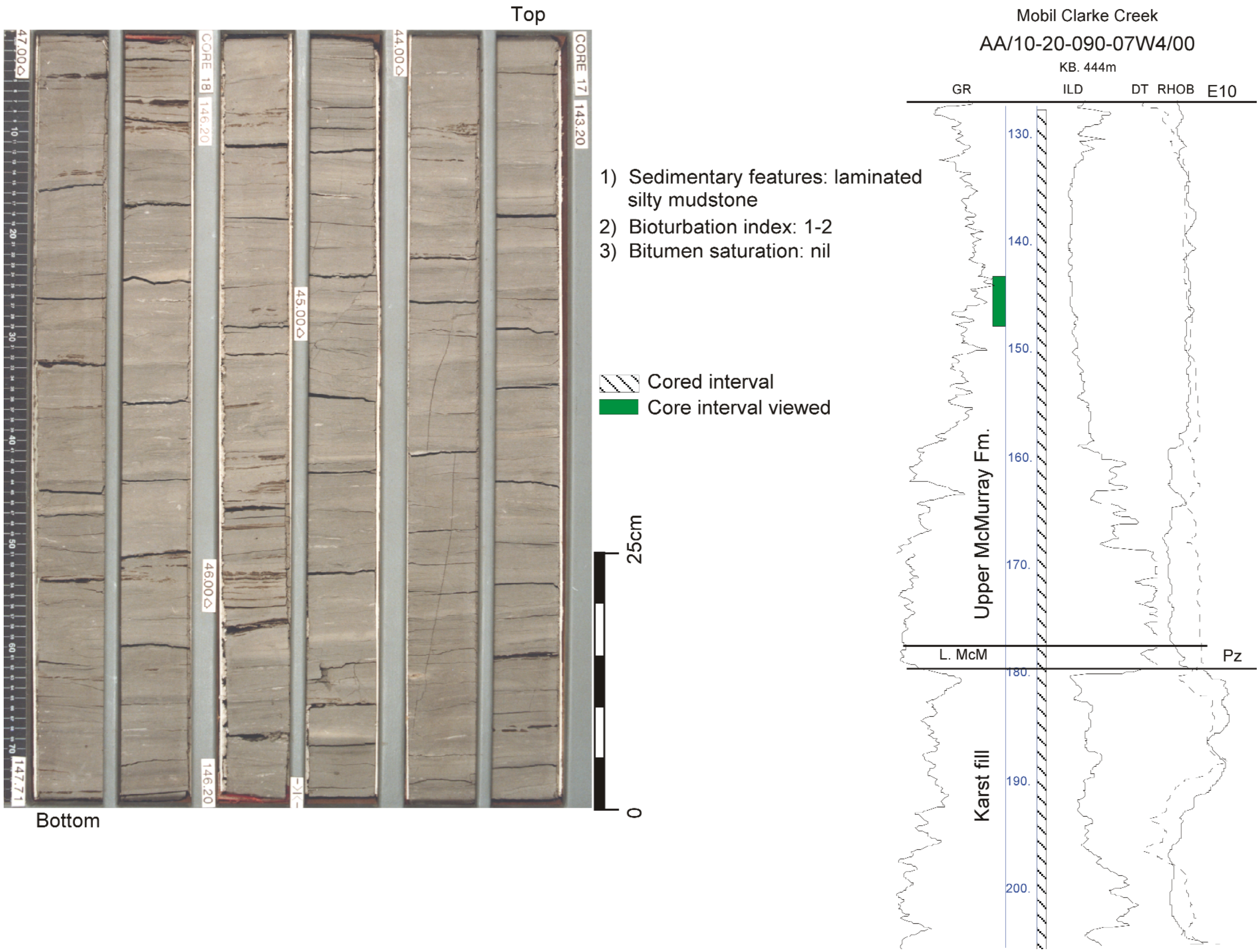

Figure 12. Thinly laminated and interbedded, silty mudstone, showing minor bioturbation in well AA/10-20-90-7W4.

mudstone with rare, mainly horizontal burrows (*Planolites*). The photographed portion of the core is at the top of a fining-upward succession, within what is overbank and vertical-accretion abandonment fill. Below these fine-grained units are thick, massive, estuarine-channel deposits, and fining-upward, interbedded sand and mudstone of the estuarine point-bar successions.

5 Dipmeter Analysis

Dipmeter data were used, in addition to core and wireline logs, to define channel complexes (Figure 7). When mapping the channel complexes, in addition to separating the multistory events, detailed analysis of the true dip and azimuth patterns can be used to identify large-scale cross-bedding and to get an idea of paleocurrent changes through time. All of the available dipmeter logs for the area were analyzed to help define the boundaries of channel complexes in the subsurface of the area. Six of these show representative patterns, and are described below. Three are along line 110 and the other three along line 111 (Figure 7).

5.1 Wells along Line 110

The dipmeter logs from well AA/07-23-090-8W4 (Figure 13) show abrupt changes in both the true dip and azimuth between the McMurray Formation and the overlying Wabiskaw Member and underlying Paleozoic successions, with the base and top of the McMurray at depths of about 172 and 120 m, respectively. Within the Lower McMurray succession, more random orientations occur from about 172 to 166 m; these are interpreted to represent trough cross-bedding within channel-sand units. This is overlain, from 167 to 163 m, by a stacked succession that shows low-angle divergences in dip that are interpreted as representing deposition from large-scale bedforms, such as braid bars, within the upper part of the Lower McMurray Formation. Intervals from 163 to 146 m and from 146 to 128 m probably correlate with multistory deposition from amalgamated point bars in the different channels within the Upper McMurray succession. The true dip shows the typical steepening and flattening of bedding orientation in point bars. The azimuth (and section profile) shows that the dip of this channel complex is to the east, which is supported by the seismic data.

In the dipmeter logs from well AB/07-24-090-08W4 (Figure 14), the base of the McMurray is marked by an abrupt change in dip direction and variation, which become much shallower and more uniform in the McMurray succession compared with the underlying units. Within the underlying Paleozoic, very high dips were recorded, with apparently opposing dip directions. These may represent fractures or rotated karst-block features below the sub-Cretaceous unconformity. Within the Lower McMurray succession, more even, low-angle bedding orientations occur from about 178 to 173 m; these are interpreted as overbank abandonment-fill mudstone. This is overlain by four stacked successions that show divergences in dip, at 173 to 166 m, 166 to 148m, 148 to 129 m and 129 to 125 m, each corresponding to different amalgamated Upper McMurray channels and together forming a channel complex. In contrast to well AA/07-23, this well shows 1) much more random dip patterns in the underlying Paleozoic; 2) higher dips, interpreted as more channel influence in the lower part of the Upper McMurray; and 3) more gradual and subtle changes in the upper part of the Upper McMurray that may reflect subtle switching of multistory estuarine point bars. The dip of these point bars is to the west.

The dipmeter data from well AA/04-20-090-07W4 (Figure 15) show flat strata in the Wabiskaw and Paleozoic and characteristic point-bar patterns in the McMurray Formation. The Lower McMurray could not be picked in the logs and was probably eroded. The Upper McMurray shows stacked channels, at 182 to 166 m, 166 to 150 m, 150 to 134 m and 134 to 124 m, that together define a west-dipping channel complex. The interval from 134 to 150 m is a nice example of downward steepening on top of quickly downward flattening (red over blue pattern), typical of a point bar. The dips are to the northwest,

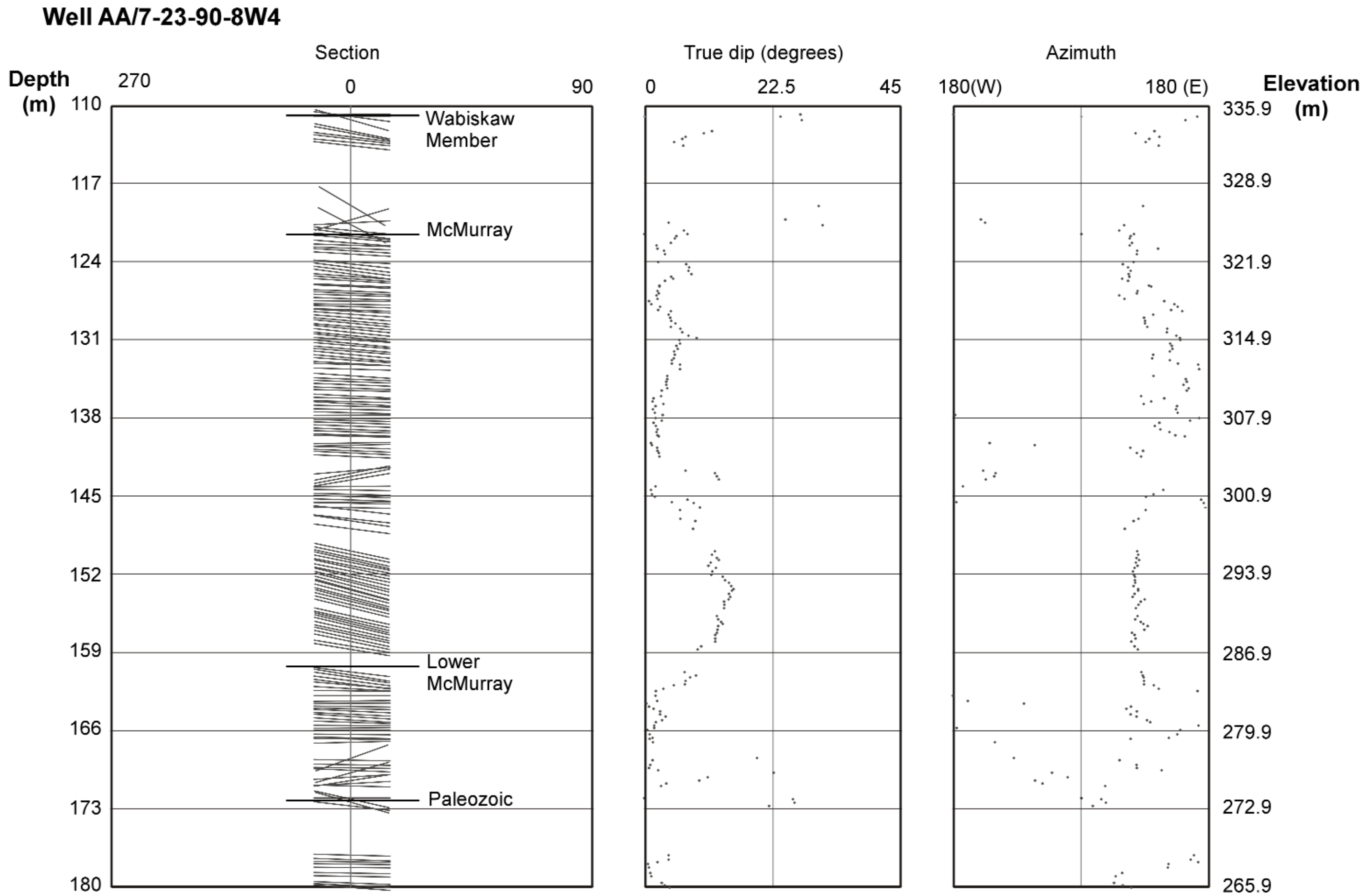

Figure 13. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AA/7-23-90-8W4; stratigraphic picks shown on section view.

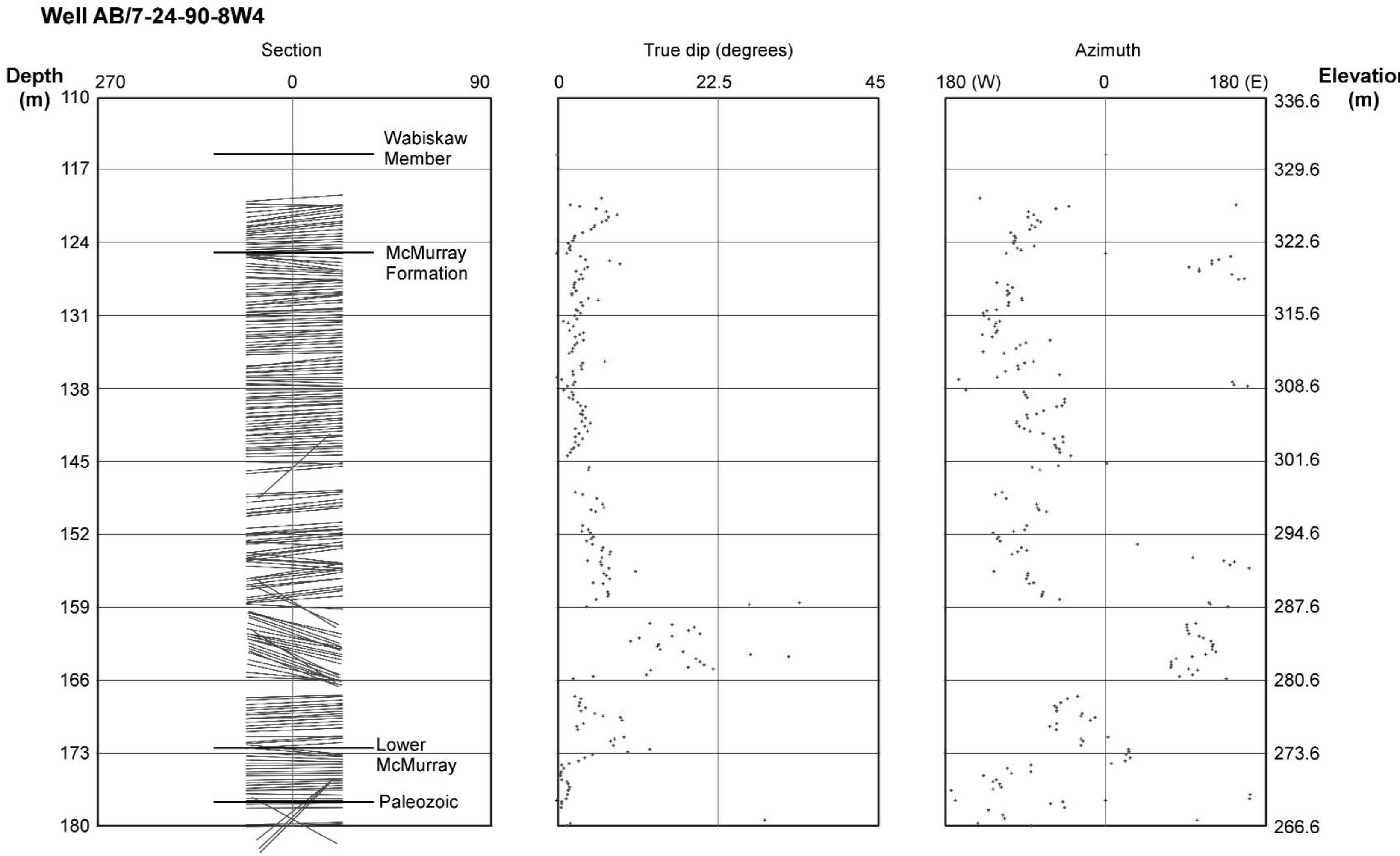

Figure 14. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AB/7-24-90-8W4; stratigraphic picks shown on section view.

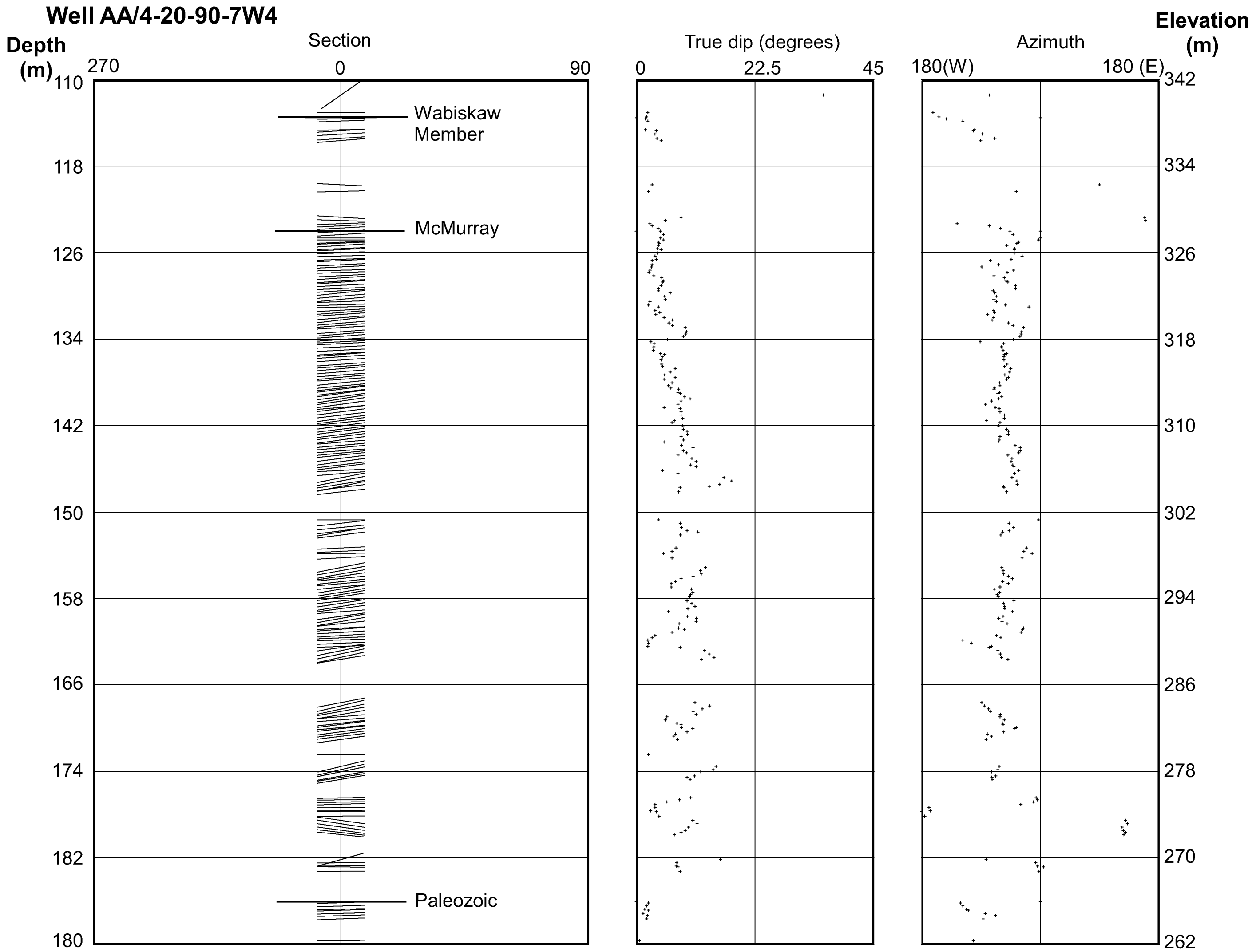

Figure 15. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AA/4-20-90-7W4; stratigraphic picks shown on section view.

except in the interval above the sub-Cretaceous unconformity, indicating that the well intersects a channel complex that was also intersected by well AB/07-24-090-08W4.

5.2 Wells along Line 111

The dipmeter data from well AA/11-07-090-07W4 (Figure 16; *see also* Figure 8) show a clear unconformity at the Paleozoic–Cretaceous contact. The Lower McMurray shows some low dip, possibly indicating trough cross-bedding in a fluvial channel. The interval from 185 to 172 m has varying dips in varying directions, indicating trough cross-bedding with some steeper parts, possibly resulting from slumping. The rest of the Upper McMurray shows a stacked succession of channels, together forming a channel complex. Individual channels are present in the intervals 172 to 165 m (also shown by the core of Figure 8), 146 to 141 m and 141 to 133 m, displaying typical point-bar patterns (red over blue). The interval 165 to 146 m probably represents various channels that cannot be precisely subdivided. The upper interval, from 133 to 124 m, is flat lying and represents embayment deposits.

Well AA/09-07-090-07W4 (Figure 17) shows the Lower McMurray (fluvial) with varying dip values and directions, indicating a variety of cross-bedding. The Upper McMurray, from 176 to 159 m, shows varying dip values in consistent westerly directions, possibly indicating trough cross-bedding. The interval from 159 to 141 m represents one point bar in a channel (red over blue pattern) dipping to the west, part of an Upper McMurray channel complex. The low dip from 141 to 125 m indicates fine-grained overbank deposits, away from the channel.

The slight dip to the east of the Paleozoic in well AA/06-08-090-07W4 mimics that of the Lower McMurray (Figure 18; *see also* Figure 10). This easterly dip distinguishes the Lower McMurray from the Upper McMurray, which shows westerly dips in stacked channels. Individual channels can be seen in the intervals from 155 to 145 m and 139 to 134 m. These channels form part of a younger channel complex, cutting into an older complex of generally east-dipping point bars that are present in well AA/2-8-90-7W4, 500 m east of the this well.

6 Cross Sections and Seismic Lines

Major bounding surfaces between the different rock units can be recognized and mapped using the subsurface data. Rock types in the Upper McMurray succession were summarized using both dipmeter and seismic surveys along the four seismic lines (Figure 7) to build representative structural sections of the area. Seismic results from the Clarke Creek area show that the major bounding surfaces are recognizable, and can be used as markers in seismic interpretation. These surfaces include the top of the Paleozoic; the top of the Lower McMurray, which has internally complex interbedding and acoustically transparent zones; and the top of the Upper McMurray, which has divergent reflectors, internally transparent zones and low-angle cross-bedding, interpreted as lateral-accretion cross-beds from the migration of point bars. The overlying Wabiskaw Member and Clearwater Formation show mainly parallel, highly reflective units that generally drape the topography along the E10 marker. Much of the chaotic pattern above the Clearwater Marker is an artifact of the seismic survey being shot in an area of muskeg, but the base of the Quaternary can be picked as a high-contrast, highly reflective surface.

6.1 Line 109

The interpretation of seismic line 109 is shown in Figure 19. The sub-Cretaceous unconformity is fairly flat, but shows some karst relief near well AA/13-21-090-07W4. The overlying Lower McMurray succession is mainly an acoustically transparent, sheet-like unit that covers the Paleozoic succession thinly, except in the west where it is 31 m thick in well AA/13-25-90-8W4. This interval represents an erosional remnant, which was left by younger Upper McMurray channel complexes. Large-scale channel forms

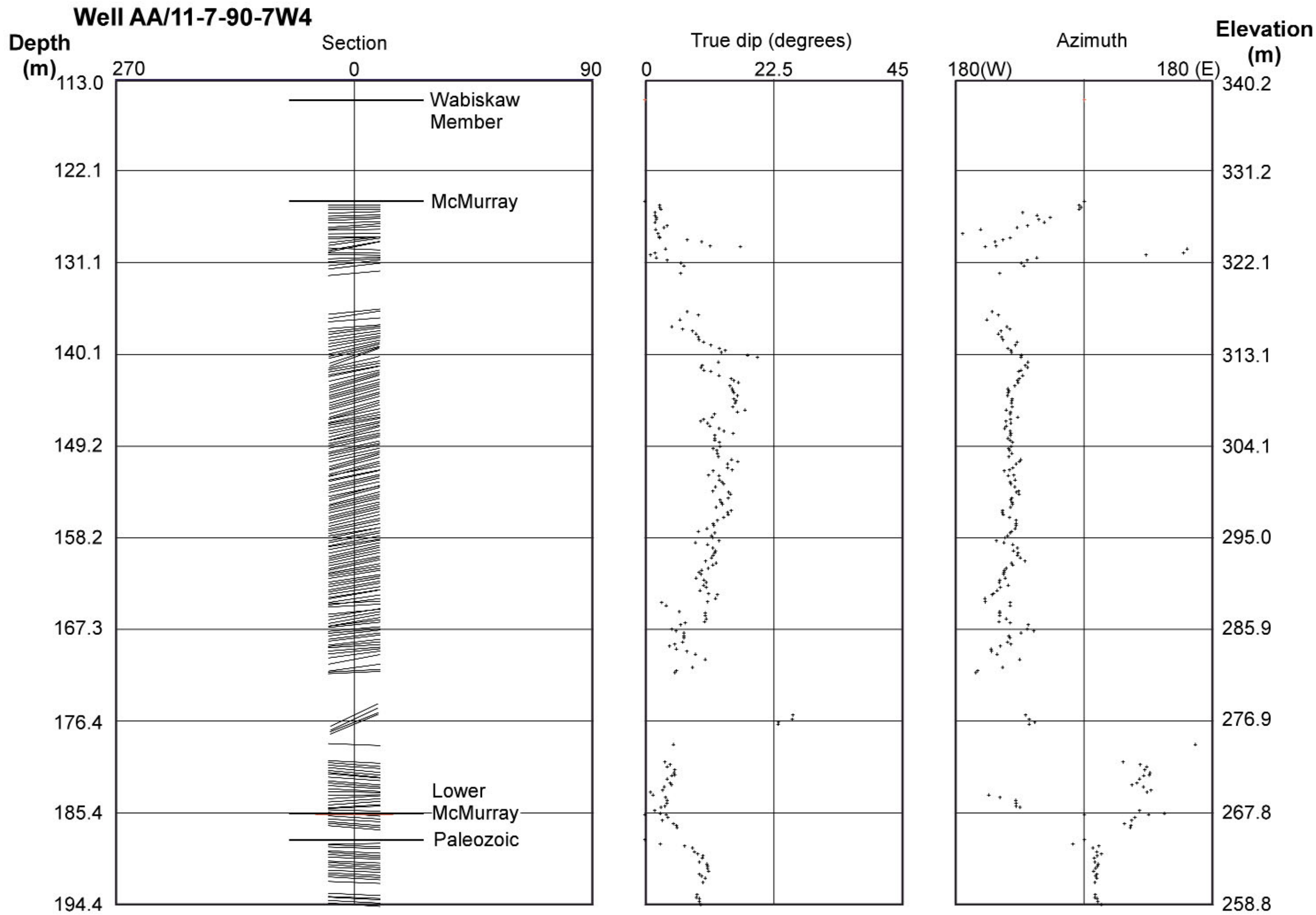

Figure 16. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AA/11-7-90-7W4; stratigraphic picks shown on section view.

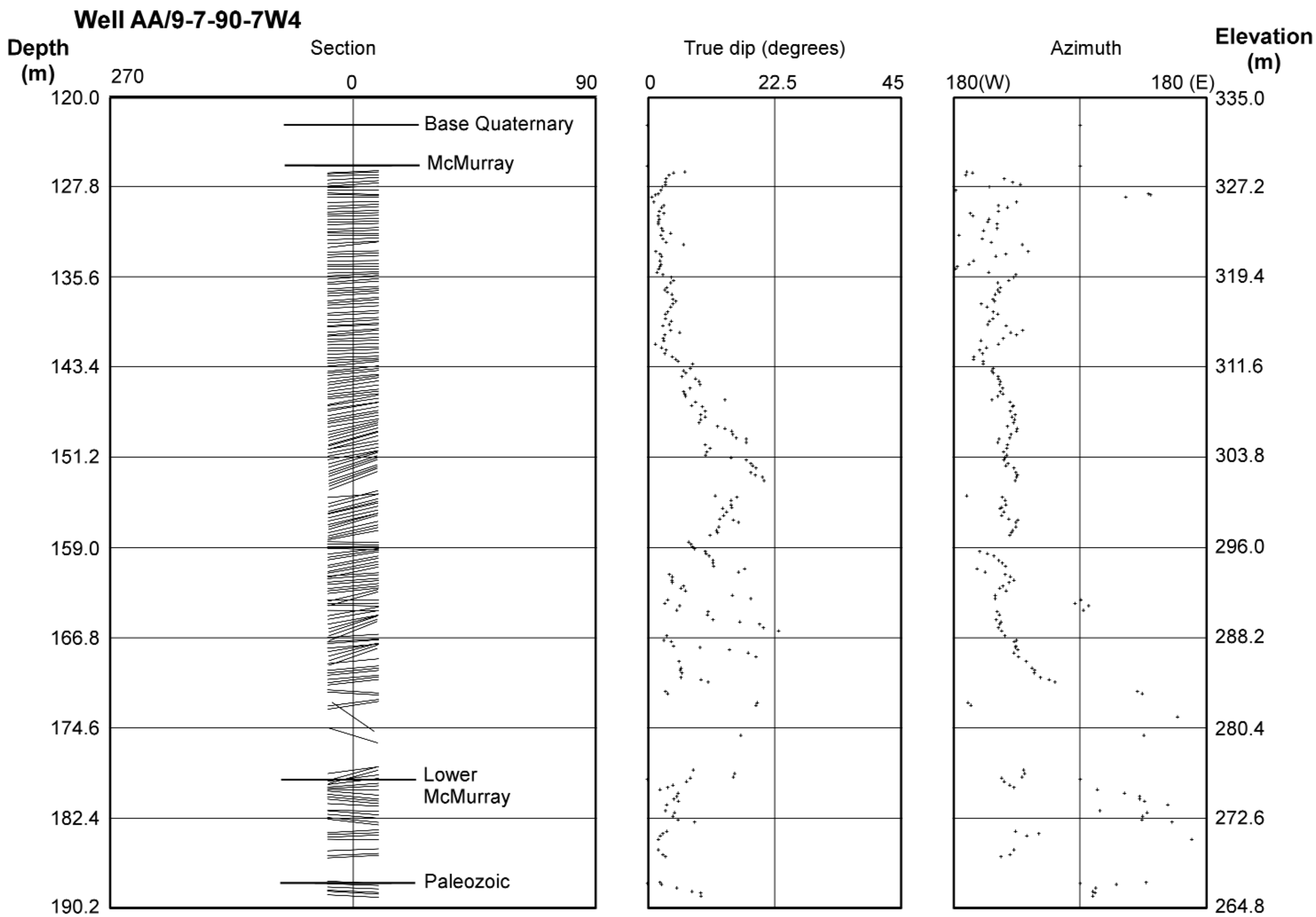

Figure 17. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AA/9-7-90-7W4; stratigraphic picks shown on section view.

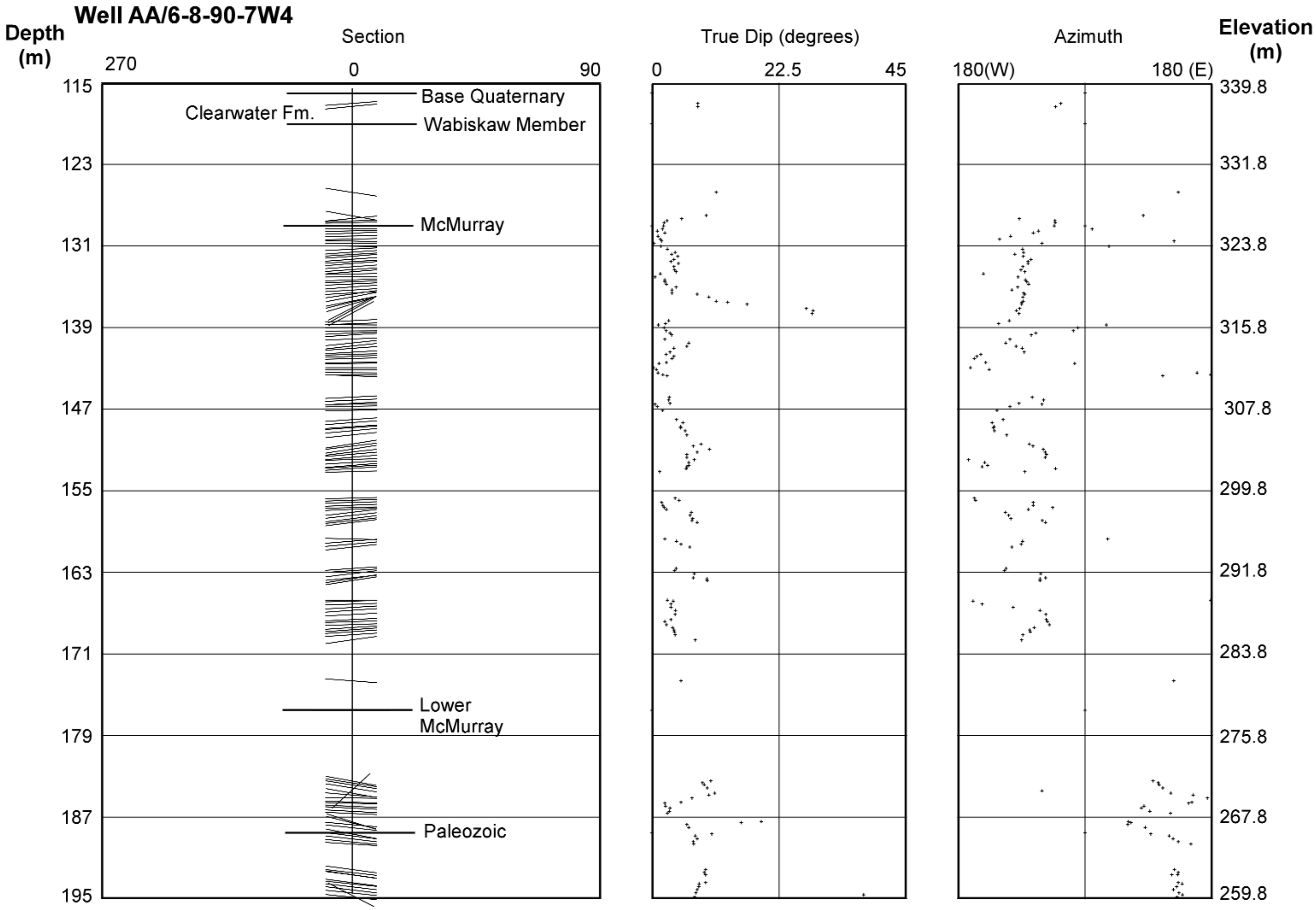

Figure 18. Dipmeter profile with stick-plot section view, true dip view and azimuth view of well AA/6-8-90-7W4; stratigraphic picks shown on section view.

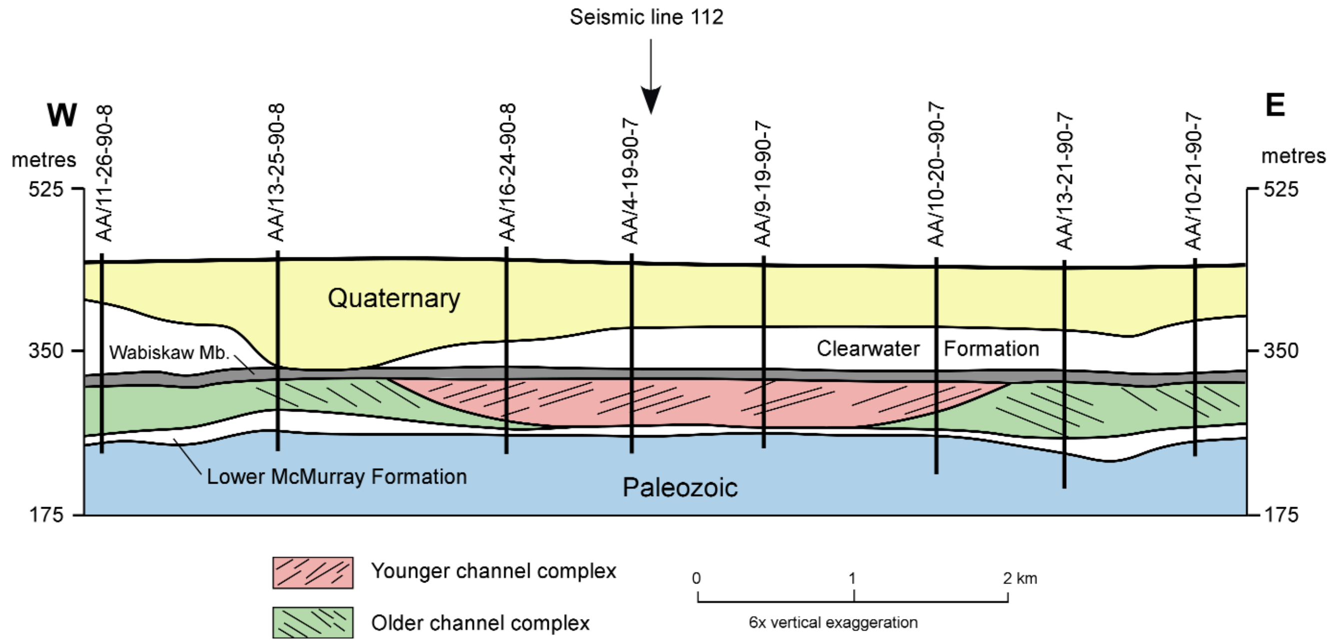

Figure 19. Structural cross section along seismic line 109, from west to east, showing changes within the Lower and Upper McMurray Formation, Wabiskaw Member, Clearwater Formation and Quaternary successions; subsurface well control and intersecting seismic line are shown; 6x vertical exaggeration.

are recognized within the Upper McMurray flow units, which crosscut into one another and show three types of internal reflectors: high angle, low angle inclined and horizontal. An older channel-point-bar complex migrated to the east, leaving a thick set of low- to high-angle cross-bedding. In the middle of the structural section, a younger flow unit incised and removed most of this deposit. After this channel was cut, it was infilled by similar meandering-channel and point-bar successions that migrated to the west. Two traces of dipping bedding on the two intersecting seismic lines (109 and 112) define a dip of 7° in direction N307°E. This direction is confirmed by dipmeter data from well AA/9-19-90-7W4.

The top of the McMurray Formation is the E10 marker, which in this area is fairly flat lying. Overlying Clearwater Formation sedimentary rocks were largely scoured out by the sub-Quaternary unconformity, and thick Quaternary units are present in this area. The sub-Quaternary unconformity cuts down to the Wabiskaw Member (near well AA/13-25-90-8W4) in a Quaternary channel, which is part of the Clarke Channel (Andriashek and Meeks, 2000). This is clearly shown by both the well and the seismic line.

6.2 Line 110

On line 110, the sub-Cretaceous unconformity is an obvious reflector that is fairly flat and lacks pronounced karst relief (Figure 20). The overlying Lower McMurray succession is mainly an acoustically transparent, thin, sheet-like unit that covers the Paleozoic succession. Minor large-scale and high-angle cross-bedding is seen both in core (i.e., AA/14-19-090-07W4) and in seismic data. The top of the Lower McMurray is difficult to distinguish from the lower part of the Upper McMurray succession, where sand-on-sand contacts are observed between channel units in the core. On the seismic images, the successions appear to be acoustically transparent (dashed lines in Figure 20). In other cases, the Lower McMurray succession has been eroded and reworked into the channel sand of the Upper McMurray (i.e., near well AA/2-19-090-07W4).

Large channel forms are recognized within the Upper McMurray channel complexes. The divergences in apparent cross-bed directions above and below the internal scours are interpreted to reflect the multistory stacking of meandering-channel–point-bar complexes upon one another. This is most readily seen in the section (Figure 20), in which an older channel–point-bar complex migrated to the east, leaving a thick set of low- to high-angle cross-bedding. In the middle of the structural section, a younger channel complex incised and removed most of this deposit, as well as the underlying Lower McMurray succession. After this channel was cut, it was infilled by similar meandering-channel and point-bar successions that migrated to the west.

The top of the McMurray Formation is marked by the E10 marker, which shows reduced paleotopography in this area compared to the Steepbank River area. The only significant relief on the E10 marker occurs as a channel fill midway between wells AA/07-23-090-08W4 and AA/07-24-090-08W4 (Figure 20). Overlying Clearwater Formation sedimentary rocks were largely scoured out by the sub-Quaternary unconformity, and thick Quaternary units are present.

There may be some structural control on the distribution of channel margins in this area. For example, the channel edge west of well AB/07-24-090-8W4 was maintained as a ‘low’ in the overlying Wabiskaw Member, with some offset up-section in the sub-Quaternary erosion surface. As shown in Figure 21, there is a major discordance along the left side of the seismic image. To the right of the discordance is a thickened section between the E10 and Clearwater markers, and there are low-angle dipping surfaces within the Upper McMurray. These features are interpreted to reflect meandering-channel (to the west) and point-bar (to the east) sedimentation and migration during Upper McMurray time, which formed part of the younger channel complex defined by the dipmeter and seismic data. The seismic image in Figure 21 is one of the best subsurface pictures of inclined heterolithic stratification in the Alberta

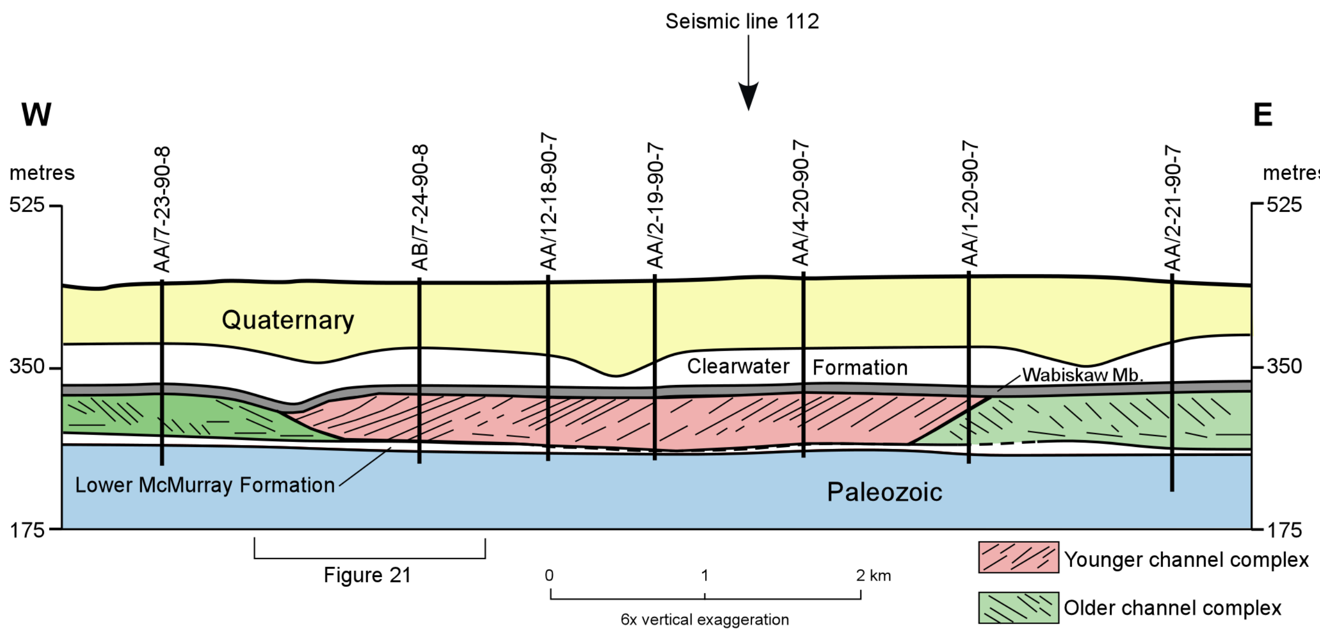

Figure 20. Structural cross section along seismic line 110, from west to east, showing changes within the Lower and Upper McMurray Formation, Wabiskaw Member, Clearwater Formation and Quaternary successions; subsurface well control and intersecting seismic line are shown; 6x vertical exaggeration; location of Figure 21 indicated; dashed lines indicate areas of acoustic transparency and uncertainty regarding the presence of Lower McMurray Formation.

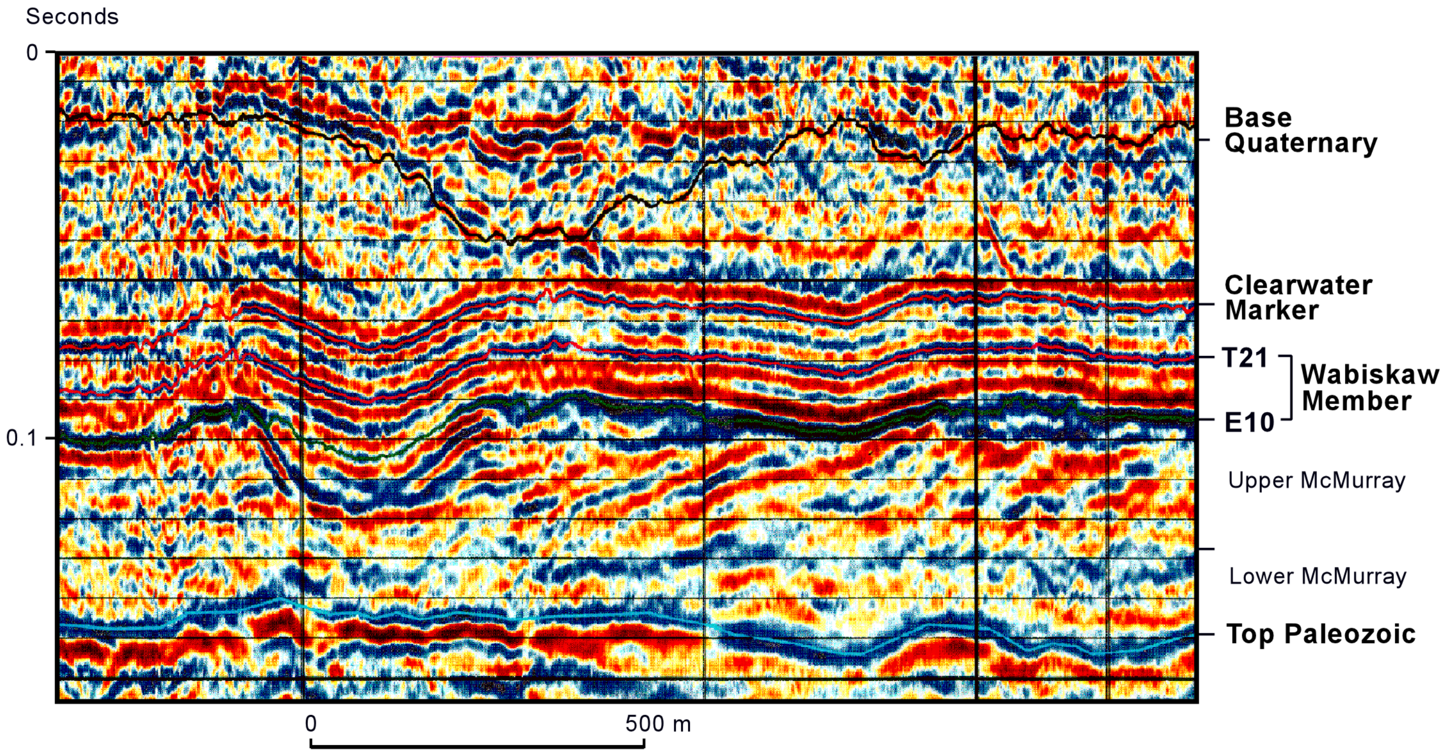

Figure 21. Example of seismic-amplitude display of confidential Mobil seismic line 110; two-way travel time for the McMurray Formation is about 70 ms, corresponding to a thickness of about 50 m; horizontal distance is about 1 km; see Figure 20 for location of section.

Sedimentary Basin. The interval from 166 to 134 m in well AA/4-20-90-7W4 shows an average dip of 7° in direction N308°E, which is confirmed by the plane dipping 9° in direction N307°E, calculated from two dipping traces on intersecting seismic lines 110 and 112.

Two distributary channels of the Quaternary Clarke Channel (Andriashek and Meeks, 2000) can be clearly distinguished on the seismic line.

6.3 Line 111

The sub-Cretaceous unconformity is clearly displayed by the seismic data, with some karst features in the eastern part of the line (Figure 22). The Lower McMurray is clearly infilling the depressions in the Paleozoic with a 15 m thick alluvial succession. The Upper McMurray channels removed most of the Lower McMurray around wells AA/11-7-90-7W4 (2.5 m thick alluvial section) and AA/2-7-90-7W4 (no alluvial determined). To the west, at well AA/12-12-90-8W4 (and possibly beyond), 11 m of fluvial deposits are present. The western part of the line, beyond well AA/11-7-90-7W4, is underlain by thick muskeg; as a result, the base of the muskeg is the only good reflector and the rest of the stratigraphy is not resolved. The eastern edge of the younger channel complex is indicated by the opposing dips in the dipmeter logs of wells AA/6-8-90-7W4 and AA/2-8-90-7W4. The westerly dip is clearly seen on the seismic image, but the easterly dip is not as clear.

One of the main channels of the Quaternary Clarke Channel (Andriashek and Meeks, 2000) is clearly imaged in the central part of the seismic line and is also clear on the logs of the wells in this area.

6.4 Line 112

Line 112 is a north-south tie line that connects the three east-west lines (Figure 23). The sub-Cretaceous unconformity is interpreted to be fairly flat, and some waves in the central part of the section near well AA/2-18-90-7W4 are assumed to be the result of thick muskeg (all reflectors, including Quaternary, show the same waves). The southern edge of the younger channel complex is displayed in the seismic image and in the dipmeter data of tie well AA/6-8-90-7W4 (tying lines 111 and 112). Much of the chaotic pattern above the Clearwater Marker is an artifact of the seismic survey being shot in an area of muskeg, but the base of the Quaternary can be picked as a high-contrast, highly reflective unit. In some cases, the sub-Quaternary unconformity cuts down to the Wabiskaw Member (wells AA/9-7-90-7W4, AA/6-8-90-7W4 and AA/4-8-90-7W4), as part of the Clarke Channel (Andriashek and Meeks, 2000). A distributary of this channel is imaged near well AA/13-28-89-7W4. Some opposing dips are shown in the older channel complex, both in the seismic image and in the dipmeter data of wells AA/11-15-90-7W4 (northwesterly dip) and AA/16-31-89-7W4 (southeasterly dip).

6.5 Summary

In summary, the integration of the various subsurface data for the Clarke Creek area shows that the seismic images give an accurate 3-D picture of the various structures in the subsurface. Two channel complexes can be recognized at Clarke Creek, both interpreted as estuarine meandering-channel–point-bar complexes. The older channel complex was oriented to the northwest, with prominent low-angle cross-bedding (seen in core, and interpreted on dipmeter logs and seismic sections) striking parallel to the axis of the main channel and dipping variably at 90° to the channel-axis trend. This cross-bedding is interpreted as being due to the lateral migration of point bars within the estuarine complex. A younger flow-unit event removed much of the older estuarine channel–point-bar complex. The axis of the younger channel trends to the north and has similarly associated lateral-accretion surfaces, due to point bars bordering the axial trend of the main channel.

Modelled seismic sections from outcrops along the Steepbank River show attributes similar to those of

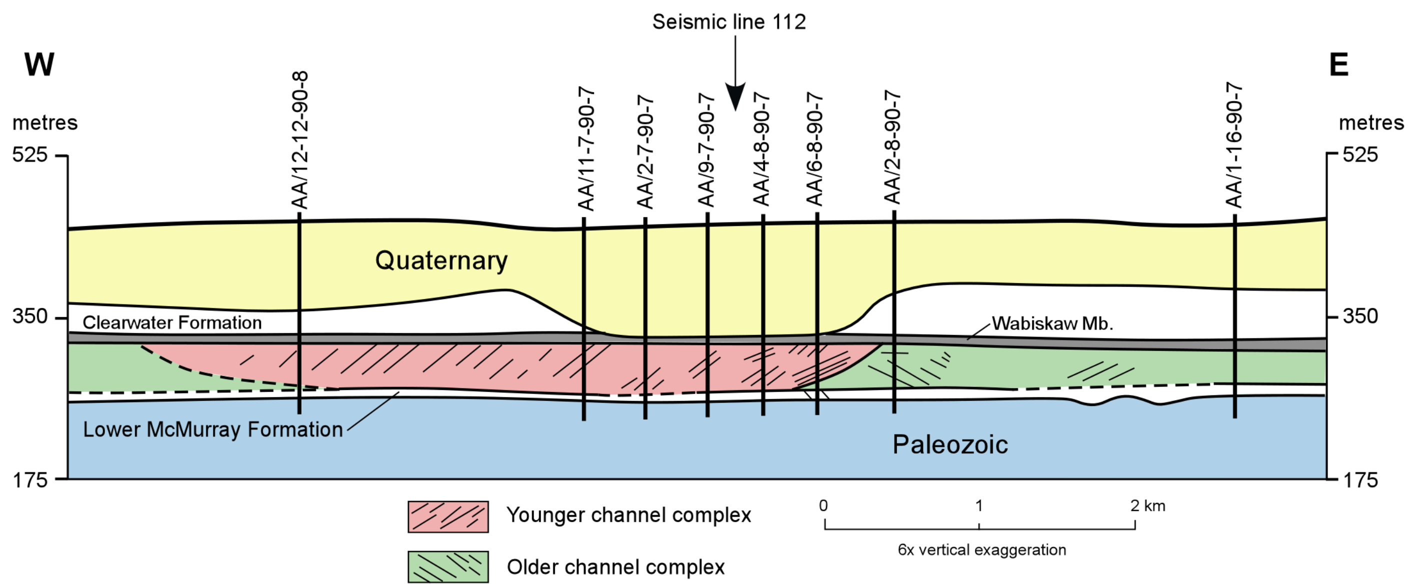

Figure 22. Structural cross section along seismic line 111, from west to east, showing changes within the Lower and Upper McMurray Formation, Wabiskaw Member, Clearwater Formation and Quaternary successions; subsurface well control and intersecting seismic line are shown; 6x vertical exaggeration; dashed lines indicate areas of acoustic transparency and uncertainty regarding the presence of Lower McMurray Formation.

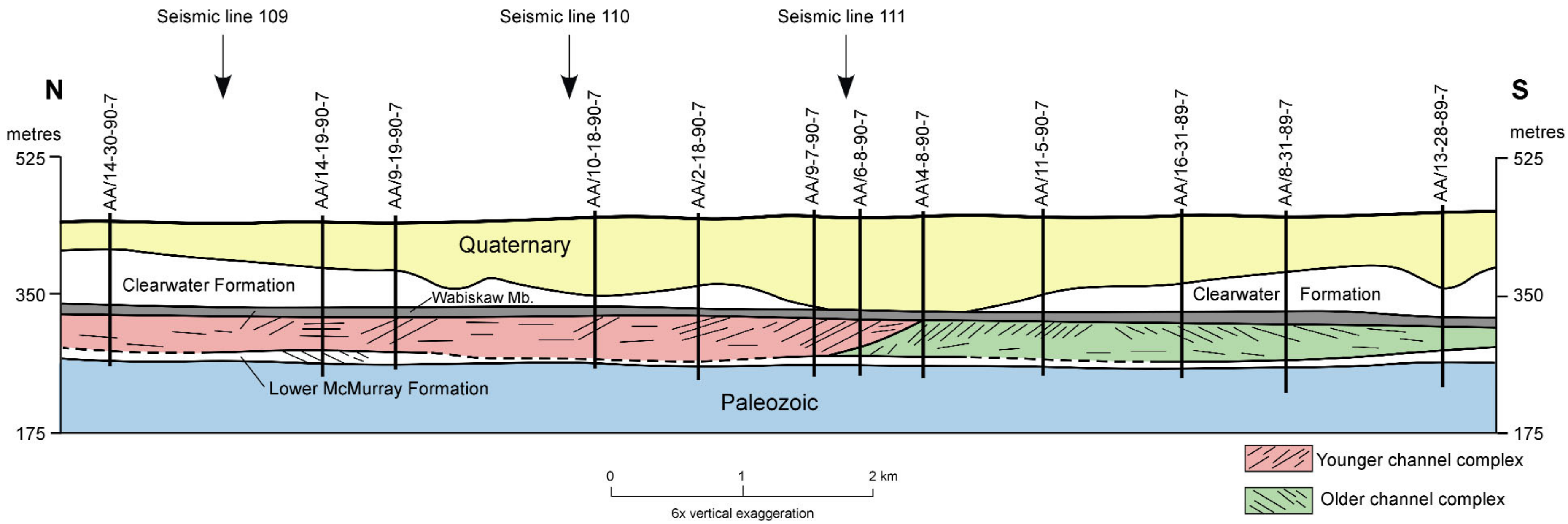

Figure 23. Structural cross section along seismic line 112, from north to south, showing changes within the Lower and Upper McMurray Formation, Wabiskaw Member, Clearwater Formation and Quaternary successions; subsurface well control and intersecting seismic lines are shown; 6x vertical exaggeration; dashed lines indicate areas of acoustic transparency and uncertainty regarding the presence of Lower McMurray Formation.

the Clarke Creek seismic lines (Langenberg et al., 2002). These attributes include scales, overall geometry and internal reflectors. Major markers are resolvable, as are channel forms, lateral-accretion cross-bedding and fault structures. An example of one of these modelled seismic lines is shown in Figure 24, for comparison with the Clarke Creek seismic lines.

7 Channel Complexes and Reservoir Characterization Maps

One of the most interesting results of the present study is the resolution of the different channel complexes within the Upper McMurray Formation. The integration of the well data with the seismic lines enabled the mapping of the different channel complexes. The structural cross sections, completed with the information from the seismic lines, show a central channel complex with lateral-accretion beds, dipping in directions between southwest and northwest, that cuts into a channel complex with generally northeasterly dipping lateral-accretion beds. Available core shows that the lower (older) channel complex appears to have minor fluvial characteristics, whereas the upper (younger) channel complex is estuarine and belongs completely to the Upper McMurray Formation. Map representation of these data show that the central channel complex is flowing in a northerly direction (Figure 7).

To obtain an assessment of the reservoir characteristics of the McMurray Formation in the Clarke Creek River area, a number of ‘field-scale’ isopach maps were constructed: sand, 6% tar mass, mudstone (shale) and gas for the McMurray Formation. The sand isopach map (Figure 25) shows thick sand units (with a cumulative thickness of more than 45 m), in the central part of the area, that generally follow the younger channel complex. The thin 20 m interval in the centre of the channel complex cannot be explained, but might be a result from remnant overbank mud deposits along the edge of channels. The 60 m of sand in a well just to the west might have resulted from infill of a karst feature in the Paleozoic. The pattern on the 6% tar-mass isopach (Figure 26) is essentially the same as that of the sand isopach, a direct result of the best bitumen being hosted within the thickest channel-sand units. The map shows that determining the 3-D geometry of the younger channel complex by seismic and dipmeter data defines the area with the most prospective oil sands.

The patterns on the mudstone (shale) isopach map (Figure 27) are the reverse of those on the sand isopach map, where the least thickness occurs along the younger channel complex.

The gas isopach (Figure 28) is mainly concentrated along the younger channel complex with a thickness of up to 10 m, with an absence of gas near the borders of the study area. This is another indication that the 3-D channel-complex characterization defines resources.

8 Conclusions

Integration of subsurface data shows that seismic surveys give an accurate 3-D picture of the various structures in the subsurface. Channel complexes are lithofacies packages defined by major bounding surfaces, with genetically related facies and consistent paleoflow patterns. Two channel complexes can be recognized in the Upper McMurray Formation at Clarke Creek, both interpreted as estuarine meandering-channel–point-bar complexes. The older channel complex was oriented to the northwest, with prominent low-angle cross-bedding (seen in core and interpreted on dipmeter logs and seismic sections) striking parallel to the axis of the main channel and dipping variably at 90° to the channel-axis trend. This cross-bedding is interpreted as being due to the lateral migration of point bars within the estuarine complex. A younger flow-unit event removed much of the older estuarine channel–point-bar complex. The younger channel axis trends to the north, and has similarly associated lateral-accretion surfaces, due to point bars bordering along the axial trend of the main channel.

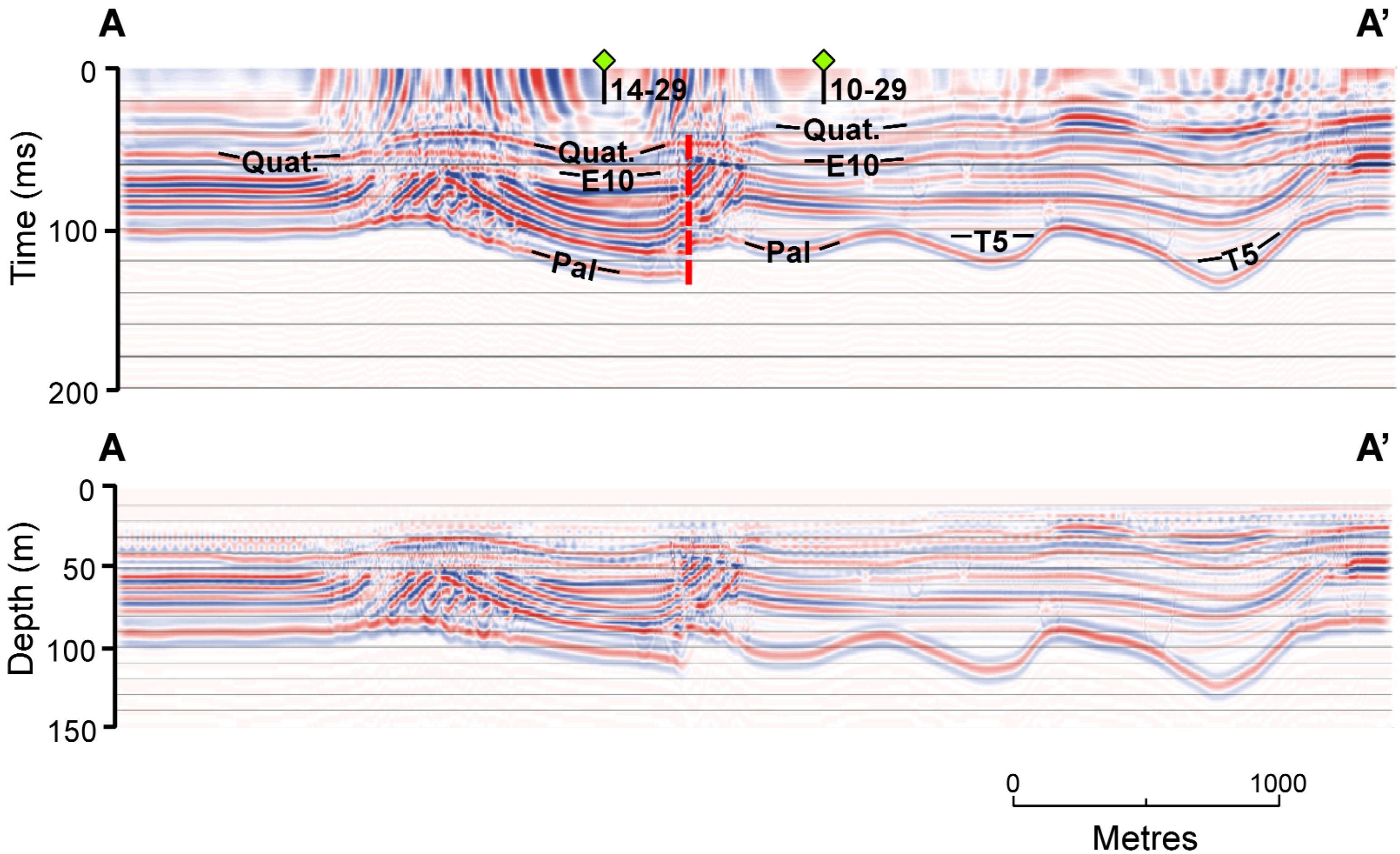

Figure 24. Modelled seismic cross section AA' of the Steepbank River area, obtained by ray-tracing of a digitized cross section, including outcrop and well sections, and showing pre-stack time migration from datum (upper) and pre-stack depth migration from datum (lower); from Langenberg et al. (2002).

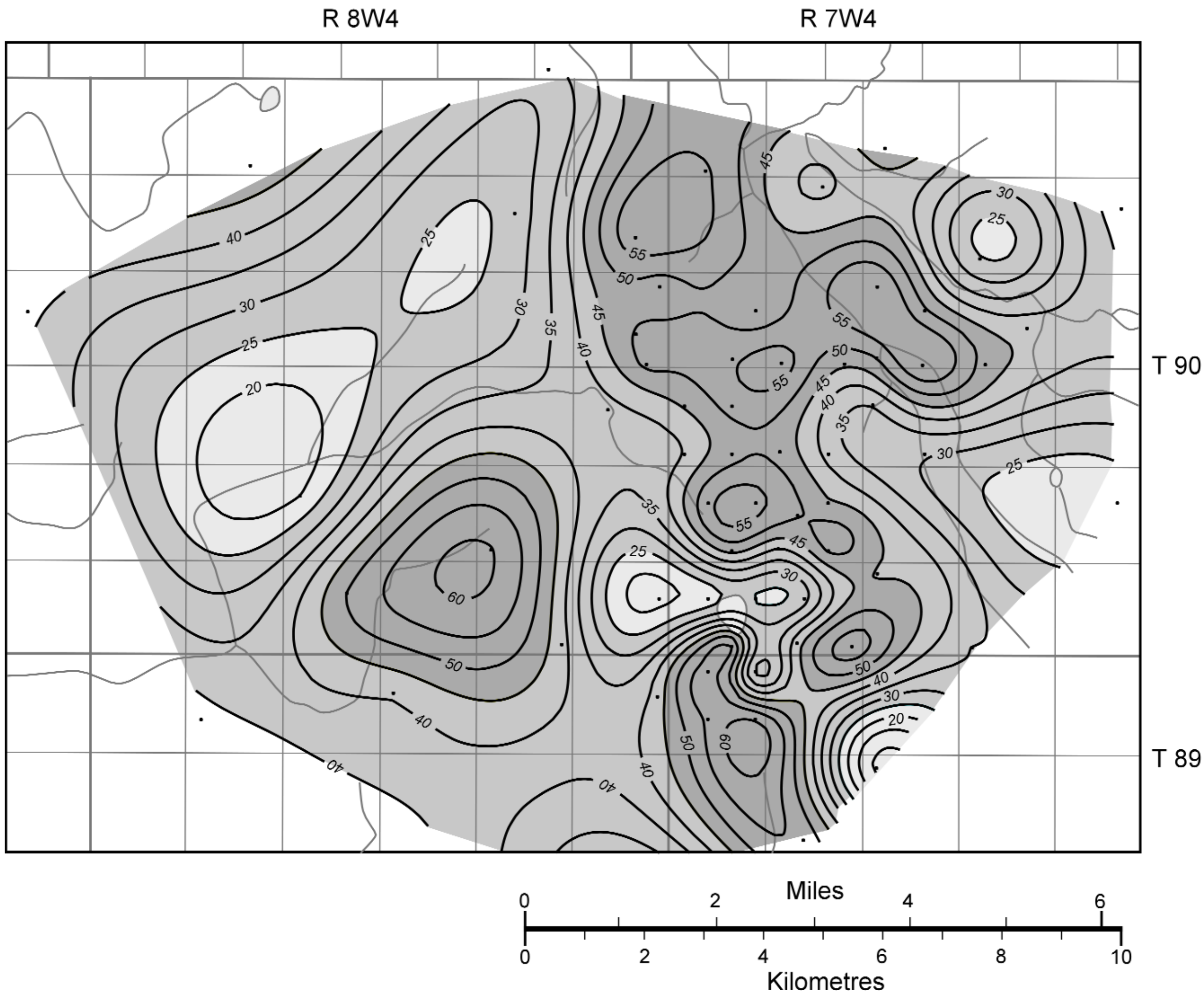

Figure 25. Sand isopachs for the McMurray Formation, Clarke Creek area; contour interval 5 m.

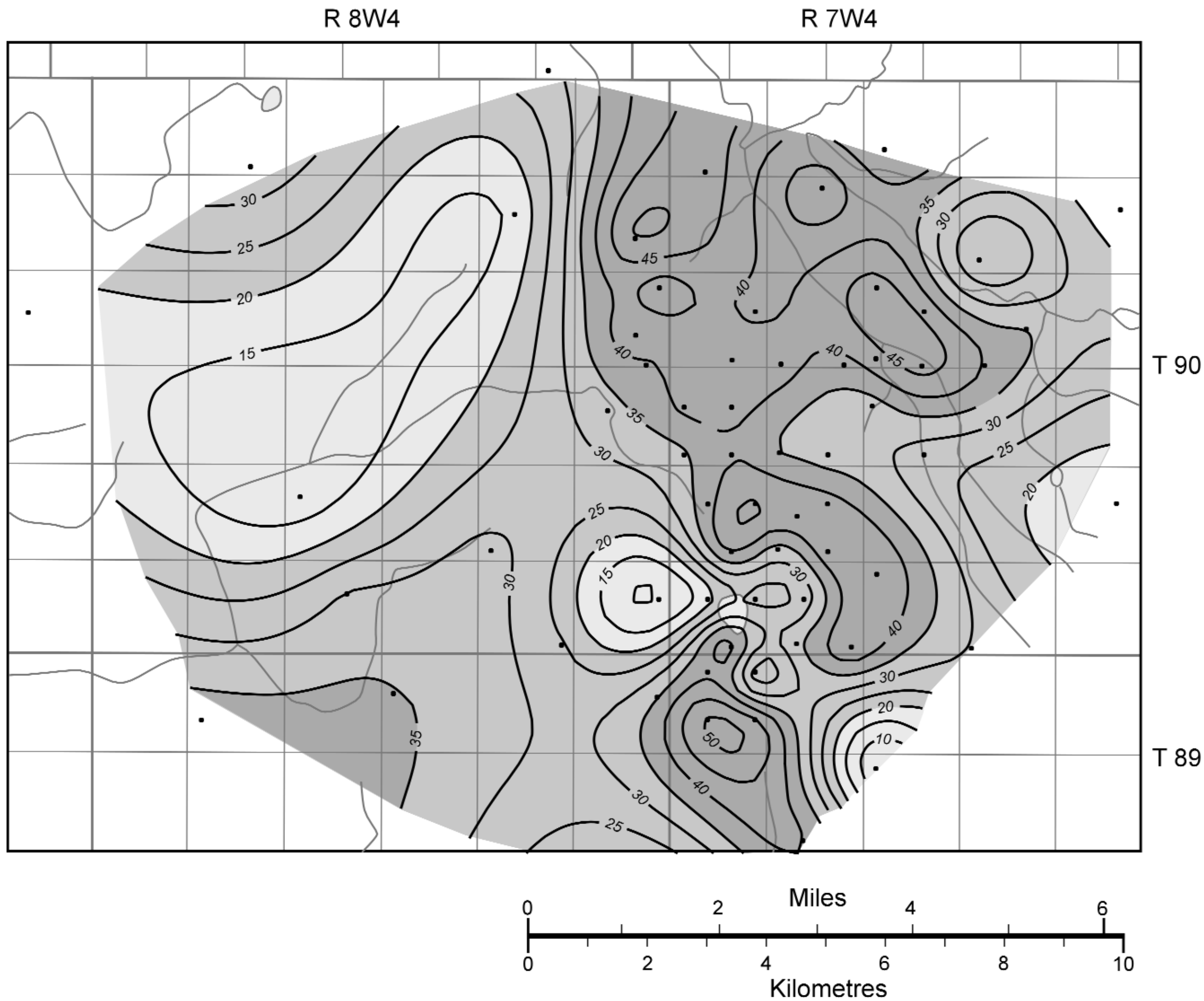

Figure 26. Tar mass (6%) isopachs for the McMurray Formation, Clarke Creek area; contour interval 5 m.

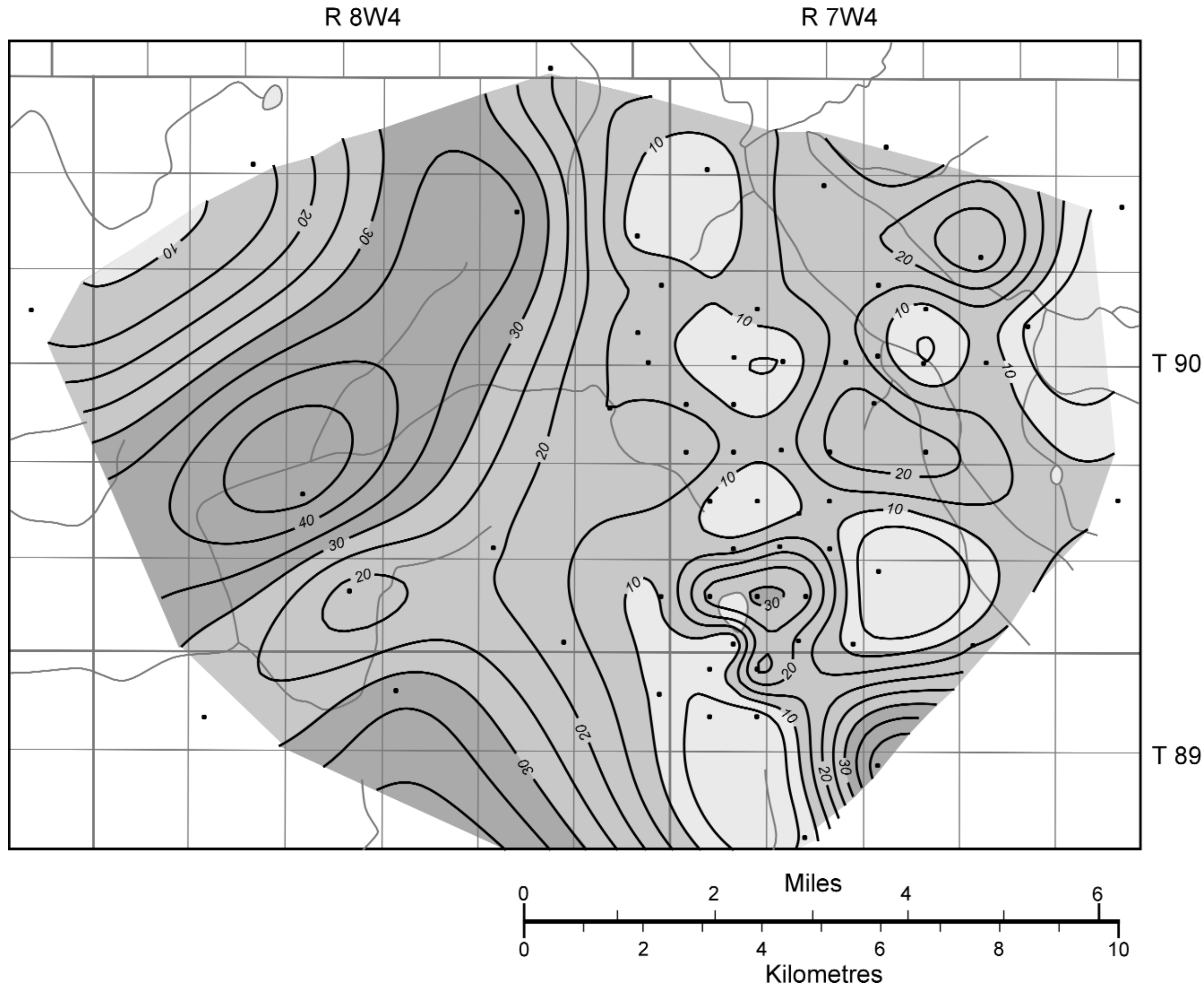

Figure 27. Mudstone (shale) isopachs for the McMurray Formation, Clarke Creek area; contour interval 5 m.

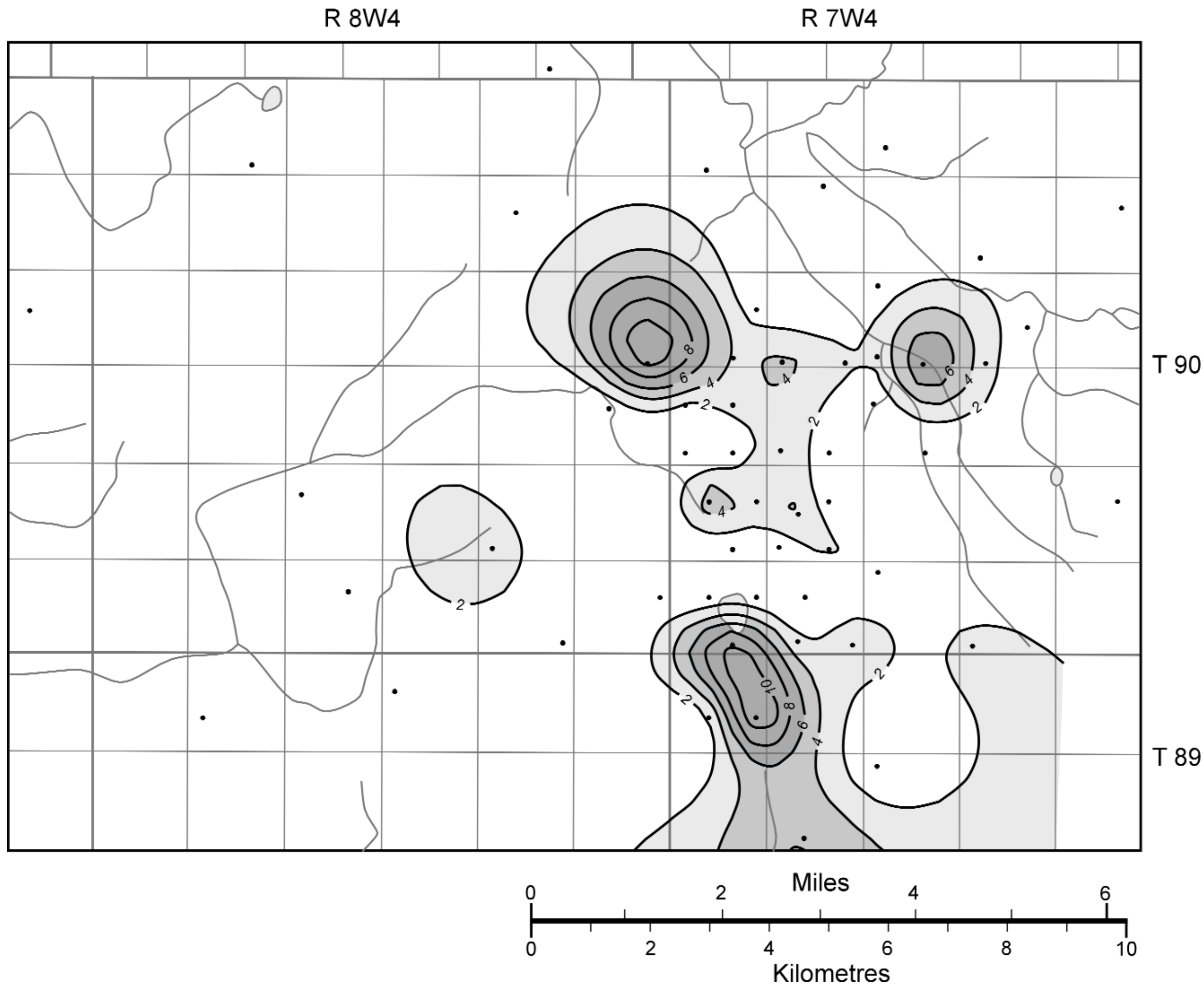

Figure 28. Gas isopachs for the McMurray Formation, Clarke Creek area; contour interval 5 m.

Previous AGS studies (Wightman et al., 1995) showed exploitable oil sand deposits in this area. Our work indicates that a large percentage of these oil sands are contained in a central, younger channel complex. Results from the present study indicate that channel complexes can be realistically imaged by seismic methods. Recognition of channel complexes could help define thick bitumen deposits in other oil sand areas.

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9 Appendix 1 – Definition of Stratigraphic Markers with Quality Codes (*modified from* Wynne et al. 1994; Hein et al., 2000)[1]

Pick	Type of surface	Description	Quality code[2]
T21	Transgressive	Wabiskaw Marker Top Wabiskaw Mb. 'A'	Good to very good
T15	Transgressive	Top Wabiskaw Mb. 'B'	Good to very good
E14	Major erosion	Wabiskaw internal incision	Good to very good
T11	Transgressive	Base first regional marine shale in the Clearwater Fm. Top Wabiskaw Mb. 'C'	Very good to excellent
T10.5	Transgressive	Top Wabiskaw Mb. 'D' incised valley-fill deposit	Excellent to very good
E10	Disconformity/ Unconformity	Top Upper McMurray Fm. Major erosion surface	Excellent to very good
E5	Disconformity/ Unconformity	Top Lower McMurray Fm. Major erosion surface	Variable Very poor to fair
Sub-Cretaceous (Paleozoic)	Unconformity	Base of McMurray Fm. Major erosion surface	Variable Very good to excellent (However, this is sometimes difficult to pick in areas of significant clastic karst-infill, or where marl is above the sub-Cretaceous unconformity)

[1] Abbreviations: Fm., Formation; Mb., Member

[2] Quality codes are relative: 'excellent to very good' can be picked on all wireline logs and seismic profiles; 'poor to very poor' are difficult to pick on wireline logs and somewhat easier to pick on seismic logs, so need to be confirmed by outcrops or core