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The Bow City structure, southern Alberta, Canada: The deep roots of a complex impact structure?

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Abstract–Geological and geophysical evidence is presented for a newly discovered, probable remnant complex impact structure. The structure, located near Bow City, southern Alberta, has no obvious morphological expression at surface. The geometry of the structure in the shallow subsurface, mapped using downhole geophysical well logs, is a semicircular structural depression approximately 8 km in diameter with a semicircular uplifted central region. Detailed subsurface mapping revealed evidence of localized duplication of stratigraphic section in the central uplift area and omission of strata within the surrounding annular region. Field mapping of outcrop confirmed an inlier of older rocks present within the center of the structure. Evidence of deformation along the eastern margin of the central uplift includes thrust faulting, folding, and steeply dipping bedding. Normal faults were mapped along the northern margin of the annular region. Isopach maps reveal that structural thickening and thinning were accommodated primarily within the Belly River Group. Evidence from legacy 2-D seismic data is consistent with the subsurface mapping and reveals additional insight into the geometry of the structure, including a series of listric normal faults in the annular region and complex faulting within the central uplift. The absence of any ejecta blanket, breccia, suevite, or melt sheet (based on available data) is consistent with the Bow City structure being the remnant of a deeply eroded, complex impact structure. Accordingly, the Bow City structure may provide rare access and insight into zones of deformation remaining beneath an excavated transient crater in stratified siliciclastic target rocks.

INTRODUCTION

Worldwide, there are currently 184 confirmed terrestrial meteorite impact structures produced by hypervelocity impacts (http://www.passc.net/EarthImpactDatabase/index.html). This figure, however, represents only a small fraction of the total number of such structures that we might expect to find in the geological record (Stewart 2011). For instance, in the area covered by the province of Alberta, approximately 500 impacts resulting in impact structures larger than 1 km in diameter are estimated to have occurred in the last 600 Myr (Mazur et al. 2000). Only relatively young impact structures such as Bosumtwi (Ghana), Barringer (Arizona), or Whitecourt (Alberta) retain their original morphology due to minimal postimpact modification through erosion or tectonism. Most impact structures preserved in the geological record are either deformed, highly eroded, buried under sediment, or a combination of these. If there is no obvious surface expression, discovery of impact structures relies to a large degree on serendipity, as they are only apparent through careful geological mapping, or, perhaps more commonly, through anomalous geophysical responses.

The progressive mapping of sedimentary basins by seismic methods, particularly using modern 3-D techniques, has accelerated the discovery of possible impact structures in recent decades. There are now numerous examples of possible buried impact structures, many of which were inadvertently discovered through anomalous borehole or geophysical responses (e.g., Pilkington and Grieve 1992; Stewart 2003; French and Koeberl 2010). The first of these may have been the 25 km diameter Steen River structure located in northern Alberta. The central uplift was drilled as a prospective hydrocarbon trap on the basis of early seismic profiling in the 1950s (Carrigy and Short 1968). A number of large structures, not all of which are confirmed impact structures, have been discovered using extensive 2-D marine seismic surveys, including Mjølnir (Gudlaugsson 1993), Silverpit (Stewart 2005), Chesapeake Bay (Poag 1996), Montagnais (Jansa et al. 1989), and Toms Canyon (Poag and Poppe 1998). The Chicxulub structure, however, remains perhaps the best example of a large, buried impact structure, the first hints of which came from scarce core material, with the architecture being subsequently refined using magnetic and gravity surveys (Hildebrand et al. 1991), followed by seismic investigations (Bell 2004) and deep drilling (Kenkmann 2004; Stoeffler 2004). Geophysical methods have also been used to delineate older, more deformed impact structures, most notably Sudbury (Milkereit 2010).

The Western Canada Sedimentary Basin hosts numerous confirmed and possible impact structures (Fig. 1), most of which were discovered during seismic exploration for oil and gas (e.g., Sawatzky 1975, 1976). Several of these, including James River (Isaac and Stewart 1993), Hotchkiss (Mazur 1999), and Purple Springs (Westbroek 1997) in Alberta, and Hartney in Manitoba (Anderson 1980) are examples of buried structures that were identified using seismic surveys, and which have not yet been confirmed as impact structures through drilling and identification of evidence for diagnostic shock metamorphism (see French and Koeberl 2010). Confirmed impact structures within the Western Canada Sedimentary Basin and the adjacent northern United States that have been delineated using seismic and well data include Viewfield (Saskatchewan), Elbow (Saskatchewan), Maple Creek (or White Valley, Saskatchewan), Eagle Butte (Alberta), Cloud Creek (Wyoming; not shown in Fig. 1), Newporte (North Dakota), Red Wing Creek (North Dakota), and Peerless (Montana). The Red Wing Creek structure is worth particular mention, as high-quality 3-D seismic volumes have recently been presented by Herber (2010). The resulting images reveal complex patterns of thrust and normal faulting across the Red Wing Creek structure, in particular, within the central uplift.

We present evidence for a newly discovered probable impact structure near the village of Bow City, Alberta. This structure is interesting because of dense well control that allows detailed subsurface stratigraphic mapping. Anomalies in the depths and thickness of various stratigraphic units mapped in the shallow subsurface led to its detection (Glombick 2010). Subsequent field mapping of deformed bedrock exposed at surface and the analysis of seismic data across the structure further support a geometry consistent with an impact origin. The structure appears to be deeply eroded (below the level of the initial transient crater), but despite this, there is still evidence for displacement of fault blocks associated with central uplift, and normal faulting with block rotations within the annulus of the structure. Observations of such deeply eroded structures are relatively rare in the literature and, as such, this structure may provide new constraints on the mechanics of impact in stratified siliciclastic target rocks.

LOCATION AND GEOLOGICAL SETTING

The Bow City structure is located in southern Alberta, centered at approximately 50.45 N and 112.36 E (Fig. 1). Regional structure in southern Alberta is dominated by the northern margin of the Kevin-Sunburst dome. The Bow Island Arch extends north-eastward from the dome, separating the Alberta and Williston basins, which together form the Western Canada Sedimentary Basin (Fig. 1). In the vicinity of the Bow City structure, the regional dip of strata is gently to the northwest (0.2° toward 310°).

The strata of the Alberta Basin can be divided into two broad successions, a Cambrian to Jurassic carbonate-dominated platformal succession overlying Precambrian basement, and a Lower Cretaceous to Paleocene succession of clastic sedimentary rocks deposited in a foreland basin adjacent to the Canadian Cordilleran orogen (Fig. 1).

The youngest rocks exposed in the vicinity of the Bow City structure are Upper Cretaceous nonmarine to marginal marine clastic sedimentary rocks of the Horseshoe Canyon Formation (Figs. 2 and 3). There is a transitional contact between sandstone, mudstone, and coal of the Horseshoe Canyon Formation and shale of the underlying Bearpaw Formation. The Bearpaw Formation is underlain by marginal marine to nonmarine clastic sedimentary rocks of the Belly River Group.

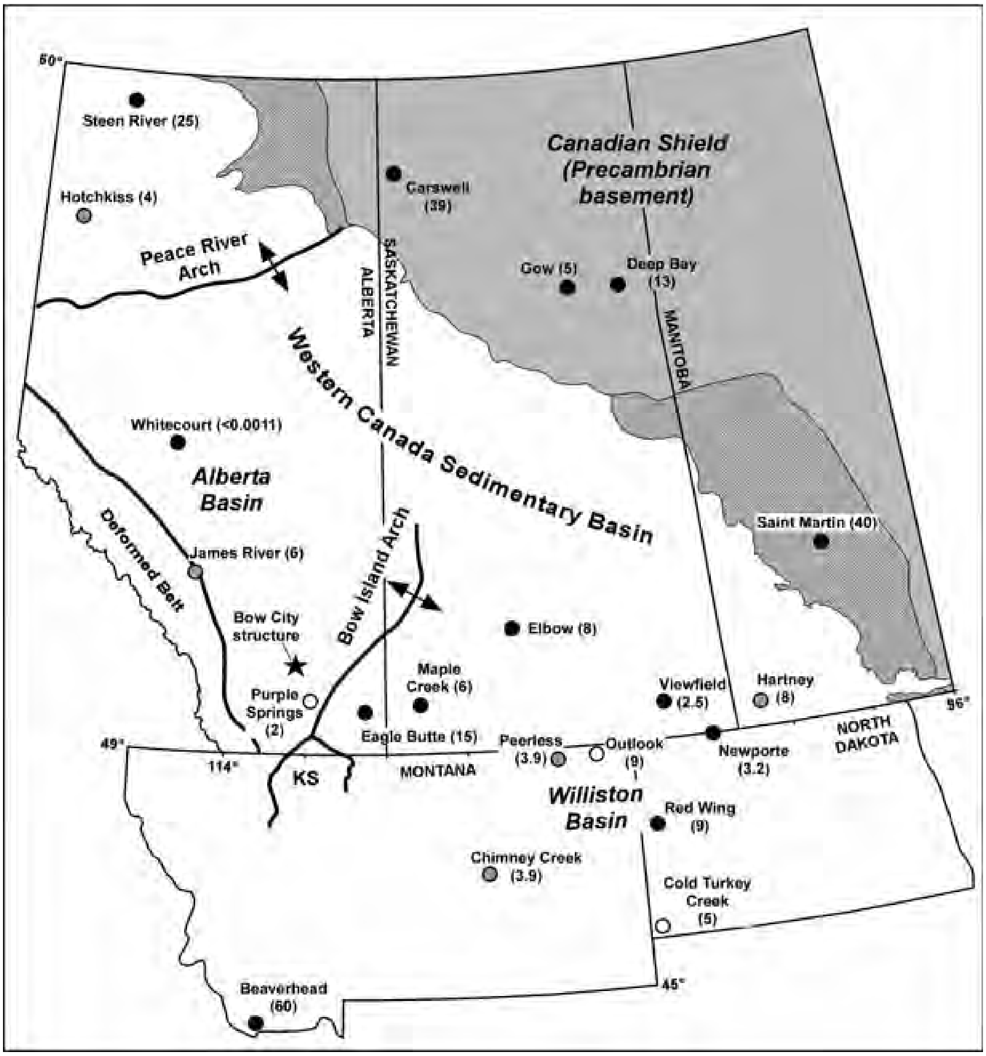

Fig. 1. Simplified geological map showing the location of the Bow City structure (black star) relative to other selected confirmed (black circles), probable (gray circles), and possible (white circles) impact structures in the Alberta and Williston basins. Approximate diameter (in km), indicated in brackets for each structure. Impact location data from the Earth Impact Database (http://www.passc.net/EarthImpactDatabase/index.html) and Rajmon (2009). Specific references for structures include: Viewfield (Sawatzky 1972, 1977; Isaac and Stewart 1993; Grieve et al. 1998); Elbow (De Mille 1960; Grieve et al. 1998); Maple Creek (White Valley; Whitaker 1976; Gent et al. 1992; Westbroek 1997; Grieve et al. 1998); Eagle Butte (Haites and van Hees 1962; Sawatzky 1976; Hanova et al. 2005); Cloud Creek (Stone 1999; Stone and Therriault 2003; not shown); Newporte (Clement and Mayhew 1979; Koeberl and Reimold 1995); Red Wing Creek (Brenan et al. 1975; Koeberl et al. 1996); and Peerless (Comstock et al. 2004). KS = Kevin-Sunburst dome. Base map modified from Mossop and Shetsen (1994; their fig. 1.1).

In southern Alberta, the Belly River Group can be subdivided into three formations. From youngest to oldest, these are the Dinosaur Park, Oldman, and Foremost formations (Fig. 3). The Dinosaur Park Formation consists of an overall fining-upward succession of marginal marine to estuarine, fine-grained sandstone, siltstone, and mudstone, with the thin coal seams of the Lethbridge coal zone in the uppermost part of the formation. A regional disconformity separates the Dinosaur Park Formation from the underlying Oldman Formation (Eberth and Hamblin 1993). The Oldman Formation can be divided into an upper "siltstone unit" and a basal sandstone unit, the base of which forms the upper contact of the underlying Foremost Formation (Hamblin 1997). The Foremost Formation is comprised of a heterolithic succession of marginal marine sandstone, siltstone, mudstone, and coal. Near the top of the Foremost Formation, an interbedded succession of coal, mudstone, and bentonite forms the Taber coal zone. The McKay coal zone is found near the base of the Foremost Formation, overlying the basal Belly River sandstone (Fig. 3).

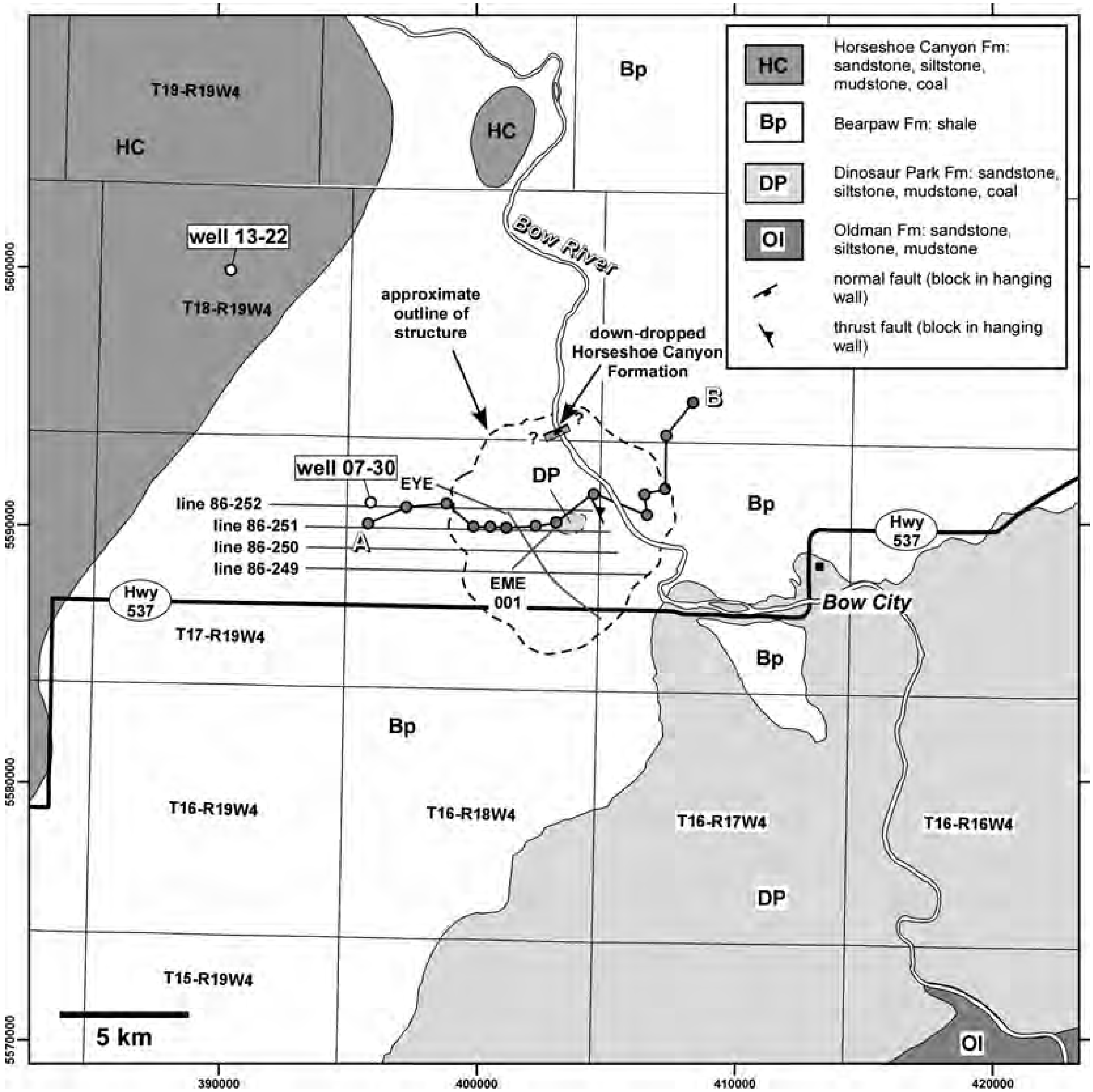

Fig. 2. Simplified geological map in the vicinity of the Bow City structure (modified from Irish 1968). Outline of the structure (based on subsurface structure maps) is shown as black dashed line. Location of seismic lines shown as solid dark gray lines. The locations of structure cross section (A–B) wells are shown as gray-filled circles. Also shown are the locations of wells 100/07-30-017-18W4/0 (07-30) and 00/13-22-018-19W4/0 (13-22), referred to in the text (white-filled circles). Highway (Hwy) 537 shown as thick, solid black line. Map grid coordinates are UTM Zone 12, NAD 83 datum.

Mudstone of the Pakowki Formation underlies the Belly River Group. It drapes a regional unconformity at the top of the Milk River Formation with relatively minor relief, known as the Milk River "shoulder," so-called because of the distinctive "shoulder-like" log signature visible on sonic, density, and resistivity logs. Underlying the Milk River Formation is the Colorado Group; a thick marine shale succession with several regressive sandstone-dominated units, including the Medicine Hat Member of the Niobrara Formation, as well as the Bow Island Formation, situated near the base of the Colorado Group. Between the base of the

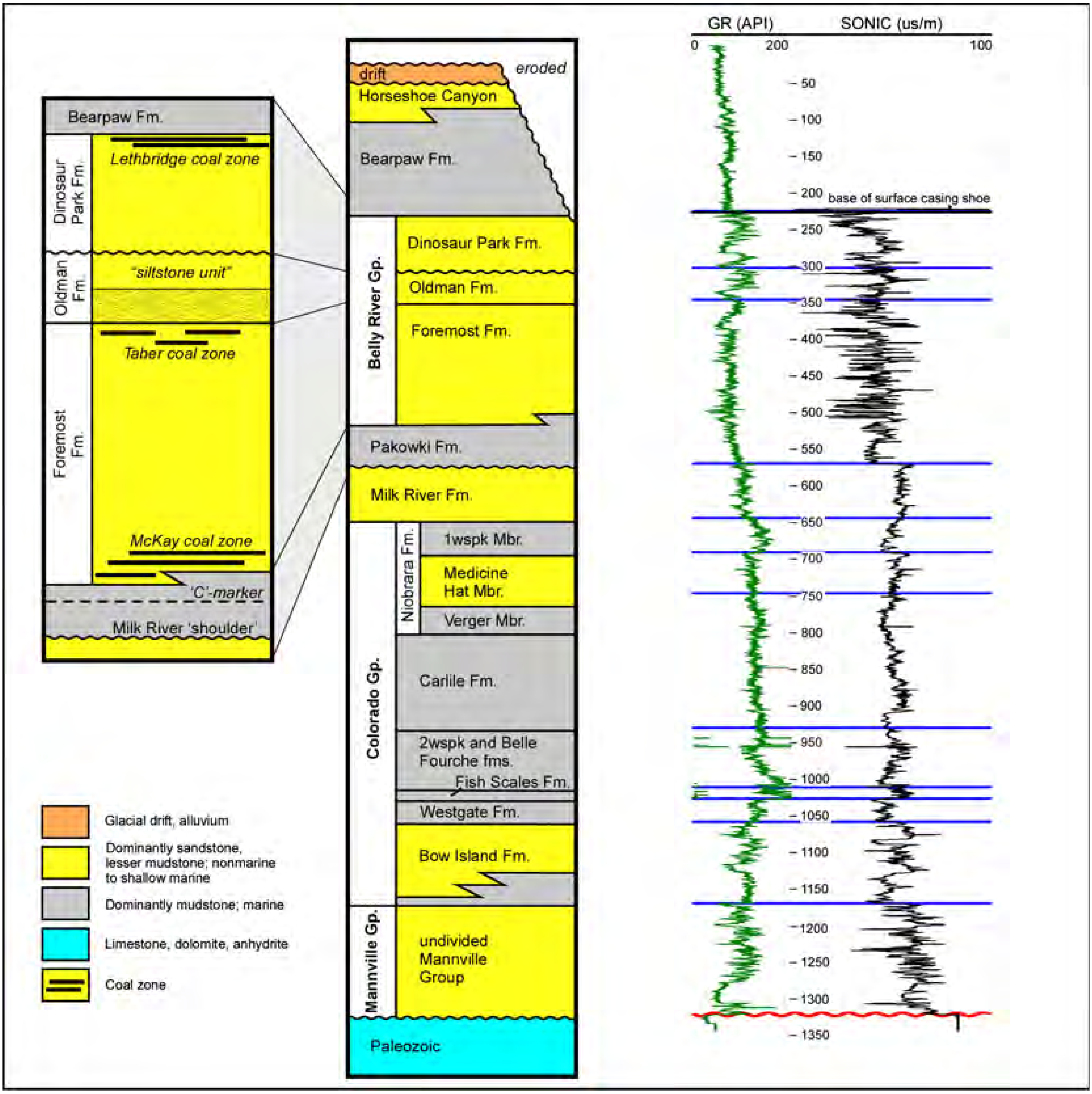

Fig. 3. Schematic stratigraphic column for the Bow City area (center), showing detailed Belly River Group stratigraphy (left), and matching geophysical log response for representative well 00/13-22-018-19W4/0 (13-22; right). The location of well 13-22 is shown in Fig. 2. Geophysical well logs include gamma-ray (GR) and sonic. Stratigraphic picks on geophysical log shown in blue.

Colorado Group and the unconformity at the base of the Cretaceous lies a complex and laterally variable assemblage of Lower Cretaceous clastic sedimentary rocks known as the Mannville Group. In the vicinity of the Bow City structure, the Mannville Group rests with angular unconformity on Mississippian carbonate rocks of the Rundle Group.

SUBSURFACE MAPPING

The combination of abundant oil and gas well data in the area and a well-defined stratigraphic succession permit the overall geometry of the Bow City structure to be constrained in the subsurface using a combination of structure and isopach maps. Following the

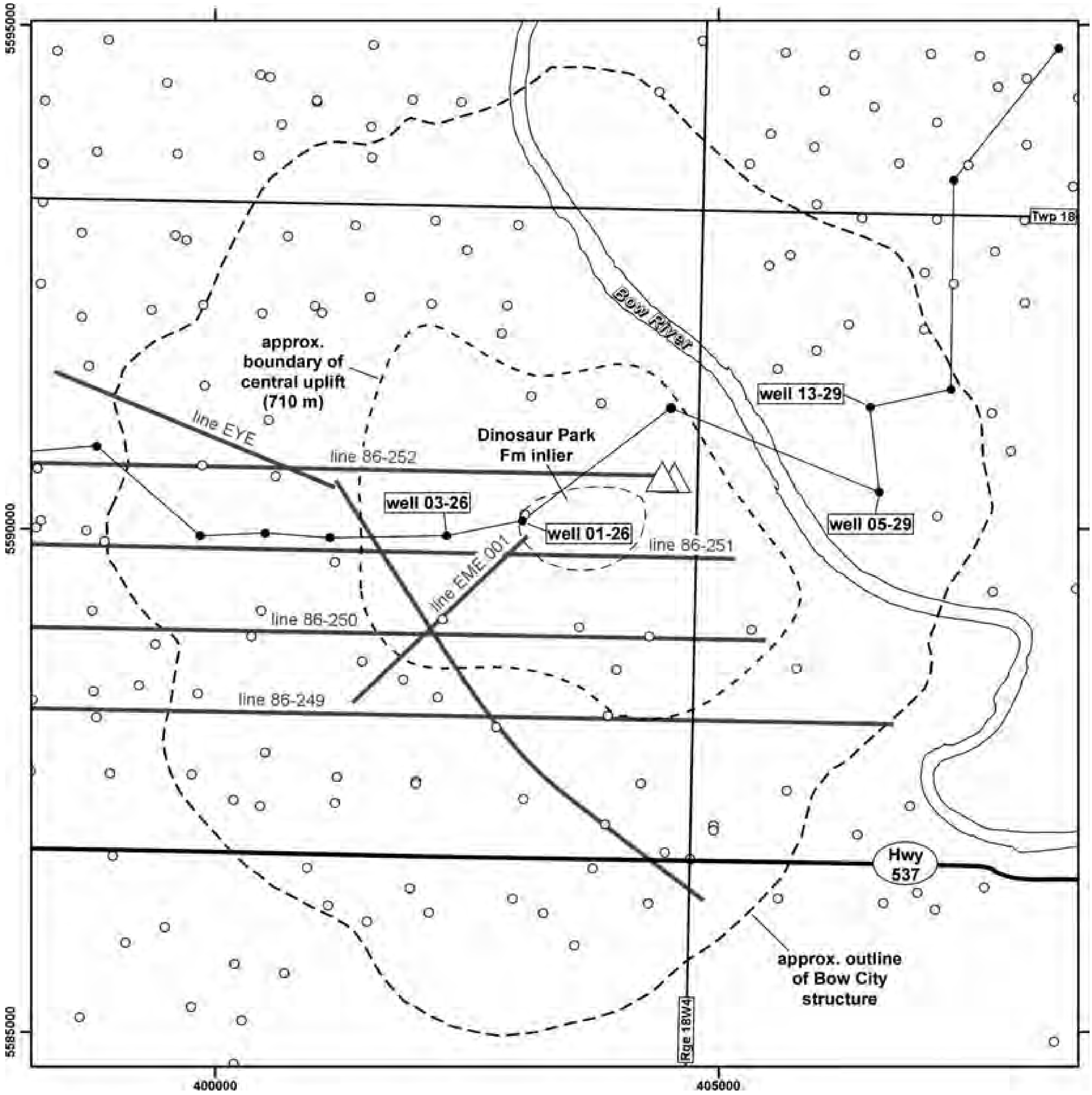

Fig. 4. Detailed map of the Bow City structure area showing well control. Surface location of wells shown as gray-filled circles. Surface location of cross section wells shown as solid black circles. Outline of the structure (based on subsurface structure maps) is shown as black, long-dashed line. The location of outcrop control data used in gridding shown as white-filled triangles. The approximate outer boundary of the central uplift (defined using the 710 m structure contour on the Belly River Group top) is shown as a black, short-dashed line. The inferred contact of the inlier of Dinosaur Park Formation rocks is shown in the center of the structure (approximated using the 820 m structure contour). Township grid shown as solid black line. The location of seismic lines shown as solid, dark gray lines. Map grid coordinates are in UTM Zone 12, NAD 83 datum. Twp = township; Rge = range; W4 = west of the Fourth Meridian.

identification of a structural anomaly on the Belly River Group top (Glombick 2010), we examined data from all wells in the surrounding area (*n* = 2930; Figs. 4 and 5f). Stratigraphic tops were picked on downhole geophysical well logs using IHS Petra® software. A suite of logs, including gamma-ray, neutron porosity, resistivity, sonic, and either bulk density or density porosity, was used whenever possible. We screened well data for

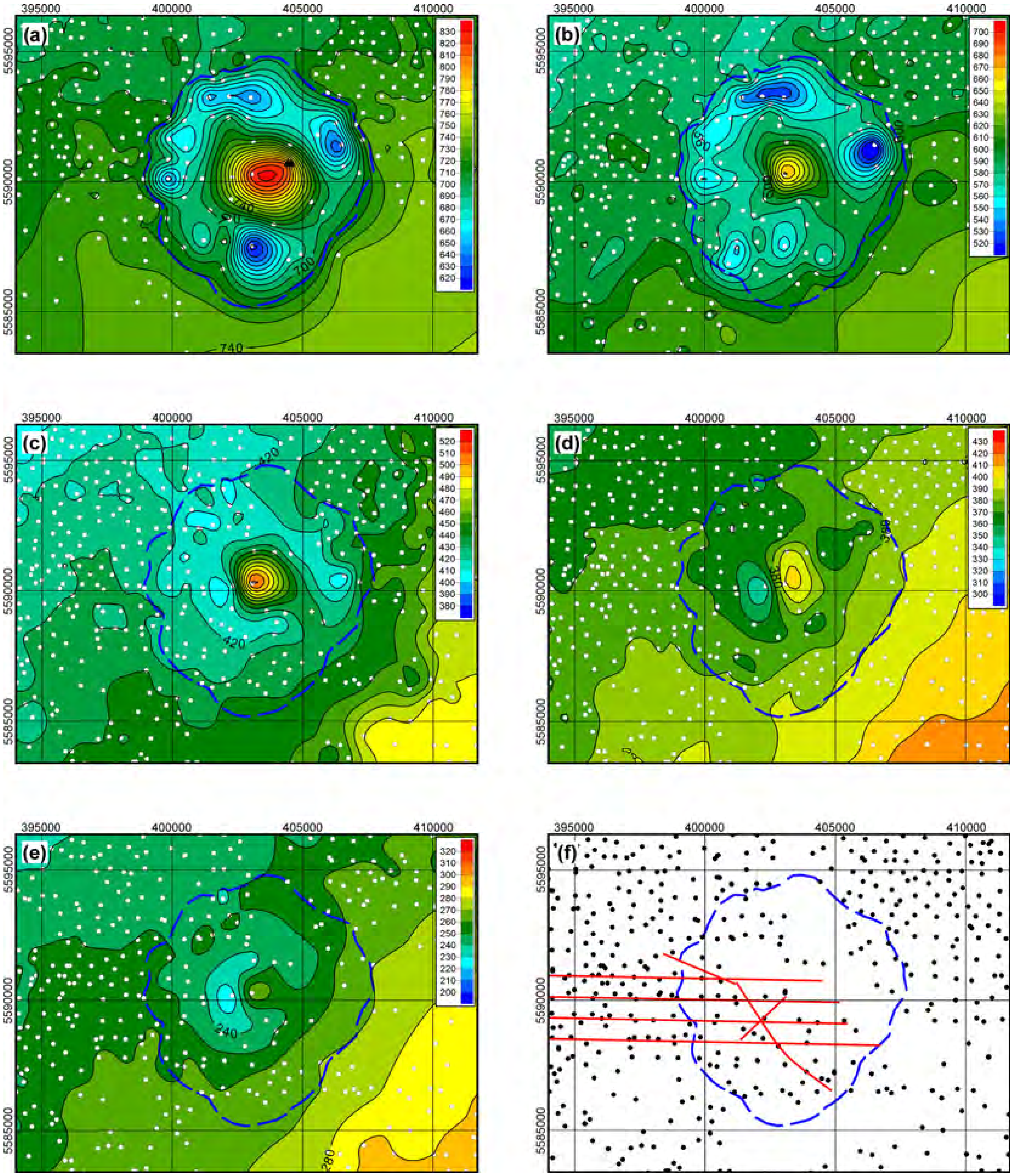

Fig. 5. Structure maps for selected stratigraphic tops: (a) Belly River Gp, (b) Foremost Fm, (c) Pakowki Fm, (d) Milk River "shoulder," (e) Medicine Hat Mbr, and (f) map showing the location of all oil and gas wells (black circles) in the area. Structure outlined in blue, location of seismic lines shown as red lines. Wells with data used in the creation of individual grids are indicated with white circles (a–e). Contour interval, in meters above sea level, is indicated for each map at top right. Data were gridded using Petra® minimum curvature algorithm, with a cell size of 200 m by 200 m. Well directional survey data were used to calculate X and Y map coordinates in deviated wells. Map grid coordinates are UTM Zone 12, NAD 83 datum.

potential errors in kelly bushing elevation and missing deviated survey data, which could produce apparent structural anomalies. For deviated wells, well directional survey data were used to calculate X and Y location data along the well bore at depth for both structure and isopach maps. For isopach maps, the XY location of the well bore at the upper surface was used. For well 00/01-26-17-018W4/0 (Hudson's Bay Oil and Gas Eyremore 1), located within the center of the structure (Fig. 4; well 01-26), a published litholog based on cuttings was the only available data (Powers 1931). As such, only selected major lithostratigraphic contacts could be picked in this well. We used two additional control points on the east side of the central uplift area in creating structure maps for the top of the Belly River Group based on X, Y, and Z (elevation) data from outcrop (Figs. 4 and 5a).

Structure and isopach maps were generated using Petra® software. Data were gridded using the minimum curvature algorithm, with a grid cell size of 200 m by 200 m. The minimum curvature method was chosen over the highly connected features method, as the latter method tended to close contours around individual data points, whereas the former method gave a more reasonable approximation of the overall geometry of the structure. Using the highly connected features produces a similar overall geometry, but with more local variation. Any data points closer than 25 m apart were excluded to avoid gridding artifacts. Default values were used for distance weighting damping, search radius, and extrapolation distance. A true vertical depth (TVD) correction was applied when calculating isopach map values.

The uppermost stratigraphic surface that can be mapped semicontinuously in the subsurface is the top of the Belly River Group (contact between Dinosaur Park Formation and the overlying Bearpaw Formation). The structure map for the top of the Belly River Group outlines a semicircular feature with a diameter of approximately 8 km (Figs. 5a and 6). A semicircular uplift is located in the center, surrounded by a structural depression with variable depth. Deformed rocks of the Dinosaur Park Formation are exposed at surface on the eastern flank of the central uplift (see Field Observations, below), providing a minimum estimate of their elevation in the center of the structure.

Some of the apparent variability in the depth of the structural depression surrounding the central uplift may be due to the location and density of data points, combined with the choice of gridding algorithm and cell size. There are relatively few data points in the southeast quadrant of the structure (Fig. 5a), where the top of the Belly River Group (Dinosaur Park Formation) is situated very close to the surface and logs are either not available or log signatures are obscured by surface casing. At least some of the variation is geologically meaningful, however, as indicated by examination of the available well control within the remainder of the depression (Fig. 5a). This variability may indicate a degree of structural complexity in this region of the structure that cannot be resolved using existing well data.

The structure on the top of the Foremost Formation is broadly similar in geometry to the structure on the top of the Belly River Group. There is a clearly defined, semicircular central uplift, surrounded by a structural low of variable depth, with the lowest areas located north and east of the central uplift (Fig. 5b). At the stratigraphic level of the Pakowki Formation top (Fig. 5c), the overall geometry of the structure is significantly different. There is no longer a clearly defined semicircular structural low surrounding an uplifted region in the center, and the central region is characterized by a more variable geometry. The eastern half of the central uplift continues to show evidence of uplift, although of less magnitude than observed at higher stratigraphic levels, while the western half of the central region shows evidence of a structural depression (Figs. 5c and 6).

At the level of the Milk River "shoulder," there is evidence of a subtle structural low surrounding an uplifted central area (Fig. 5d). The structural depression is deepest immediately west of the central region, showing considerable asymmetry. In the interval between the Milk River "shoulder" and the top of the Colorado Group (top of First White Specks Member of the Niobrara Formation), there is a transition from the center of the structure being an obvious structural high to a subtle structural low (compare Figs. 5d and 5e). With increasing depth, this low becomes less pronounced, so that at the top of the Mannville Group, the difference between the regional surface and the lowest point in the central depression (calculated by using a first-order residual surface) is approximately 20 m. At the sub-Cretaceous unconformity (erosional top of the Mississippian Rundle Group; not shown), it is unclear whether there is any negative relief related to the structure, or whether relief is related to draping over paleotopography associated with the unconformity.

Isopach maps yield additional insight into the Bow City structure, particularly with respect to differential thickening and thinning of stratigraphic units within the structure. For instance, the Dinosaur Park Formation (Fig. 7a) shows significant thickening within the central uplift and thinning in the surrounding low area, although the amount of thinning is not uniform. The amount of thickening in the central uplift is not well constrained, as the underlying Oldman Formation could

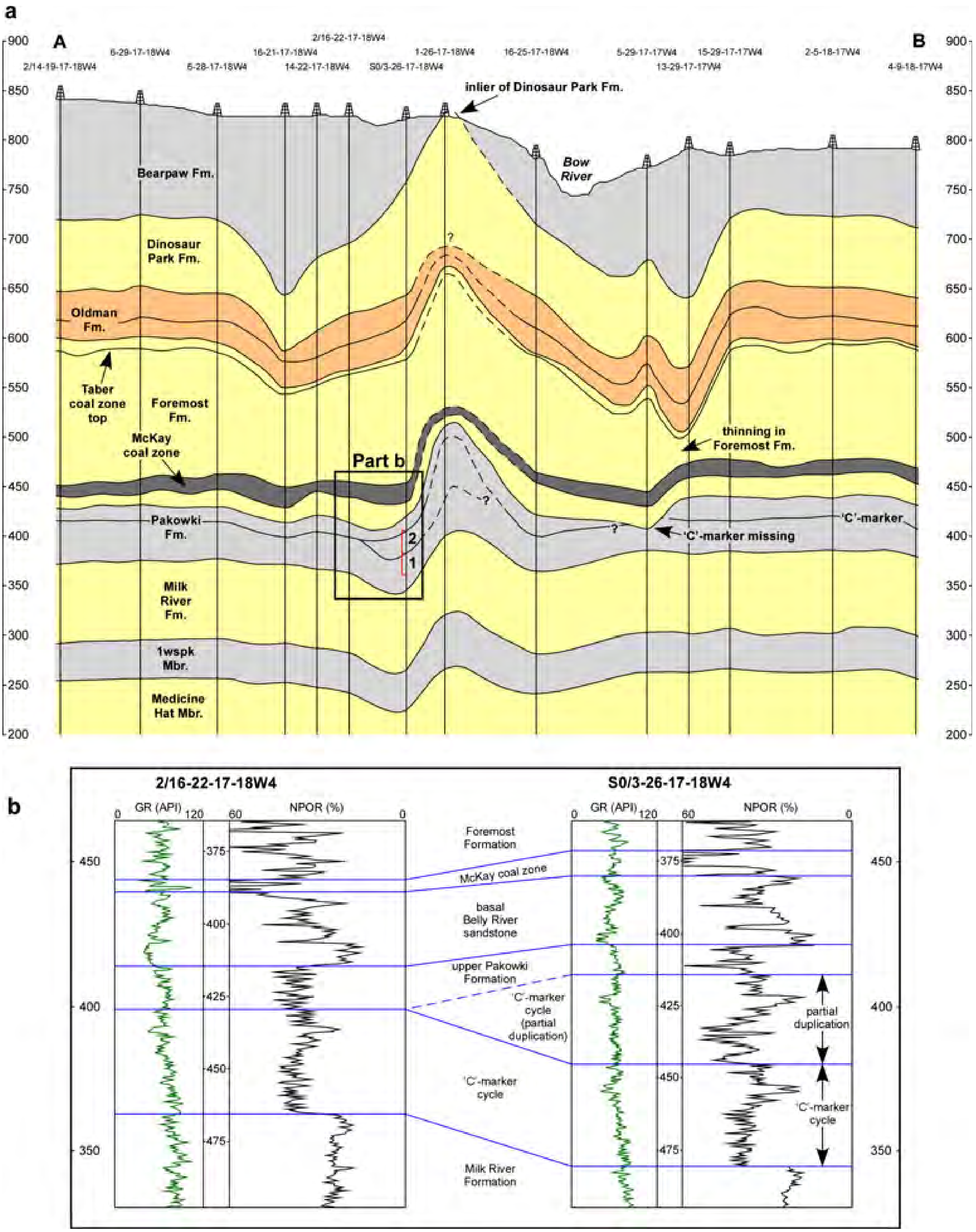

Fig. 6. a) Structural cross section A–B through the Bow City structure. Location of section line shown in Fig. 2. Line work has, in part, been modified from structure grids (Fig. 5) that have been projected onto the line of section. b) Detail from wells 02/16-22-17-18W4 and S0/03-26-17-18W4 showing repeated (partial) section of "C"-marker cycle (Pakowki Formation). Measured depths (m) shown along well bores. Elevation in meters above sea-level shown on section ends. Log abbreviations: GR = gamma-ray; NPOR = neutron porosity (sandstone calibration).

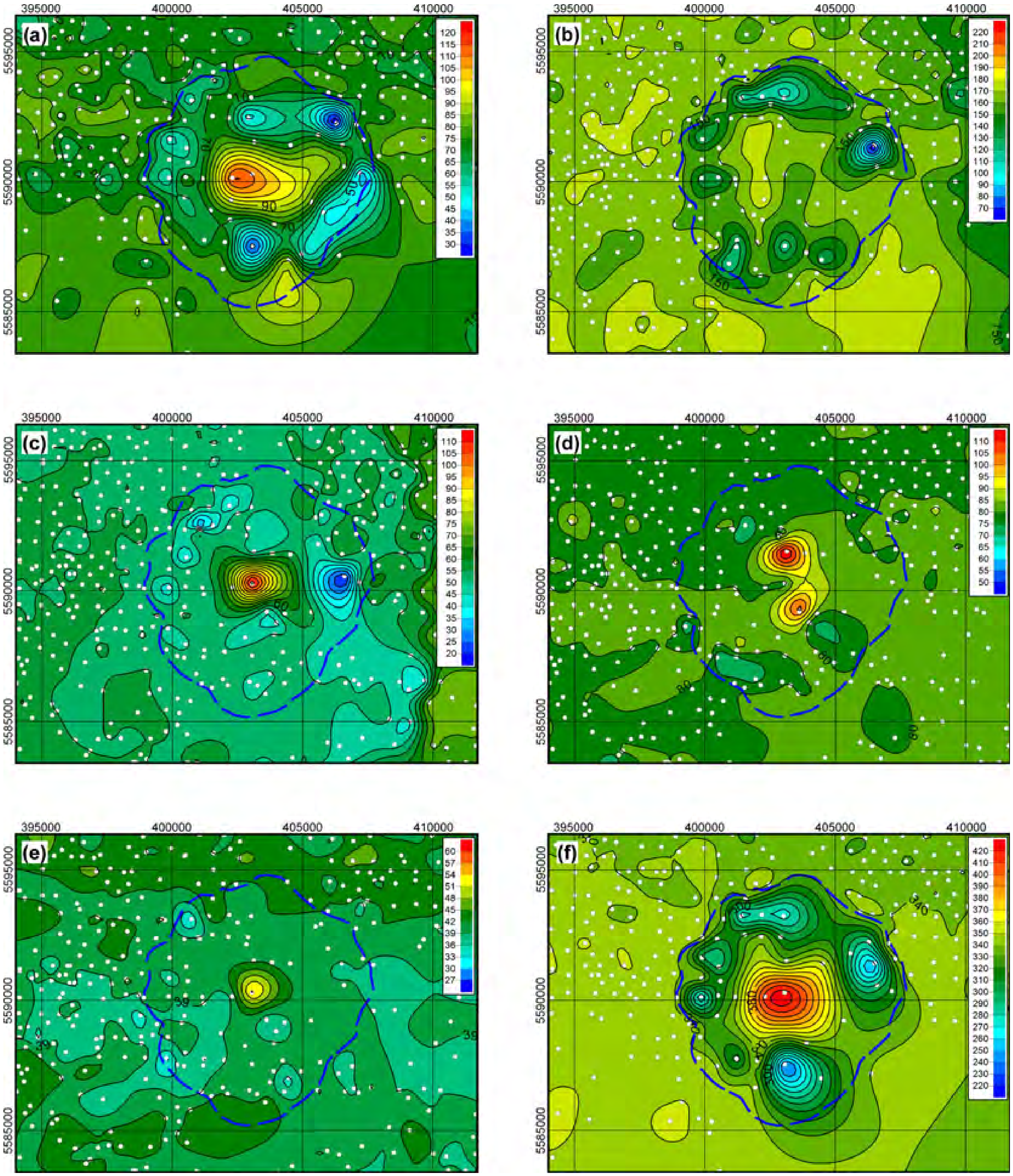

Fig. 7. Isopach maps for selected stratigraphic intervals: (a) Dinosaur Park Fm, (b) Foremost Fm, (c) Pakowki Fm, (d) Milk River Fm, (e) First White Specks Mbr, (f) Belly River Gp top to Milk River "shoulder." Contour interval in meters is indicated for each map at top right. Wells with data used in the creation of individual grids are indicated with white circles. Data were gridded using Petra® minimum curvature algorithm, with a cell size of 200 m by 200 m. Well directional survey data were used to calculate X and Y map coordinates in deviated wells. Map grid coordinates are UTM Zone 12, NAD 83 datum.

not be picked in well 00/01-26-17-018W4/0 (Fig. 6). Therefore, the grid for top of Oldman Formation is probably too low, resulting in an anomalously thick region within the central uplift on the isopach map for the overlying Dinosaur Park Formation (Fig. 7a).

The isopach map for the Foremost Formation (Fig. 7b) is characterized by thinning within the structural depression surrounding the central uplift. There is little or no evidence of thickening in the central uplift area. The thinning is most dramatic east-northeast of the central uplift, where it is constrained by well data (Fig. 6; well 00/13-29-17-017W4/0). This contrasts with the isopach map for the underlying Pakowki Formation (Fig. 7c), which shows evidence of significant thickening within the central region and patchy areas of thinning within the surrounding area, with the exception of east of the uplift, where thinning is more pronounced. Thickening of the Pakowki Formation to the east of the Bow City structure (at far right in Fig. 7c) is depositional in nature.

More information about the nature of thickening and thinning of the Pakowki Formation within the structure can be found by examining geophysical downhole well logs for individual wells. For instance, in well S0/03-26-017-18W4/0, the logs show that almost all of the "C"-marker cycle (a distinctive coarsening-upward cycle present within the Pakowki Formation between the Milk River "shoulder" and the "C"-marker top) is duplicated (Figs. 6a and 6b). This well is located within the central uplift region. The duplication of the "C"-marker cycle suggests that thickening of the Pakowki Formation within the central uplift is the result of (thrust) fault duplication of part of the section. Conversely, in well 00/05-29-017-17W4/0, the entire "C"-marker cycle is missing and the Pakowki Formation is anomalously thin as a result, whereas the underlying Milk River Formation and overlying upper part of the Pakowki Formation show no evidence of thickening or thinning in this well (Fig. 6a).

The interval from the Milk River "shoulder" to the top of the Colorado Group shows localized thickening within the central uplift (Fig. 7d). There is some evidence of slight thinning in the northwest and southwest quadrants of the surrounding area, but the remainder shows no evidence of thinning. Similarly, the underlying First White Specks Member of the Niobrara Formation is anomalously thick in the central uplift area (Fig. 7e).

An isopach map of the entire interval between the top of the Belly River Group (top Dinosaur Park Formation) and the Milk River "shoulder" is shown in Fig. 7f. This map shows the variation in the combined thickness of the Belly River Group (Dinosaur Park, Oldman, and Foremost formations) and the underlying Pakowki Formation. Comparison of the isopach maps for these formations (Figs. 7a–c) with deeper units (Figs. 7d and 7e) shows that the bulk of structural thickening and thinning present within the structure has been accommodated by formations within the Belly River Group and, to a lesser degree, the underlying Pakowki Formation. In addition, the Foremost and Dinosaur Park formations show the most dramatic thickening and thinning, whereas the isopach map for the Oldman Formation (not shown) shows relatively minor thinning in the semicircular structural low surrounding the central uplift. While some of this difference may be due to the fact that the Oldman Formation is thinner than the Foremost and Dinosaur Park formations, lithological differences may be significant. Both the Dinosaur Park and Foremost formations contain coal zones with interbedded thin bentonite units (Fig. 3), and these may have preferentially accommodated strain during deformation. The McKay coal zone, situated near the base of the Belly River Group (Foremost Formation), is well developed in this area. The partial duplication of the "C"-marker cycle noted in well S0/03-26-017-18W4/0 (Fig. 6b) suggests that the structural thickening within the central uplift was at least, in part, due to discrete rather than penetrative strain.

FIELD OBSERVATIONS

As a result of glaciation and subsequent erosion, the Bow City structure has no obvious morphological expression at the surface (Fig. 8). Previous geological mapping in the area, however, identified anomalous structure and map patterns in bedrock. In 1929, two exploration wells were drilled within an inlier of upper Belly River Group rocks exposed within the central uplifted area (Powers 1931). Stewart (1942, 1943) mapped a series of northeast-trending normal faults near the northern margin of the structure, along the Bow River, and estimated approximately 90 m of vertical stratigraphic offset. He also noted anomalously steep dips and mapped a faulted inlier of Belly River Group rocks in the vicinity of the central uplift.

Although most of the area is covered by a thin veneer of undeformed glacial deposits, bedrock is exposed along the Bow River and in a number of small drainage gullies extending westward from the western bank. We made a traverse along the western bank, from south to north, to supplement earlier field observations, examine geological structure, and to collect hand samples. All coordinates are given using a NAD 83 (UTM, Zone 12) datum.

The traverse began southeast of the structure, within a subhorizontal, undeformed succession of

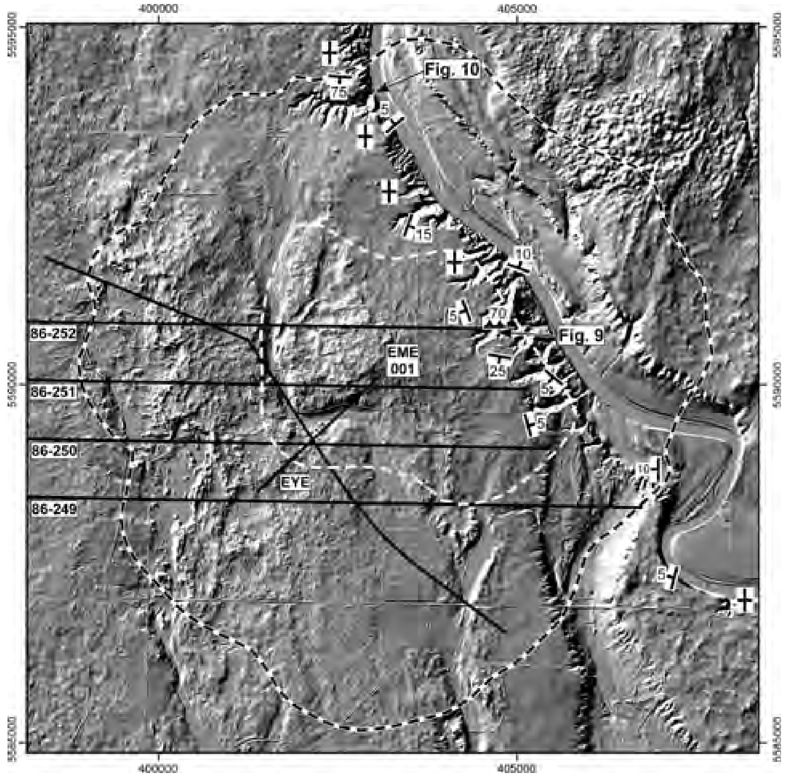

Fig. 8. Shaded light detection and ranging (LiDAR) digital elevation model of the Bow City area showing approximate outline of structure (thick, dotted black line), location of seismic lines (solid black lines), structure measurements from outcrop, and location of photographs shown in Figs. 9 and 10. Light source angle and azimuth for hill shading: 315° and 45°, respectively. The approximate outer boundary of the central uplift (defined using the 710 m structure contour on the Belly River Group top) is shown as a white dashed line. Map grid coordinates are in UTM Zone 12, NAD 83 datum.

Dinosaur Park Formation strata dominated by sandstone (Fig. 8). This succession is overlain to the northwest by similarly flat-lying mudstone of the Bearpaw Formation, which contains several prominent bentonite units. The top of the Dinosaur Park Formation is located on the west side of the river, just north of N5587000. Dips in this area are generally <5°, with varying azimuths. Coarsening-upward intervals of mudstone passing upward into very fine-grained sandstone become dominant within the Bearpaw Formation succession farther to the northwest (up-section). These strata of the (upper) Bearpaw Formation are generally subhorizontal, but small-scale thrust faults, not seen farther south, are present in outcrops north of N5590000. Farther northwest, strata of the upper Dinosaur Park Formation reappear within a gully (E404580, N5590700). Dips here are relatively steep locally, and a number of high-angle thrust faults are present (Fig. 9). In the upper walls of the gully, Bearpaw Formation strata conformably overlie this faulted Dinosaur Park Formation inlier. Strata of the Bearpaw Formation are also exposed farther north, along the west side of the Bow River, where they dip northward, generally at low angles (0–15°), but locally more steeply (up to 38°), with some associated thrust faulting (fault plane noted dipping 70° toward 300°).

The Bearpaw Formation becomes increasingly sandier up-section to the northwest, eventually passing upward into the Horseshoe Canyon Formation, which consists mainly of interbedded sandstone, carbonaceous mudstone, and coal at E403250, N5593500. The Horseshoe Canyon Formation succession, cut by numerous small-scale normal faults, forms an outlier extending north to the southern edge of a side gully (E402950, N5593900), where it is bounded to the north by steeply dipping, highly faulted strata of the Bearpaw/Horseshoe Canyon transition zone (Fig. 10). A short distance farther north, these strata pass into relatively flat-lying Bearpaw Formation mudstone at the northwest end of the traverse (E403000, N5594000).

SEISMIC DATA

We examined a number of vintage 12-fold seismic profiles acquired in the mid-1980s, most of which are oriented east–west (Figs. 2 and 4). Synthetic seismic traces were generated in Petrel® software using sonic

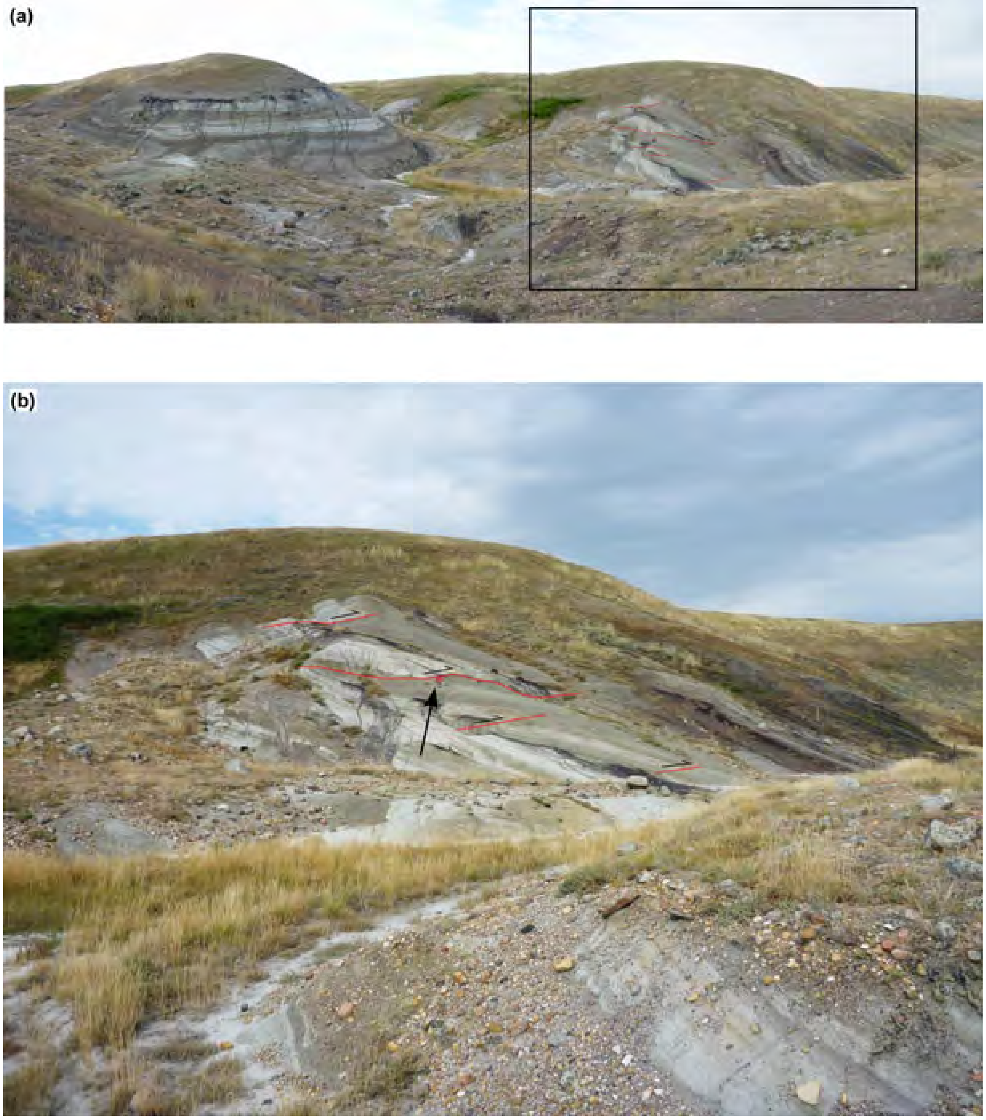

Fig. 9. Outcrop photographs from the Bow City structure: a) panoramic view (looking north) of beds of the Dinosaur Park Formation (Belly River Group); note nearly horizontal strata on left and increasing dips visible to the right of the photograph; b) close-up from (a), showing thrust faults (outlined in red). Geologist kneeling on outcrop (black arrow) for scale. Location: E404580, N5590700, UTM Zone 12, NAD 83 datum.

and density logs (Fig. 11). To ensure the quality of the generated traces, the sonic log was processed first to remove spurious spikes and a specific wavelet window was selected for each well to make the best extraction. A strong correlation of horizons between the synthetic seismogram and shifted seismic data was obtained, and this correlation lends strong confidence to the interpretation of the various seismic horizons.

Images of four east–west-trending seismic lines, located within the southwestern part of the Bow City structure (Fig. 4), are shown in Fig. 12. The deeper parts of the sections are not shown at the request of the data donors. The lines extend from outside the structure into the structural low (annular region). Three of the lines, 86-252, 86-251, and 86-250, extend into the central uplift area (Fig. 4). The seismic profiles were optimized to image deeper formations and are not ideal for showing relatively shallow structures. Despite this, a number of key features can be distinguished. We have assumed that the geological units, and hence the corresponding seismic events, are laterally continuous.

Three major aspects apparent in the seismic sections are:

1. A seismically “transparent zone” spatially associated with the central uplift.
2. Listric normal faults with significant apparent vertical displacement, as well as tilting of reflections in the hanging wall, interpreted to have formed

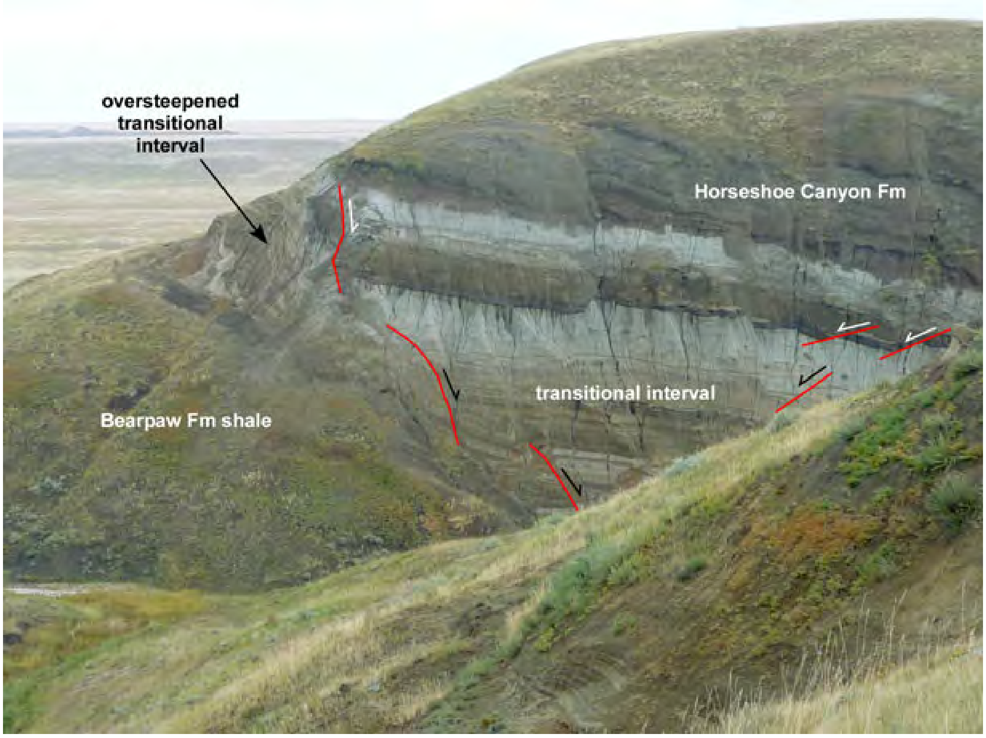

Fig. 10. Outcrop photograph of transition from Bearpaw to Horseshoe Canyon Formation (looking ENE) preserved within the structural depression on northern side of the structure. The height of the visible exposed face from bottom to top (base of grassed area) in the middle part of the photograph is approximately 30 m. Location: E402950, N5593900, UTM Zone 12, NAD 83 datum.

during late stages of crater formation. The outermost fault defines the outer limit of the Bow City structure.

3. A package of layered reflections, which are interpreted to represent preimpact sedimentary strata. That is, the seismic sections reveal that the original sedimentary strata remain largely in place and therefore below the depth of transient crater excavation.

The Belly River Group top, the base of the McKay coal zone, the Pakowki Formation top, and the Milk River Formation top are highlighted in Fig. 12. The latter three formations form a distinctive package of reflectors, hereafter referred to as the MPM package. Deeper seismic events, beginning with the Second White Specks Formation, situated below 500 ms, are not shown in Fig. 12, but in full sections they show no evidence of structural disruption. The vertical resolution limit, using a ¼ wavelength Rayleigh criterion, is approximately 10 m at 50 Hz. Due to limits in vertical resolution, the seismic images alone cannot rule out the possibility that vertical displacements smaller than 10 m exist at the level of the Second White Specks Formation, although displacements are not supported by the subsurface mapping from well data.

The three northernmost profiles exhibit a highly disturbed zone (indicated by transparent yellow shading in Fig. 12), in which little or no continuity of seismic events is visible. Similar seismically "transparent zones" (i.e., lacking in coherent reflections) have been observed in seismic images of the central peak from other impact structures, such as Bosumtwi (e.g., Karp et al. 2002) and Red Wing Creek (Herber 2010). It is possible that the seismic energy was incoherently scattered within this zone and could not effectively image complex structure (e.g., L'Heureux et al. 2009). This, in turn, may indicate that the presumed impact disrupted the structure into blocks smaller than the predominant seismic wavelengths (approximately 30–50 m).

The MPM package is continuous (at the vertical resolution of the seismic data) from the relatively flat-lying areas outside of the structure (not shown), across profiles 86-249 and 86-250. The MPM package remains undisturbed through line 86-249. In line 86-250, however, it rises in an anticline that peaks at a common midpoint (CMP) 270, beneath the "transparent zone," and appears broken to the east of this point (Fig. 12f). Similar effects are seen in high-quality seismic images of the Red Wing Creek structure, North Dakota (Herber 2010). If this anticline is real, it provides some constraints on models of the crater formation. However,

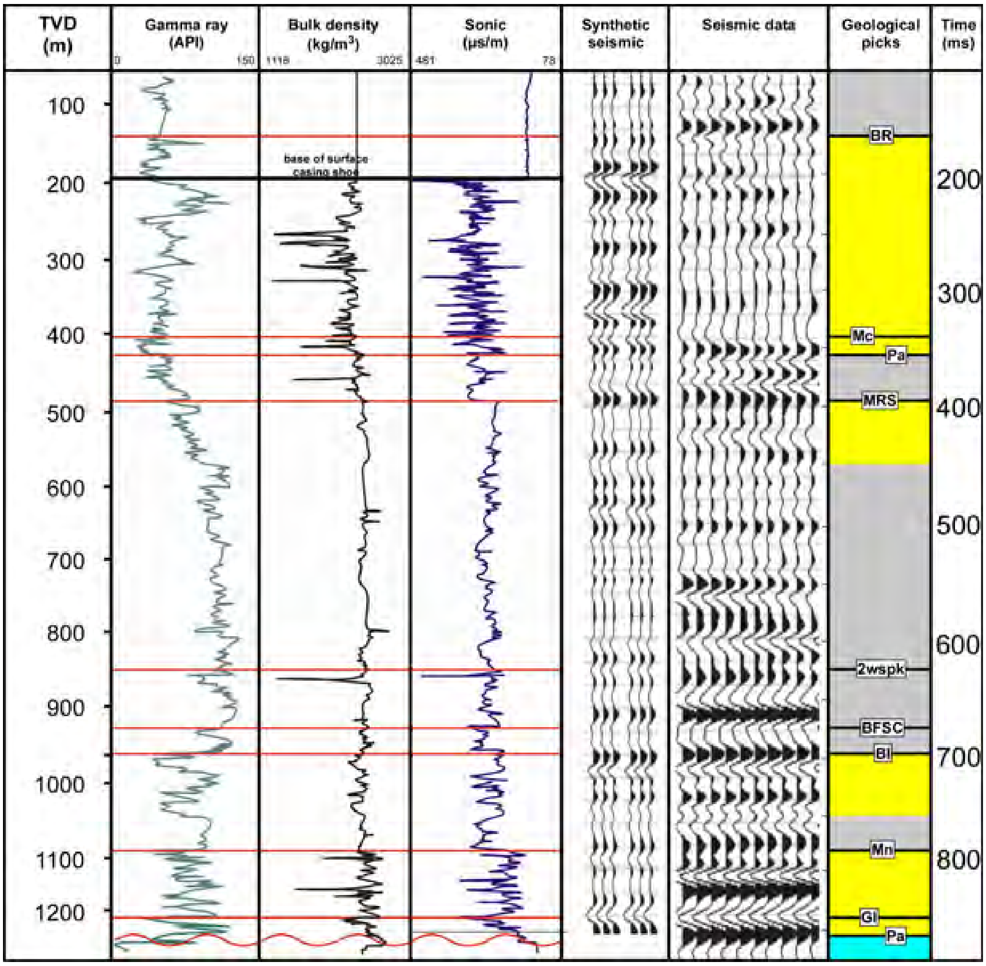

Fig. 11. Synthetic seismogram generated from well 100/07-30-017-18W4/0. Calibrated sonic log and density log were used. Predictability is 60.4% and wavelet phase is 21.5. Gamma-ray log also shown. Geological picks are: BR = top Belly River Gp; Mc = base McKay coal zone; Pa = top Pakowki Fm; MRS = Milk River "shoulder"; 2wspk = top Second White Specks Fm; BFSC = base of Fish Scales Fm; BI = top Bow Island Fm; Mn = top Mannville Gp; Gl = Glauconitic sandstone.

it could also be a seismic "pull-up" feature: an artifact caused by relatively higher seismic velocities in materials immediately overlying the anomalous structure. There is insufficient information on the seismic velocities in both of these structures to make a clear interpretation. Evidence from surface (Karp et al. 2002) and borehole seismic (Schmitt et al. 2007) measurements over the Bosumtwi structure, for example, suggest that the seismic velocities within the brecciated central peak are lower than the surrounding undeformed rock mass. If this is the case at Bow City, then the anticline cannot have been produced by anomalously high velocities, and it is a real feature.

In lines 86-251 (Fig. 12d) and 86-252 (Fig. 12b), within the yellow "transparent zone" the reflectors of the MPM package are discontinuous and significantly raised at least 50 ms (approximately 60 m) above their regional trend. The elevated reflections suggest upward displacement of strata within the central uplift. The patterns are difficult to follow, however, and are probably affected by both anomalous velocities within the "transparent zone" and by out-of-plane reflections resulting from complex structure.

An additional piece of evidence supporting the existence of a central uplift is seen in the strong curved reflection between 100 ms and 150 ms and CMPs 20 to 100 in profile 86-251 (Fig. 12d, top right), interpreted as the Belly River Group top. The curved geometry of the reflector suggests that the strata were folding during central uplift formation.

To the west of the structure, the reflector interpreted as the Belly River Group top is nearly horizontal. Moving eastward, into the structure, however, the top Belly River Group reflector is displaced significantly downward and rotated in a counterclockwise sense (looking north) by what appears to be a listric normal fault (Fig. 12, right; thick pink line). This downward displacement defines

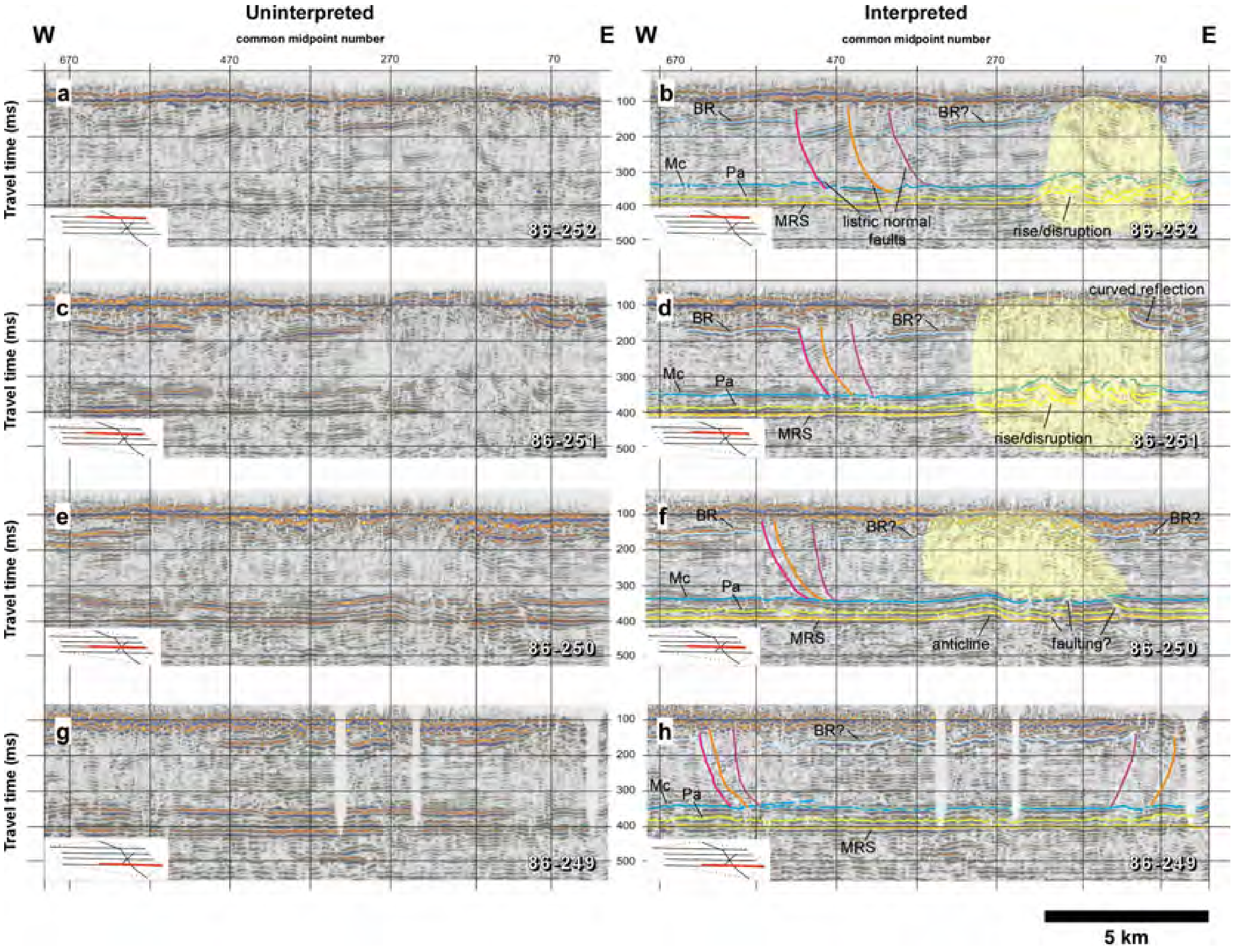

Fig. 12. Uninterpreted (left panels) and corresponding interpreted (right panels) seismic images for east–west seismic profiles through part of the Bow City structure. “Transparent” seismic zone present within central uplift indicated by yellow shading. Annotated features are discussed in text. Insets at bottom left of panels show the position of each figured profile segment (highlighted in red) in relation to the other seismic profiles. See Fig. 2 for profile locations. Interpreted horizons include: Belly River Group top (BR, light blue); McKay coal zone base (Mc, dark blue-green); Pakowki Formation top (Pa, yellow); and Milk River “shoulder” (MRS, orange). Interpreted listric normal faults shown as pink, dark orange, and purple lines.

the outer edge of the structure. In profile 86-252, at least three faults disrupt the continuity of the Belly River Group top reflection between CMPs 410 and 520 (Fig. 12b). A smaller fault is also probably present to the right of CMP 370. The interpreted faults are consistent with slumping of a transient crater outer wall during the modification stage of complex crater formation.

These same three faults appear to extend south and east, cutting obliquely through the three profiles to the south. It is possible, however, that these may not be the same faults. It is also difficult to assess whether the fault terminations at depth are appropriately placed. Additional insight may be gained from the subsurface mapping. There is evidence for only slight structural depression at the level of the Milk River Formation top and almost none at the top of the Medicine Hat Member of the Niobrara Formation. Accordingly, it is reasonable to conclude that the faults root in one or more décollements within the lower Belly River Group, perhaps within the McKay coal zone, or within the underlying Pakowki Formation.

The listric normal faults are shown in a two-way-time structural model in Fig. 13. The model shows (1) uniform and nearly horizontal surfaces outside the structure; (2) the series of three listric faults, visible in Fig. 12, which have been connected in the model; and (3) complicated structure present within the central uplift.

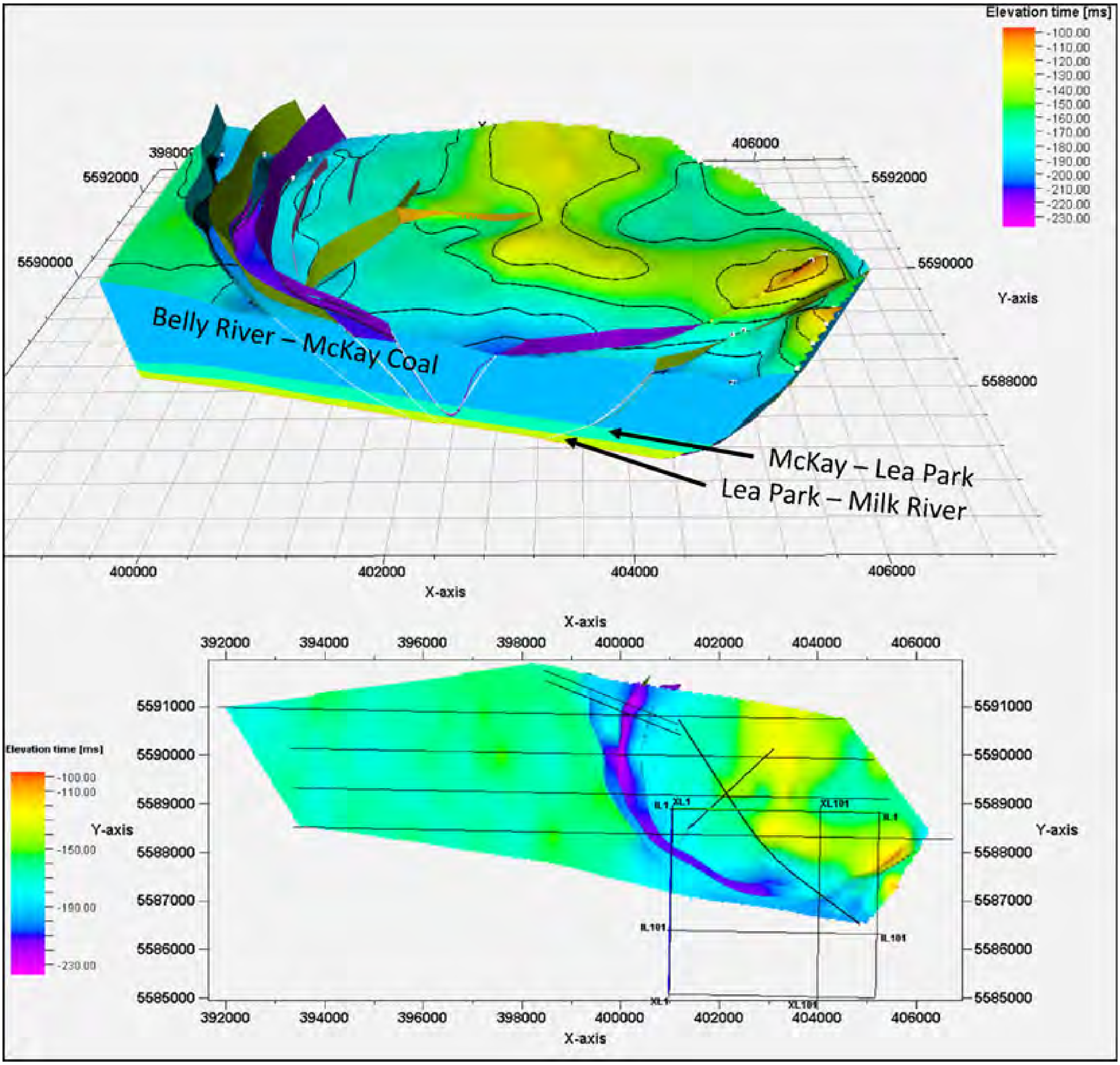

Fig. 13. Two-way-time (TWT) structure model of the southwest quadrant of the Bow City structure. The uppermost surface is the Belly River Group top (20 ms contours); bottom surface is the Milk River "shoulder." Geological units are indicated. Fault surfaces are projected upward toward the ground surface. View is toward the north. Surfaces contoured in Petrel® using convergent gridding algorithm with a 50 m by 50 m grid size. Grid coordinates in UTM Zone 12, NAD 83 datum.

DISCUSSION

Geometry and Structural Style

The geometry and structure of the Bow City structure are revealed through the integration of outcrop, well, and seismic data. The general shape of the structure, as indicated from the structure maps, is a semicircular, bowl-shaped depression with a structural uplift in the center. The apparent diameter of the structure is approximately 8 km. The amount of structural uplift in the center decreases with depth, from a maximum of approximately 200 m at the top of the Belly River Group, to 10–15 m at the top of the Medicine Hat Member (Niobrara Formation). The Dinosaur Park and Foremost formations thicken dramatically in the central uplift area and thin within the surrounding structural depression. The same pattern, although with less dramatic thickening and thinning, is also noted within the underlying Pakowki Formation. The Milk River Formation and the underlying First White Specks Member (Niobrara Formation) show minor thinning in the central uplift area.

It is apparent from well and outcrop data that localized thickening and thinning was accommodated by thrust and normal faults, respectively. Based on observations from well logs and outcrop, stratigraphic units are intact, but, locally, section is anomalously thick or thin due to faulting—either duplication due to thrust faulting or thinning due to section being displaced laterally or cut out by listric normal faults. For instance, well S0/03-26-017-18W4/0, located within the central uplift, shows structural duplication of a distinctive coarsening-upward succession in the Pakowki Formation ("C"-marker succession; Fig. 6b). In the structural depression surrounding the central uplift, or annular region, the same succession has been partially cut out through faulting. This is consistent with observations from outcrop, which record evidence of thrust faulting on the eastern margin of the central uplift and normal faulting within the annular region.

Additional constraints on the nature and style of deformation are provided by seismic data. On lines 86-251 and 86-252, a series of three listric, east-side-down normal faults are visible within the annular region. Reflectors within the fault blocks have been down-dropped and rotated relative to outside the structure. The central uplift is characterized by a seismically "transparent zone." Curved reflectors visible along the west side of the central uplift may be evidence of folding during central peak formation.

Possible Origins of the Bow City Structure

Circular geological features can be produced by a number of geological processes, including igneous activity (diatremes, maars, calderas, volcanoes, or plutons), dissolution and collapse of salt or carbonate rocks by groundwater (dolines), salt or shale diapirism, regional tectonism (circular fold-interference patterns), glaciation (kettle holes), carbonate mounds, and by meteorite impacts (Stewart 1999, 2003). We briefly examine various alternative possibilities for the origin of the Bow City structure.

Many volcanic calderas have a similar structure to complex impact craters with collapsed rims and even central uplifts. There is clear evidence of Eocene (approximately 50 Ma) magmatism approximately 200 km to the south of the Bow City structure in the Sweetgrass Hills on the Montana–Alberta border, where dykes are both exposed and interpreted from airborne magnetic surveys (see Rukhlov and Pawlowicz 2012, and references therein). To our knowledge, however, there is no evidence for Eocene magmatism or volcanism in the Bow City area. Additionally, there is no evidence of igneous material in drill cuttings from wells within and surrounding the Bow City structure. The exposed rim of the structure is defined by deformed clastic sedimentary rocks that are expected in this region and no proximal volcanic deposits are seen. Finally, the seismic profiles show clear continuity of the seismic reflections beneath the Bow City structure. The lack of deeper disruption, while not precluding possible magmatism that could remain unresolved in the seismic images, argues against volcanic activity or emplacement of an igneous body at depth.

Circular dolines, formed by the collapse of surface materials due to dissolution and removal of underlying rock masses, have in the past been misinterpreted as possible impact structures. Such features are produced when a substantial volume of soluble evaporite or carbonate rock is removed by groundwater flow. Such structures exist to the east, in southwest Saskatchewan (Gendzwil and Hajnal 1971). While a thick succession of Mississippian and Devonian carbonate and lesser evaporite rocks underlies the Cretaceous sedimentary rocks in the Bow City area, there are a number of arguments against a collapse hypothesis for the Bow City structure. First, the structure is 8 km in diameter and includes a clear central uplift; dolines of this size are not known, nor do they have central uplifts. Secondly, the structure is underlain by over 700 m of insoluble siliciclastic sandstone and shale (as measured from the Milk River "shoulder" to the top of the Paleozoic carbonate succession). Finally, again, there is no loss of continuity of the seismic reflections within the siliciclastic Cretaceous strata beneath the structure. A collapse feature could not form from dissolution of the deeper carbonates or evaporites without detectably disrupting the overlying stratigraphy.

Circular structures can also be formed by salt diapirism. This process is considered unlikely for the Bow City structure as no salt diapirs are known in the area. There is also a coherent mappable stratigraphy through the Bow City structure and a lack of any evidence for salt in drill cuttings. The amount of uplift associated with the central uplift decreases with depth, and the underlying Cretaceous clastic sedimentary rocks are either weakly uplifted or, at deeper structural levels, slightly lower than regional. As such, a salt diapir origin for the Bow City structure can be ruled out.

Regional tectonics can form domal or circular features through folding or faulting. The eastern edge of the Cordilleran deformed belt is located more than 120 km to the west of the Bow City structure and structure maps show no evidence for regional deformation outside the structure. Deformation related to the Bow City structure decreases with depth and is restricted to a localized circular region, outside of which strata are undeformed and gently dipping, with no evidence for anomalous structure such as pull-apart fault basins or polygonal faulting. This suggests that the Bow City structure is unlikely to have been formed by regional tectonism.

Kettle holes related to glaciation can form round structures, but they are typically a few hundred meters across and are developed in till, not bedrock. Glacial thrusting can include bedrock and is known to have occurred within areas of the North America Interior Plains, including parts of Alberta, Saskatchewan, and North Dakota (Kupsch 1962; Moran et al. 1980; Bluemle and Clayton 1984). There are several reasons why glacial thrusting is considered to be a highly unlikely explanation for the Bow City structure. Existing maps of the surficial geology for the Bow City area show the region to be underlain by thin (typically a few meters thick), undeformed stagnation moraine deposits (Shetsen 1987; and references therein). An area of ice-thrust moraine, which may or may not involve bedrock, is present several kilometers to the north (Shetsen 1987), but does not extend into the area of the Bow City structure. In addition, glacial thrust forms, typically are one of three types: (1) transverse-ridge forms, (2) hill-depression forms, and (3) irregular forms (Bluemle and Clayton 1984). The circular geometry of the Bow City structure and lack of any related deformed glacial deposits preclude transverse-ridge forms. Hill-depression forms are typically characterized by a depression, often filled by a pond or lake, with a hill of ice-thrust material located a short distance down-ice direction (Bluemle and Clayton 1984). This model also does not fit the Bow City structure, as the deformation is restricted to bedrock, there is no topographic depression, and no evidence of a hill of ice-thrust material. In addition, hills and depressions are on the (maximum) order of 30 m high and deep, respectively, whereas the deformation at Bow City extends to depths of around 500 m (Bluemle and Clayton 1984). The circular nature of the Bow City structure, the lack of evidence for glacial thrusting in the area, and the depth to which the deformation affects the bedrock (>500 m), all make a glacial origin for the structure highly unlikely.

The geological and geophysical evidence presented above is most consistent with an impact origin for the Bow City structure. The semicircular geometry of the structure, combined with a circular central structural uplift surrounded by a structural depression, is consistent with an impact structure. The listric normal faults present within the annual region and the evidence for thrusting and duplication of section within the central uplift are observed in other known impact structures. Given the lack of evidence for volcanic or intrusive rocks, carbonate or evaporite dissolution, and paucity of evidence for regional tectonism in the area, we consider an impact origin for this structure by far the most likely. Thus far, field studies have failed to yield requisite macroscopic evidence for shock metamorphism, such as shatter cones, possibly due to the degree of erosion.

Scaling Relationships and Erosion

Planetary scientists have used a number of scaling relationships to try to better understand the physics of impact structures. These relationships, often determined on the basis of empirical observations and informed to some degree from nuclear explosion tests, have been summarized by Melosh (2011). Assuming the Bow City structure is an eroded remnant of an impact structure, the equations can be used to provide some constraints on the size of the impact. However, given the inferred degree of erosion (outlined below), these estimates are considered to be approximate, as the apparent diameter of the structure may be less than the original diameter.

The rim-to-rim diameter of a complex crater D, relative to that for the transient crater (D_t) (all diameters are in kilometers):

$$D = 1.17 * (D_t^{1.13}/D_{s\text{-}c}^{0.13}) \tag{1}$$

where $D_{s\text{-}c}$ is a reference diameter at which the transition between a simple and a complex crater occurs, usually taken to be 3.2 km on Earth. The rim-to-rim diameter of the Bow City structure is estimated to be between 8 and 9 km, assuming that the outermost normal faults delineate the boundary of the crater. Unfortunately, no seismic data are currently available to constrain the easternmost extent of the crater. Therefore, the estimate relies on a combination of the seismics and structure and isopach maps derived from borehole data. Using this diameter provides an estimate of the initial transient crater diameter (D_t) of 6.3 km < D_t < 7 km.

Melosh (1989, p. 119) also notes that the shape of the transient crater is parabolic with:

$$D_t/4 \lesssim H_t \lesssim D_t/3 \tag{2}$$

where H_t is the transient crater depth from the original surface. This would suggest that the crater would have excavated and removed material to a depth ranging from approximately 1.6 to 2.4 km. The MPM reflector package remains in place (Fig. 12), indicating that the lower limit of excavation was above this level. As the McKay coal zone is currently at a depth of approximately 400 m, this suggests that more than 1 km of sedimentary rock has been removed. This is a conservative estimate, as the top of the Belly River Group, which lies approximately 250 m above the MPM within the annular region, remains mostly in place, although it is faulted along the margin of the central uplift.

Several lines of evidence suggest that the Bow City structure has experienced a significant amount of postimpact erosion. The lack of any obvious morphological expression at the surface suggests that the structure was eroded prior to and perhaps during glaciation. Based on the outcrop and borehole data, it appears that no ejecta blanket, breccia, suevite, or melt sheet is preserved in the annular trough region. All of these factors support at least a moderate degree of erosion.

In addition, an estimate of erosion can be obtained from the structural uplift recorded within the center of the structure. Based on data from 24 terrestrial complex impact structures, Grieve and Pilkington (1996) proposed the relationship:

$$SU = 0.086D^{1.03} \tag{3}$$

where SU = the amount of stratigraphic uplift undergone by the deepest lithology exposed at the surface in the center, and D = rim-to-rim diameter. As is apparent from the structure maps of the Bow City structure and other structures, this relationship provides a minimum constraint, as the amount of stratigraphic uplift observed in the central uplift decreases with depth (Brenan et al. 1975; Grieve 1987). Using a conservative rim-to-rim diameter of 8 km for the Bow City structure yields a calculated structural uplift of 732 m. The stratigraphic uplift of the Belly River Group top, which is exposed in the central uplift region, was calculated by removing a first-order trend structure surface and finding the difference between the maximum and minimum residuals in the central uplift and annular trough, respectively. This method yields a calculated stratigraphic uplift of 200 m. Clearly, this is much less than is expected, given the present rim-to-rim diameter. The most reasonable explanation for the discrepancy is that there has been a significant amount of erosion of the structure, with the result that only the deeper structural levels (beneath the transient crater) are preserved.

Several lines of evidence suggest that a substantial thickness of Upper Cretaceous to lower Paleogene sedimentary rocks has been eroded from the Western Canada Sedimentary Basin since the cessation of thrusting in the fold-and-thrust belt in the Early Eocene. Based on the moisture content of coals, Nurkowski (1984) calculated that 900–1900 m of overburden has been removed during postorogenic uplift and erosion, with approximately 1500 m having been eroded in the vicinity of the Bow City structure. Based on vitrinite reflectance of coals from the southern Alberta Plains, England and Bustin (1986) calculated that between 5 and 9 km of overburden has been removed since the end of thrusting, with this number decreasing toward the east. England and Bustin (1986) also reviewed stratigraphic evidence for erosion in the southern Plains, suggesting that 1450–1500 m of strata have been removed since Oligocene time. Khidir and Catuneanu (2009) analyzed authigenic clays in Upper Cretaceous to Paleocene strata bordering the study area on the west and suggested that burial depths ranged from 1500 to 2500 m. Combining these studies, a best estimate for thickness of strata removed during postorogenic uplift and erosion in the Bow City area is considered to be 1500 m. This estimate of eroded overburden thickness is consistent with the lack of evidence of a transient crater at Bow City with a presumed 1.6–2.4 km depth.

Age of the Structure

Due to the degree of erosion, there are few constraints on the age of the Bow City structure. The youngest rocks involved in the deformation are those of the Horseshoe Canyon Formation, which are preserved in the annulus along the northern margin, where they have been down-dropped by normal faults. The contact between the Bearpaw and Horseshoe Canyon formations is time-transgressive, younging from west to east. The rocks of the Horseshoe Canyon Formation exposed in the Bow City area are believed to belong to the Drumheller Member of Eberth and Braman (2012), as the maximum eastward limit of the underlying Strathmore Member lies to the west. The best estimate for the age of the Horseshoe Canyon Formation in this area is approximately 73 Ma, which is considered the best estimate for the upper limit on the age of the Bow City structure. The lower age limit is more difficult to constrain, but the impact must have predated Laurentide glaciation in the area as it is overlain by undeformed till.

Relationship with Hydrocarbon Production

Impact structures, particularly complex impact structures, form potential traps for hydrocarbons

(Donofrio 1981; Masaitis 1989; Isaac and Stewart 1993). In particular, the raised rim, central uplift, or faulted blocks situated within the annular region may form reservoirs if a suitable trapping mechanism is present. Examples of impact structures with hydrocarbon production from the Alberta Basin include Steen River (Robertson 1997; Mazur 1999) and Eagle Butte (Sawatzky 1976; Hanova et al. 2005).

The central uplift of the Bow City structure was first drilled for oil in 1929 (Hudson's Bay Oil and Gas Eyremore 1-S) to a depth of 1758 m, and the well was subsequently abandoned. It is unclear why this location was chosen, but faulting and structural uplift were probably observed during reconnaissance mapping prior to mapping by Stewart (1942). The well is situated within the inlier of Belly River Group rocks (Dinosaur Park Formation) surrounded by rocks of the overlying Bearpaw Formation. Powers (1931) mentioned the inlier of Belly River Group rocks, as well as structural test holes drilled in the area, but did not mention anomalous faulting or deformation.

In the vicinity of the Bow City structure, natural gas and coal-bed methane (CBM) are produced from the Belly River Group, Milk River Formation, Medicine Hat Member (Niobrara Formation), Second White Specks Formation, Bow Island Formation, and the Mannville Group. Oil and natural gas are produced from deeper targets, including the Mannville Group and underlying Paleozoic rocks. As deformation and uplift associated with the Bow City structure appear to be restricted to the shallow subsurface, we confine our observations to the Medicine Hat Member and overlying units. A comparison of gas production rates from units above the Second White Specks Formation in wells within and immediately adjacent to the Bow City structure to those in wells outside the structure indicates that wells within the structure have lower rates or no production. Although a detailed analysis is beyond the scope of this study, we suggest that, in the case of the Bow City structure, deformation and fracturing combined with erosion may have resulted in the lack of a coherent seal (Kirschner et al. 1992).

Implications for the Future Discovery of Impact Structures in Mature Basins

The Bow City structure appears to represent a possible complex impact structure discovered in a mature hydrocarbon-producing basin with a long history of exploration and development. Despite the earlier observation of anomalous structure by Stewart (1942) and the availability of abundant well logs and seismic data in the area, the possible impact origin of the structure has remained unrecognized until recently (Glombick 2010). The Bow City structure is perhaps unusual, in that, due to erosion, it has no obvious morphological expression at the surface, and deformation related to the structure is largely confined to the upper 500 m of the bedrock succession. This makes it difficult to image using existing seismic data optimized for deeper targets. In the future, impact structures discovered in mature and emerging basins may be expected to have similar characteristics. The tectonic setting of the target rocks (a thick succession of coastal plain to transgressive marine rocks deposited in an actively subsiding foreland basin) may also be important, as high subsidence and sedimentation rates in foreland basins adjacent to an active orogen may facilitate the preservation of impact structures in the geological record. Other impact structures in the Western Canada Sedimentary Basin hosted by rocks of the Bearpaw Formation, Belly River Group, and Pakowki Formation include Eagle Butte, Alberta (Sawatzky 1976; Hanova et al. 2005), and Maple Creek, Saskatchewan (Gent et al. 1992).

CONCLUSIONS

The semi circular Bow City structure was revealed during subsurface regional mapping of near-surface formations using geophysical well logs. Legacy 2-D seismic profiles over the structure show normal faulting near the outer rim of the structure, and a highly deformed seismically "transparent zone" near the center that is consistent with deformation expected during the crater modification stage. This deformation is also seen in the limited outcrop with rotated sedimentary rocks disrupted by numerous thrust and normal faults. The structural data support the hypothesis that the Bow City structure was produced by a hypervelocity impact. Alternate hypotheses for formation of the structure have been considered and rejected on the basis of geological observations.

An unusual aspect of this structure is that it is highly eroded, with all evidence of the transient crater having been removed. While in some respects this may be disappointing, it does allow more ready access to the deeper roots of the structure. The resulting data may provide important constraints on dynamic modeling of the modification stage of crater formation.

Confirmation of an impact origin requires definitive evidence of shock metamorphism that we do not have at this time. No such evidence has yet been recovered from outcrop or drill cuttings. Given the degree of erosion of the structure, it may be that the structurally disturbed formations that remain may never have experienced sufficiently severe shock conditions to damage the minerals. Consequently, conclusive affirmation that the Bow City structure is a remnant impact structure may not be forthcoming. Despite this, we believe it is difficult to avoid the conclusion that it represents the remains of an impact structure.

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