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Preliminary 3D Modelling and Structural Interpretation of Southeastern Athabasca Basin

Z. Li[1], K.M. Bethune[1], G. Chi[1], S.A. Bosman[2] and C.D. Card[2]

[1] - Department of Geology, University of Regina, 3737 Wascana Parkway, Regina, Saskatchewan S4S 0A2
[2] - Saskatchewan Geological Survey, 2101 Scarth Street, Regina, Saskatchewan S4P 2H9

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Abstract

The southeastern portion of the Athabasca basin hosts the largest high-grade unconformity-related uranium deposits in the world, including the McArthur River and Key Lake deposits. As a first step of an effort to reconstruct and model the fluid flow related to uranium mineralization, a 3D model of the sub-Athabasca unconformity and basin stratigraphy has been constructed using publicly available geological, geophysical and drill-hole data. Several cross-sections have been built and integrated into the 3D model to constrain the spatial configuration of Athabasca Group units. Faults have been identified using an iterative approach where potential fault lineaments were identified using the basement geophysical signature then confirmed by the presence of spatial relationships to offsets of the unconformity surface. Using this approach, three dominant sets of faults, inferred to be sub-vertical, have been identified in the study area: northeast trending, north-northwest trending and northwest trending. In the 3D model, the unconformity surface shows an approximately northeast-trending zone of elevated topography where elevations change abruptly (SE to NW) from about -100 m to +200 m (referenced to mean sea level). This topographic ridge of the unconformity surface is associated with the Phoenix - McArthur River deposits trend. A preliminary cross-section illustrates that this topographic high may be controlled by northeast-trending reverse faults that have uplifted the basement. Regional clay anomalies in the Athabasca Group and the majority of deposits and prospects are also broadly coincident with this feature. Future work will be focussed on increasing resolution of the model in this and other key areas to gain a better understanding of the geometry and kinematics of regional plus local structures and their control on fluid flow and uranium mineralization.

1. Introduction

The Athabasca basin (Fig. 1) hosts the world's largest known high-grade unconformity-related uranium deposits. Exploration has been most intense in the eastern Athabasca basin and many studies have been conducted to determine the genesis of the uranium ore deposits in these areas. A common feature of unconformity-related uranium deposits is their close spatial association with reactivated basement faults intersecting the unconformity surface (Jefferson et al., 2007; Ruzicka, 1993). However, the results of the EXTECH IV Project (Jefferson et al., 2007), along with more recent studies, indicate that significant gaps remain in our understanding of these deposits and that refinements to this general model are warranted. One important gap concerns the special physiochemical factors that focused fluid flow at specific sites within the basin, especially along fault zones and within wider structural zones, and why some faults are more prospective than others. While recent studies advocate that fluid flow was either downward into basement fault zones (“ingress” deposits), or upward and outward from such zones (“egress” deposits), and that these systems were potentially linked (Jefferson et al. 2007), the mechanisms involved remain poorly understood, as discussed by Chi et al. (2013). For example, there is the question of whether ingress flow and egress flow were associated with alternating compressional and extensional stress fields, accompanied by fluid pressure fluctuation (Cui et al., 2012), or alternatively whether changes in fluid pressure caused episodic faulting under constant stress conditions, as exemplified by the fault valve model (Sibson, 1988). Finding answers to these questions is of economic significance because they will help discriminate between fault-fluid-alteration/lithology combinations favourable for uranium mineralization and those that are unfavourable, not only in the Athabasca basin, but also in other prospective Proterozoic basins. The interaction between faulting and fluid flow is therefore a universal theme applicable to exploration of unconformity-related uranium deposits as well as other deposit types which use an integrated 3D approach (e.g., Rawling et al., 2006; Skytta, 2012).

We have selected a 100 km by 60 km zone (Fig. 1) along the southeastern Athabasca basin to study the relationship between structures, fluid flow and uranium mineralization. The first stage of this project involves analysis of the surface/subsurface regional geology and construction of a 3-dimensional (3D) model to image the fundamental lithological, structural and alteration features. Once the model is completed, numerical modelling of fluid flow will be conducted to test various combinations of lithology, orientations of structures, stress fields and thermal conditions. This paper presents preliminary results of the 3D modelling.

2. Regional geological setting

2.1 Basement geology

The study area is located near the southeastern margin of the late Paleoproterozoic Athabasca basin. This portion of the basin overlies older Precambrian rocks of the Wollaston and Mudjatik domains of the Hearne Subprovince, both of which are part of the larger Churchill Structural Province of the Canadian Shield (Hoffman, 1988; Lewry and Sibbald, 1977; Fig. 1).

The Wollaston domain is a northeast-trending fold and thrust belt that is bounded to the east by the Peter Lake and the Rottenstone domains and to the west by the Mudjatik domain (Lewry and Sibbald, 1977; Fig. 1). It comprises older Archean granitoid gneisses and an Early Paleoproterozoic supracrustal sequence, the Wollaston Supergroup (Yeo and Delaney, 2007) that was intensely deformed during Hudsonian orogenesis. The Wollaston Supergroup unconformably overlies Archean granitoid gneisses and comprises three dominantly metasedimentary packages that record deposition through rift, passive margin, and foreland basin environments (Tran, 2001; Yeo and Delaney, 2007). The minimum age of the Wollaston Supergroup is constrained by the crosscutting 1.865–1.850 Ga Wathaman batholith (Van Schmus et al., 1987; Fig. 1).

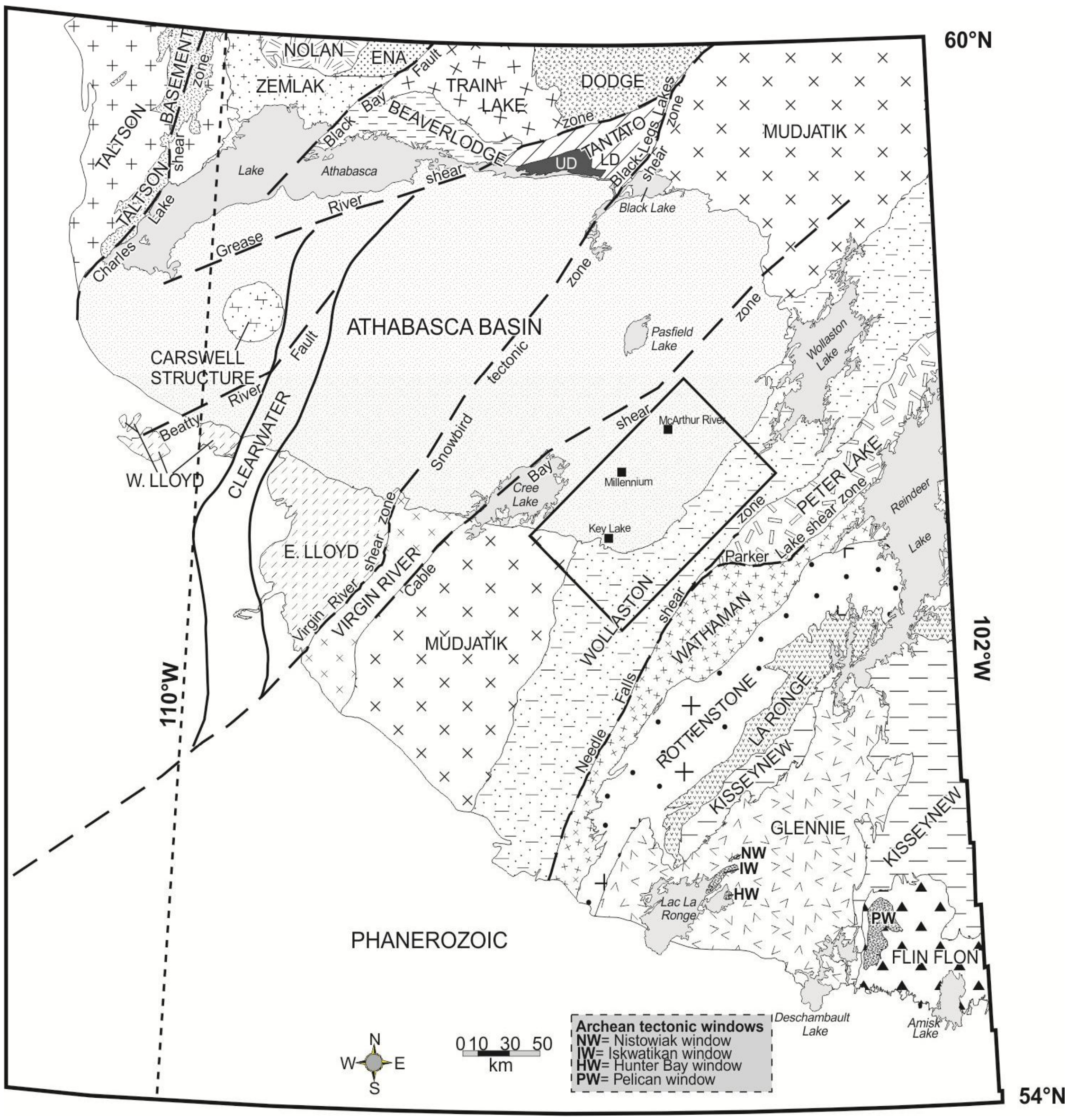

Figure 1. Precambrian domain map of Saskatchewan (modified from Card et al., 2007). The rectangle outlines the study area.

The Mudjatik domain is characterized by a dome-and-basin structural style resulting from fold interference during Hudsonian orogenesis. It grades through a transition zone, corresponding to the Cable Bay shear zone along much of its length, to the more linear, northeast-trending structures of the Virgin River domain in the west (Fig. 1). To the east, the Mudjatik-Wollaston domain boundary is similarly characterized by a change in structural style from dome-and-basin in the Mudjatik domain to linear in the Wollaston domain (Lewry and Sibbald, 1977), as upright northeast-trending folds become tighter and more dominant. This boundary is considered by most researchers to be transitional with regard to observed lithological units, with an increase in the proportion of Wollaston Supergroup metasedimentary rocks toward the east (e.g., Annesley et al., 2005; Tran, 2001; Yeo and Delaney, 2007). The oldest rocks in the Mudjatik domain are Archean granitoid gneisses. U-Pb zircon age determinations have indicated that some of these gneiss units may be as old as ca. 2.9–2.8 Ga (Orrell et al., 1999), but the majority are in the range 2580–2560 Ma (Annesley et al., 1997).

2.2 Athabasca Group

The Athabasca basin occupies an area of about 100,000 km^2 in northern Saskatchewan and northeastern Alberta (Fig. 1). It contains late Paleoproterozoic sedimentary rocks (Athabasca Group) unconformably overlying a basement regolith up to 50 m thick (Hoeve and Sibbald, 1978). The stratigraphic succession of the basin consists predominantly of quartz arenite and quartz-rich sandstone with subordinate conglomerate and siltstone (Ramaekers et al., 2007). The Athabasca Group has a total preserved stratigraphic thickness of about 1500 m in the central part of the basin, although much has been eroded and an aggregate stratotype thickness of 3800 m has been proposed (Ramaekers et al., 2007). The preserved sedimentary record of the Athabasca Group includes the following formations, in order from oldest to youngest: the Fair Point, Read, Smart, Manitou Falls, Lazenby Lake, Wolverine Point, Locker Lake, Otherside, Douglas, and Carswell. The eastern part of the Athabasca basin is made up exclusively of the Read and Manitou Falls formations that are dominated by sandstone of fluvial origin (Ramaekers et al., 2007, Fig. 2).

A maximum depositional age of ca. 1803 Ma has been determined for the Athabasca Group based on a U–Pb zircon ages of pegmatites from the Wollaston domain (Annesley et al., 1997). A somewhat younger maximum age of ca. 1750 Ma is indicated by $^{207}Pb/^{206}Pb$ and U–Pb rutile ages of metapelites from the Mudjatik domain (Orrell et al., 1999). In addition, $^{40}Ar/^{39}Ar$ dating of K-bearing minerals in pre-Athabasca Group (basement) metamorphic rocks indicates substantial post-Hudsonian uplift and cooling by ca. 1750 Ma, the latter representing a maximum age for the formation of the basin (e.g., Alexandre et al., 2009).

U–Pb dating of detrital zircon grains of the Athabasca Group by Rainbird et al. (2007) provides broadly similar age constraints on basin development. The youngest detrital grain in the Fair Point Formation indicates that deposition began after 1815 Ma, corroborating maximum depositional ages from basement rocks reported above, while the youngest detrital grain in uppermost Wolverine Point Formation indicates that it continued until at least 1650 Ma. Furthermore, an age of 1644 ± 13 Ma was obtained for zircon grains from reworked tuff layers in the Wolverine Point Formation (Rainbird et al., 2007). This detrital zircon study also indicates that sediment provenance varied with time. For example, the Fair Point Formation contains substantial populations of 2.61–2.52 Ga and ca. 1.9 Ga zircon grains, indicating provenance from the western Rae Province, Sask Craton, and the Trans-Hudson Orogen. In contrast, two samples from the Manitou Falls Formation (Bird and Dunlop members) contain mainly ca. 2.58 Ga and ca. 1.85–1.83 Ga zircon grains, suggesting provenance from the Hearne Province and Trans-Hudson Orogen, respectively (Rainbird et al., 2007).

2.3 Younger rocks

The Athabasca Group sedimentary rocks and the basement complexes are cut by northwest-trending mafic dykes of the McKenzie swarm (Cumming and Krstic, 1992). These sub-vertical dykes range in width from one to several hundred meters and have been precisely dated at 1267 ± 2 Ma (LeCheminant and Heaman, 1989).

Another suite of olivine diabasic and gabbroic rocks, the 1.11 Ga (MacDougall and Heaman, 2002) Moore Lakes Complexes, intruded the Wollaston domain basement and the Athabasca Group (MacDougall and William, 1993) along the southeastern perimeter of the Athabasca basin, forming a complex of sill-like intrusions (Fig. 2).

3. 3-Dimensional modelling

3.1 Selection of study area, data sources and database configuration

As a first step in modelling, an approximately 100 by 60 km rectangular area of the southeastern Athabasca basin was selected for study, encompassing the major northeast-trending corridor hosting several major deposits stretching from Key Lake in the south to McArthur River in the north (Fig. 1). For optimal geological and structural information, the rectangular area was oriented with the long dimension parallel to regional structural trends. A GIS database was then configured in ArcGIS comprising relevant topographic (DEM), geological and geophysical information. These data were mainly extracted from the Saskatchewan Geological Atlas (Saskatchewan Geological Atlas, 2013), but additional high-resolution aeromagnetic data (i.e., Card et al., 2010) was supplied by the Saskatchewan Geological Survey.

Following configuration of the ArcGIS database, relevant layers of information were spliced along model boundary lines and imported into GoCAD (Mira Geoscience, 2012) to facilitate imaging in 3D. For reference, the average topographic elevation of the Athabasca basin region is ca. 500 m above sea mean level and all elevation information in this study is given in metres relative to mean sea level. The Z dimension of the 3D model volume was therefore set as -1000 to +700 m (Fig. 2, based on the highest topographic point and lowest elevation of the unconformity surface, +600 m and -200 m, respectively) enabling visualization to a reasonable distance below the unconformity surface. The X-Y-Z coordinate information for 536 comprehensive (complete) drill-hole logs was then imported, representing the entire SGS suite of full-log data for this area/volume, along with another 1,540 points representing X-Y-Z coordinates of drill-hole intersections of the unconformity surface (Bosman et al., 2010).

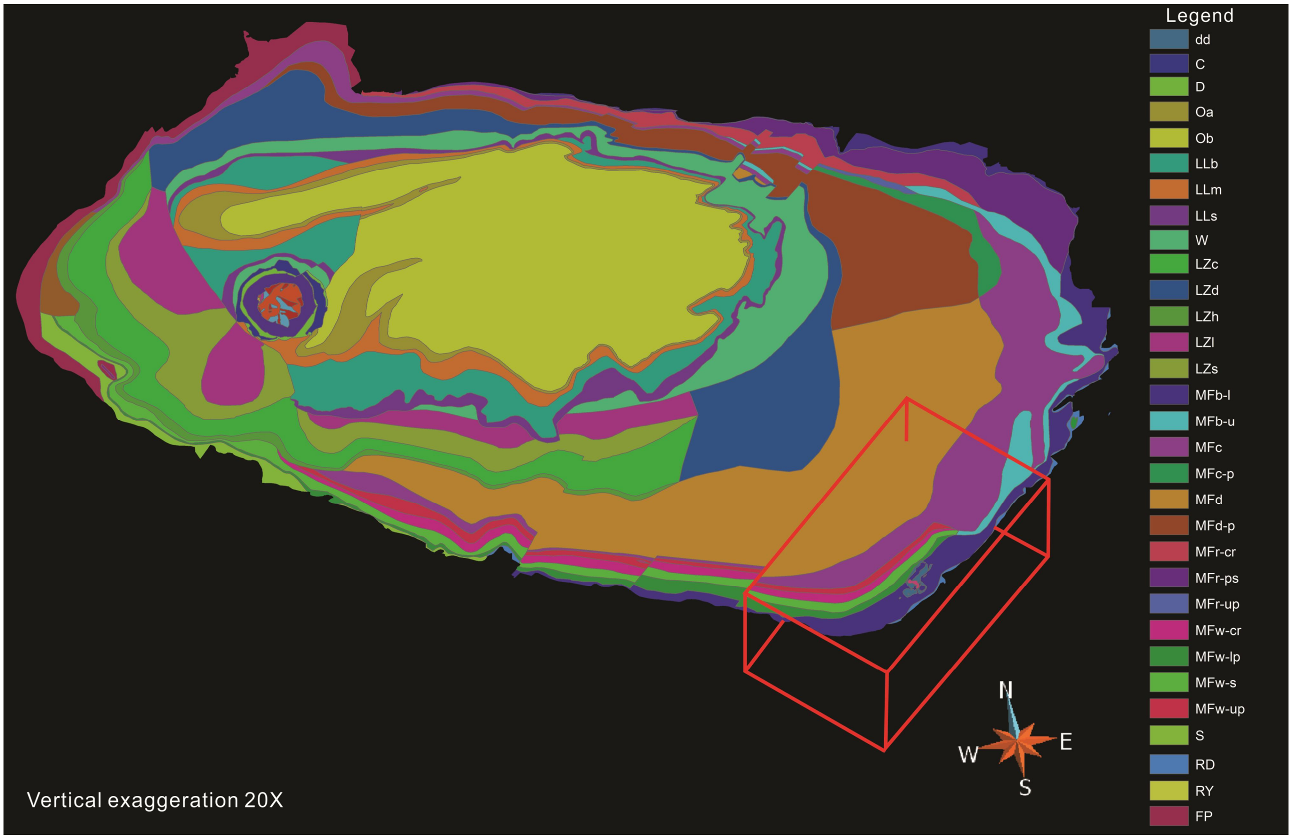

Figure 2. Geological framework of the Athabasca basin, with location of the 60 km wide, 100 km long and 1.7 km deep 3D model architecture shown in the southeast corner of the basin. Athabasca Group Formation/member abbreviations: dd=diabase, C=Carswell, D=Douglas, O=Otherside, LL=Locker Lake (m=upper pebbly, b=conglomerate, s=lower pebbly), W=Wolverine Point, LZ=Lazenby Lake, MF=Manitou Falls (members: b=Bird (l=lower, u=upper) c=Collins (p=pebbly), d=Dunlop (p=pebbly), r=Raibl (up=upper pebbly, cr=clay-intraclast-rich, ps= pebbly), w=Warnes (up=upper pebbly, cr= clay intraclast rich, s=quartz arenite, lp=lower pebbly)), S=Smart, RD=Read, RY=Reilly, FP=Fair Point.

3.2 Structural Interpretation

It is well known that unconformity-related uranium deposits are closely associated with faults that have offset the unconformity surface. The knowledge of basement structures below the Athabasca basin is therefore important to both uranium research and exploration. Even though the Athabasca Group contains diagenetic hematite (Kotzer et al., 1992), it is essentially nonmagnetic (Thomas and McHardy, 2007). As a result, the magnetic effects of Athabasca cover overlying basement rocks are negligible and patterns and intensities of magnetic anomalies can be used to investigate the structure and composition of the underlying basement (Thomas and McHardy, 2007). Previous work has shown that airborne magnetic surveys provide an effective means of mapping basement geology beneath the Athabasca Group, especially faults and basement lithologies (e.g., Madore et al., 2000; Pilkington, 1989; Pilkington and Roest, 1992; Thomas and McHardy, 2007).

Reactivated basement structures can normally be identified by sharp linear changes in geophysical signature on aeromagnetic maps, particularly the first vertical derivative (1 VD) of the total magnetic intensity (TMI). A useful approach in fault analysis is to first conduct a two-dimensional lineament trend analysis using aeromagnetic data and later establish whether mapped lineaments coincide with offsets of the unconformity in the subsurface.

Figure 3 shows a regional aeromagnetic map with an outline of the study area and the projected positions of major lithostructural domain boundaries below Athabasca Group cover. One can see that the Mudjatik–Wollaston transition coincides with a pronounced northeast-trending regional magnetic low, known to correlate with a zone of graphitic pelitic and semi-pelitic gneiss in the underlying basement, as compared to granitoid units in the magnetic highs (Earle and Sopuck, 1989; Thomas and McHardy, 2007). As mentioned above, faults have been identified using an iterative approach, first identifying potential fault lineaments using the basement geophysical signature and then checking if these linear features have any spatial relationship to offsets of the unconformity surface. Using this approach, three dominant sets of sub-vertical faults have been identified (Fig. 3): northeast-trending, north-northwest trending and northwest trending (Fig. 4). The largest population of northeast-trending fault lineaments have strikes ranging from 030° to 075°, with an average of 050°, whereas the less prolific north-northwest-trending lineaments have strikes ranging from 340° to 360°, with an average of 352°. The smallest grouping of northwest-trending lineaments encompasses strikes ranging from 300° to 330° (average ~315°).

The northeast-trending faults are by far the most dominant and most likely related to Hudsonian structures/fabrics in the Wollaston and Mudjatik domains (Annesley et al., 2005). Some appear to be localized along zones of structural weakness such as contacts between Archean inliers and Wollaston Supergroup supracrustal rocks. Some of the north-northwest trending faults are likely related to the Tabbernor fault system but further investigation is required to confirm this relationship.

As discussed further below, several of the major deposits, as well as many minor prospects/showings, are localized along a series of linked northeast-trending faults, broadly coinciding with the Mudjatik–Wollaston transition magnetic low and informally known as the Phoenix–McArthur River trend.

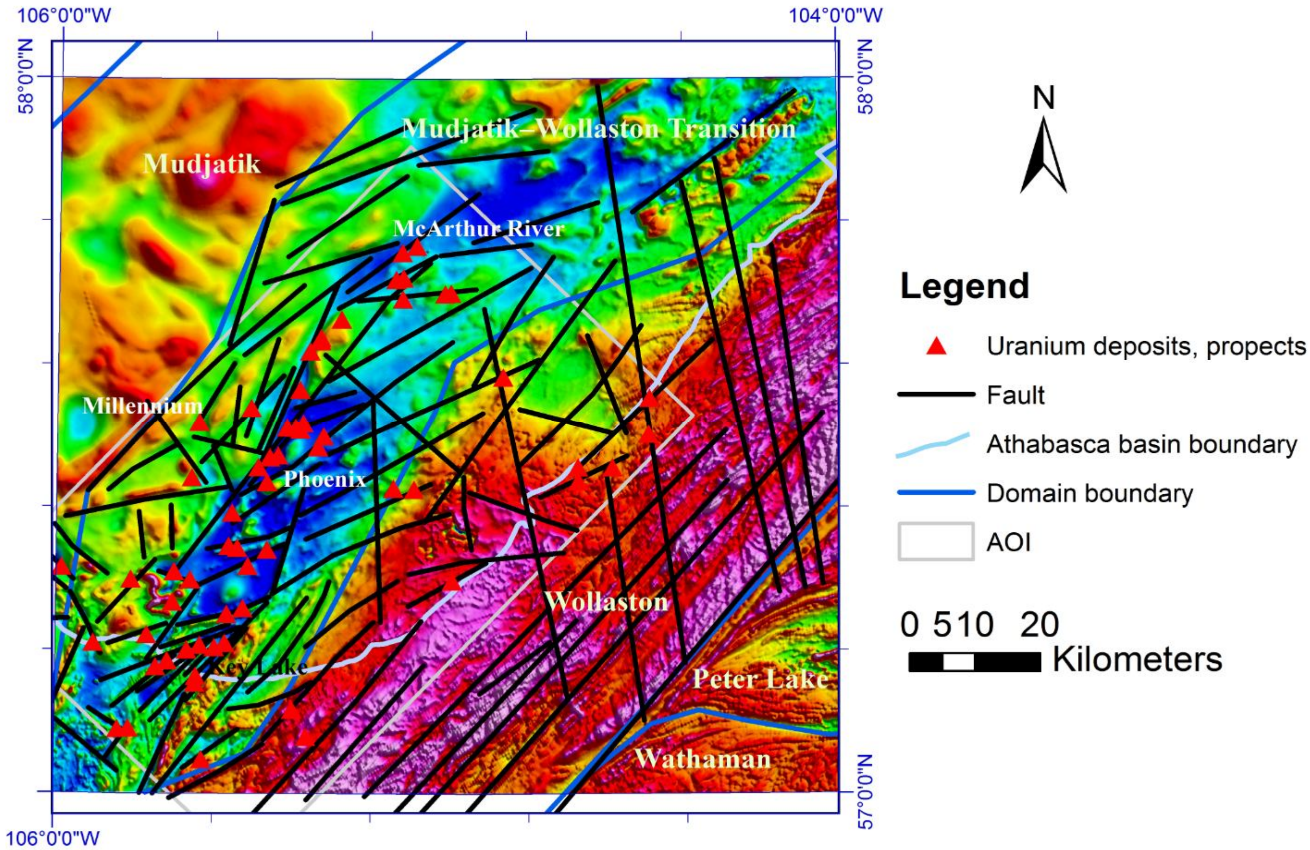

Figure 3. Distribution of basement faults in the study area as interpreted from the aeromagnetic data from Card et al. (2010). The red triangles indicate the uranium deposits, prospects and occurrences within the study area.

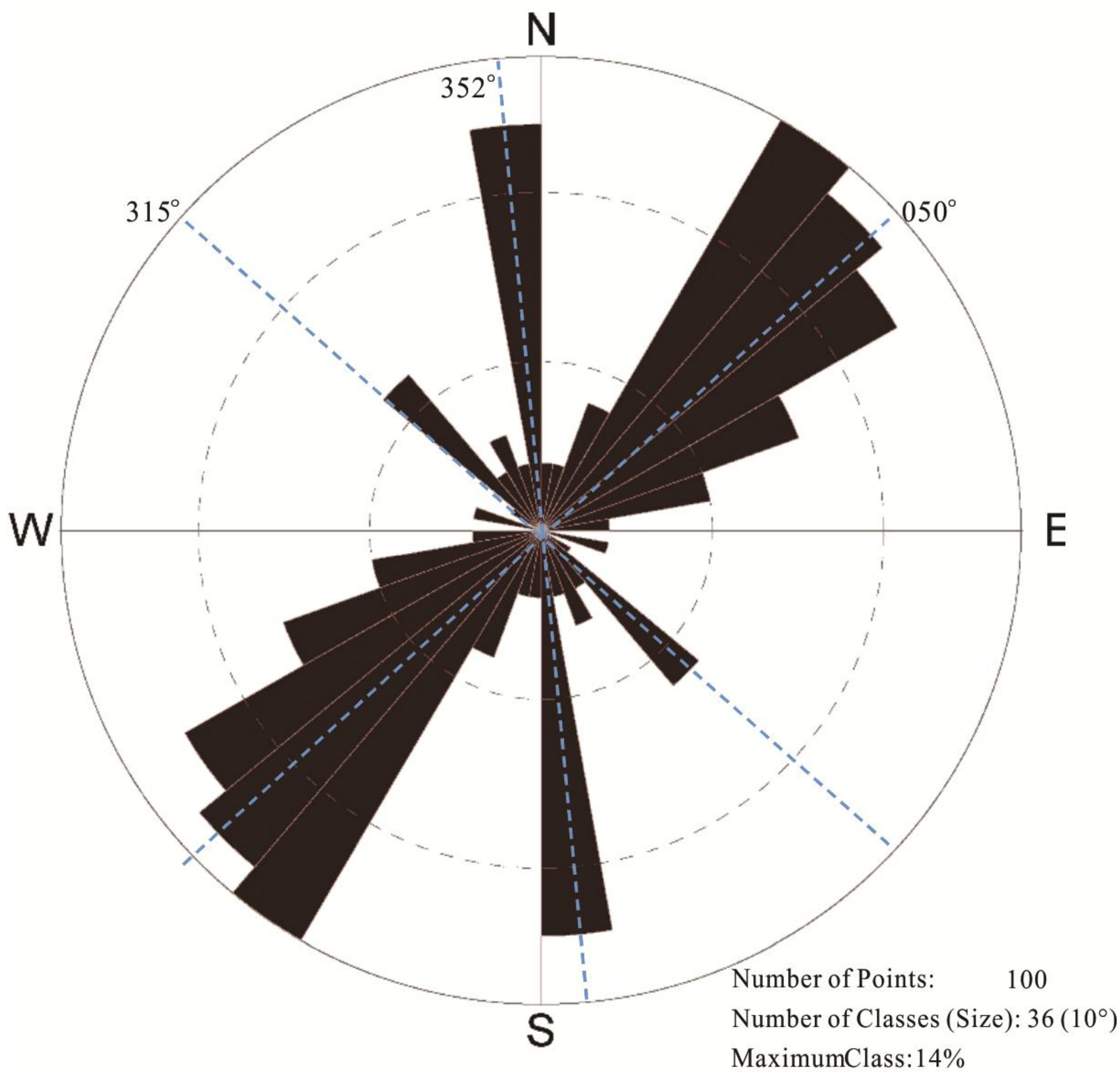

Figure 4. Rose diagram of basement faults illustrating three dominant orientations: NE set trends approximately 050°, NNW set trends approximately 352° and NW set trends approximately 315°.

3.3 Imaging key surfaces

3.3.1 Topographic surface

In 3D geological modelling, it is necessary to build a topographic model (i.e., Digital Elevation Model, DEM) of the area/volume of interest. The DEM defines the highest elevation of the model and registers all the drill-hole information to the ground surface to maintain model consistencies.

The 3D topographic surface of the area, which is the upper surface of overburden, was obtained using Shuttle Rader Topography Mission 2 (SRTM2) data. Supplied by the Saskatchewan Geological Survey, the detailed DEM (pixel size 200 m) served as a base on which generalized geological and geomorphologic linear features were projected (Fig. 5). The lower surface of the overburden, which separates the overburden from the underlying Athabasca Group, was also constructed by compiling the elevation of the initial contact with the Athabasca Group in all available drill-hole logs (Fig.5).

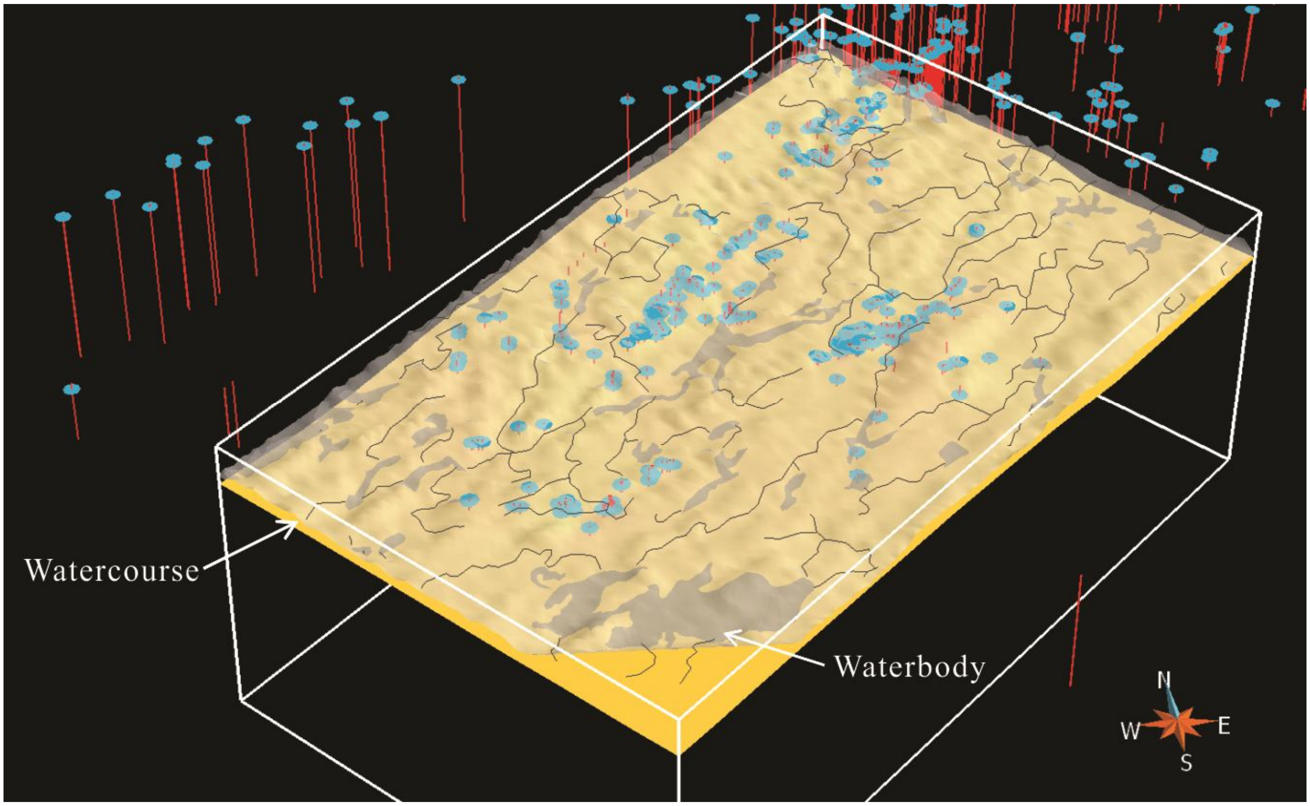

Figure 5. Upper surface of overburden (i.e., topographic surface, grey in color); and lower surface of the overburden (top of Athabasca Group, yellow in color). Red lines are drill-hole traces and blue pies are markers of lower surface of the overburden.

3.3.2 Selected stratigraphic contacts and the unconformity surface

To monitor effects of stratigraphy on fluid flow, and potentially uranium mineralization, it was deemed important to model key stratigraphic contacts as well as the unconformity surface. As illustrated in Figure 6, the contact between the Dunlop (MFd) and Collins (MFc) members of the Manitou Falls Formation was modelled based on drill-hole markers and some interpretation. This contact follows the trend of depth change of the basin, generally increasing in depth radially inward from the basin margin toward the interior (northwest side of model).

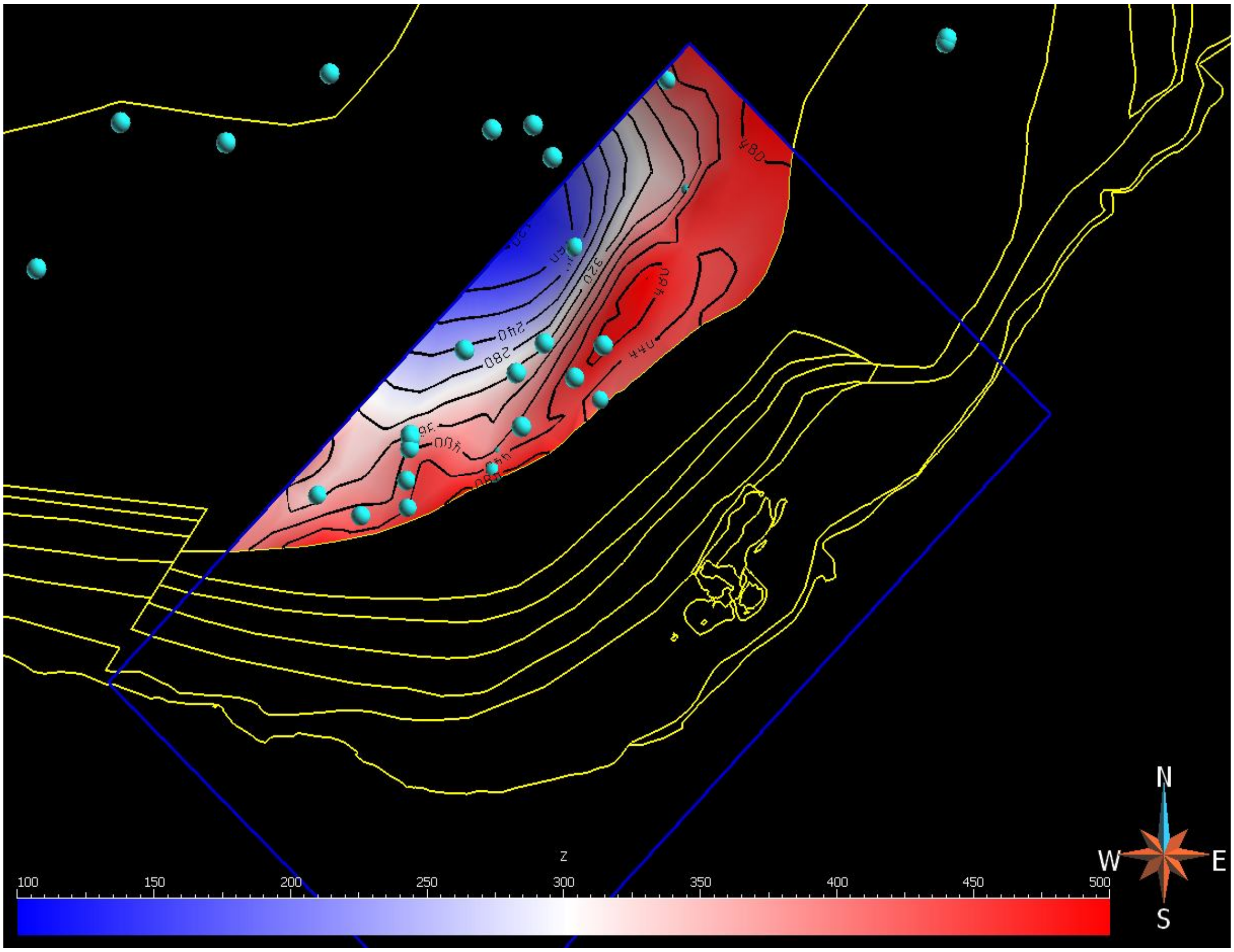

Figure 6. Contact between Dunlop (MFd) and Collins (MFc) members of the Manitou Falls Formation. Blue spheres show the drill-hole markers used to constrain the contact.

At the outset of modelling, attention was also given to the unconformity surface, particularly any irregularities that might be detected related to fault offsets. As with the MFd/MFc contact discussed above, the unconformity surface generally increases in depth radially inward from basin margins (Fig. 7). However, there is a notable and relatively sharp southeast to northwest increase in depth across northeast-trending fault lineaments related to the Phoenix – McArthur River trend (see Figs. 3, 7c). The elevation of the unconformity surface changes abruptly from ca. -100 m to +200 m across this topographic ridge, effectively representing a basement fault scarp (Figs. 7a and b). In Fig. 9c, the 2D aeromagnetic image with interpreted basement fault lineaments are draped onto the unconformity surface, highlighting the close spatial relationship of faults with this scarp. The change in topography appears to be related at least in part to reverse displacement along steeply southeast-dipping fault zones, as documented in the Phoenix and McArthur deposits (e.g., Kerr, 2010; Marlatt et al., 1992), although this has yet to be confirmed by more detailed structural analysis.

In Figure 7, uranium deposits, prospects and occurrences are projected onto the unconformity surface and divided into the three deposit end-members: basement-hosted, unconformity-hosted, and unconformity- plus basement-hosted. From this figure, it is evident that the Phoenix - McArthur River deposits trend is associated with a substantial (~300 m high) topographic ridge and faulted offset of the unconformity surface (Figs. 3 and 7c).

3.4 Cross-section construction

Four cross-sections were built and integrated into the 3D model to constrain the spatial configuration of Athabasca Group units and the unconformity surface (Fig. 8). To better illustrate true thicknesses and geometric relationships, all four cross-sections were constructed at a high angle or perpendicular to the strike of regional northeast-trending structures (Fig. 8a). Drill-holes at certain locations were selected as pillars (blue short lines, Fig. 8a) to build each cross-section in GoCAD. In a given section, successive stratigraphic contacts in respective drill-hole pillars were connected to constrain the cross-sectional form of related stratigraphic surfaces.

The faults shown in these cross-sections were determined using an iterative approach, first checking to see if the section line traversed any faults identified in basement structural-lineament analysis (from aeromagnetic maps) and then checking to see if an identified lineament coincided with any offset of the unconformity surface. The position and related dip of the fault along the line of section was then be determined by: 1) projecting the position of the basement fault lineament to the ground surface; and 2) connecting this point on the section line with the point of offset of the unconformity on the section line below. The most reasonable interpretation was then chosen to satisfy these spatial relationships. Figure 8(b) illustrates that along the southernmost section (Crosssection_04, Fig. 8a), paired, southeast- and northwest-dipping reverse faults may have been responsible for the basement topographic ridge described above (Fig. 7).

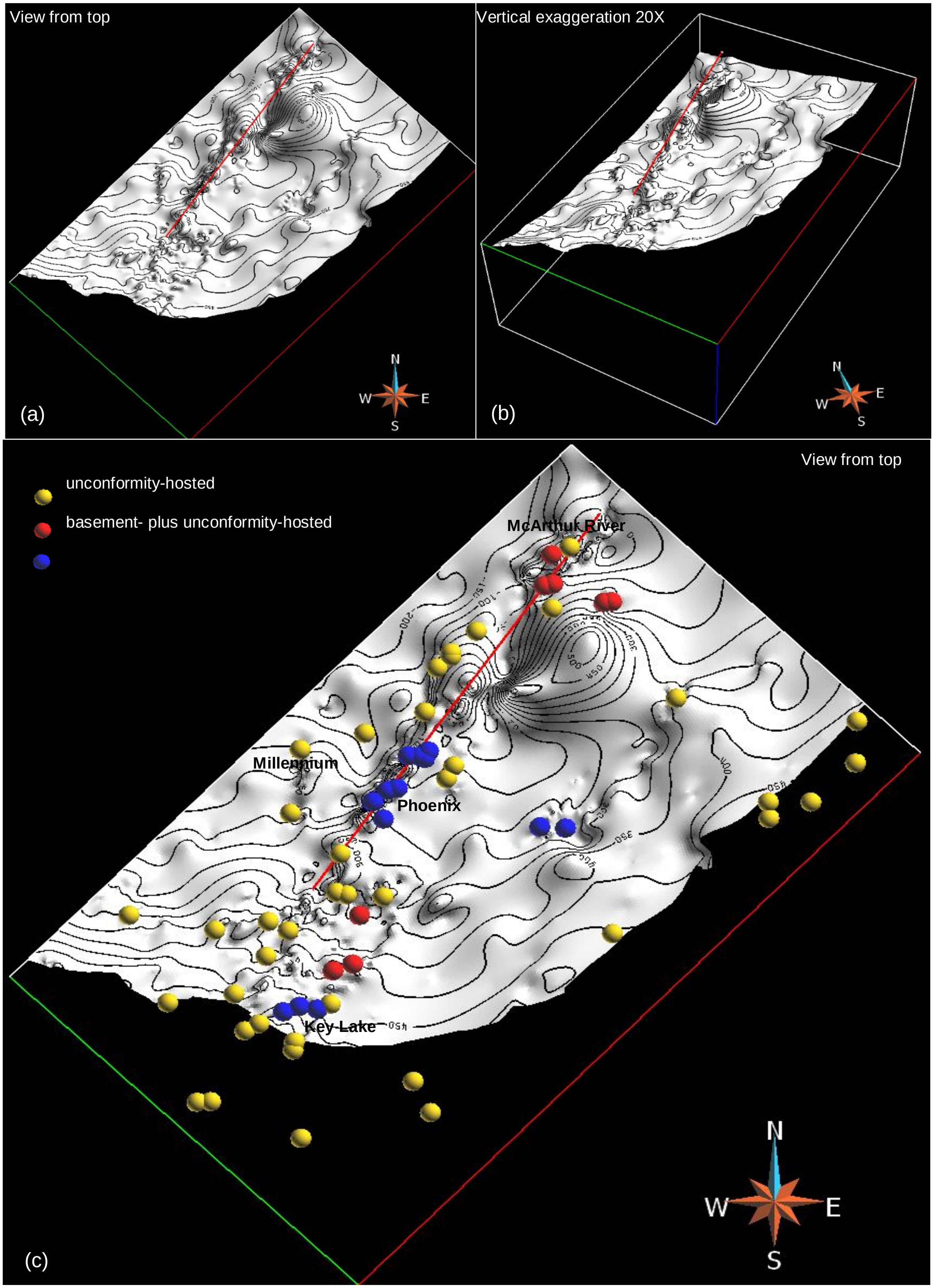

Figure 7. (a and b) Contour maps showing the elevations of the sub-Athabasca unconformity in the study area. (c) Three types of unconformity-related uranium deposits (basement-hosted, unconformity-hosted, and basement- plus unconformity-hosted) are draped onto the unconformity surface. The red solid line shows the approximately northeast-trending basement topographic ridge.

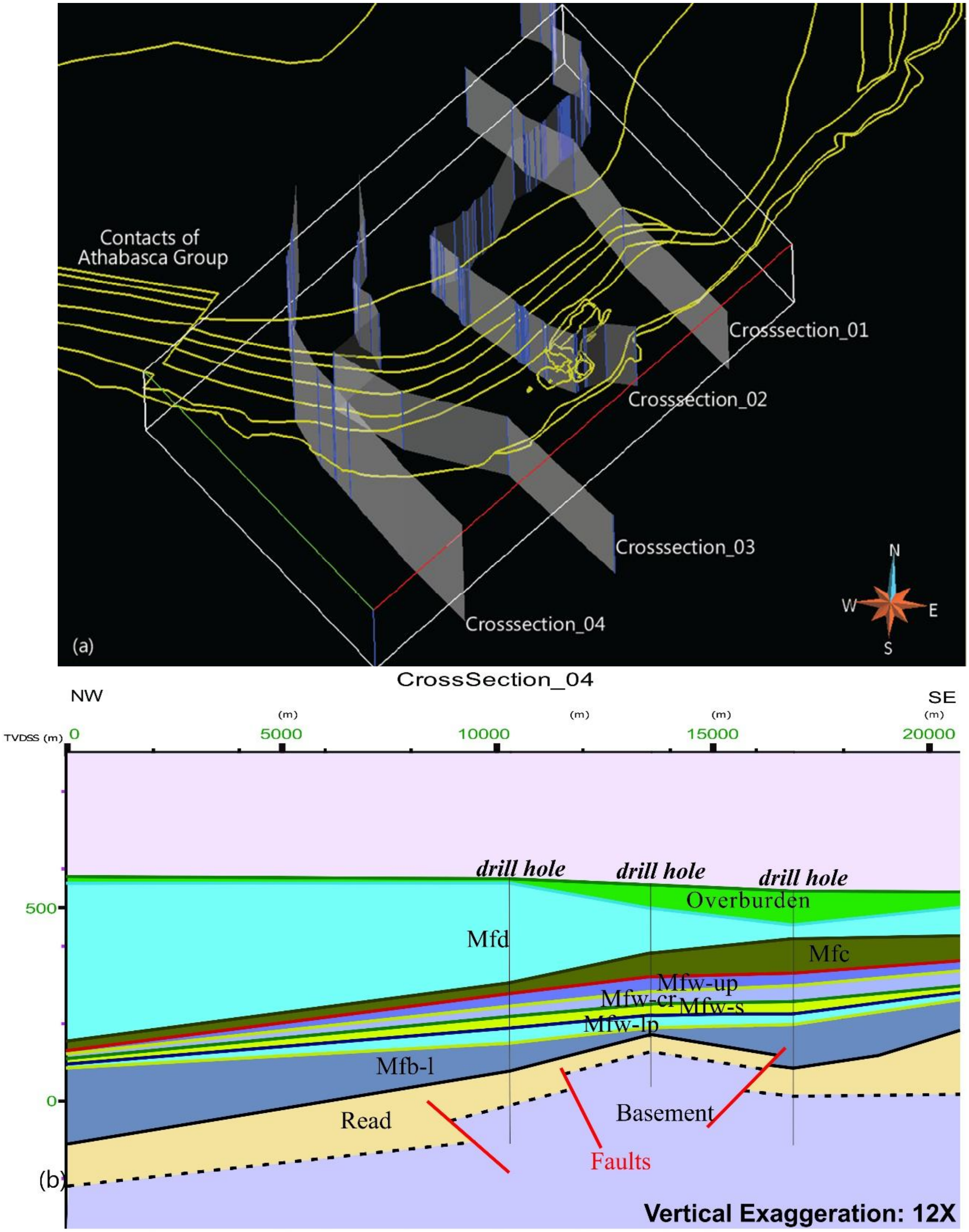

Figure 8. (a) 3D model showing the locations of four cross-sections build with GoCAD, and (b) a portion of cross-section_04.

3.5 Relationship between regional alteration anomalies and topographic highs of the unconformity surface

In the southeastern Athabasca basin, a district-scale alteration halo superimposed on the regional diagenetic signature (primarily dickite) was previously recognized by Earle and Sopuck (1989). This up to 30 km wide alteration corridor, dominated by illite alteration, extends for more than 100 km in a northeast trend from Key Lake to Cigar Lake and encompasses most known uranium deposits and prospects in the southeastern Athabasca basin (Figs. 7c, 9a). The axis of this regional illite anomaly also contains subparallel linear zones of anomalous chlorite and dravite.

Basement rock compositions and structures (Fig. 9c) likely played an important role in the alteration mineral chemistry of the overlying Athabasca Group. One apparent spatial association is the overlap of the illite alteration corridor with a 5 to 20 km wide aeromagnetic low (Fig. 9c), where the underlying Wollaston Supergroup includes abundant graphitic metapelite units. In addition, chlorite alteration dominates in the eastern part of this illite anomaly, roughly coinciding with the zone of abrupt elevation change of the unconformity surface (Fig. 9b, 9c).

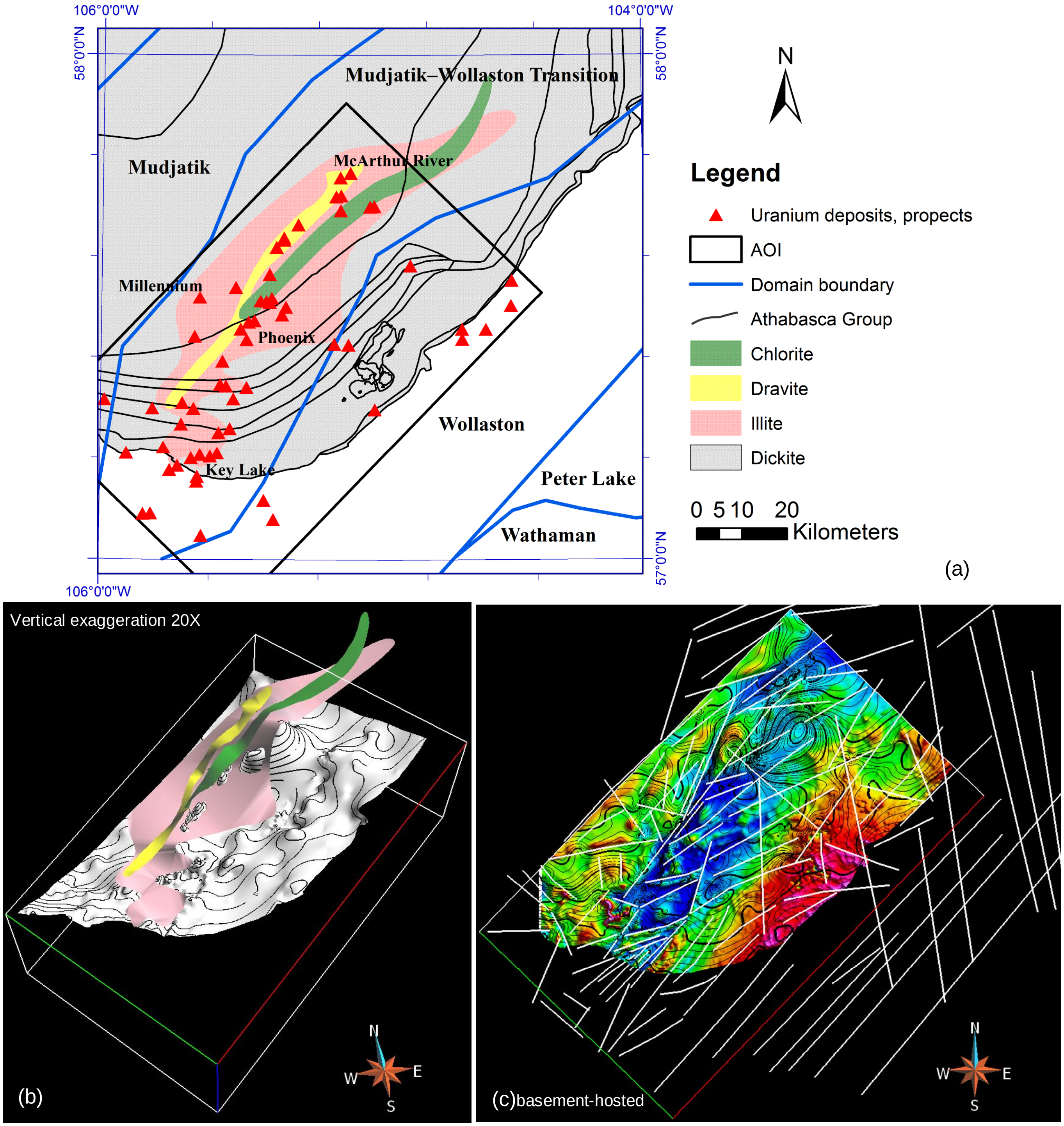

Figure 9. (a) Lithogeochemical map of the southeastern Athabasca basin, showing regional illite, chlorite, and dravite anomalies in surficial materials and outcrops of the Athabasca Group (after Earle and Sopuck, 1989); (b) Regional illite, chlorite, and dravite anomalies draped onto the unconformity surface between the Athabasca Group and the basement using GoCAD; (c) Aeromagnetic image and interpreted basement faults draped onto the unconformity surface.

4. Discussion and summary

The Mudjatik–Wollaston transition zone coincides with a significant aeromagnetic low that is known to reflect an increased abundance of pelitic and semi-pelitic gneiss units in the basement. Previous work from the exposed basement to the southwest (e.g., Tran, 2001) indicates that the graphitic pelitic units correspond to zones of weakness between more competent units and were foci for local deformation during regional folding, thrusting, and later brittle deformation. There is evidence that some of these faults were long-lived, having been active both pre- and syn-basin development, and subsequently reactivated (e.g., Jefferson et al., 2007). The pre- and syn-Athabasca Group faults likely produced paleotopographic features on the unconformity surface such as fault scarps, topographic highs and paleovalleys (e.g., Harvey and Bethune, 2007). These features may have been enhanced by differential erosion and/or subsequent reactivation, which in turn may have served to focus fluid flow (and related mineralization).

Preliminary structural analysis and 3D modelling in this study confirms these general relationships, with the recognition of numerous NE-trending faults within the Mudjatik–Wollaston transition zone. Most importantly, the 3D model highlights an approximately northeast-trending zone of elevated topography of the unconformity surface, or basement ridge, which is supported by recognition of talus breccia in the basal Read Formation at the Phoenix deposit by Bosman and Korness (2007) and also Kerr (2010). Furthermore, the basement ridge coincides with the Phoenix – McArthur River deposits trend. This zone of topographic change, likely in part related to reverse faulting, broadly overlaps with the regional illite-chlorite-dravite alteration corridor that encompasses most uranium deposits in the region. In addition to these northeast-trending faults, our work has identified subsidiary sets of northwest- and north-northwest trending faults. Further modelling at a more detailed scale is required to better determine the orientations, timing, kinematics and significance of all of these fault sets in relationship to fluid flow and mineralization.

Acknowledgements

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