Preliminary 3D geomodelling and simulation of coupled fluid flow and compressional deformation in the Athabasca Basin

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Introduction

The Athabasca Basin (Fig. 1) hosts the world's largest known high-grade unconformity-type uranium deposits. A common feature of these deposits is their close spatial association with reactivated basement faults intersecting the unconformity surface. Although it is generally recognized that uranium mineralization is related to circulation of basinal fluids, it remains poorly understood what unique physical/chemical factors focused fluid flow at specific sites, especially along fault zones and within wider structural zones. We have selected a 100 km by 60 km zone (Fig. 1) in the southeastern Athabasca Basin to study the relationship between structures, fluid flow and uranium mineralization. The project involves analysis of the surface/subsurface regional geology and construction of a 3-dimensional model (using GOCAD) to image the fundamental lithological, structural and alteration features. Once the model is built, numerical modelling (using FLAC3D) of fluid flow will be conducted to test various combinations of lithologies, orientations of structures, stress fields and thermal conditions. As a starting point, a simplified conceptual 3D model has been constructed to explore the interaction between fluid flow and mechanical compression in various scenarios.

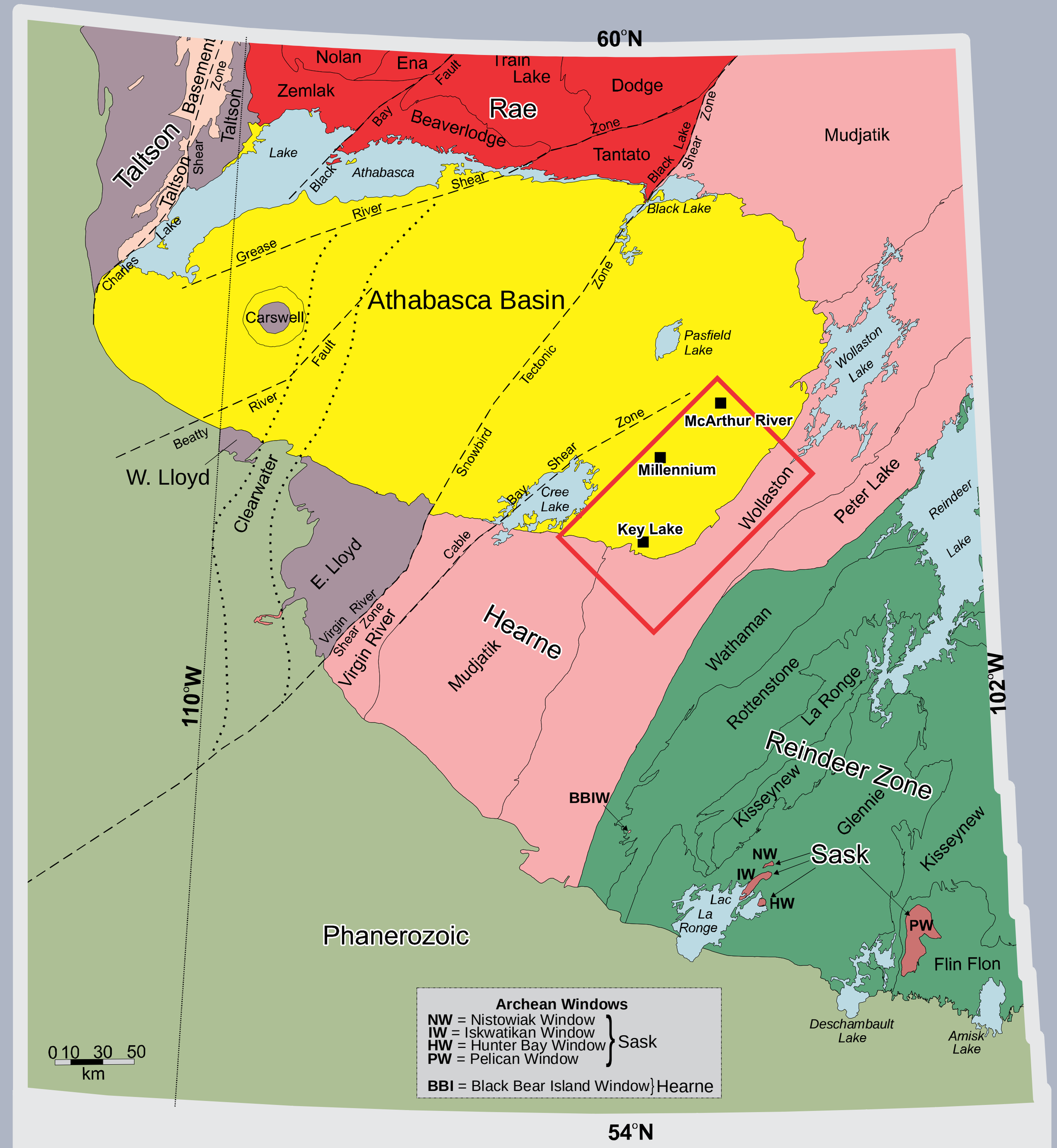


Fig.1. Geological map of northern Saskatchewan (modified from Card et al., 2007).

Basement structures

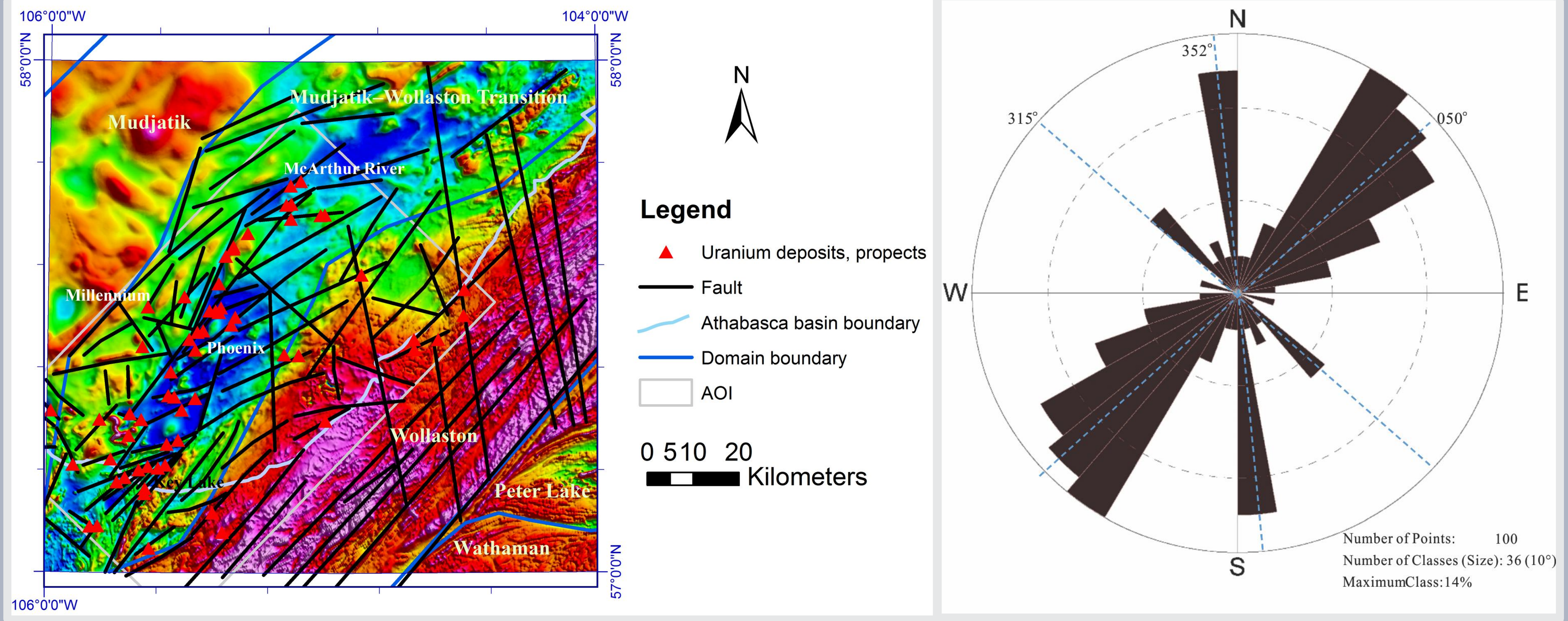


Fig. 2. Distribution of basement faults in the study area as interpreted from the aeromagnetic data from Card et al. (2010). Rose diagram of basement faults illustrating three dominant orientations.

3D geomodelling

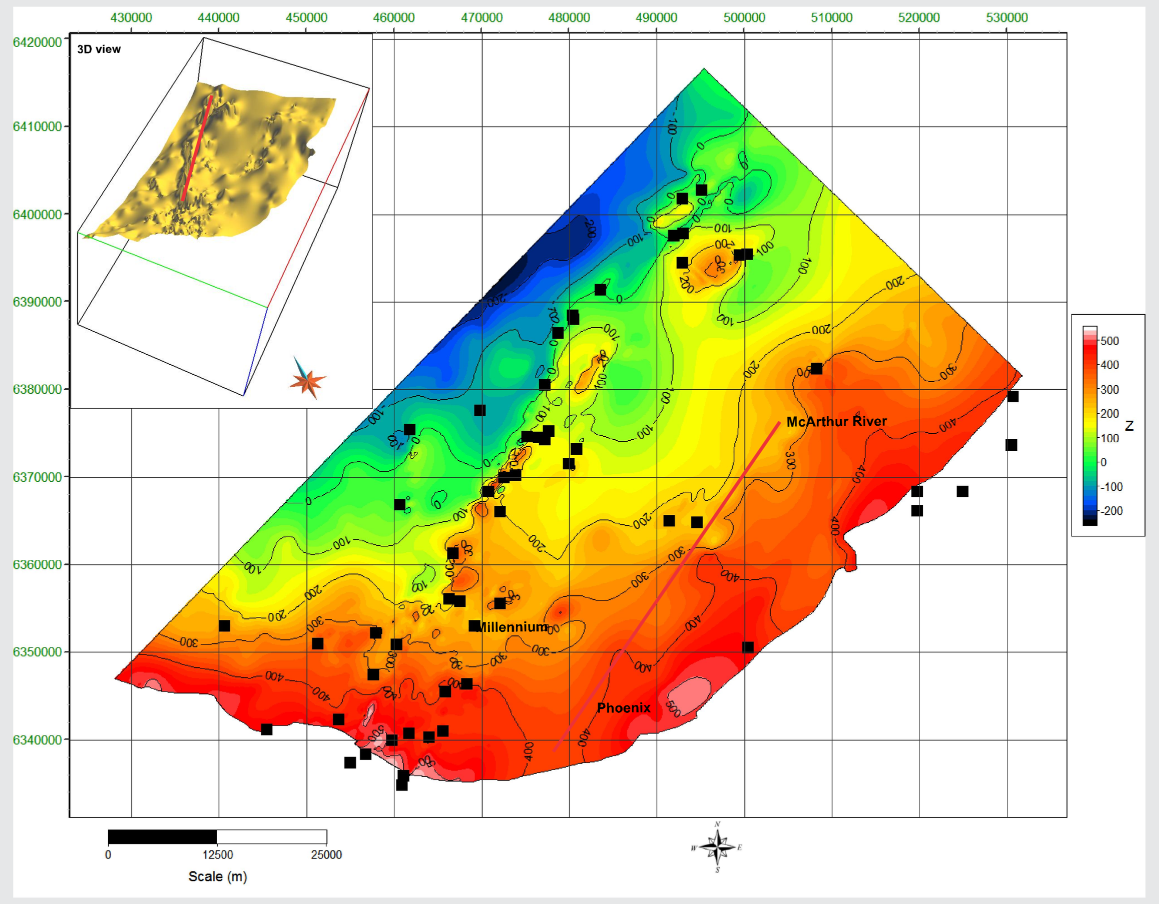


Fig. 3. Contour maps showing the elevations of the sub-Athabasca unconformity in the study area. The red solid line shows the approximately northeast-trending basement topographic ridge associated with the Phoenix/McArthur River deposit trend.

FLAC3D modelling

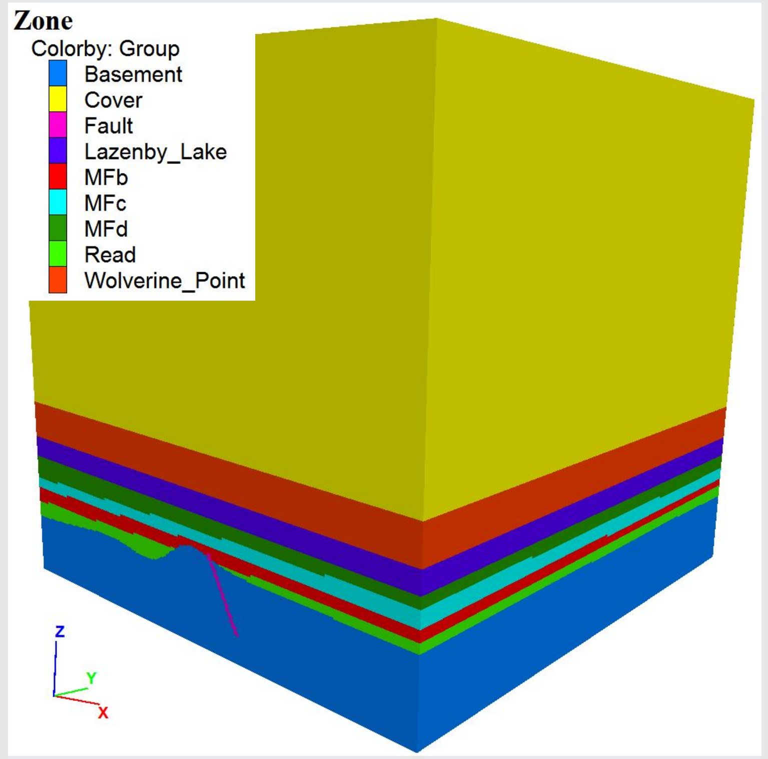


Fig. 4. Block model constructed in FLAC3D showing the stratigraphy in eastern Athabasca Basin.

Preliminary numerical modelling

A simplified 3D model was constructed in order to test the software FLAC3D. The model consists of a low-permeability basement layer overlain by a homogeneous sandstone layer that is in turn covered by a relatively low permeability layer representing eroded sedimentary rocks. The fault (in light blue) is simulated as narrow weak zone (Fig. 5. and Table 1). Four scenarios were used to test the interaction between fluid flow and mechanical compression. All models were therefore subjected to compressional deformation, which was simulated by applying velocity fields to the vertical boundaries, generating strain rates on the order of e-11/sec. Fluid flow was coupled with mechanical deformation during simulations.

Table 1. Major physical parameters of various hydrological units.

Property	Density (kg/m^3)	Bulk modulus (Pa)	Shear modulus (Pa)	Cohesion (Pa)	Tensile strength (Pa)	Friction angle	Dilation angle	Porosity
Cover	2,400	2.80E+10	1.70E+10	3.00E+06	1.80E+06	30°	4°	0.15
Sandstone	2,500	3.20E+10	4.00E+09	3.00E+06	2.20E+06	30°	4°	0.2
Basement	2,650	4.95E+10	2.90E+10	4.00E+06	2.20E+06	30°	3°	0.1
Fault	2,400	2.33E+10	3.00E+07	2.00E+02	1.20E+06	30°	4°	0.2

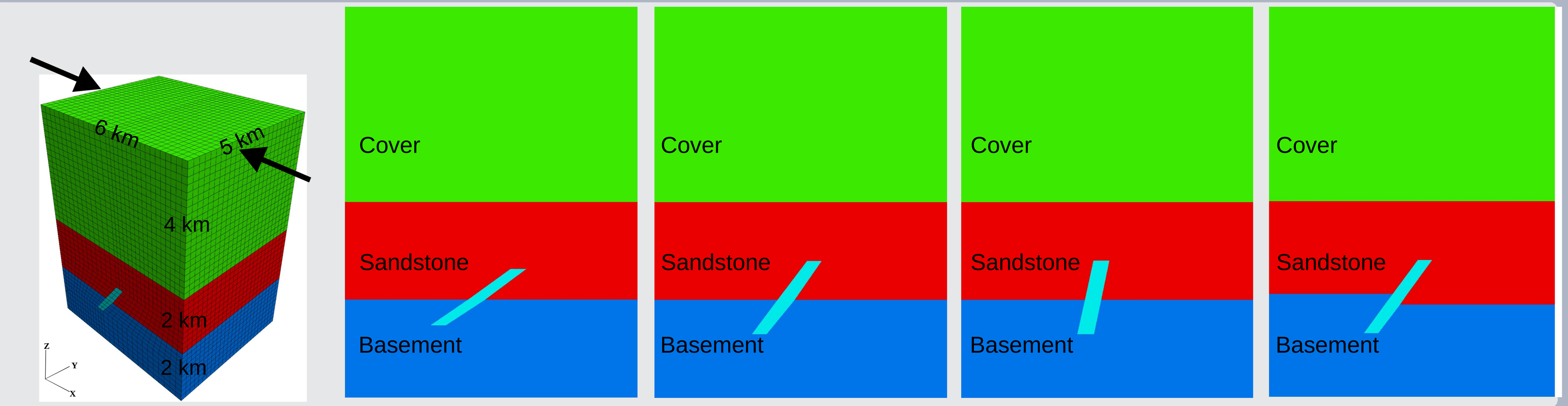


Fig. 5. 3D geometry and related sectional views of the initial geometries of four simple models. Black arrows show the maximum principle stress σ_1.

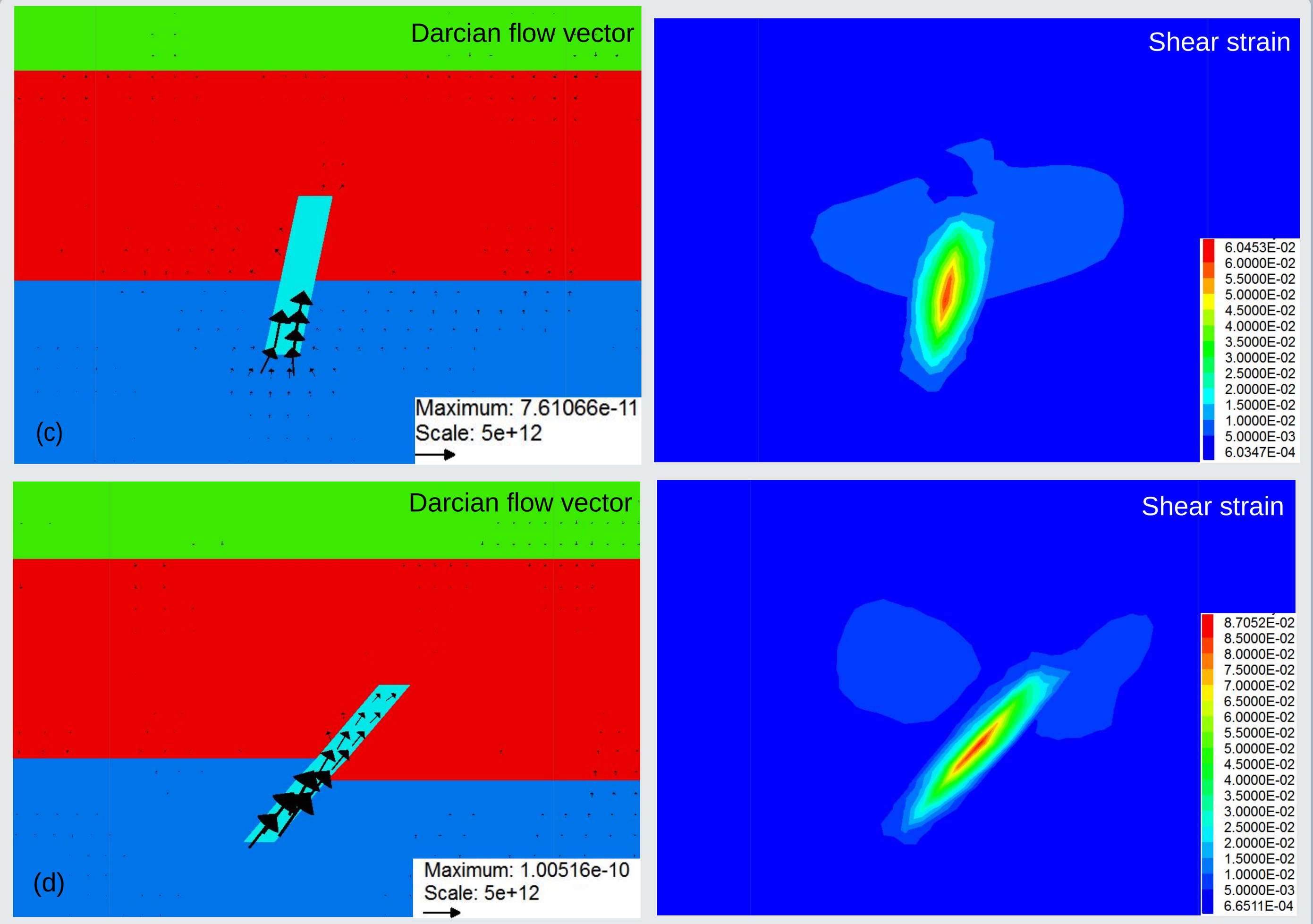
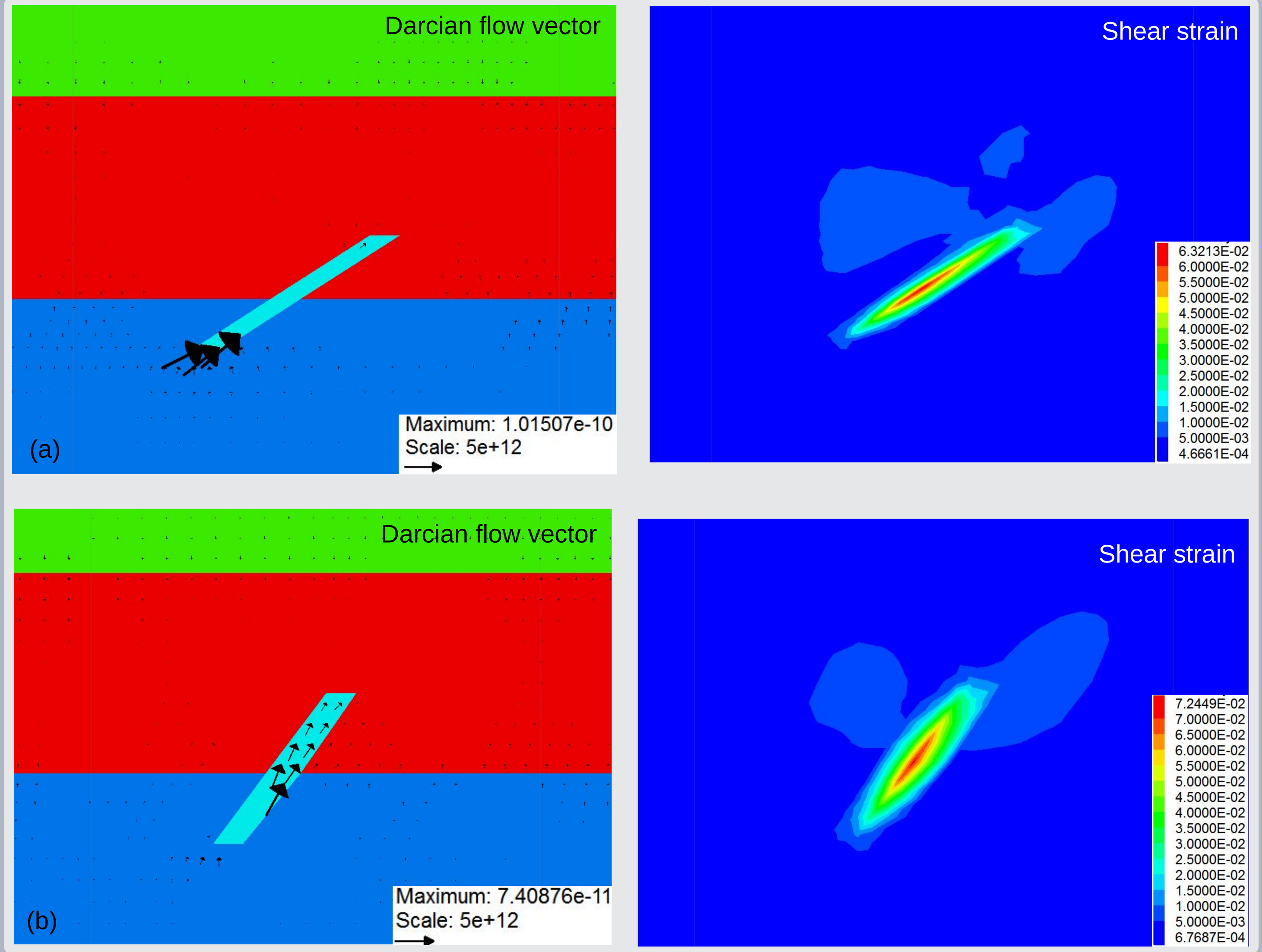


Fig. 6. Sectional plots of fluid flow vectors (left) and shear strain development (right) for each model after 0.1% shortening. Black arrows indicate the direction of fluid flow and length of arrows indicates magnitude of Darcian fluid-flow (m/s). Shear strain is recorded by γ (gamma) values.

Modelling results



Summary of preliminary results

1) A generalized 3D model of the southeastern part of the Athabasca Basin has been constructed using the drill-hole log data, mainly showing key geological surfaces i.e., unconformity.
2) 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.
3) The unconformity surface in the 3D model shows an approximately NE-trending zone of elevated topography associated with the Phoenix/McArthur River deposit trend.
4) A simplified 3D model of the Athabasca Basin also has been constructed using FLAC3D to test the software. Several scenarios have been tested to explore the coupled interaction between fluid flow and mechanical compression.
5) During compressive deformation, fluids migrate up the fault. This is due to the rapid increase of pore pressure in the low-permeability basement, the fault being an area of dilation and low fluid pressure relative to the surrounding rocks from which pore fluids cannot easily escape.
6) Flow patterns are almost the same among the models. However, the model with the most shallowly dipping fault has greater flow rates than the other models. This is due to the fact that the shallowly dipping fault undergoes more dilation because its orientation is closest to the direction of the maximum principal stress. The model with offset on the fault also shows a greater flow rate; this needs to be more fully explored but suggests an increase in dilation controlled by differences in properties between units.
7) The fault zones represent the most significant loci of shear strain in all models; the dip of the fault also strongly controls the orientation of the high strain zone which propagates into the sandstone.

Acknowledgements: This project is supported by TGI-4 (Targeted Geoscience Initiative 4), a collaborative federal geoscience program led by Natural Resources Canada. Access to the GoCAD license was provided by the Saskatchewan Geological Survey.

Reccommended citation
Li, Z., Chi, G., Bethune, K.M., Bosman, S., and Card, C., 2014. Preliminary 3D geomodelling and simulation of coupled fluid flow and compressional deformation in the Athabasca Basin; Geological Survey of Canada, Open File 7612, 1 poster. doi:10.495/293929

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doi:10.4095/293929
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