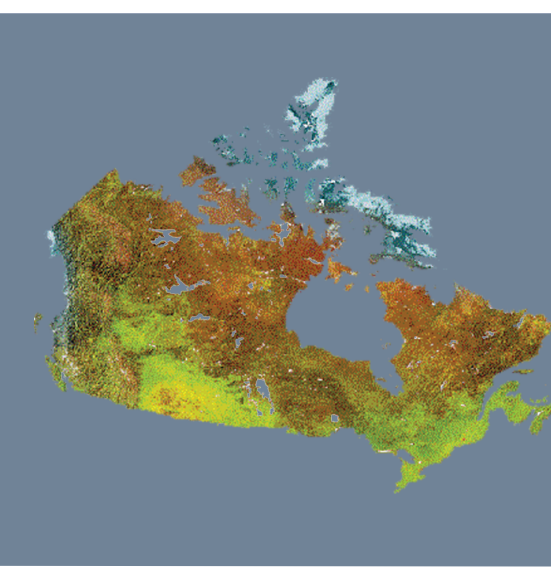
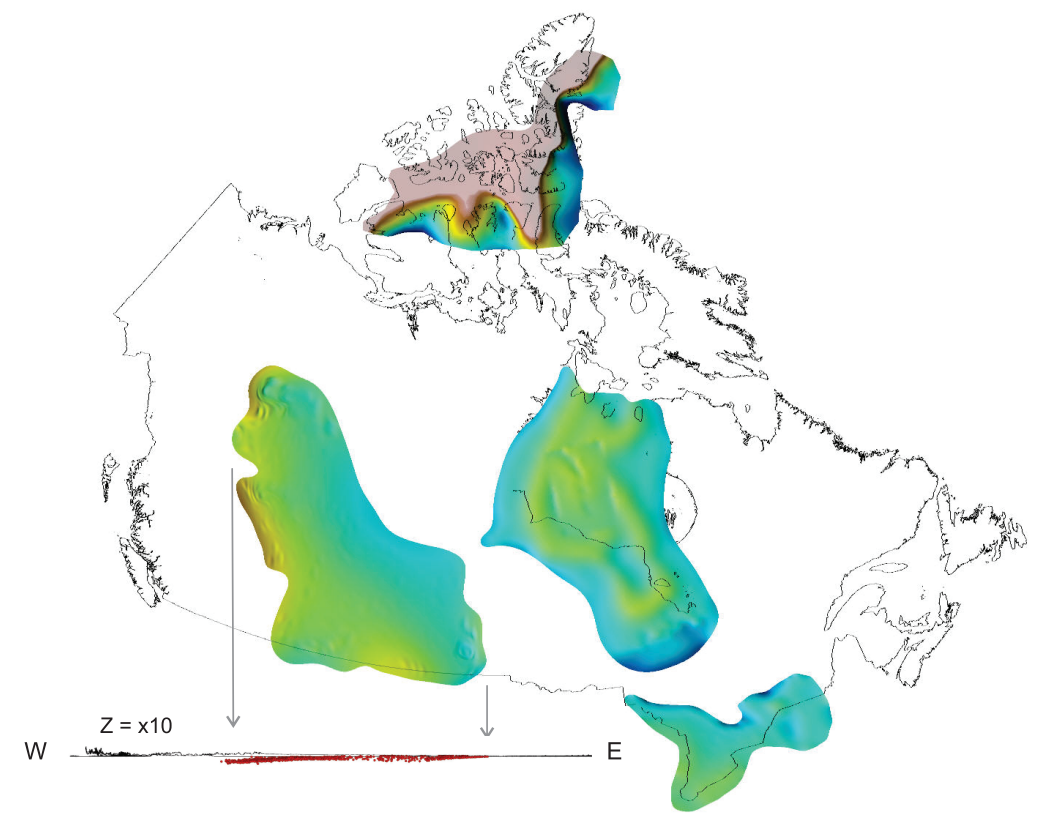
Geological Survey of Canada
Scientific Presentation 65

Celebrating 175 yrs

DEVELOPING THE BEDROCK LAYER FOR CANADA 3-D: THE PRECAMBRIAN-PHANEROZOIC BOUNDARY

E.A. de Kemp[1], E.M. Schetselaar[1], M. Hillier[1], and R. Montsion[2]





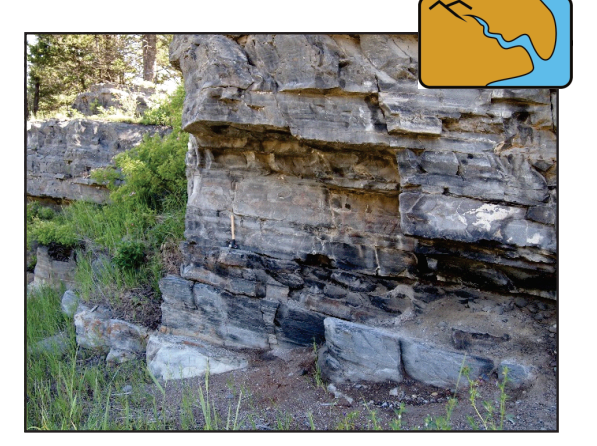
Abstract

One of the most significant tectonostratigraphic features of the geology of Canada is the boundary separating 'cover' rocks of the Phanerozoic Eon and older 'basement' rocks; dominantly metamorphic and crystalline rocks of the Precambrian shield. In the context of the Canada-3D initiative to develop a 3D geological model of Canada from the surface to the Moho, we have begun to integrate data constraints for modelling this boundary, including geological map, drillhole and seismic data. The 3D surface development is being undertaken through the application of data (geostatistical, implicit modelling (GOCAD/SKUA and SURFE) and knowledge (SPARSE) driven methods). More accurate 3D delineation of this key boundary will help support applications such as the separation of bulk rock properties into cover and basement classes which could in turn be used for geophysical and mineral potential modelling. Coupled with heat flow and fracture density estimates; it could also contribute to future development of national-scale 3D favourability maps for geothermal energy and CO_2 sequestration potential. The project combines a large amount of data from various sources collected over the last 175 years since the initiation of geological mapping by the Geological Survey of Canada in 1842 by Sir William Logan.

The Precambrian-Phanerozoic boundary is dominantly an angular unconformity between the crystalline bedrock of the Canadian Shield and Phanerozoic sedimentary cover sequences, spanning a hiatus of several hundreds of millions to more than two billion years. In rare cases such as the Rapitan Group in the MacKenzie Mountains, it is a conformable stratigraphic contact between Neoproterozoic and Cambrian formations. There are also many parts of Canada's subsurface which have no geologic record of the boundary where the crust is mainly composed of either younger Paleozoic and Mesozoic mobile belts (Central Newfoundland and British Columbia), or exposed basement of the Precambrian Shield. The geological data that constrain the Precambrian-Phanerozoic interval are spatially heterogeneous, and vary in quality from excellent observations from petroleum wells in the Western Canada and Williston Basins, to less reliable well logs in Southern Ontario, to interpretive map traces in the overburden covered Hudson Bay low lands. Seismic reflection and refraction data from Lithoprobe and industry surveys will support deeper interpretations of the boundary, and be integrated with constraints obtained by geological mapping in the more complex regions of the Canadian Cordillera and Appalachian orogens. Canada-3D is modelling other tectonostratigraphic features (crustal scale fault networks and major lithostratigraphic horizons) within the bedrock layer, above and below the Precambrian-Phanerozoic boundary, but by focusing early on this significant boundary we gain insight to the data distribution, the required methodology and processing gaps that exist tackling this problem at a national scale. As the project proceeds there will be a need for development of 3D tools to support uncertainty estimation, sparse data interpolation and extension, and interpretation workflows designed to cope with the many challenges presented by limited sampling of complex geologic terrains.

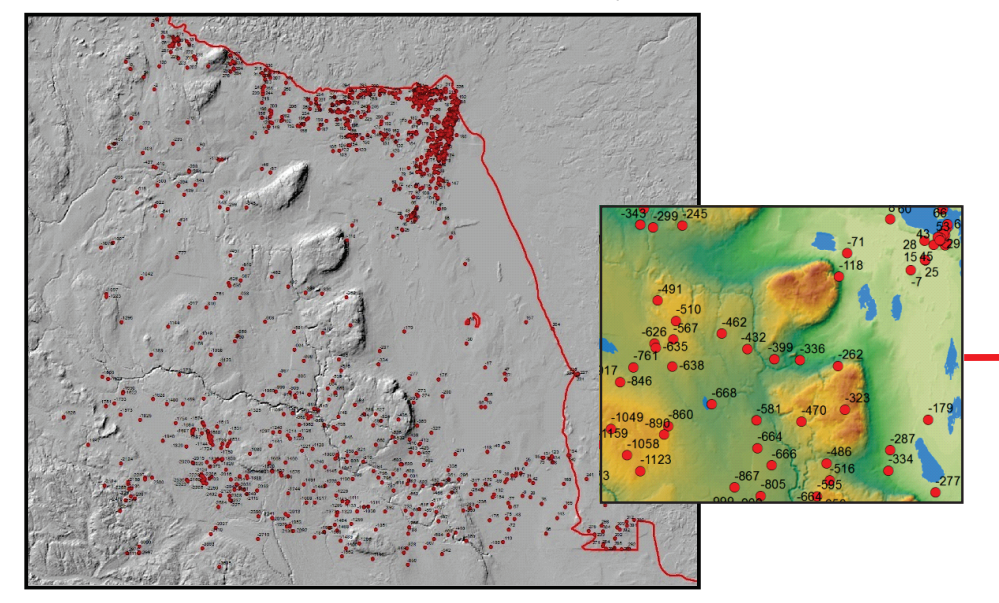
Basin Regions

The hydrocarbon prospective Phanerozoic basins of western, central and northern Canada (Western, Williston and Hudson Bay) have been extensively explored with deep drilling and seismic surveying to target and characterize reservoirs. Many of the holes pierce through the Precambrian-Phanerozoic boundary. These on-contact constraints are dense enough to model a surface with geostatistical or implicit interpolation tools. Having better spatial definition of this critical bedrock layer above the basement cover boundary will provide stake holders with a significant advantage. For example, for mineral prospectivity analysis that involves geophysical inversion where bedrock type and thickness is important, as well as 3D mapping of geothermal energy and CO2 sequestration potential.

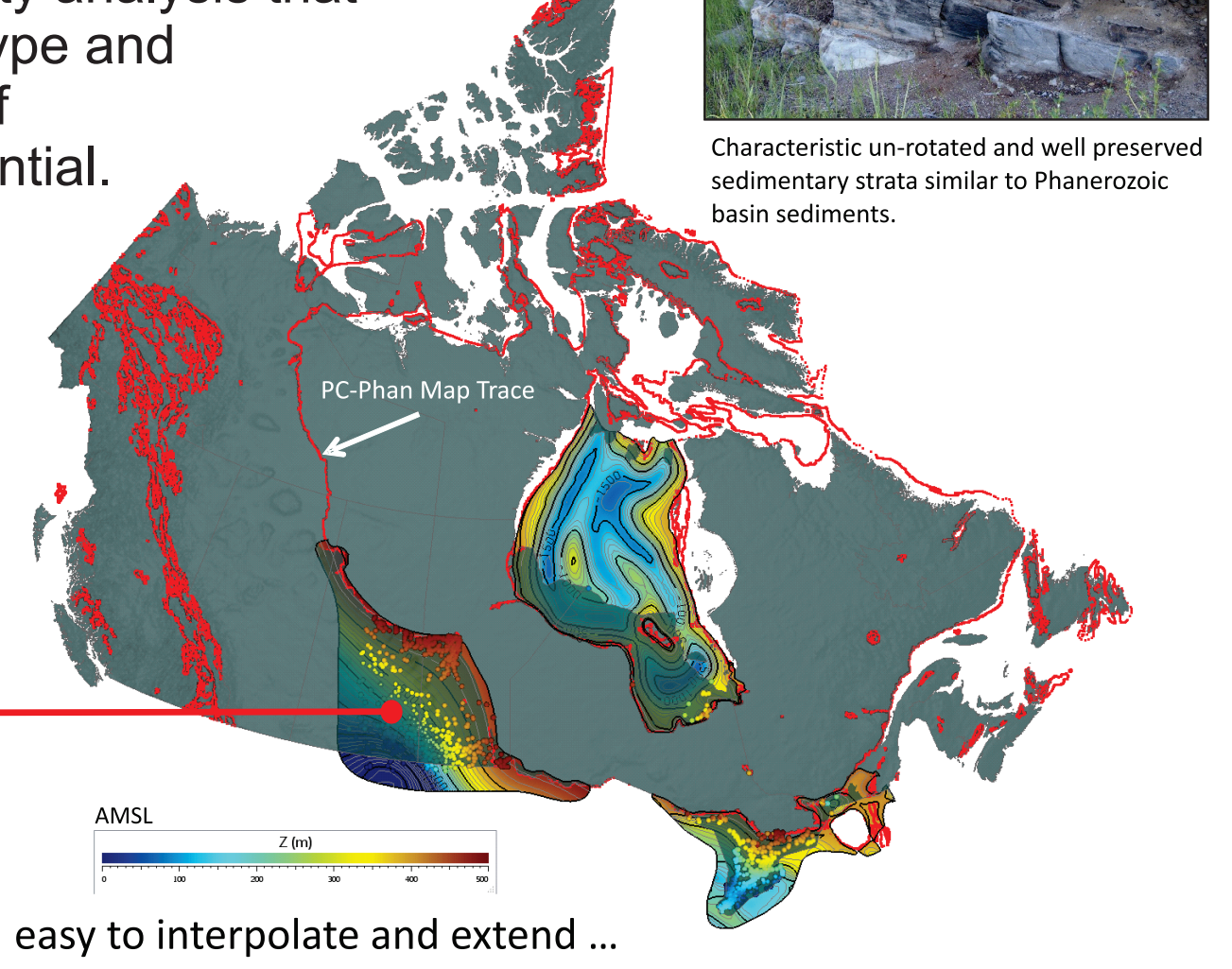


Characteristic un-rotated and well preserved sedimentary strata similar to Phanerozoic basin sediments.

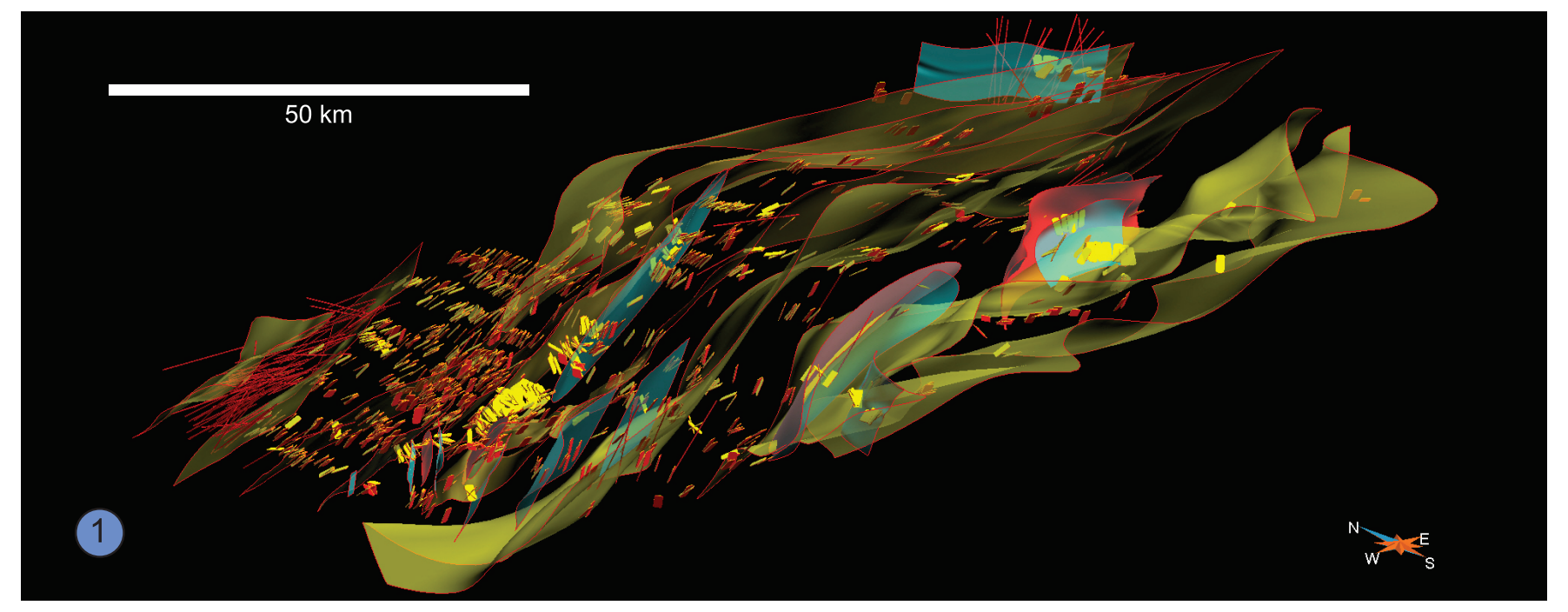
Williston Basin PC-Phan observations at depth

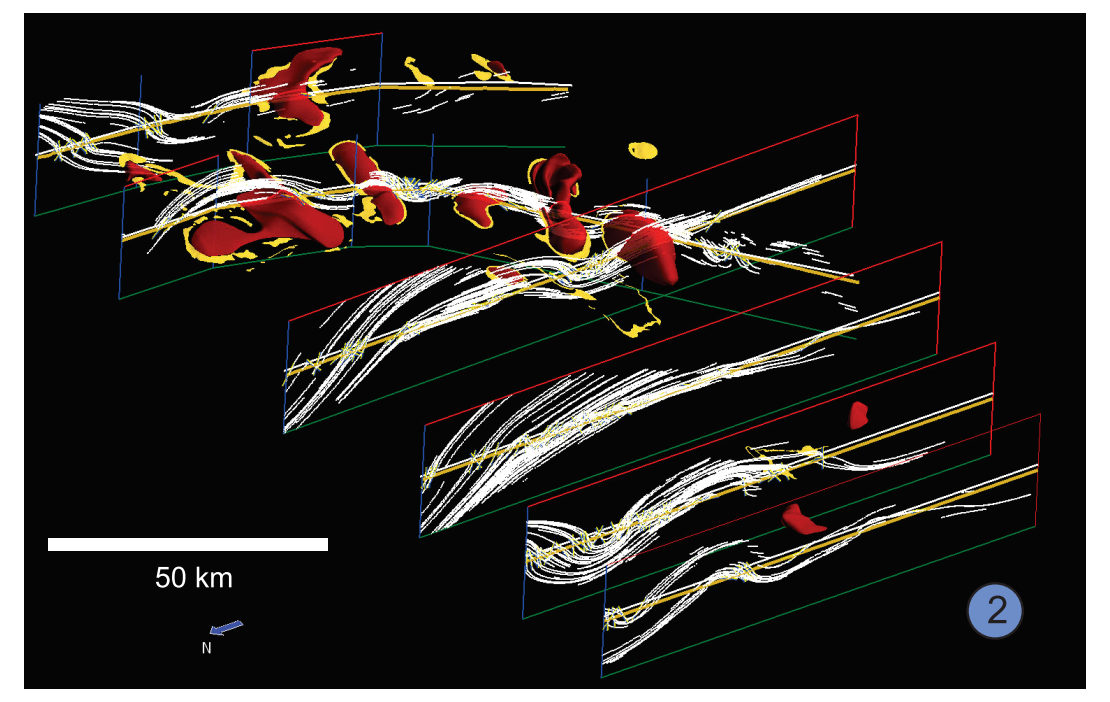


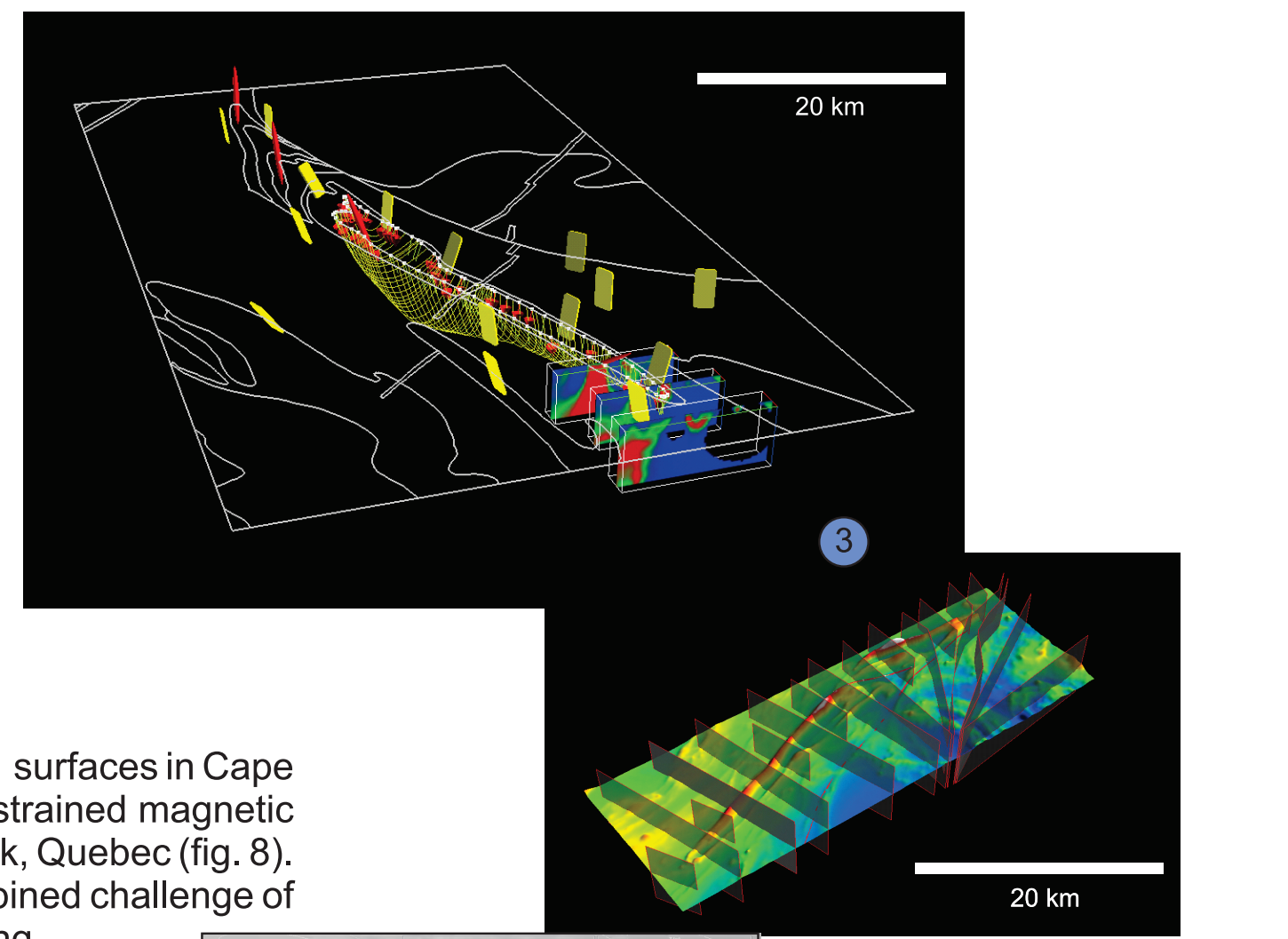
Courtesy Manitoba Geological Survey

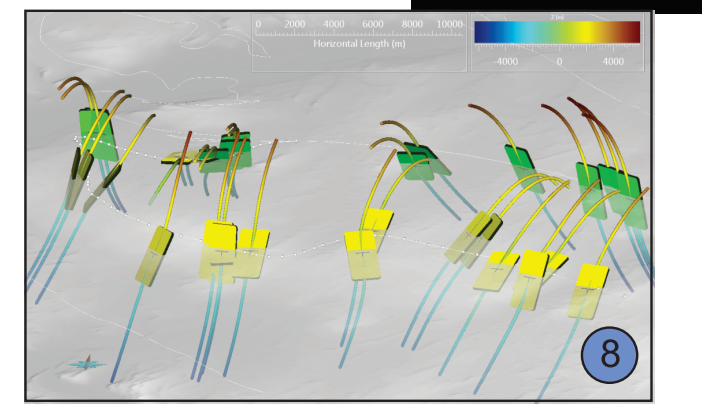


easy to interpolate and extend …









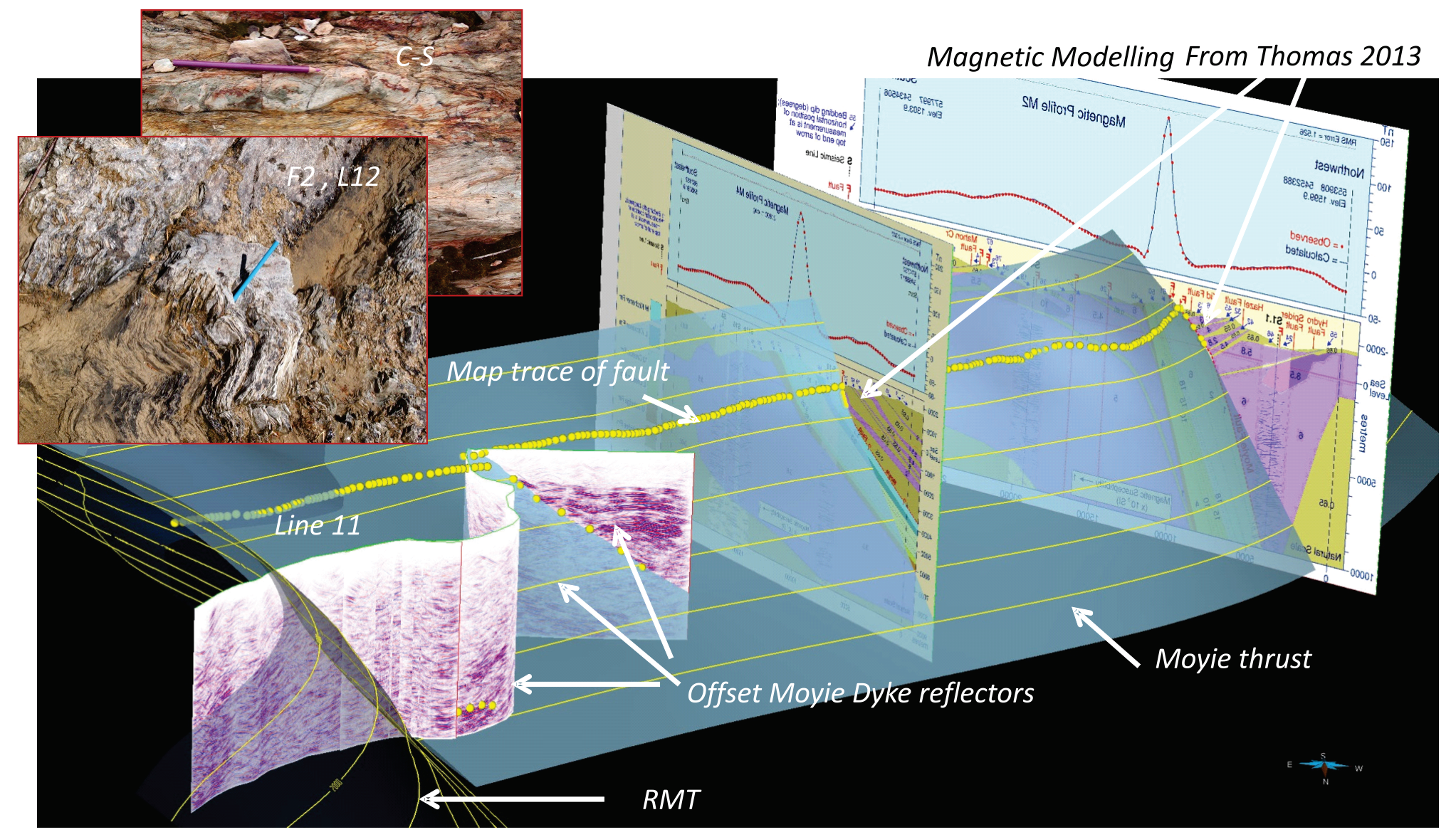
Regional 3D Modelling with Sparse Data

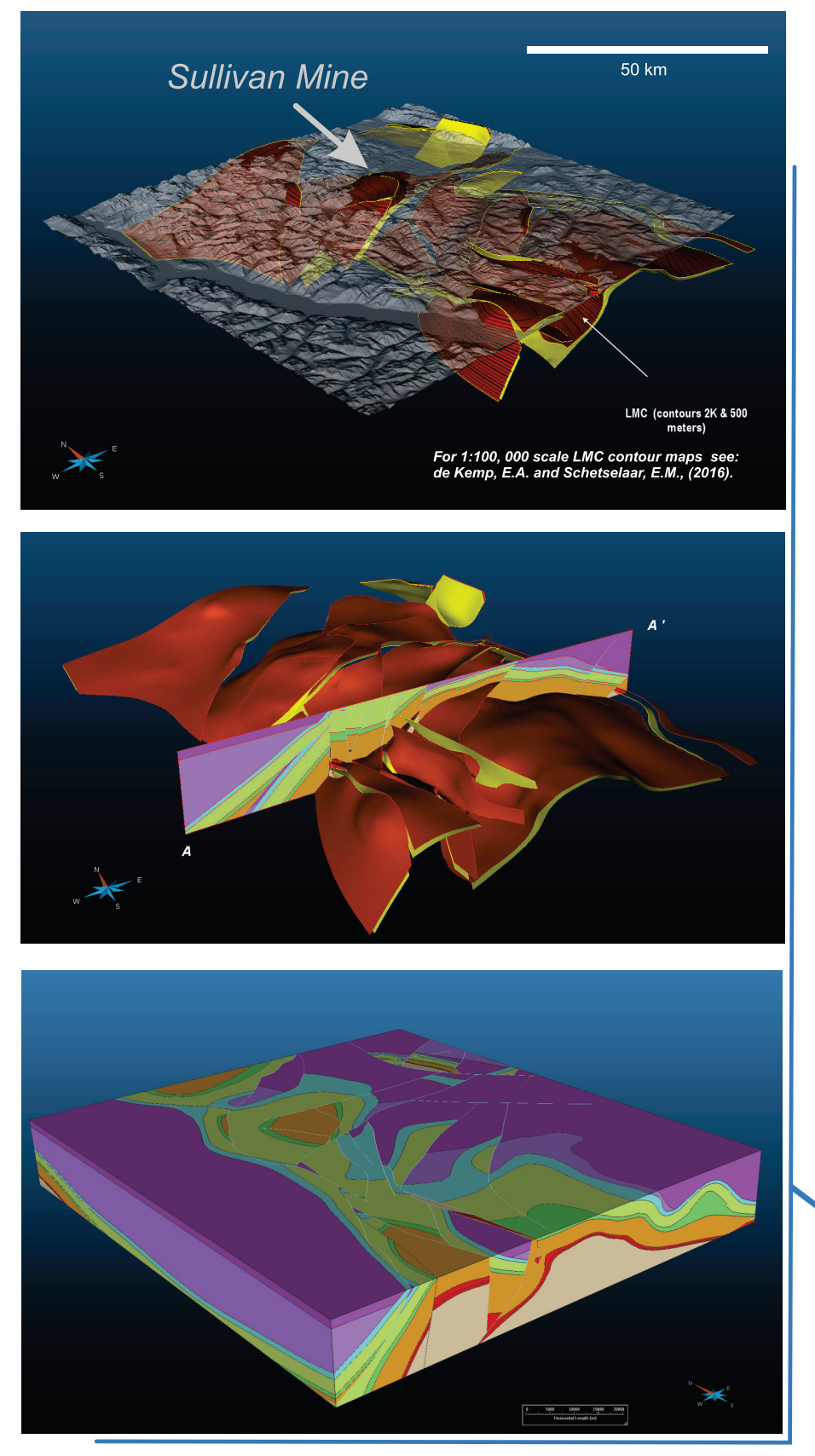
Examples of 3D regional models derived from interpretation of field observations and extended map patterns of important geologic features. Thrust fault surfaces in Cape Smith Belt (fig.1); Archean basement and Paleoproterozoic supracrustal cover contact (fig.2) with 3D formlines (white), Central Baffin Island; unconstrained magnetic inversion with structural dips (yellow tablets) in Archean metavolcanics, Assean Lake, Manitoba (fig. 3); Antiformal structure using 3D formlines Kuujjuak, Quebec (fig. 8). New algorithms and workflows will be needed to support the 3D interpretation of Canada's important bedrock features. This environment, with the combined challenge of sparse data and complex geology, will need a multi-disciplinary (geophysics-geology) approach with an emphasis on simulation and uncertainty modelling.

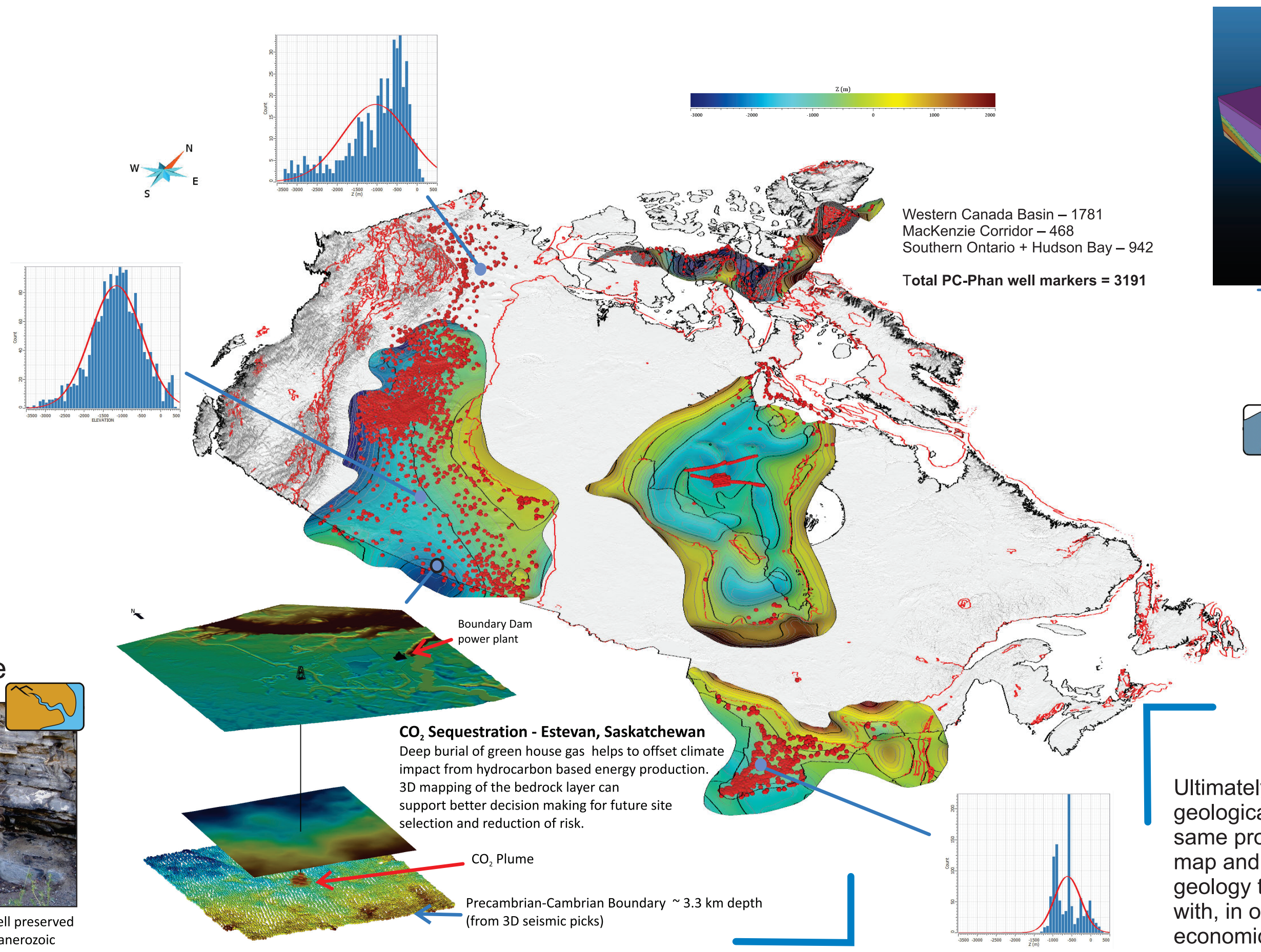
3D Model – Fault Network

3D regional models from the Purcell Anticlinorium, Southeastern British Columbia (fig.5). Integration of geophysics (Lithoprobe and Industry Sesimics, Potential fields inversions) and geology (structural observations, lithostratigraphic markers and traces) is essential in interpreting bedrock geology for Canada 3D.

Magnetic Modelling From Thomas 2013







Western Canada Basin – 1781
MacKenzie Corridor – 468
Southern Ontario + Hudson Bay – 942

Total PC-Phan well markers = 3191

CO_2 Sequestration - Estevan, Saskatchewan
Deep burial of green house gas helps to offset climate impact from hydrocarbon based energy production. 3D mapping of the bedrock layer can support better decision making for future site selection and reduction of risk.

References

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de Kemp, E.A. and Schetselaar, E.M., 2016. ***Structural and Depth Contours of the Lower-Middle Aldridge Contact, East Kootenay Region, Southeastern British Columbia***, Geological Survey of Canada, Open File 7903 3 - 1:100 000 maps with 3D model.

de Kemp, E.A., Schetselaar, E.M., Hillier, M.J., Lydon. J.W., Ransom, P.W., Montsion, R., and Joseph, J., 2015*. ***3D Geological modelling of the Sullivan time horizon, Purcell Anticlinorium and Sullivan Mine, East Kootenay Region, southeastern British Columbia***, Open File 7838, p. 204-225.

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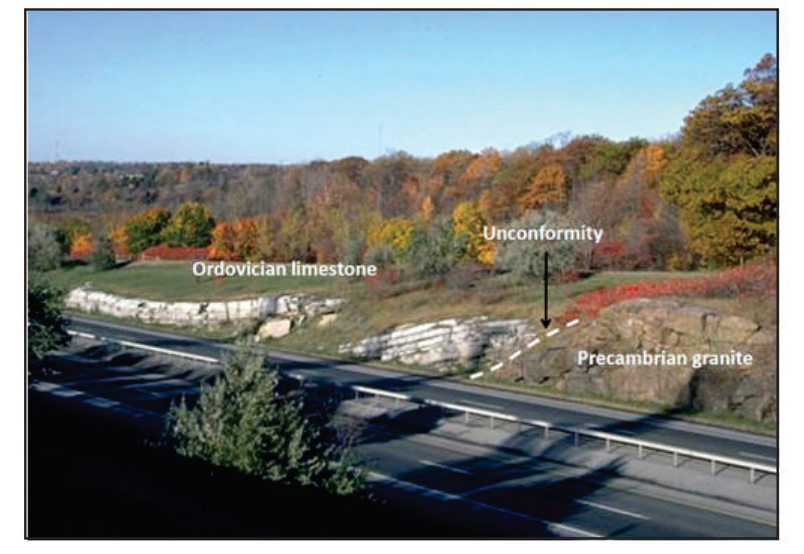
Pinet, N., Lavoie, D., Dietrich, J., Hu, K. and Keating, P., 2013, **Architecture and subsidence history of the intracratonic Hudson Bay Basin, northern Canada**, Earth-Science Reviews, Vol. 125, p.1-23.

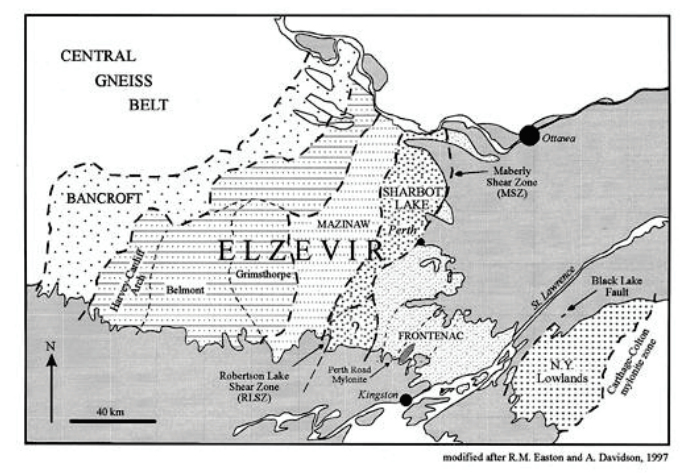
More deformed strata typical of mountainous orogenic belts of the western Cordillera of Canada and the eastern Canadian Appalachins. These rocks may also act as host rock to the Precambrian-Phanerozoic contact making interpretation difficult.

Missing Time

Canada's Precambrian-Phanerozoic boundary is, for the most part, preserved as an angular unconformity, formed from pre-to early Phanerozoic erosional events. This time gap in the rock record in some areas represents a planetary scale resurfacing by Neoproterozoic glaciation and what is referred to as a snowball earth. More recently, the boundary is exposed for us to see at ground surface from recent glacial events throughout the Pleistocene Epoch. We can visit this important geologic feature at an outcrop on Hwy 401 between Ottawa and Kingston Ontario.



View to north of road cut on Highway 401 showing Ordovician limestones unconformably overlying Precambrian granite. This outcrop is located a few hundred meters southeast of the railway cut at Kingston Mills desribed by Logan in 1842.
(From Helmstead 2011)



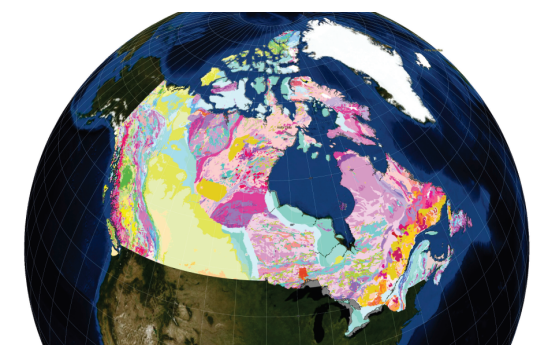
Tectonic map showingthe complex structure of the Grenville Province in southeastern Ontario. Note that the Frontenac terrane borders against a composite island arc terrane (Elzevir) to the northeast that seperates it from the Central Gneiss Belt which belonged to the pre-Grenvillian margin of Laurentia.
(also From Helmstead 2011)

The Future

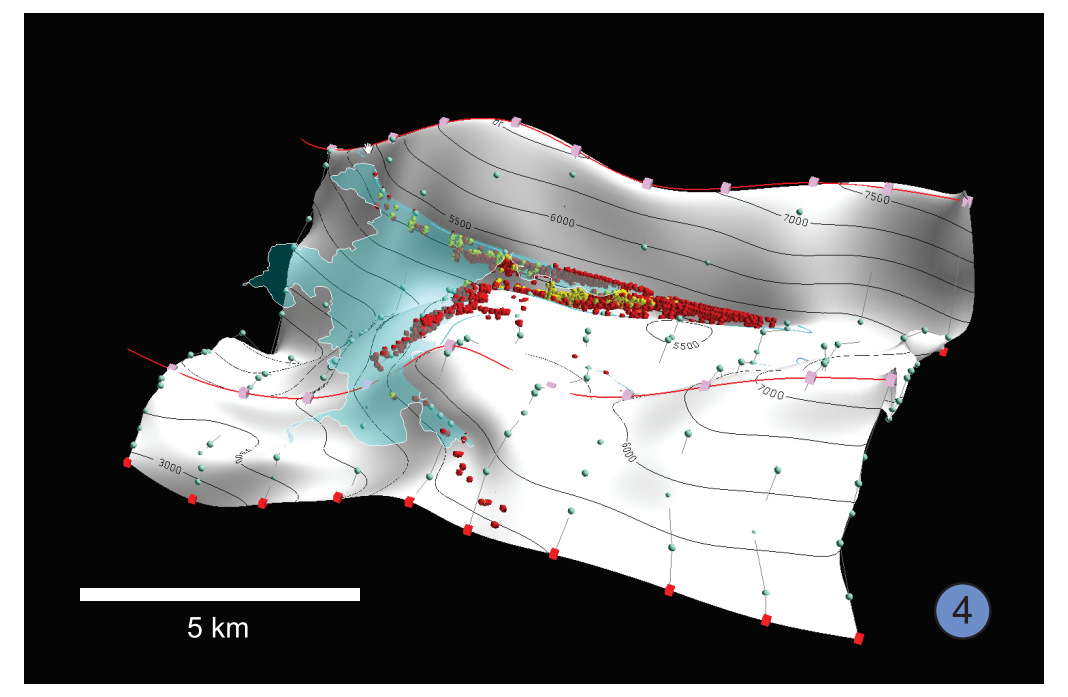
THE FUTURE OF GEOSCIENCE

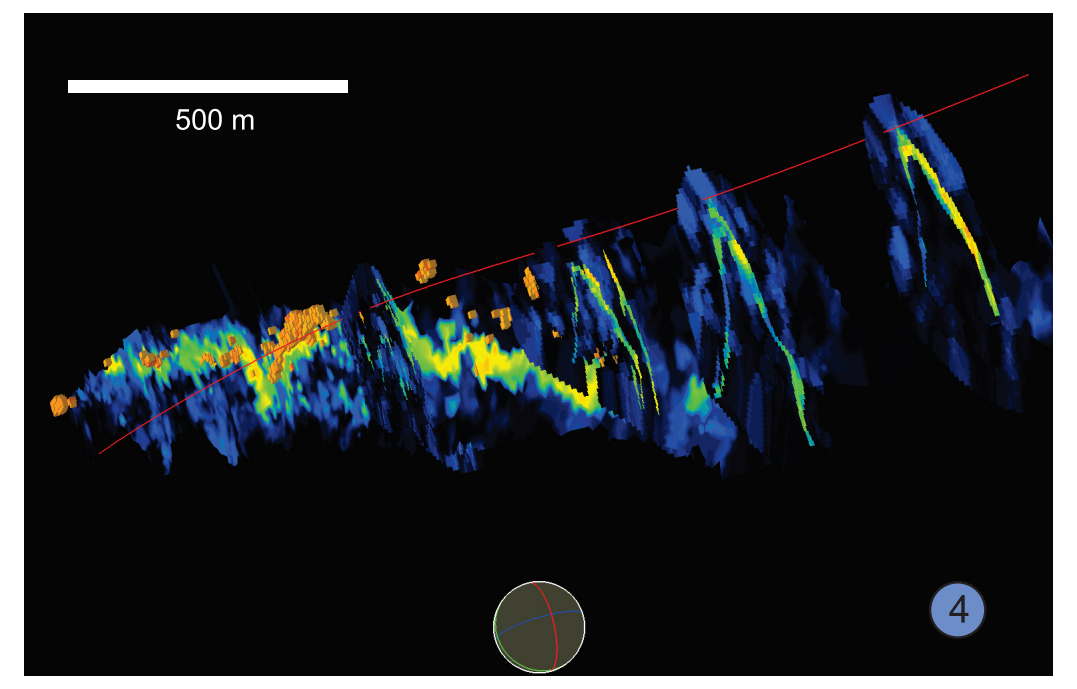
Ultimately, the world's geological surveys have the same problem, namely trying to map and understand the geology that they are endowed with, in order to enhance economic, environmental and public safety conditions.

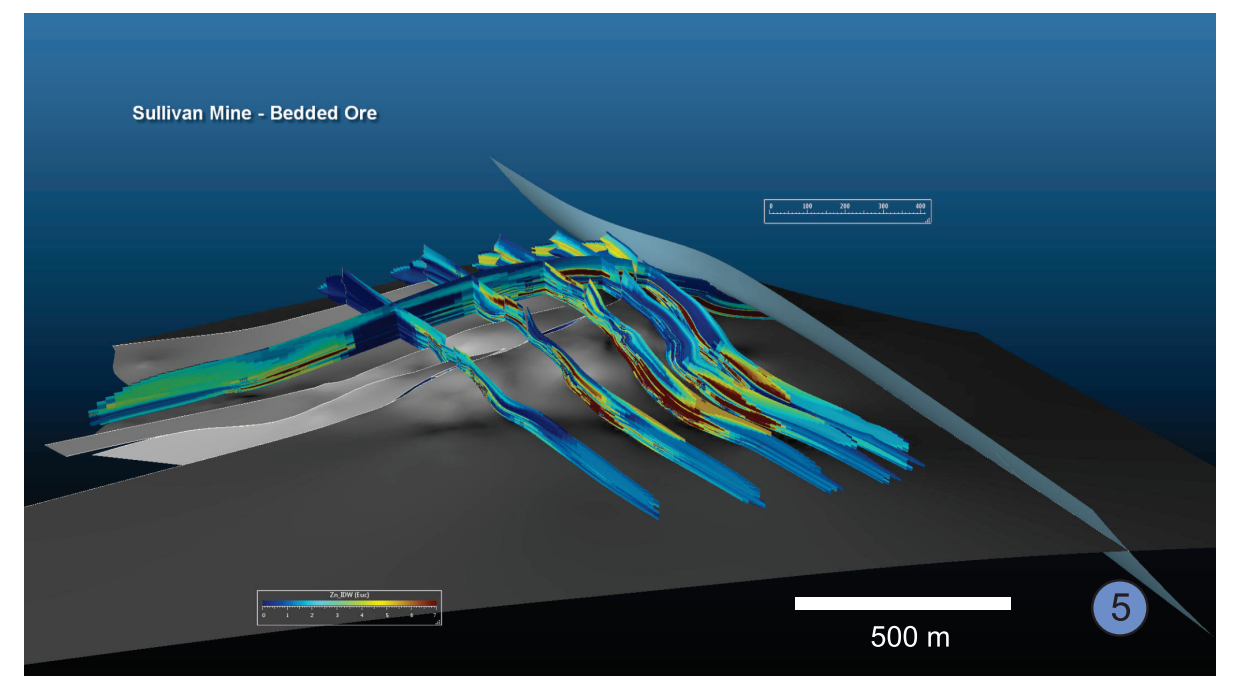
Canada 3D will be integrated into a global initiative, through OneGeology, which is moving toward a consistent and sustainable vision of a seamless geologic 3D map/model of our planet. All of the earth's complex geological history is interconnected regardless of national boundaries. Keeping in touch with best practices and innovation for sparse regional 3D modelling is key to achieving our goals in Canada 3D.

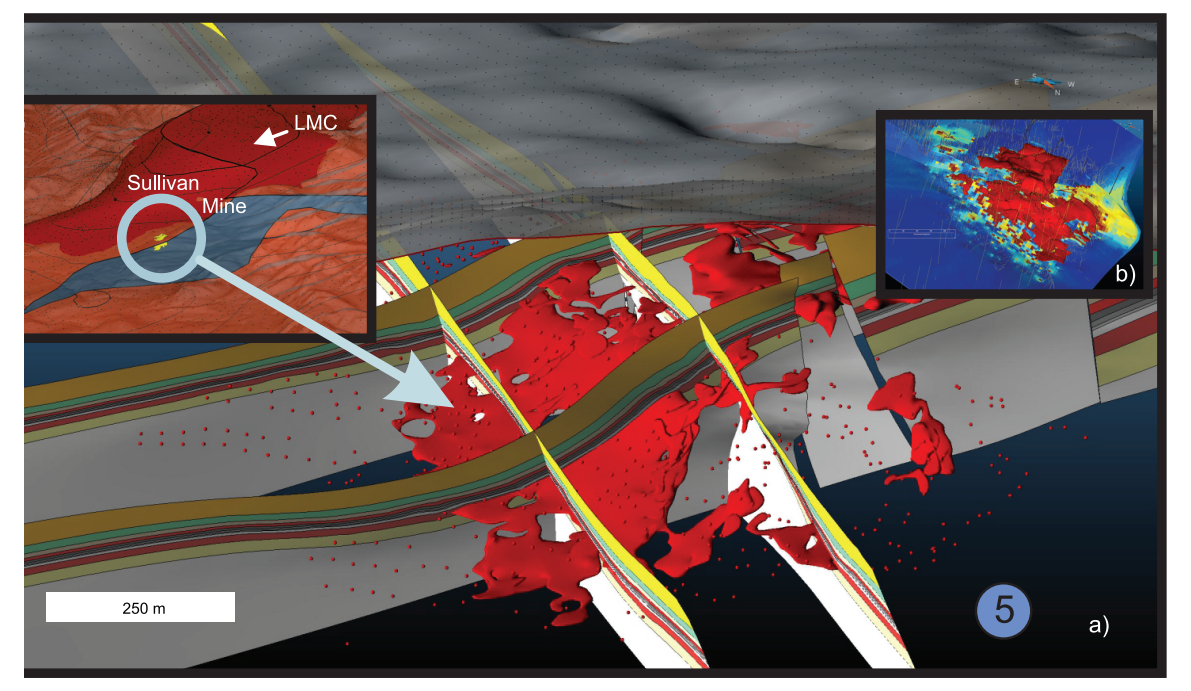


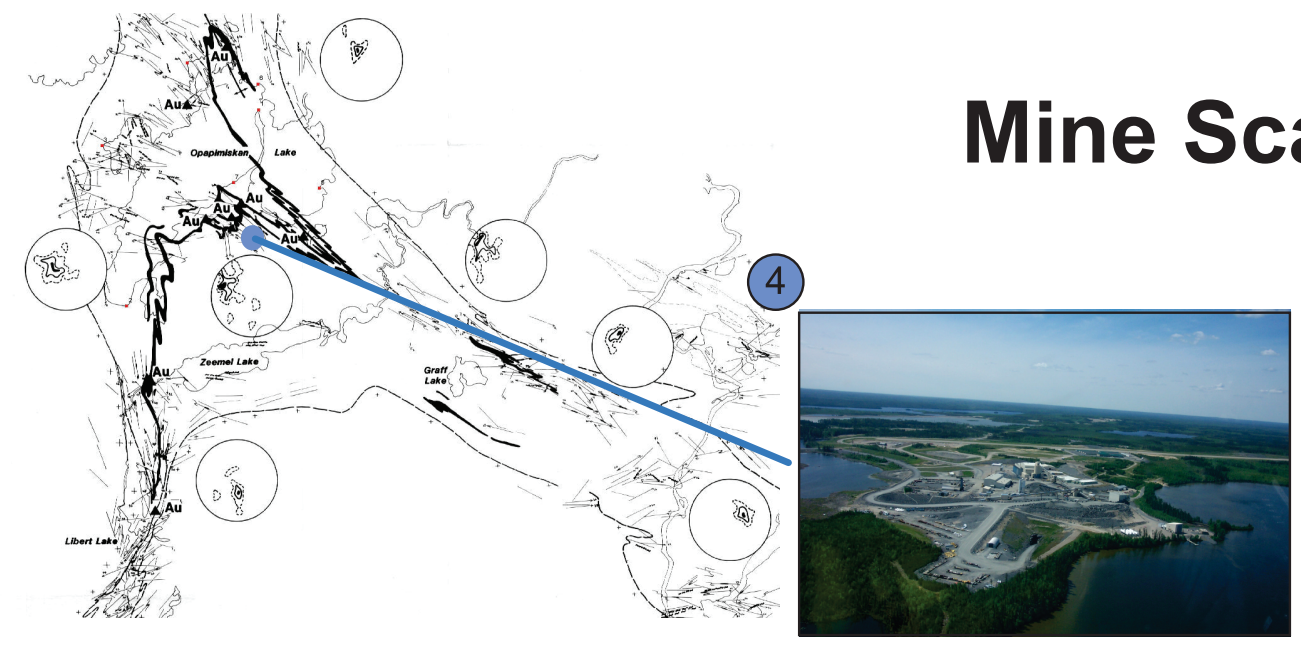
http://www.onegeology.org/docs/3D-Geology-Brochure.pdf







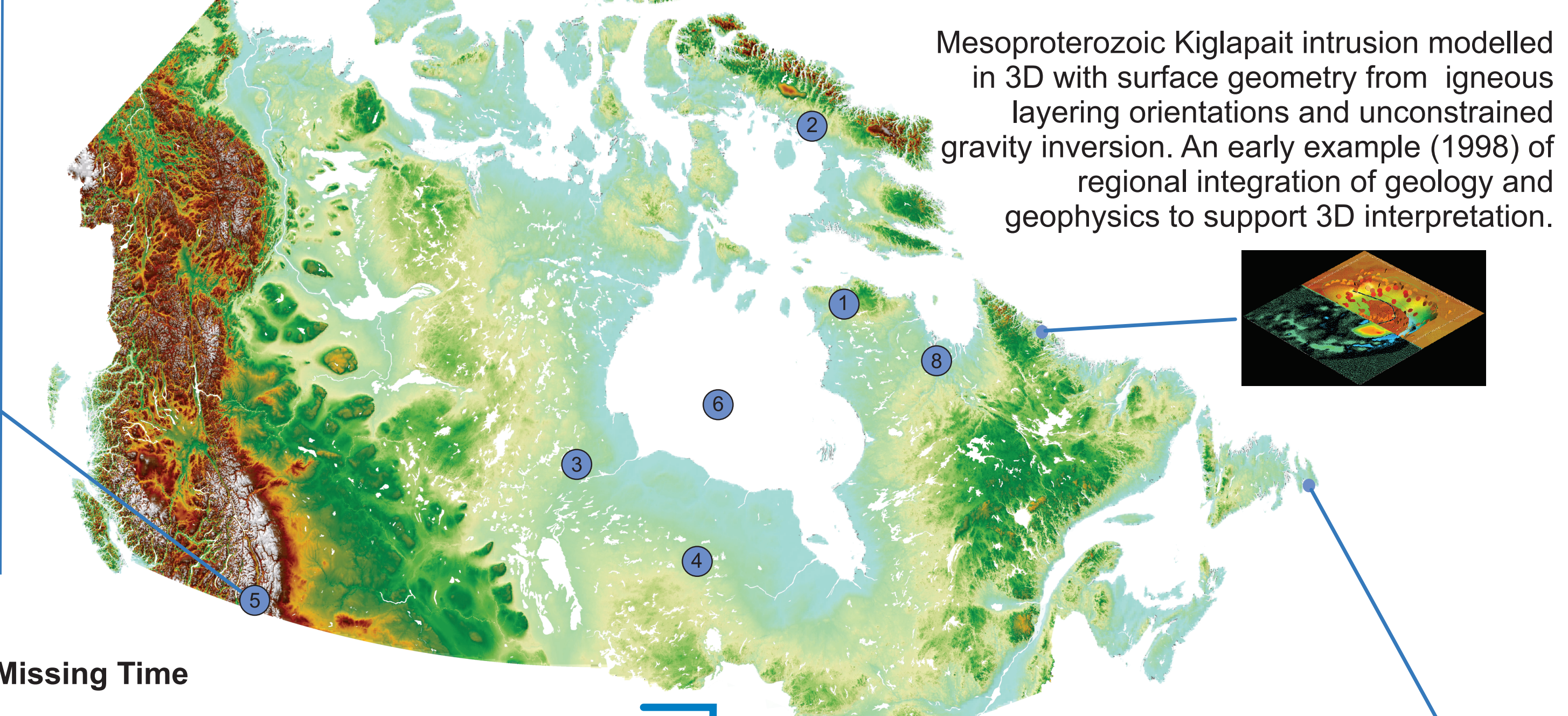




Mine Scale 3D Modelling with Dense Data

Mine scale 3D models (fig.4-5) are confined to 1 - 3 km depth and are now standard requirements for mineral exploration and resources estimation. Methods based on geostatiscical or parametric modelling (Kriging, Radial Basis Functions, Bezier, Nurbs) are used in what is generally a data rich environment with good at depth constraints to control stratigraphic and structural geometries. The more data driven tools work well in this setting. These local 3D models may serve as control and tie-line sites for the more interpreted and thus more uncertain regional scale models.

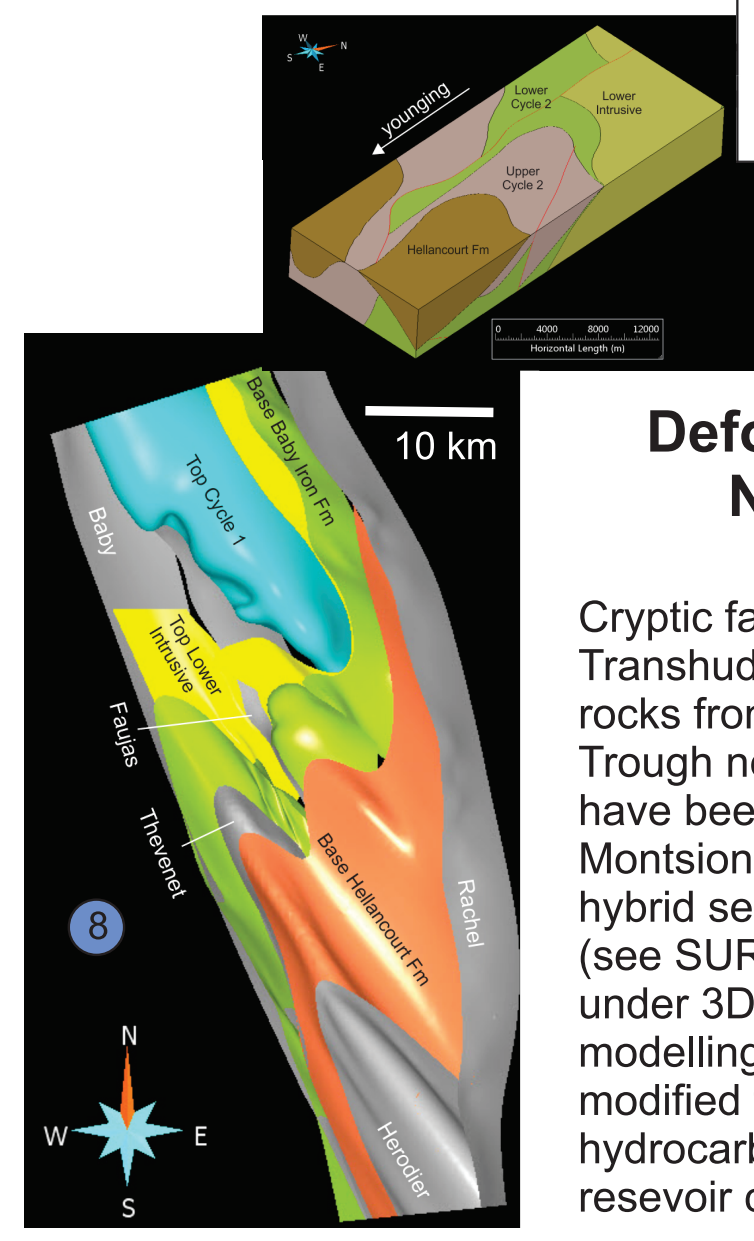
Hudson Bay, Precambrian - Phanerozoic contact model (fig.6) below. 3D visualization of contoured surface(left); full volumetric block model (middle); stratigraphic-structural sections, right. Red-yellow-blue layers represent Precambrian basement, lower Paleozoic (yellow) and Middle Devonian (blue) strata.



Mesoproterozoic Kiglapait intrusion modelled in 3D with surface geometry from igneous layering orientations and unconstrained gravity inversion. An early example (1998) of regional integration of geology and geophysics to support 3D interpretation.

		Older faults									
		Olmstead	Point Reef/ Hérodier	Boulder	Rachel	Canoe	Central Nappes	Highfall	North-Shear	South-Shear	Ujaralialuk
Younger Faults	Olmstead		0	0	0	0	0	0	0	0	0
	Point Reef/ Hérodier	0		0	0	1	0	0	0	0	0
	Boulder	0	0		0	0	0	0	0	0	0
	Rachel	0	1	0		0	0	0	0	0	0
	Canoe	0	0	0	0		0	0	0	0	0
	Central Nappes	0	0	0	0	1		0	0	0	0
	Highfall	0	0	0	0	0	0		0	0	0
	North-Shear	0	3	0	0	0	0	0		0	0
	South-Shear	0	3	0	0	3	0	0	0		0
	Ujaralialuk	0	0	0	0	0	1	1	0	0	

Fault to fault adjacency matrix. See Montsion 2017 and Burns 1975 for details.

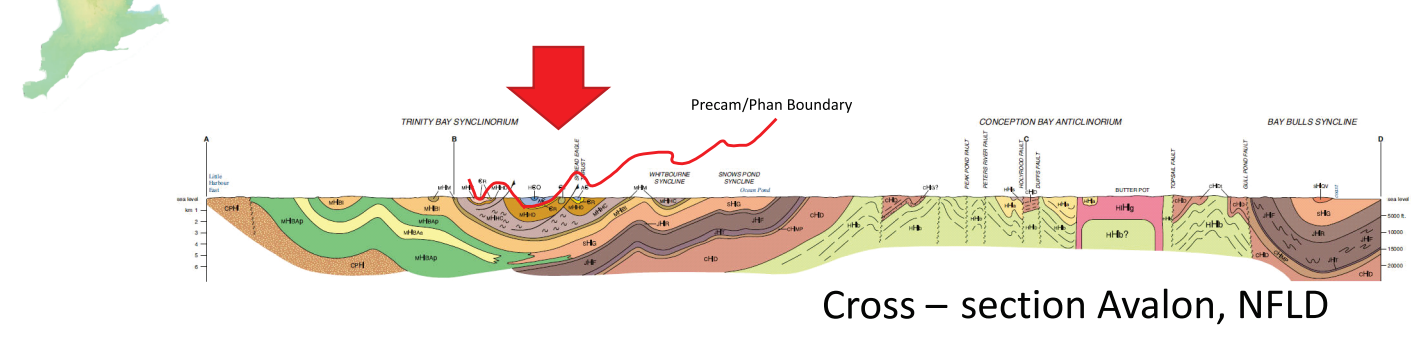


Deformed Fault Networks

Cryptic fault networks from Transhudson basement rocks from the Labrador Trough near Kuujjuak (fig. 8) have been modelled by Montsion (2017) using a hybrid set of tools; in house (see SURFE, SPARSE, SFI under 3D mathematical modelling to the right) and modified from those used in hydrocarbon exploration and resevoir characterization.

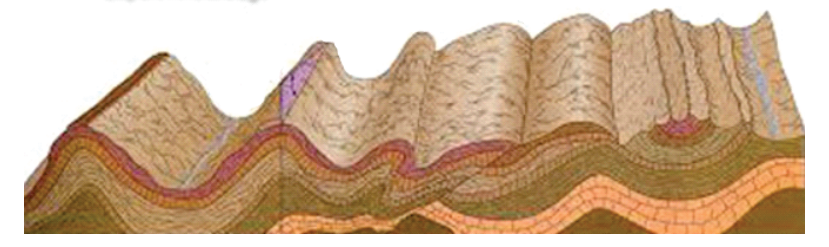
Complex Bedrock Regions

In the Canada in Shield, the Appalachian orogeny of eastern Canada and the mountainous Cordillera of western Canada, the bedrock geology is much more complicated than the Phanerozoic cover rocks. The sparse data distribution, lack of depth constraints and complex geology make bedrock mapping dependent on expert knowledge and published geological cross sections. The Precambrian-Phanerozoic boundary is for the most part an unconformity and rarely exposed through a continuous stratigraphic sequence such as depicted here in the famous Fortune Head, NFLD site. At Fortune, within the Chapel Island Formation, the boundary is actually uncertain as new discoveries, from lower strata, are made of the trace fossil Phycodes pedum, which defines the Precambrian-Phanerozoic boundary at this location.



Cross – section Avalon, NFLD

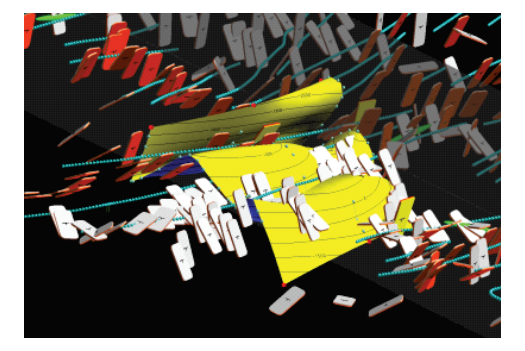
Expert Knowledge



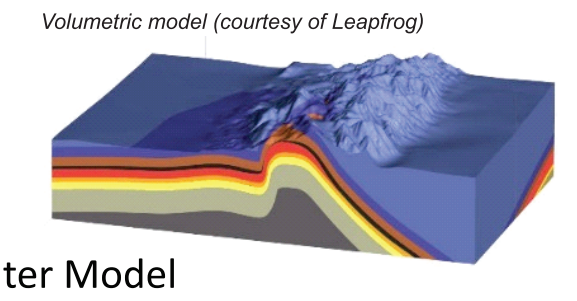
Conceptual Model

Complex Regions More Deformed
Appalachians - Cordillera

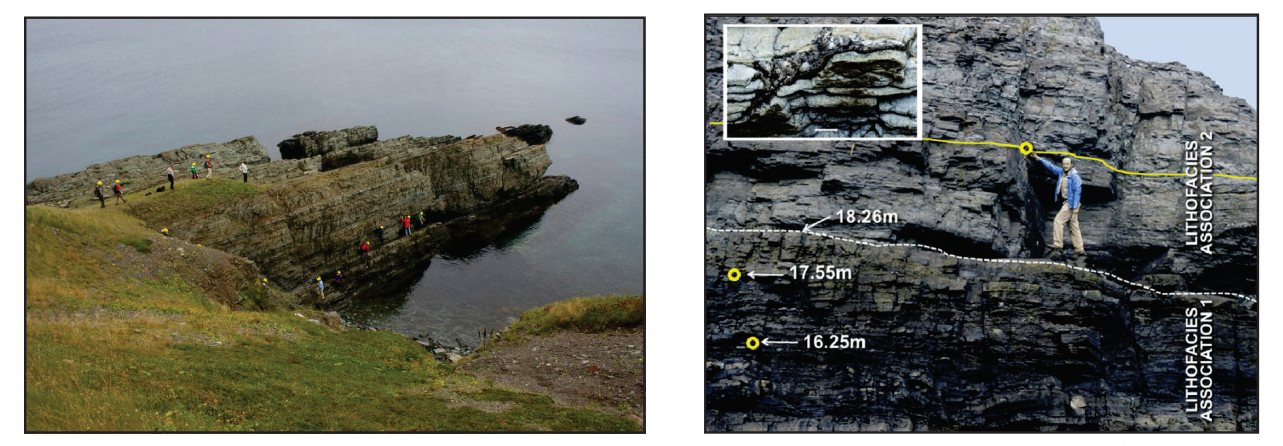
Fold modelling in turbiditic sediments using field observations and SPARSE 3D tools.



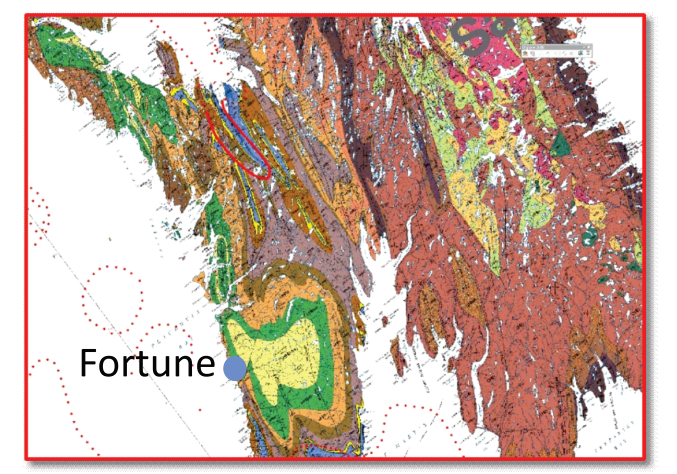
Volumetric model (courtesy of Leapfrog)



Computer Model



Fortune Head - Precambrian - Phanerozoic boundary locality



Avalon Peninsula, NFLD

FORTUNE HEAD
ECOLOGICAL RESERVE
PRECAMBRIAN-CAMBRIAN BOUNDARY

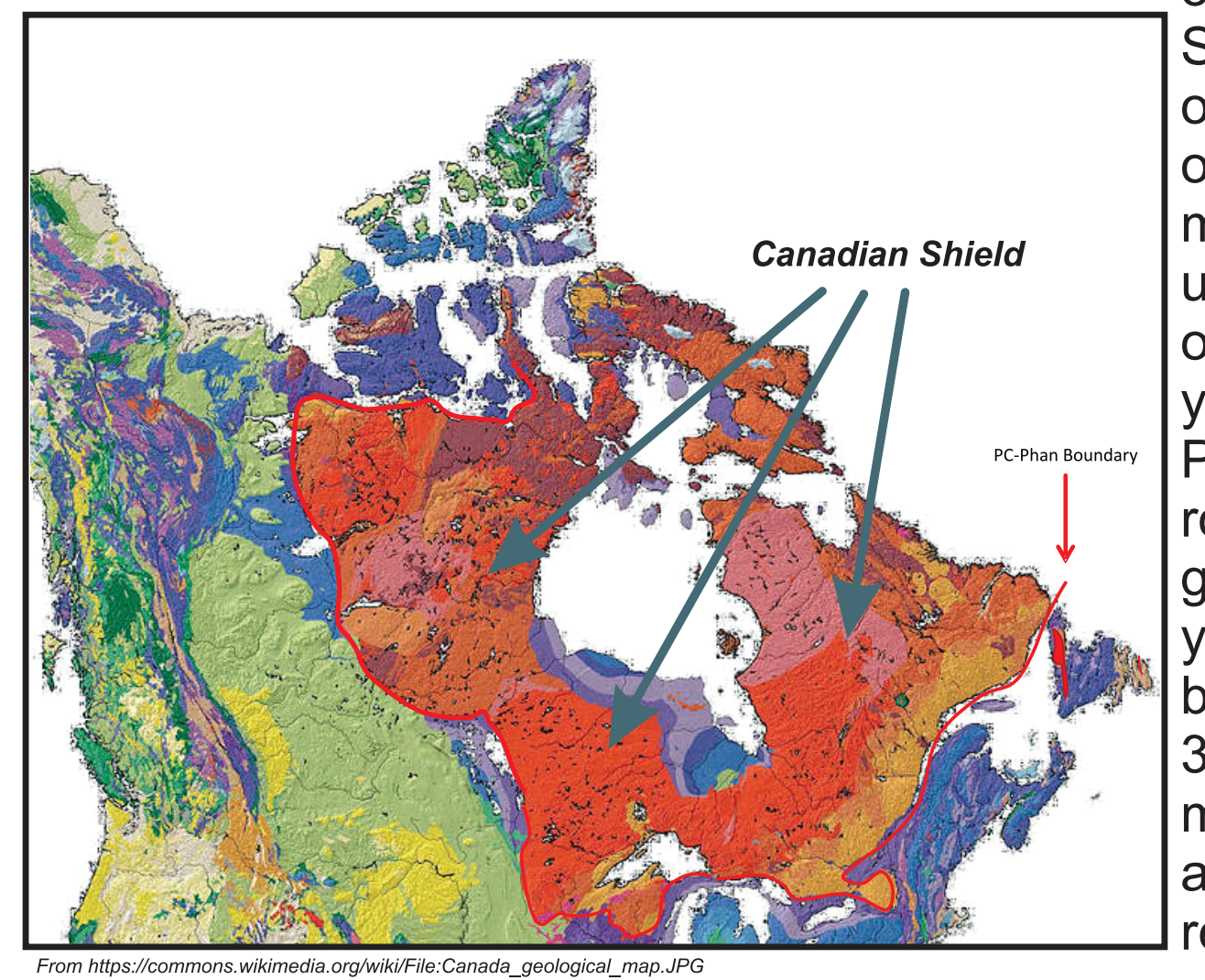
In 1992, the global stratotype for the Precambrian-Cambrian boundary was defined by the International Commission on Stratigraphy as being located here at Fortune Head. It is located at 2.4 metres above the base of member 2 of the Chapel Island Formation, and is exposed on the coast, 250 metres northeast of this plaque. This boundary corresponds to the lowest occurrence of the ichnofossil *Phycodes pedum*.

This site is designated as an Ecological Reserve by the Government of Newfoundland and Labrador. No collection of fossils or rocks is permitted without a permit for scientific research, obtainable from the Parks Division, Department of Tourism and Culture.

This plaque was erected by
the Canadian National Committee for
the International Geological Correlation Programme and
the Government of Newfoundland and Labrador,
with the assistance of the Town of Fortune;

JUNE 1994

The Precambrian-Phanerozoic boundary is a significant national scale boundary that juxtaposes older largely crystalline basement of the Canadian Shield (red and orange regions on adjacent map), with unconformably overlying younger Phanerozoic rocks (purples, greens and yellows). The boundary is a 3D surface that may be exposed at places (see red trace on map). At depth, the boundary is intersected by several thousand well bore holes, mainly in the Hudson, Williston and Western Canada basins.

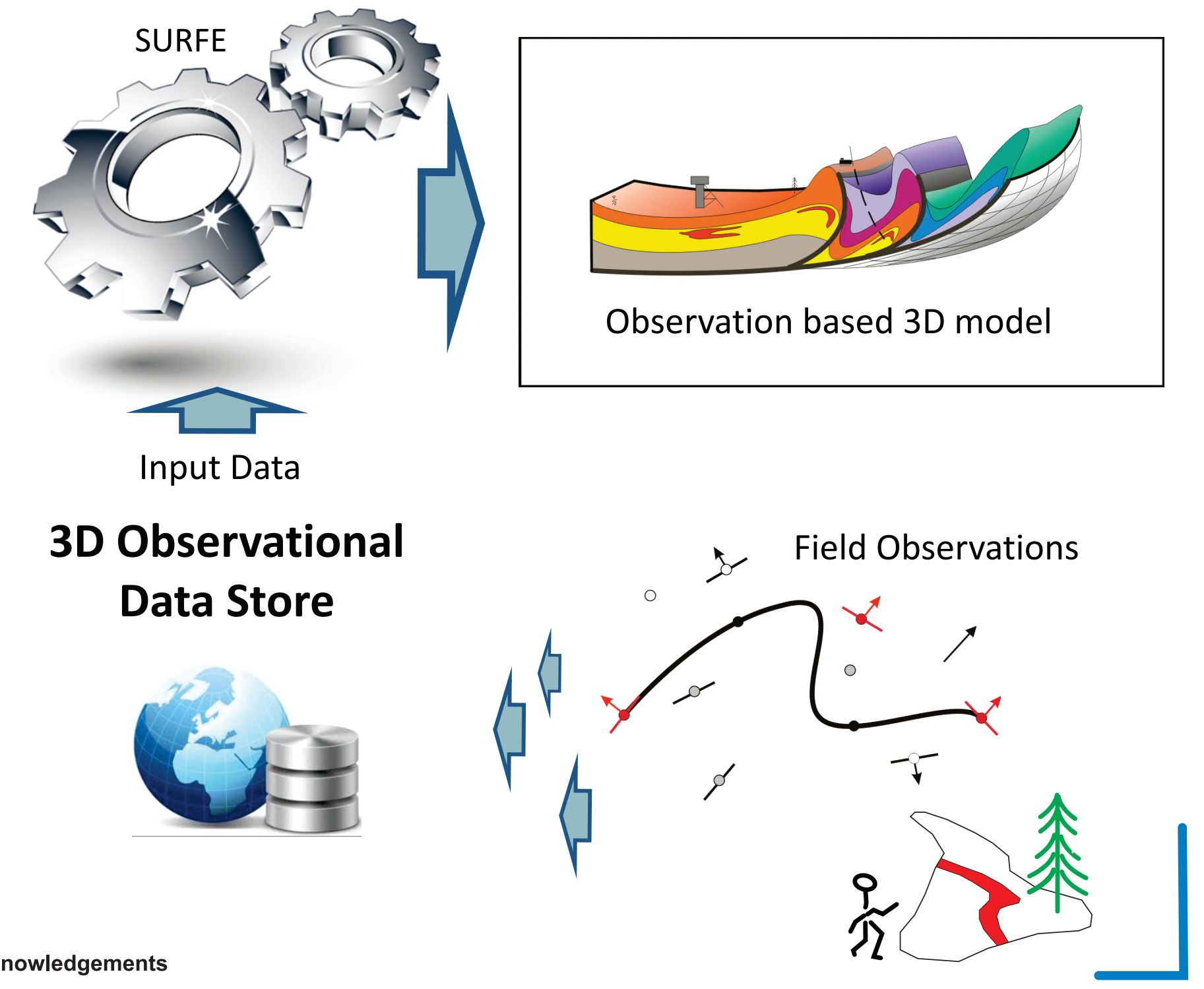


From https://commons.wikimedia.org/wiki/File:Canada_geological_map.JPG
Joint USGS,GSC,Mexico geologic terrain map of North America 2003 (wiki open source)

3D Mathematical Modelling

A 3D geometry calculation engine, based on an implicit estimation scheme, has been developed by the Geological Survey of Canada and applied within the Canada 3D project (see below). The implicit approach is now more widely used in 3D geological modelling (ie. Geomodeller, SKUA, Leapfrog) but we extend and enhance the approach with what we call SURFE (an application of the General Radial Basis Function, see Hillier et al., 2015, for details). It can take advantage of a variety of off contact observations including regional traverse data such as structural and lithostratigraphic observations for constraints. This development allowed us to model faults and horizons (fig. 5 & 8) which are traditionally better constrained in 3D geological modelling workflows using 3D seismic surveys. In the absence of these dense seismic data we needed to develop a method which could better interpolate and extend estimations into the subsurface, where there are very few hard constraints.

The SURFE method could prove useful in upscaling and integrating mine and regional data by making it easier to develop consistent models that use both dense and sparse data. Exploration strategies could benefit from this approach by undertaking 3D modelling exercises, and with less risk, target for deeper ore, or better constrain conceptual geologic models with insight provided by the 3D geospatial model. Geological surveys looking to leverage public historical archives of regional field information could also benefit from SURFE with regional to national scale 3D projects such as Canada 3D.



SURFE

Observation based 3D model

Input Data

3D Observational Data Store

Field Observations

Acknowledgements

Many thanks to all Provincial and Territorial Governments who provded data and support through access to geoscience data sets used in developing Canada's bedrock layers. Well data from Geological Atlas of the Western Canada Sedimentary Basin, SPG and ARC; http://ags.aer.ca/reports/atlas-of-the-western-canada-sedimentary-basin.htm, Southern Ontario well data from Oil Gas and Salt Resources library http://www.ogsrlibrary.com/, Seismic data courtesy of Lithoprobe, http://lithoprobe.eos.ubc.ca/ and Aquistore, http://aquistore.ca/. Hudson Bay seismic interpretation modified from Pinet et al. (2013). Thanks to Charles Logan for data management and modelling support for Southern Ontario. Arctic Islands data and 3D interpretation courtesy of Chris Harrison. Academic software (Gocad/SKUA/SPARSE/Mira Mining) was generously provided through the RING Consortia, Paradigm and Mira Geoscience. Critical review by Brian Roberts is much appreciated.

Natural Resources Canada Ressources naturelles Canada

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Canada