Geological Survey of Canada
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INITIATING TRANSFORMATIVE GEOSCIENCE PRACTICE AT THE GEOLOGICAL SURVEY OF CANADA: CANADA IN 3D

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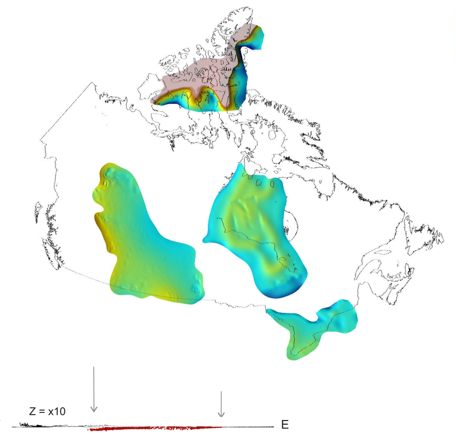


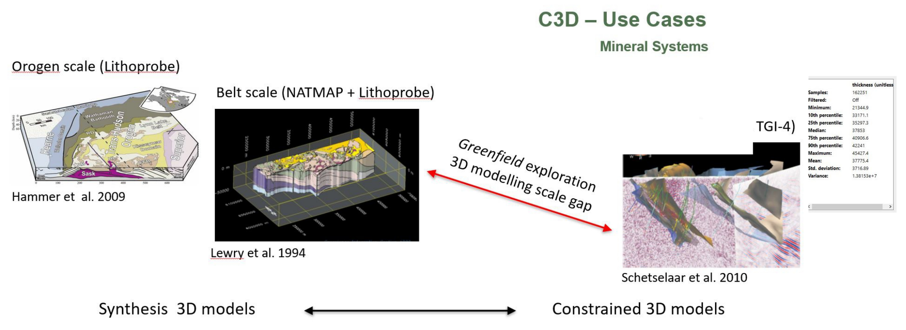
Abstract

Application of 3D technologies to the wide range of Geosciences knowledge domains is well underway. These have been operationalized in workflows of the hydrocarbon sector for a half-century, and now in mining for over two decades. In Geosciences, algorithms, structured workflows and data integration strategies can support compelling Earth models, however challenges remain to meet the standards of geological plausibility required for most geoscientific studies. There is also missing links in the institutional information infrastructure supporting operational multi-scale 3D data and model development.

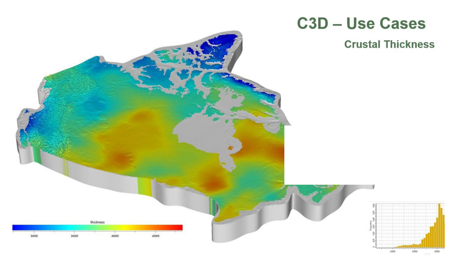
Canada in 3D (C3D) is a vision and road map for transforming the Geological Survey of Canada's (GSC) work practice by leveraging emerging 3D technologies. Primarily the transformation from 2D geological mapping, to a well-structured 3D modelling practice that is both data-driven and knowledge-driven. It is tempting to imagine that advanced 3D computational methods, coupled with Artificial Intelligence and Big Data tools will automate the bulk of this process. To effectively apply these methods there is a need, however, for data to be in a well-organized, classified, georeferenced (3D) format embedded with key information, such as spatial-temporal relations, and earth process knowledge. Another key challenge for C3D is the relative infancy of 3D geoscience technologies for geological inference and 3D modelling using sparse and heterogeneous regional geoscience information, while preserving the insights and expertise of geoscientists maintaining scientific integrity of digital products. In most geological surveys, there remains considerable educational and operational challenges to achieve this balance of digital automation and expert knowledge.

Emerging from the last two decades of research are more efficient workflows, transitioning from cumbersome, explicit (manual) to reproducible implicit semi-automated methods. They are characterized by integrated and iterative, forward and reverse geophysical modelling, coupled with stratigraphic and structural approaches. The full impact of research and development with these 3D tools, geophysical-geological integration and simulation approaches is perhaps unpredictable, but the expectation is that they will produce predictive, instructive models of Canada's geology that will be used to educate, prioritize and influence sustainable policy for stewarding our natural resources.

On the horizon are 3D geological modelling methods spanning the gulf between local and frontier or green-fields, as well as deep crustal characterization. These are key components of mineral systems understanding, integrated and coupled hydrological modelling and energy transition applications, e.g. carbon sequestration, in-situ hydrogen mining, and geothermal exploration. Presented are some case study examples at a range of scales from our efforts in C3D.

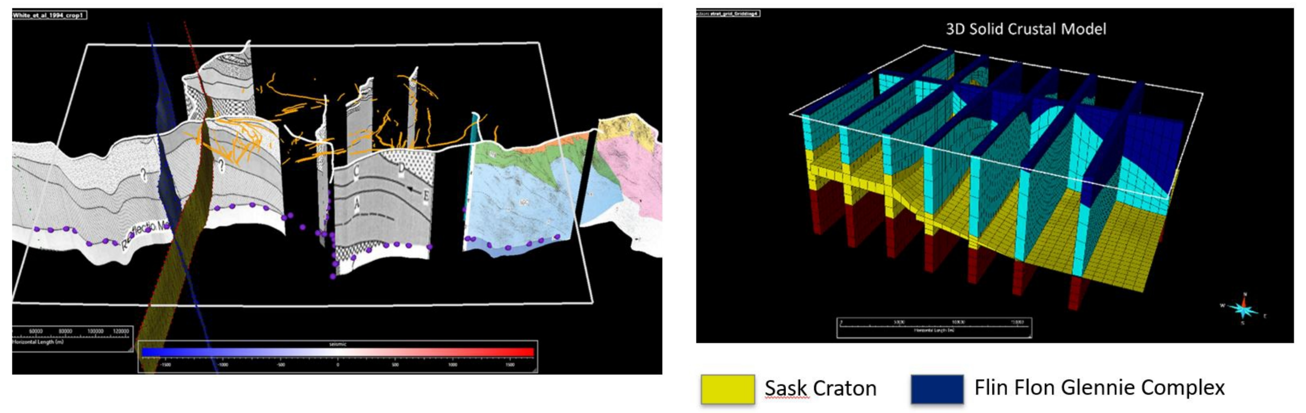


Crustal Thickness Estimation



C3D – Use Cases

Mineral Systems – Tectonic Interpretation



White, 2020

Webinars

Carter, T.R., Brunton, F.R., Clark, J.K., DeKemp, E., Logan, C.E., and Russell, H.A.J. 2020. 3-D geological and hydrogeological modelling of the bedrock geology of southern Ontario. NWMO 2020 geoscience webinar, June 16th 2020. (Related video: https://youtu.be/RgMdIHJaZ54).

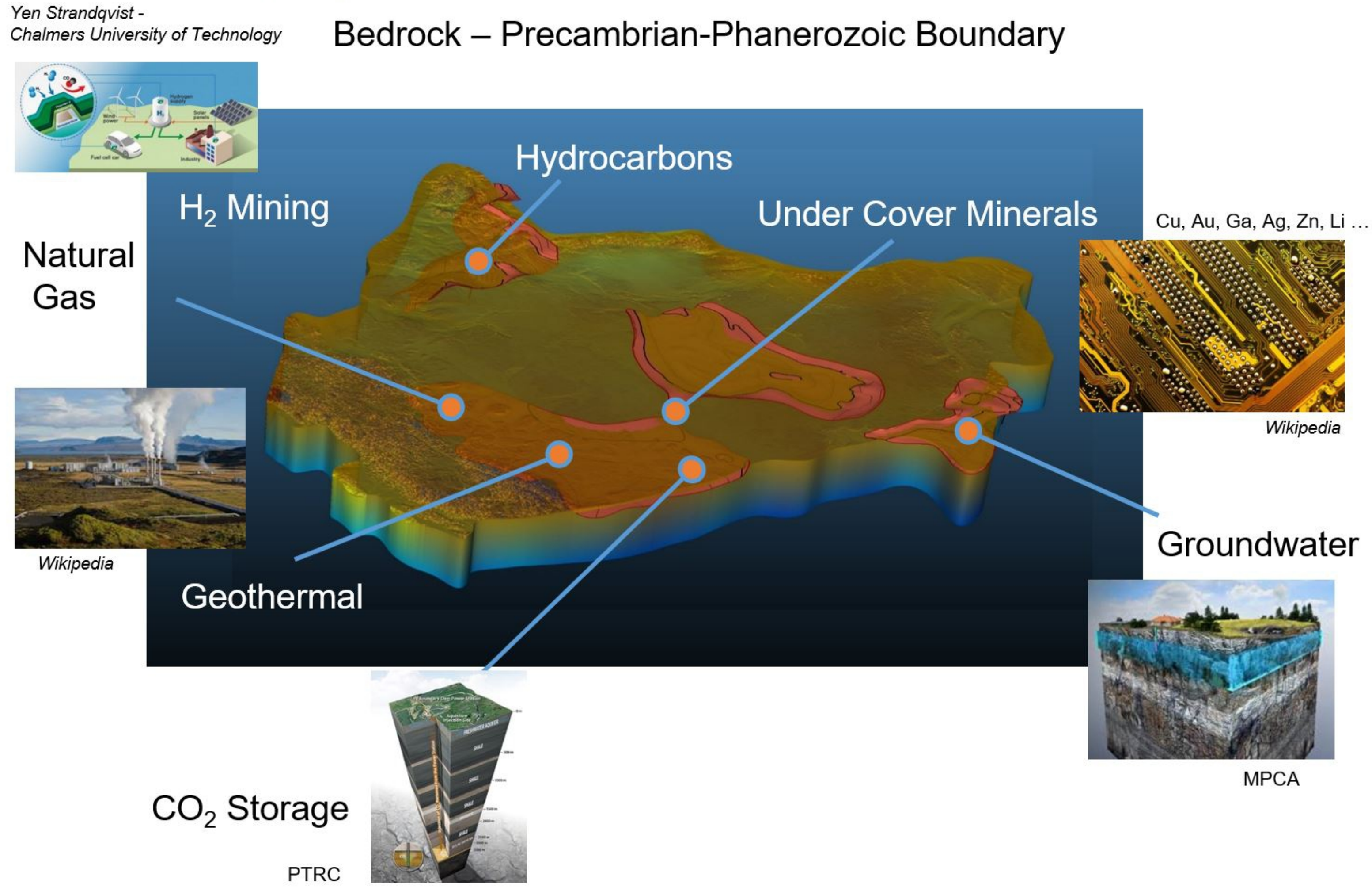
Hillier, M. (2021) Using Graph Neural Networks for 3D Structural Geologic Modelling. LOOP 3D European Modelling Forum, 03 March 2015.

Parquer, M. (2021) Automated 3D Geological Consistency Checking. LOOP 3D European Modelling Forum, 03 March 2015.

Russell, H. et al. "Responding to Societal Needs with 3D Geology, an International Perspective (C3D). International 3D geological Modelling Collaboration. https://www.youtube.com/watch?v=euvo6TwjAFA&list=PLTBBygdCOWWcCbSjvjbVoKHutmfqSAQdf&index=1&t=55s

Sun, S., Brunton, F.R., Carter, T.R., Jin, J., Clark, J.K., Yeun, K., and Russell, H.A.J. 2020. Geographic analysis of the porosity and permeability variations in the Lockport Group, SW Ontario. NWMO 2020 geoscience webinar, June 16th 2020. https://youtu.be/rY9cd7ds_PQ

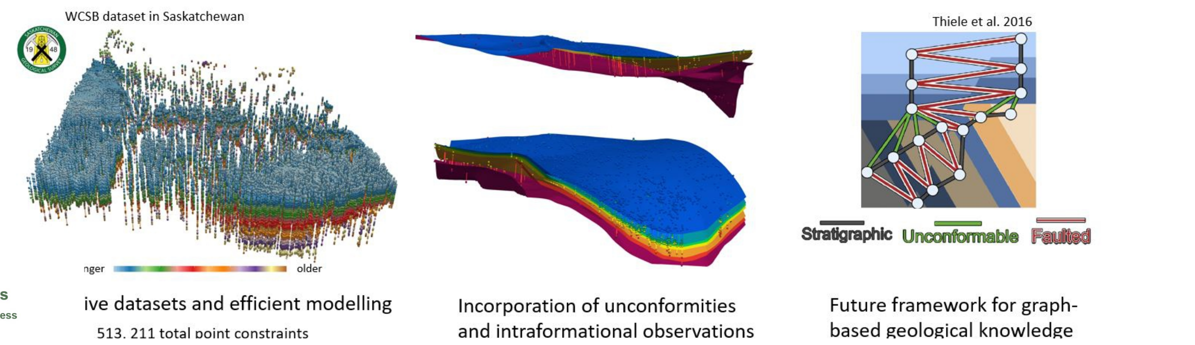
C3D Vision: 3D (4D) Geoscience for a Sustainable Circular Green Economy



Big Data and Knowledge Integration for Regional Stratigraphic Modelling

Method Development for 3D Structural Geological Modelling

- Developing new approach using emerging deep learning methods
  - Considerable flexibility on types of geological constraints included into modelling process
  - Scalable for massive datasets leveraging cloud computing infrastructure
  - Suitable foundation for incorporating relational-based knowledge constraints using graph data structures.

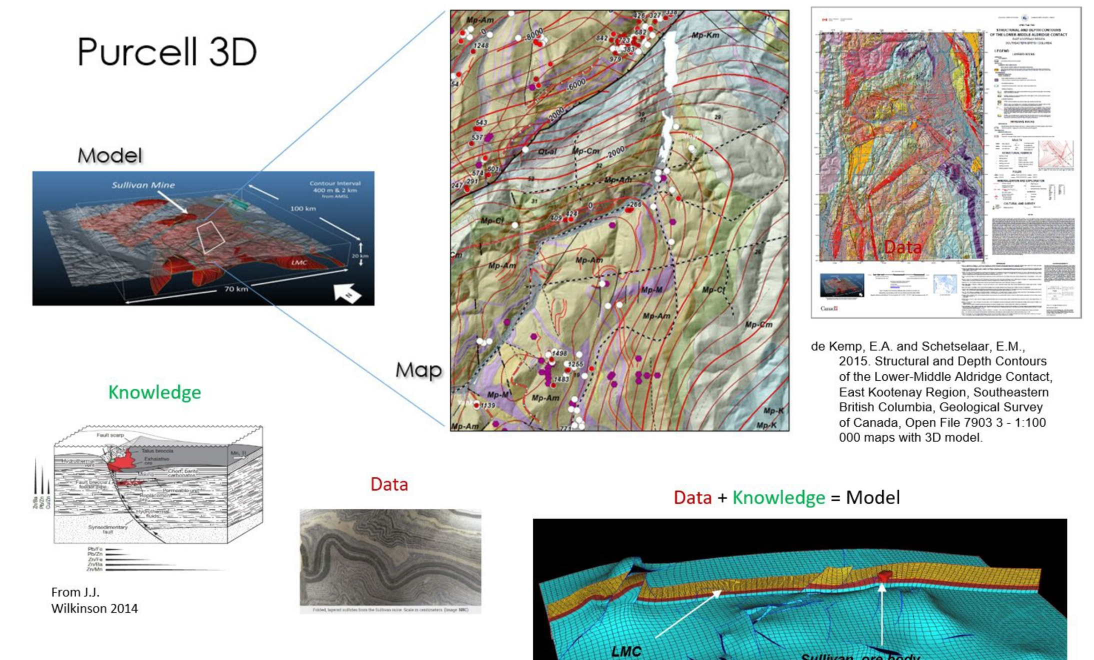


ive datasets and efficient modelling
513, 211 total point constraints

Incorporation of unconformities and intraformational observations

Future framework for graph-based geological knowledge

Predictive Region Model



de Kemp, E.A. and Schetselaar, E.M., 2015. 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 et al., 2016, Interpretation, Vol. 4, No. 3, p. SM33–SM50
http://dx.doi.org/10.1190/INT-2015-0191.1.

C3D - A National Geological Surveys Committee Project ***C3D https://canada3d.geosciences.ca/***

Metals for the Low Carbon Economy

- Increased demand;
- Copper
- Aluminum
- Nickel
- Au – H_2 Fuel Cells Electronics

Electric Vehicles:	Energy Storage: (1000%)	Solar Photovoltaics: (300%)	Wind: (250%)
Cobalt x30	Aluminum	Aluminum	Aluminum
Lithium	Cobalt	Copper	Chromium
Copper	Iron	Indium	Copper
Aluminum	Lead	Iron	Iron
Nickel x2	Lithium	Lead	Lead
	Manganese	Molybdenum	Manganese
	Nickel	Nickel	Molybdenum
		Silver	Neodymium
		Zinc	Nickel
			Zinc

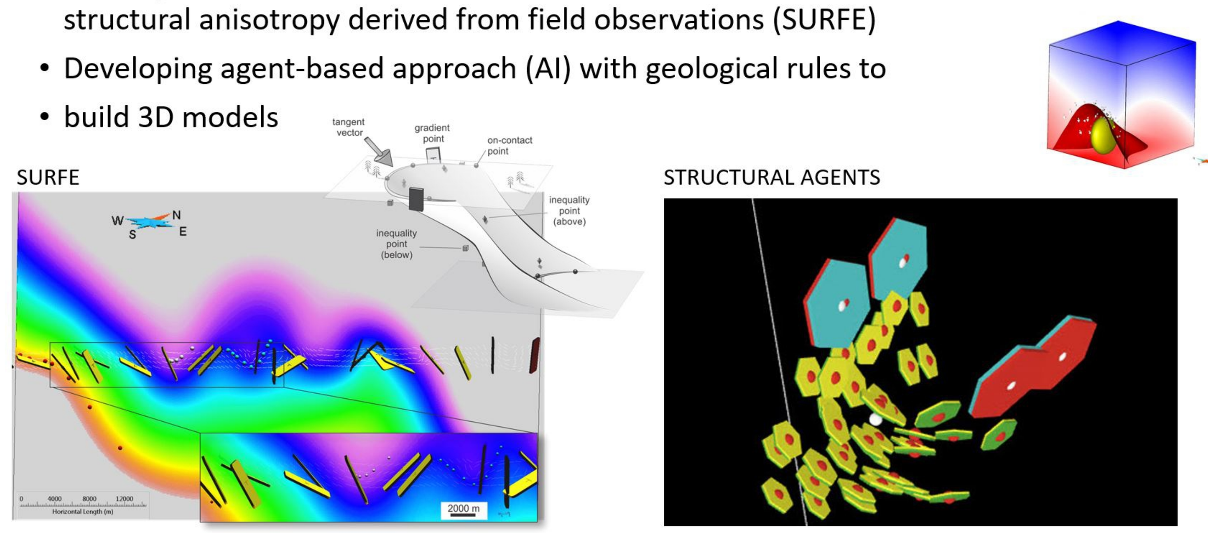
Information from summary article by Carrie Carlson – *FEECO International* on; *The Growing Role of Minerals and Metals for a Low Carbon Future*. Report, Washington, DC: The World Bank Group, 2017.

3D Workflow of the future…

- Multi-scaler (outcrop to global, mine – regional integration)
- Multi-Parameter (geophysics – geology – geochemistry)
- Circular workflow (many updateable models)
- Challenging terrains (Sparse-Regional)
- Uncertainty Modelling
- Geological Reasonableness (All the Data + Knowledge; GeoEvent History)
- Simulation – Process Coupled – Implicit+
- Collaboration Practice **M** = f(Geophysics:Geology)

Method Development for 3D Structural Geological Modelling

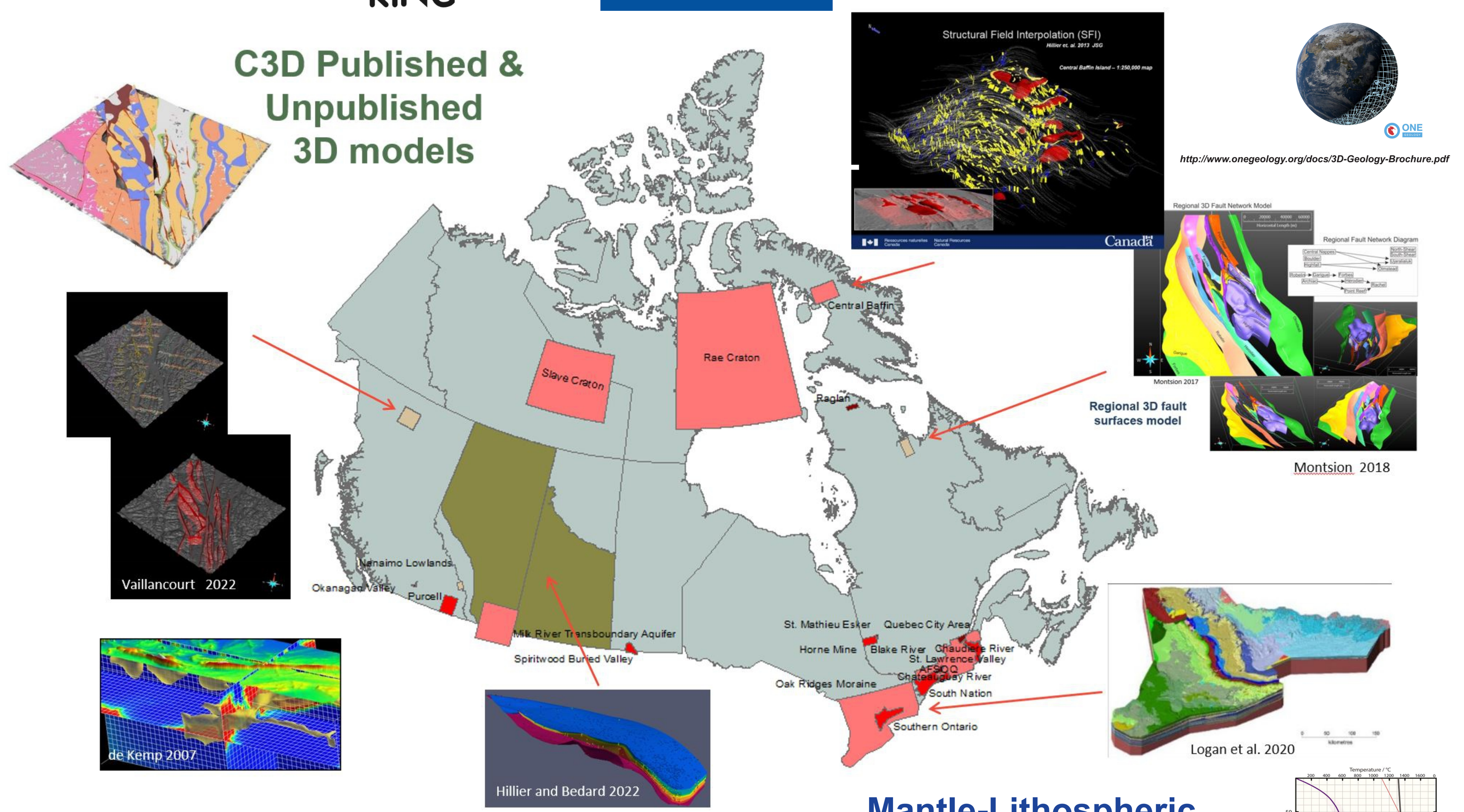
- Developed new mathematical constraints to include rock unit observations and structural anisotropy derived from field observations (SURFE)
- Developing agent-based approach (AI) with geological rules to
- build 3D models



Hillier M. (2021) Radial Basis Functions. In: Daya Sagar B., Cheng Q., McKinley J., Agterberg F. (eds) Encyclopedia of Mathematical Geosciences. Encyclopedia of Earth Sciences Series. Springer, Cham. https://doi.org/10.1007/978-3-030-26050-7_263-1, 2021.

de Kemp, E. A.: Spatial agents for geological surface modelling, Geosci. Model Dev., 14, 6661–6680, https://doi.org/10.5194/gmd-14-6661-2021, 2021.

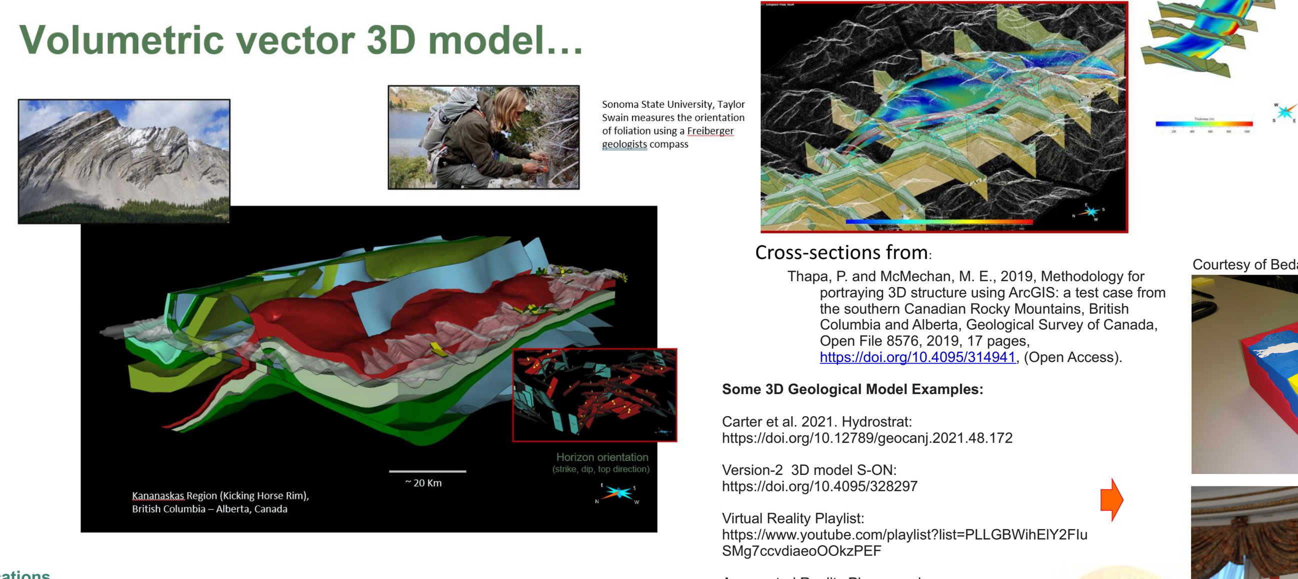
C3D Published & Unpublished 3D models



Methods for 3D Structural Geological Modelling

- Two types of approaches
  - Explicit: Requires significant expertise, extensive amount of time to construct model, not updatable or reproducible
  - Implicit: Solves issues with explicit approaches
    - Improvements required to produce better geometric representations that are geologically reasonable for complex structural settings
      - Incorporate more geological knowledge constraints
      - Integrating other geological datasets (geochemical, geophysical, etc)

Volumetric vector 3D model…



Cross-sections from:
Thapa, P. and McMechan, M. E., 2019, Methodology for portraying 3D structure using ArcGIS: a test case from the southern Canadian Rocky Mountains, British Columbia and Alberta, Geological Survey of Canada, Open File 8576, 2019, 17 pages, https://doi.org/10.4095/314941. (Open Access).

Some 3D Geological Model Examples:

Carter et al. 2021. Hydrostrat: https://doi.org/10.12789/geocanj.2021.48.172

Version-2 3D model S-ON: https://doi.org/10.4095/328297

Virtual Reality Playlist: https://www.youtube.com/playlist?list=PLLGBWihEIY2Flu SMg7ccvdiaeoOOkzPEF

Augmented Reality Playground: https://ar.ogsrlibrary.com/

Publications

A sampling of recent (2020-2022) mine to national scale 3D modelling (e.g., methods, models, integration and science), follow:

Schetselaar, E.; Bellefleur, G.; Hunt, P. , Integrated analyses of density, P-wave velocity, lithogeochemistry, and mineralogy to investigate effects of hydrothermal alteration and metamorphism on seismic reflectivity: a summary of results from the Lalor volcanogenic massive-sulfide deposit, Snow Lake, Manitoba, Geological Survey of Canada, Bulletin 617, 2022 p. 329-344, https://doi.org/10.4095/327999, (Open Access).

Skipton, D.R., St-Onge, M.R., Kellett, D.A., Joyce, N.L., and Smith, S., 2022, Rapid postorogenic cooling of the Paleoproterozoic Cape Smith foreland thrust belt and footwall Archean basement, Trans-Hudson orogen, Canada, in Whitmeyer, S.J., Williams, M.L., Kellett, D.A., and Tikoff, B., eds., Laurentia: Turning Points in the Evolution of a Continent: Geological Society of America Memoir 220, p. 1–30, https://doi.org/10.1130/2022.1220(06).

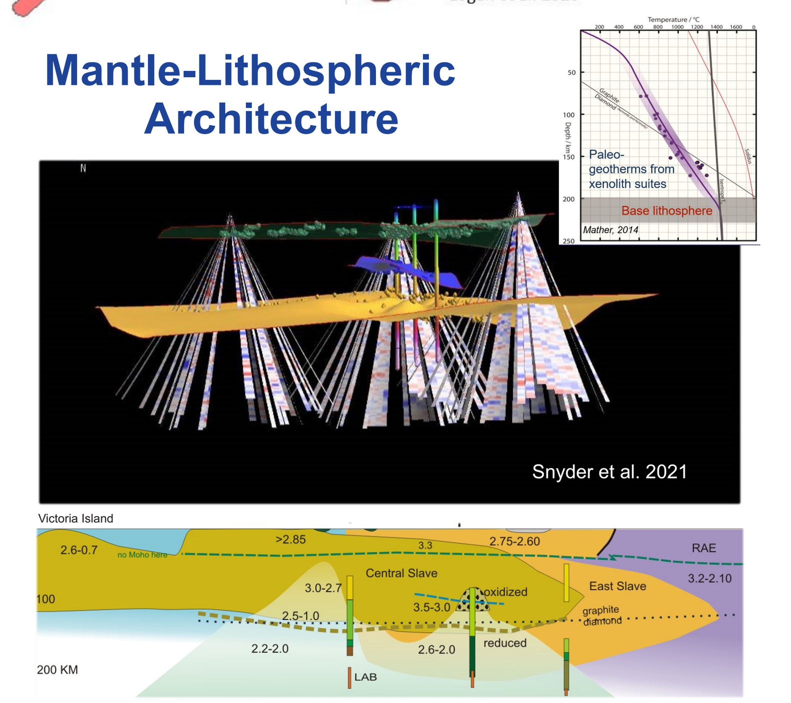
https://doi.org/10.1029/2020GC009566, (Open Access).

von Harten, J.; de la Varga, M.; Hillier, M.; Wellmann, F. Informed Local Smoothing in 3D Implicit Geological Modeling. Minerals 2021, 11, 1281. https://doi.org/10.3390/min11111281.

Weller, O., Mottram, C., St-Onge, M.R., Möller, C., Strachan, R., Rivers, T., Copley, A., 2021. The metamorphic and magmatic record of collisional orogens. Nature Reviews Earth and Environment, 19 p., https://doi.org/10.1038/s43017-021-00218-z.

White, Don et al. Borehole seismic methods for geologic CO2 storage monitoring, The Leading Edge (2021), 40(6):434, http://dx.doi.org/10.1190/tle40060434.1

Mantle-Lithospheric Architecture



Courtesy of Bedard, K. (LCNP Lab)
Courtesy of Russell, H. (S. Ont.)

Vital Pearson and Eric de Kemp discuss Blake River and Central Camp 3D model, Quebec City, 2008.

Knowledge Transfer and Public Engagement

Acknowledgements

Many thanks to all Provincial and Territorial Governments who provided 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; https://ags.aer.ca/atlas-the-western-canada-sedimentary-basin/atlas-well-control-data, 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, Emerson and Mira Geoscience.

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This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

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Canada