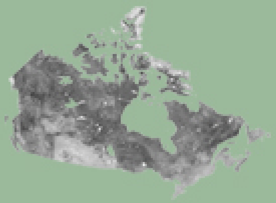
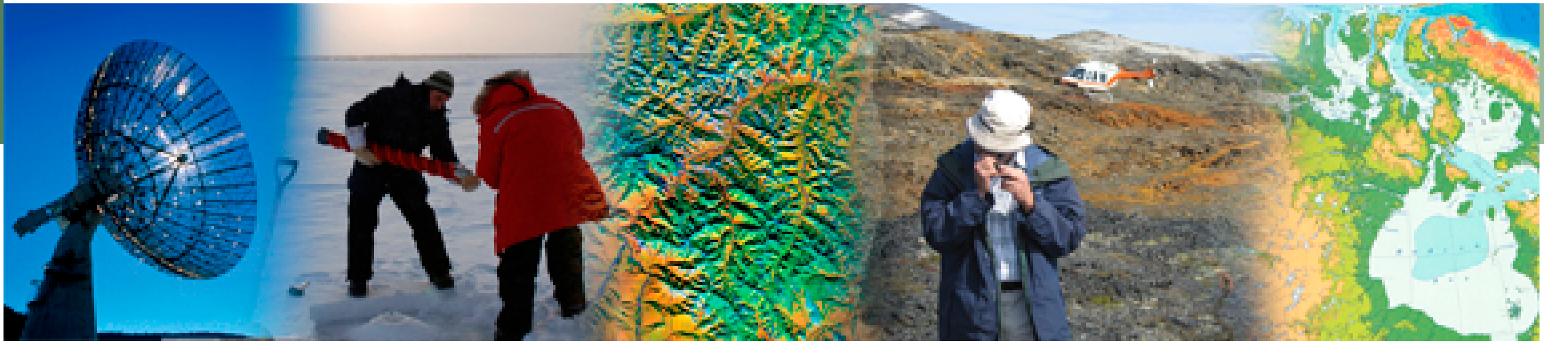
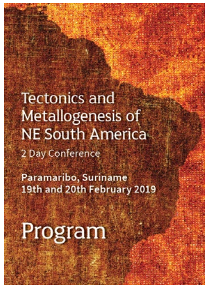




Complex 3D Integration for Mineral Exploration

Eric de Kemp
Geological Survey of Canada

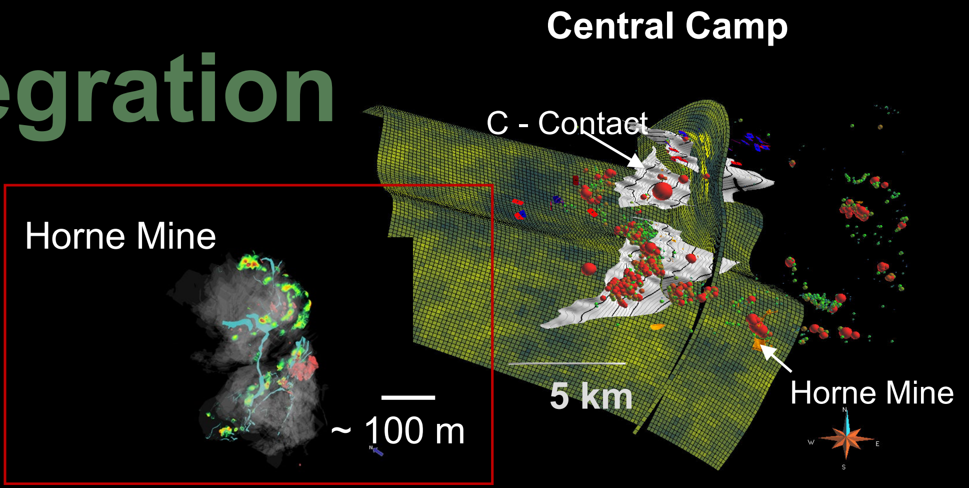


Tectonics and
Metallogenesis of
NE South America
2 Day Conference

Paramaribo, Suriname
19th and 20th February 2019

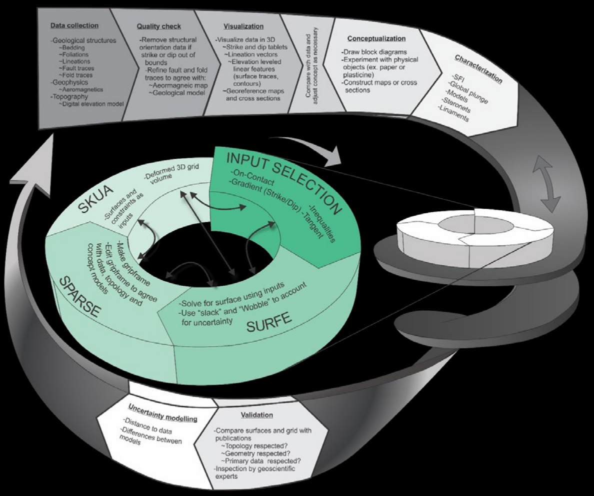
Program

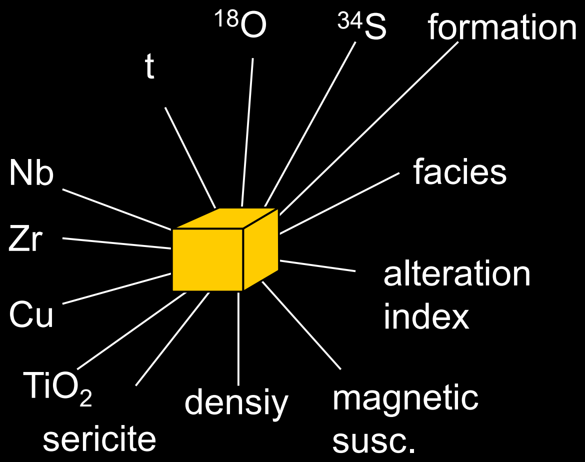
Complex Data Integration

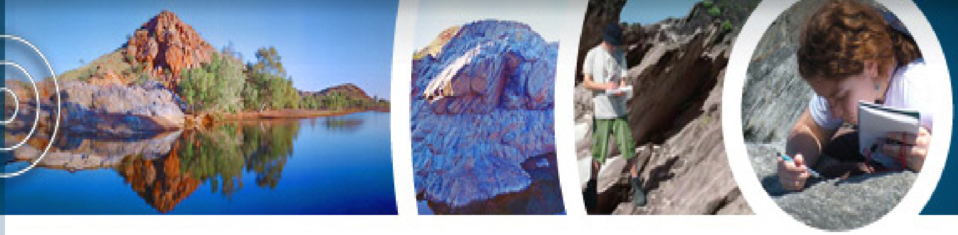


CDI = MMI

- Multi-scalar
- Multi-parameter
- Iterative







Greenfields Exploration

“ Greenfields Exploration is the process whereby broad target areas are selected on the basis of favorable geology and/or geophysics with little or no evidence of the target mineralization”.

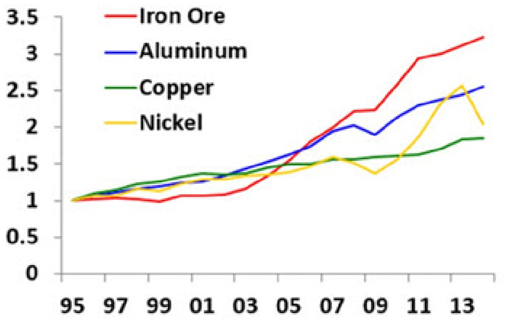
CET ~ 2006

Beyond the headframe …

Greenfields

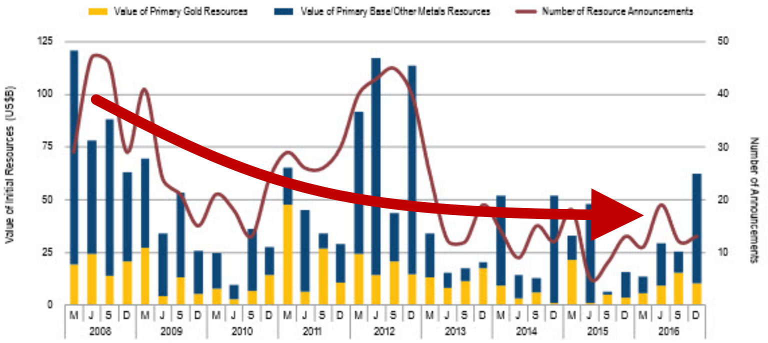
- Increasing consumption and production
- Depletion of finite resource

Chart 3. World Metal Production
(1995=1)



Sources: IMF, Primary Commodity Price System; and IMF staff calculations.

Figure 4: Initial Resource Values



Note: As defined in S&P Global Market Intelligence's Monthly Industry Monitor, initial resources include initial estimates for both new deposits and new zones at mines and projects with previously defined reserves and/or resources.

S&P GLOBAL MARKET INTELLIGENCE

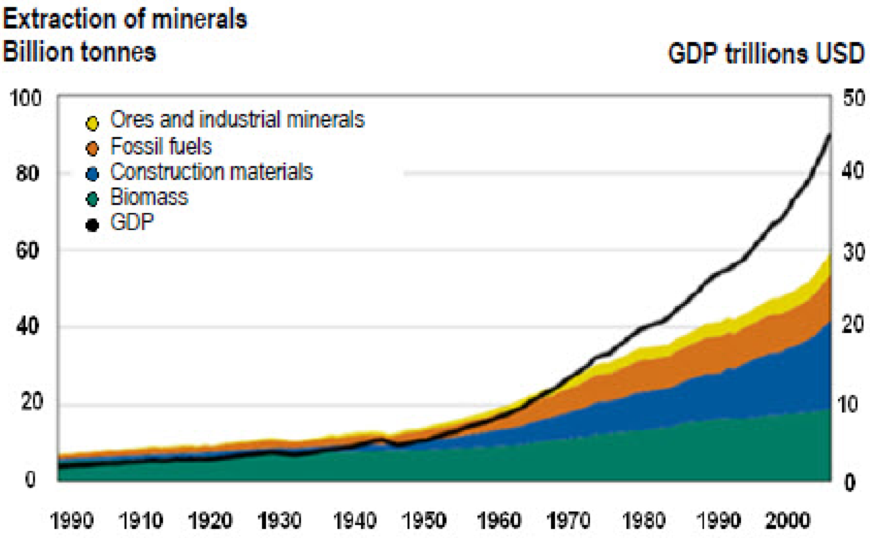
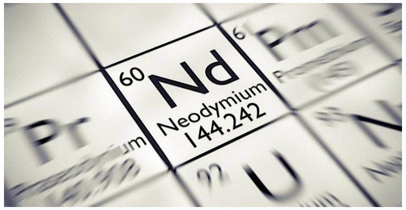
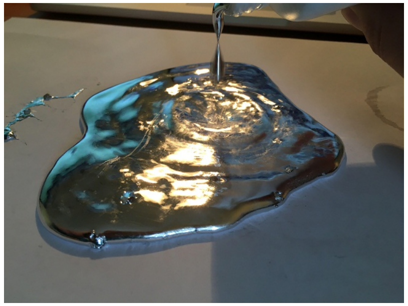


Fig. 2. Growth in demand for mineral resources in the world economy (SERI 2011)

SERI (2011): Global resource extraction by material category 1980–2008.
http://www.materialflows.net

Metals for the Low Carbon Economy





- Increased demand;
- Copper
- Aluminum
- Nickel

Au – H_2 Fuel Cells
Electronics

Electric Vehicles:

Cobalt **x30**
Lithium
Copper
Aluminum
Nickel **x2**

Energy Storage:
(1000%)
Aluminum
Cobalt
Iron
Lead
Lithium
Manganese
Nickel

Solar Photovoltaics:
(300%)
Aluminum
Copper
Indium
Iron
Lead
Molybdenum
Nickel
Silver
Zinc

Wind:
(250%)
Aluminum
Chromium
Copper
Iron
Lead
Manganese
Molybdenum
Neodymium
Nickel
Zinc

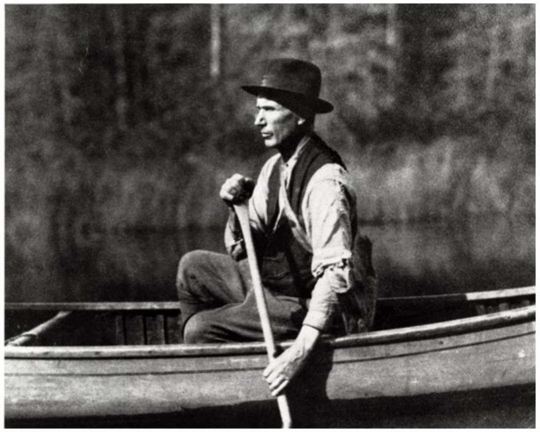
Information from summary article by Carrie Carlson – *FEECO International* on; ***The Growing Role of Minerals and Metals for a Low Carbon Future***. Report, Washington, DC: The World Bank Group, 2017.

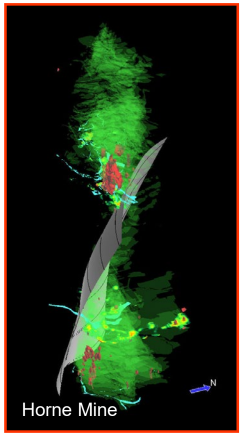
Gallium
31
Ga
69.723

Greenfields

- Many major giant class ore deposits were once in a Greenfields setting.

Discovery site of nickel-copper ore
1883, Copper Cliff – Sudbury Camp.





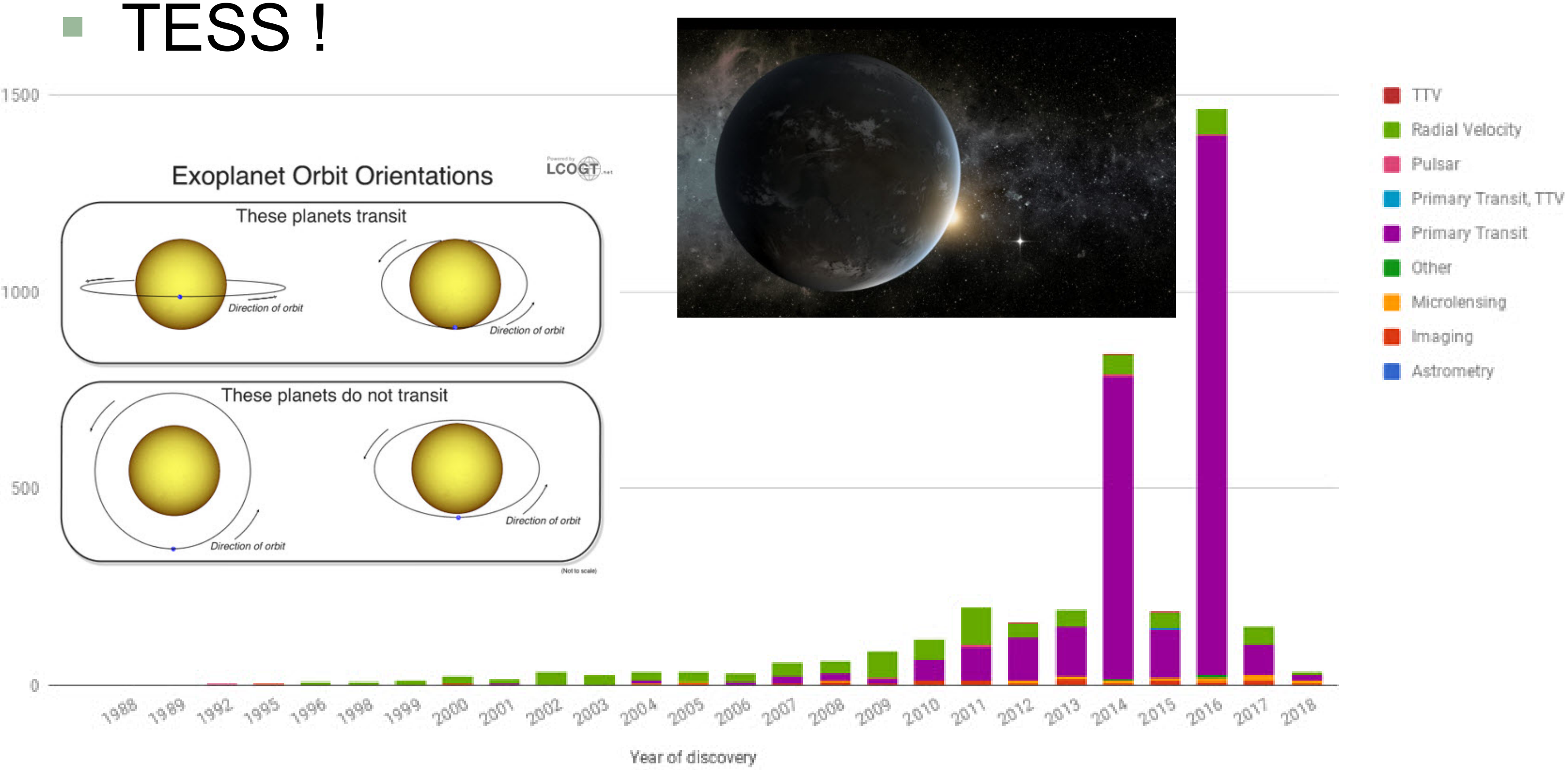
Edmund Henry Horne 1864-1953
Discovered ore ~1920, that led to development
of the Giant Horne Mine, Rouyn-Noranda, Québec

Courtesy Mines Branch
Government of Newfoundland and Labrador

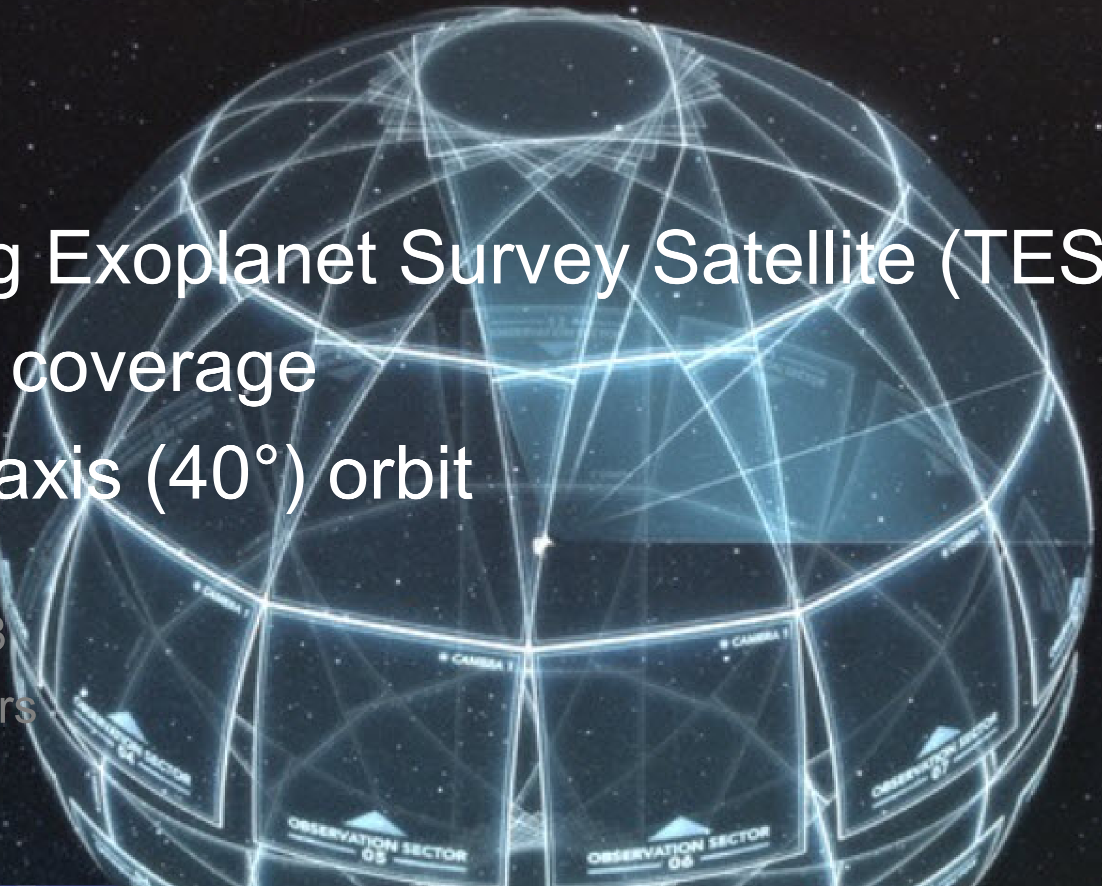
Exploration camp – Michelin property –
Central Mineral Belt, Labrador.

Greenfields – Galactic Scale

- Not necessarily linear function of investment
- Technology and practice impact critical
- Discoveries in < 25 years… from 0 to ~ 4000
- TESS !



Greenfields – Search for Exoplanets

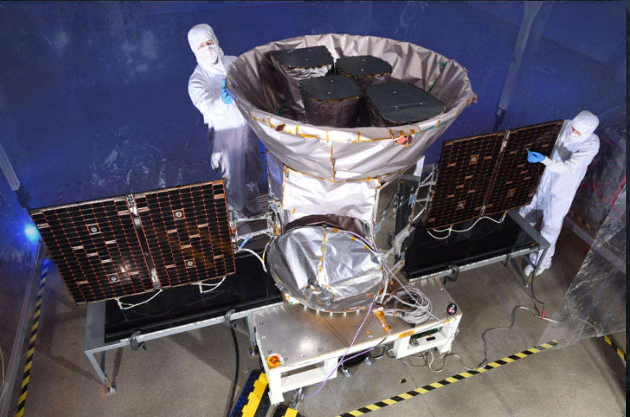


- Transiting Exoplanet Survey Satellite (TESS)
- 85% Sky coverage
- Wide off axis (40°) orbit

Launch April 18, 2018

200,000 stars – 2 years

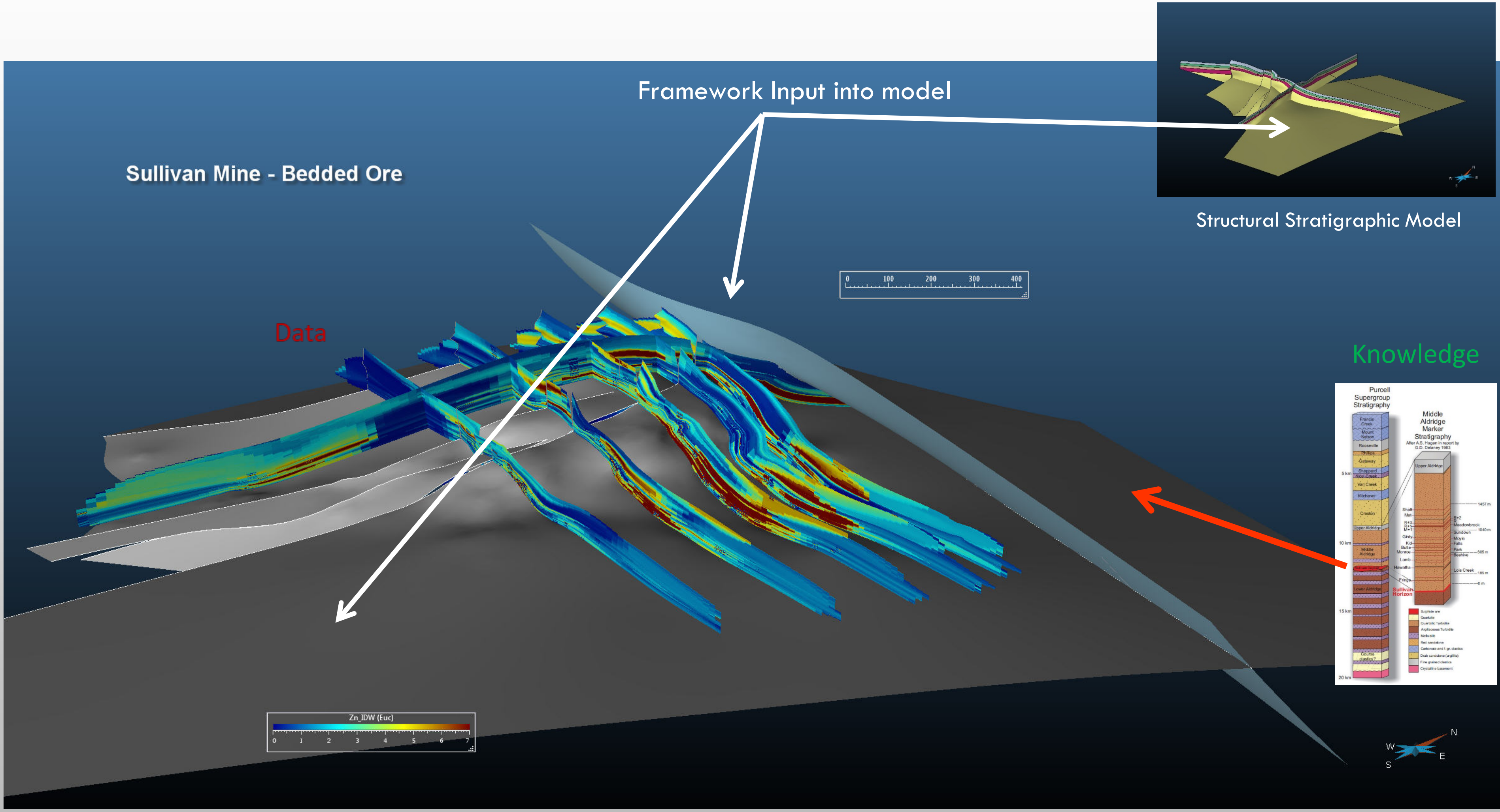
Data



- Multi-scalar
- Multi-parameter
- Iterative

Knowledge of star and planetary genesis

3D Mine Modelling



Framework Input into model

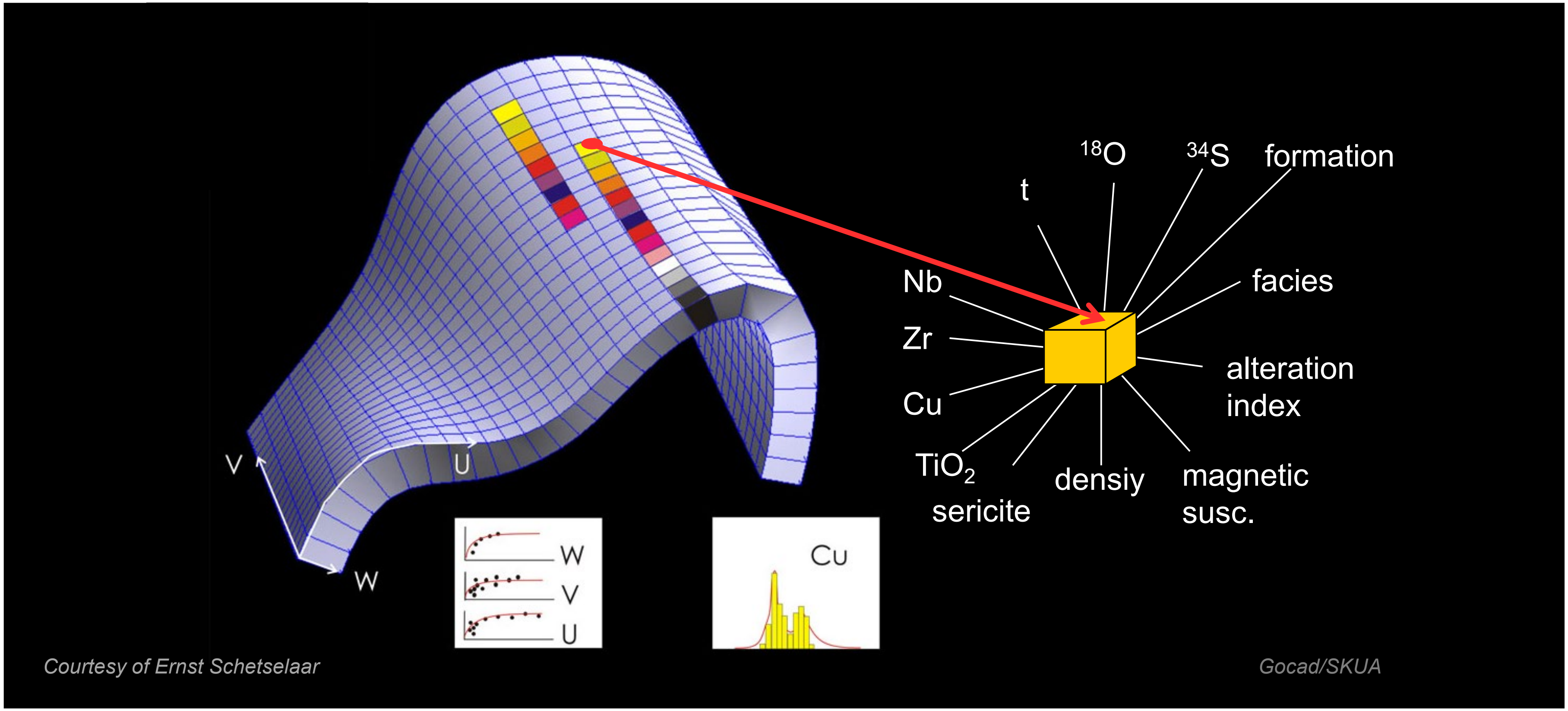
Sullivan Mine - Bedded Ore

Data

Structural Stratigraphic Model

Knowledge

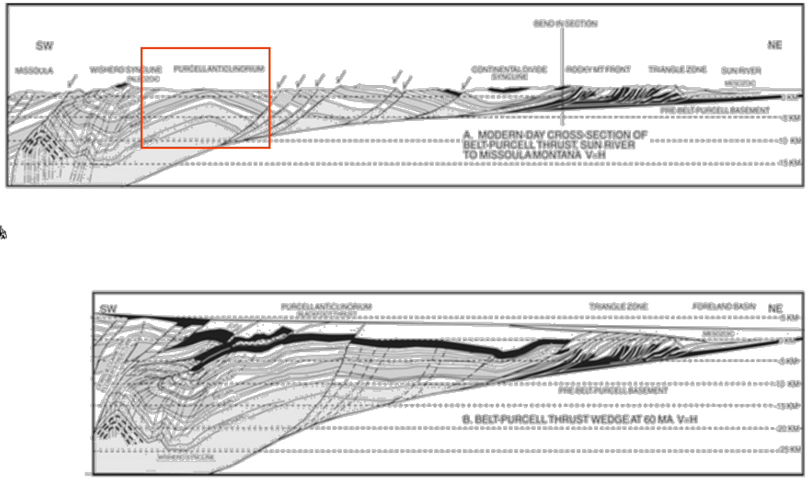
3D Multi-Parameter Container



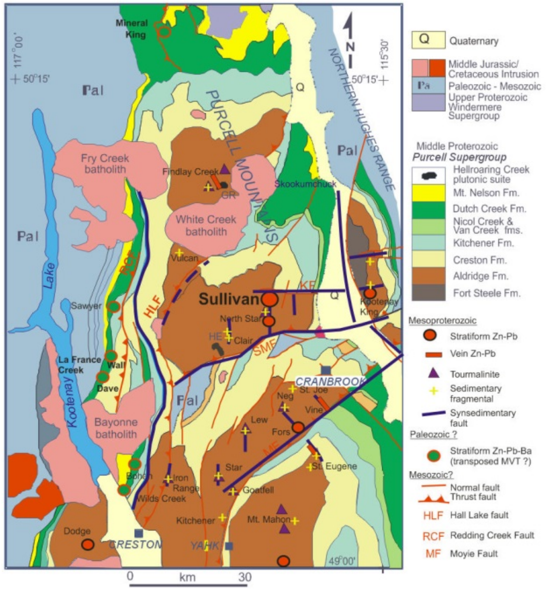
Courtesy of Ernst Schetselaar

Gocad/SKUA

3D Modelling of the Purcell Basin

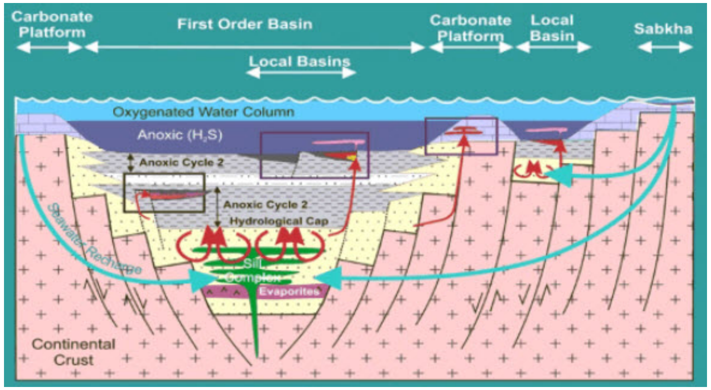


Sears J Geological Society of America Special Papers 2007;433:147-166



> “A project to make a 3D regional model – beyond the head frame…”

SEDEX System



Goodfellow and Lydon 2007

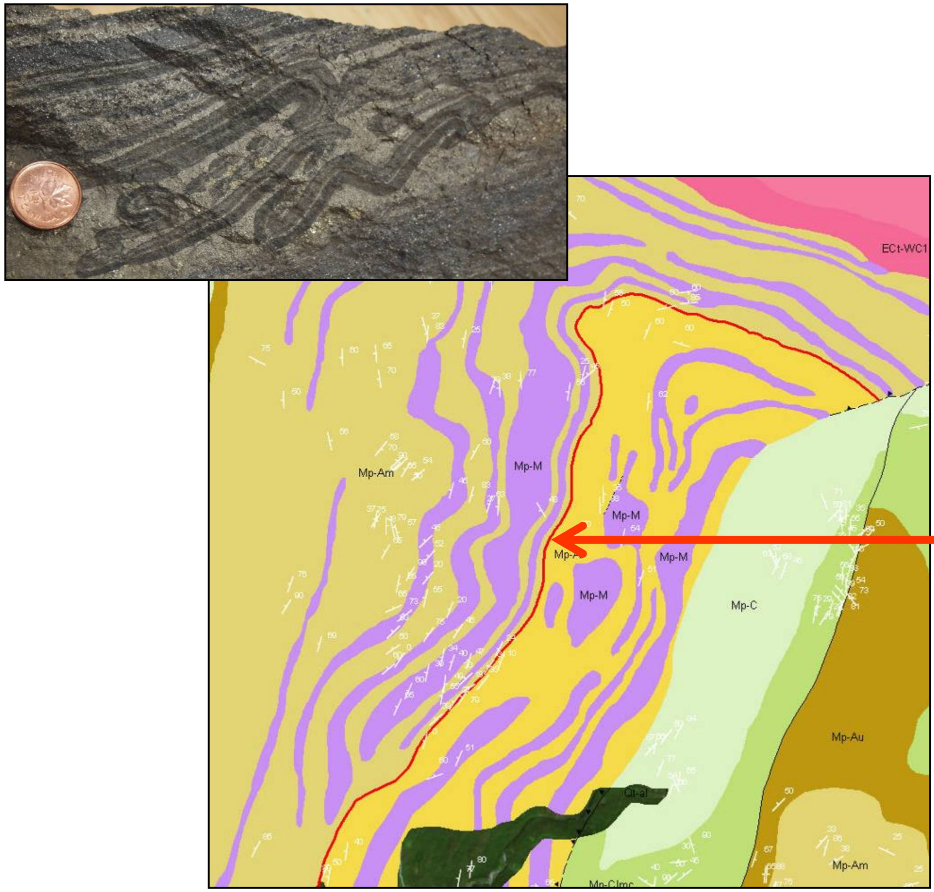
Modern Red Sea and Dune Fields

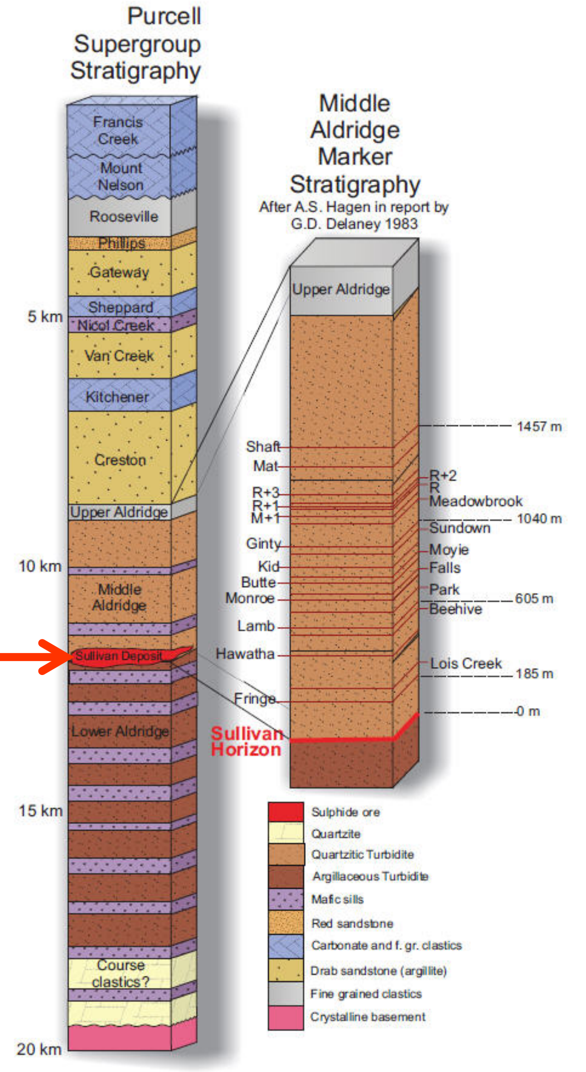
Wikipedia

World Atlas

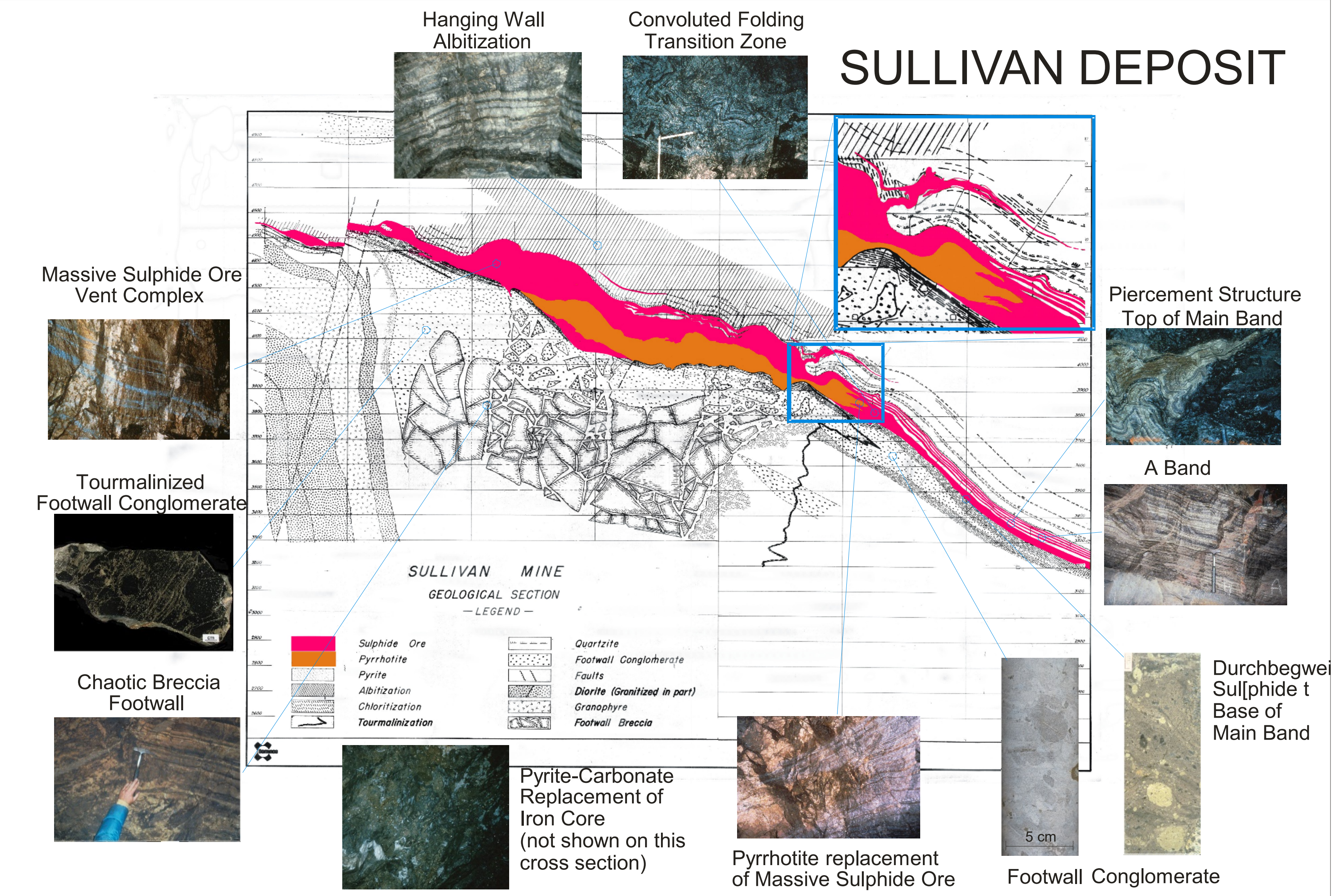
‘Barcode’ siltite markers provide unique 3D modelling constraints in hanging wall of the Sullivan horizon

Sullivan horizon (contact between Middle – Lower Aldridge Formation = LMC)





SULLIVAN DEPOSIT



Hanging Wall Albitization

Convoluted Folding Transition Zone

Massive Sulphide Ore Vent Complex

Tourmalinized Footwall Conglomerate

Chaotic Breccia Footwall

Piercement Structure Top of Main Band

A Band

Durchbegweit Sul[phide t Base of Main Band

Pyrite-Carbonate Replacement of Iron Core (not shown on this cross section)

Pyrrhotite replacement of Massive Sulphide Ore

Footwall Conglomerate

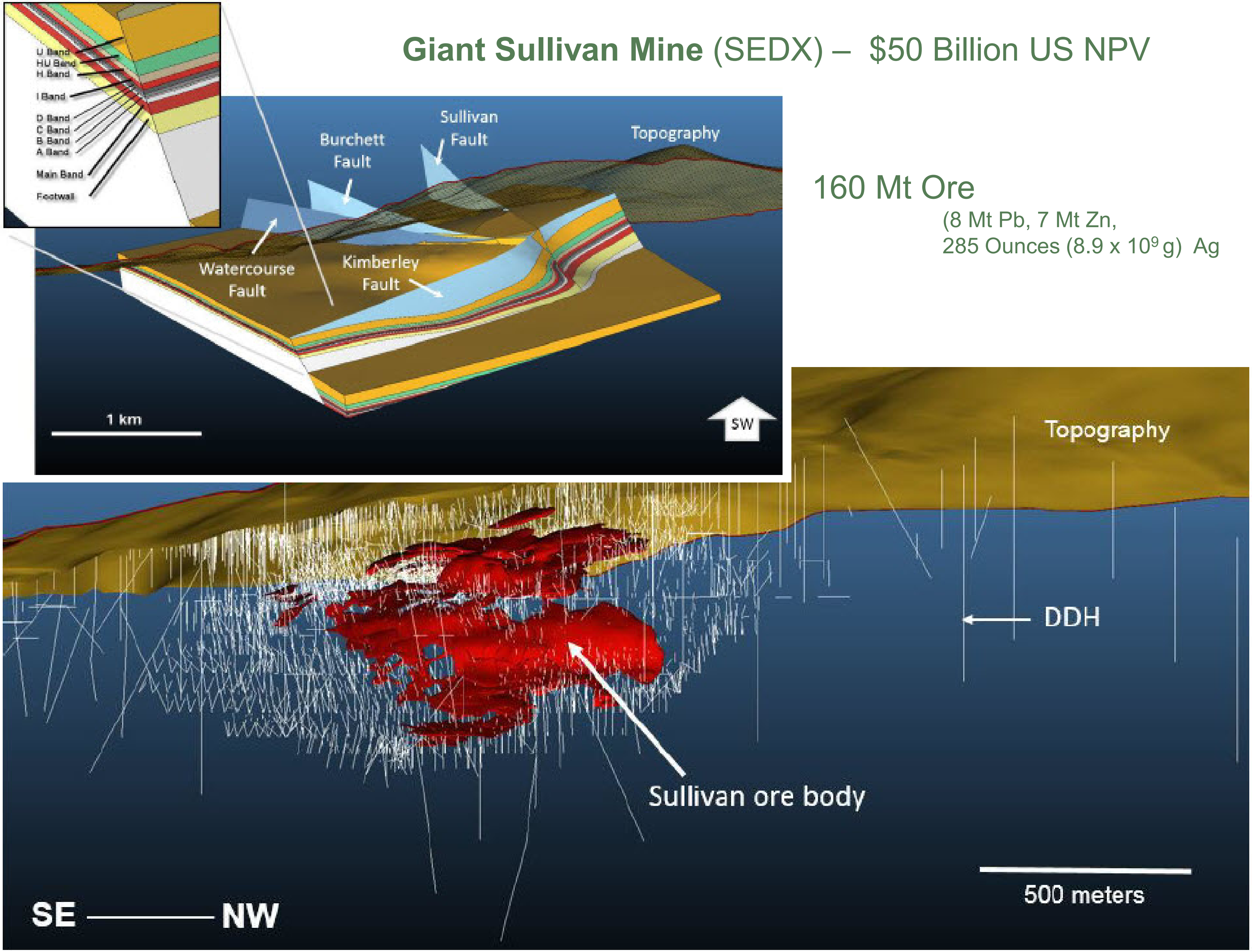
John Lydon 2015

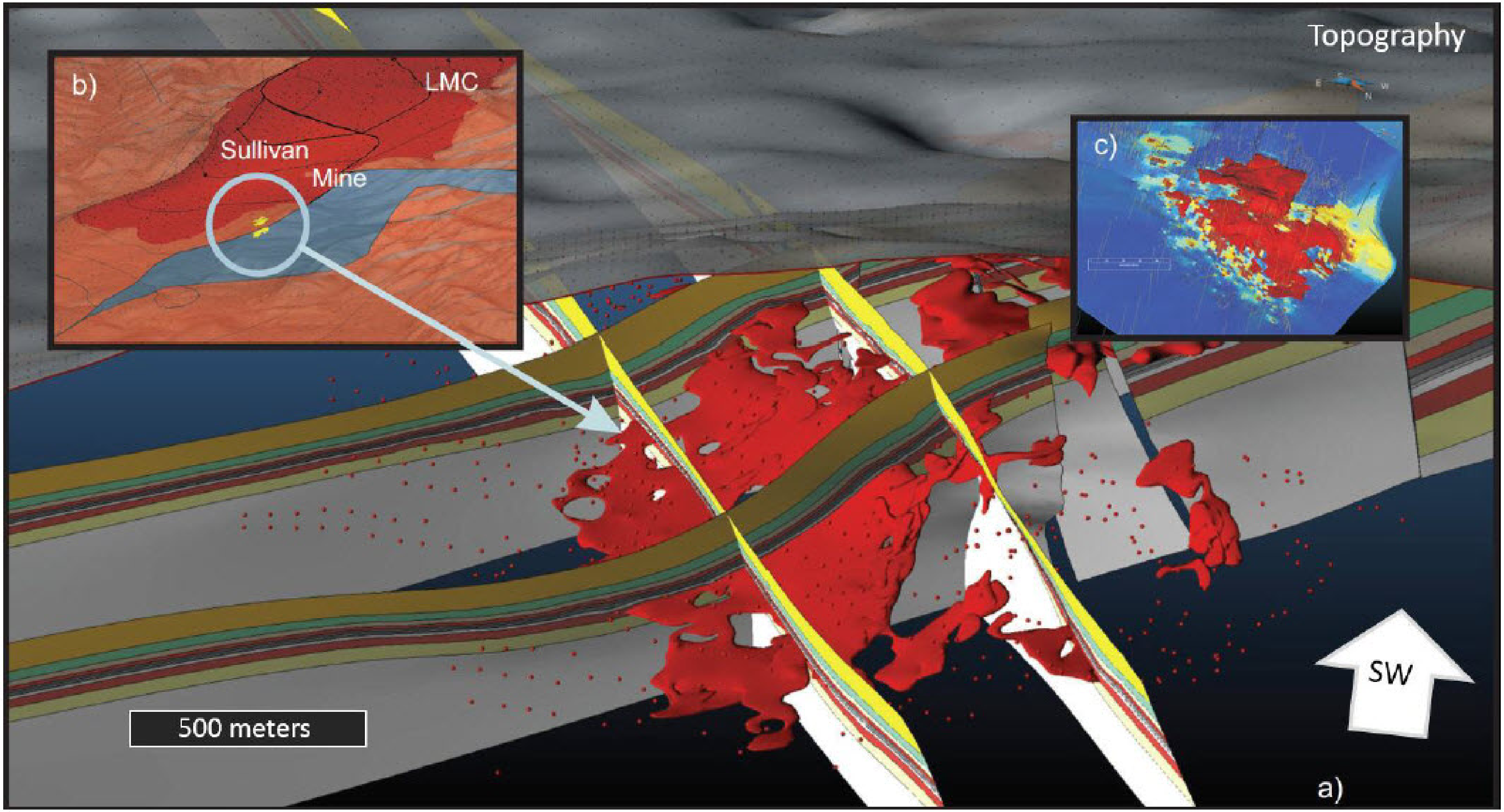
SEDX - Sedimentary Exhalative mineral system

Giant Sullivan Mine (SEDX) – $50 Billion US NPV

160 Mt Ore

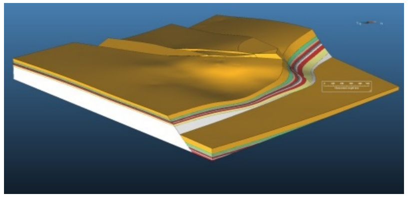
(8 Mt Pb, 7 Mt Zn,
285 Ounces (8.9 x 10^9 g) Ag

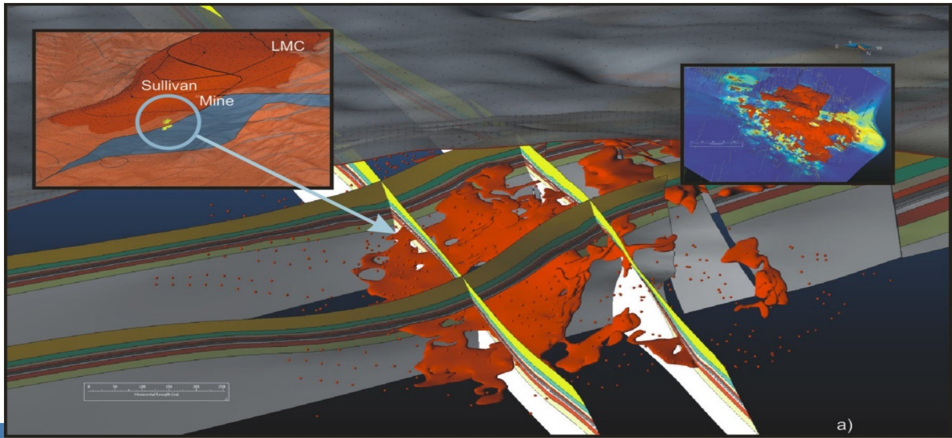


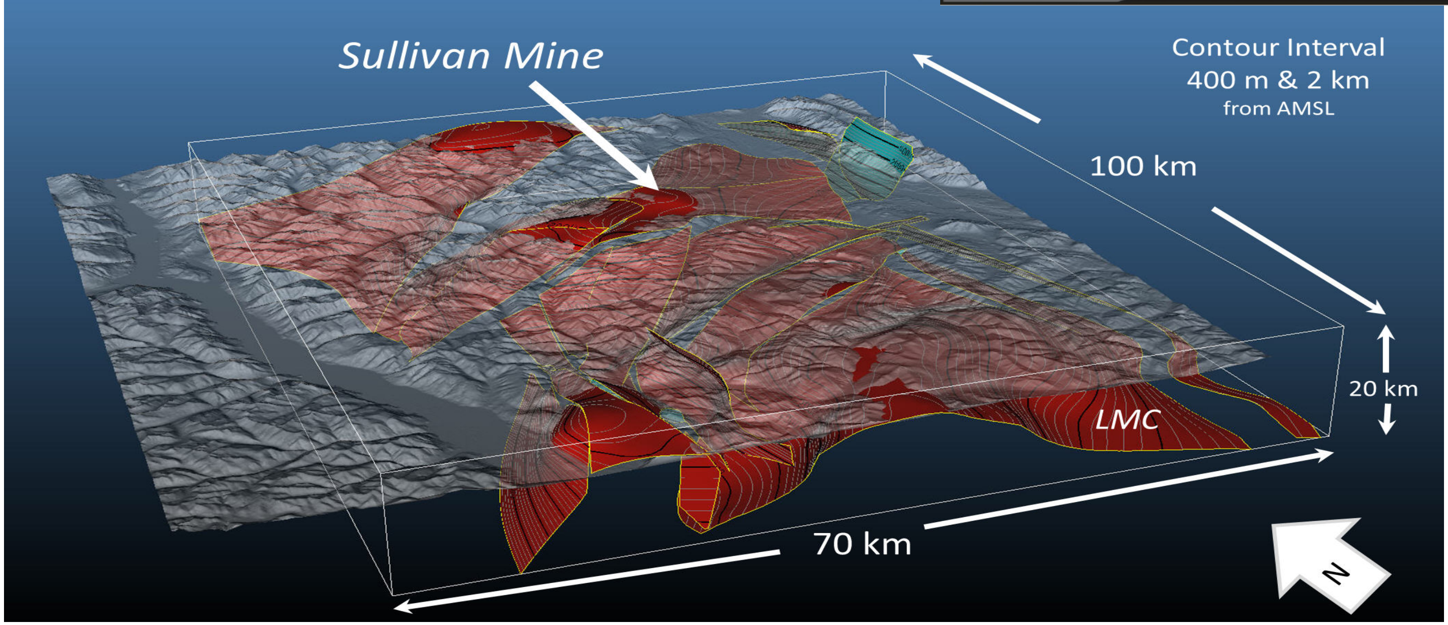

Topography
E
N
W
b)
LMC
Sullivan
Mine
c)
SW
500 meters
a)

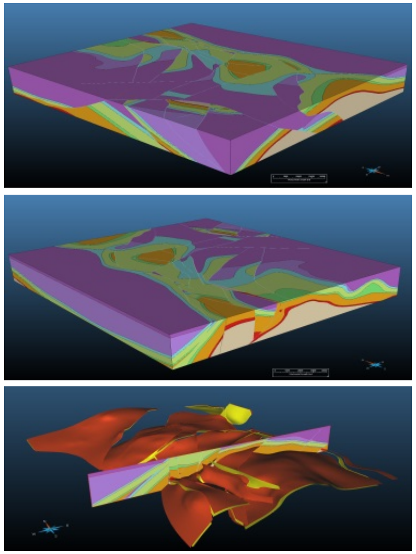
Multi-Scalar

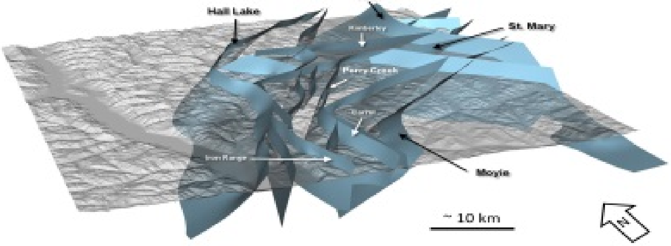
Purcell 3D





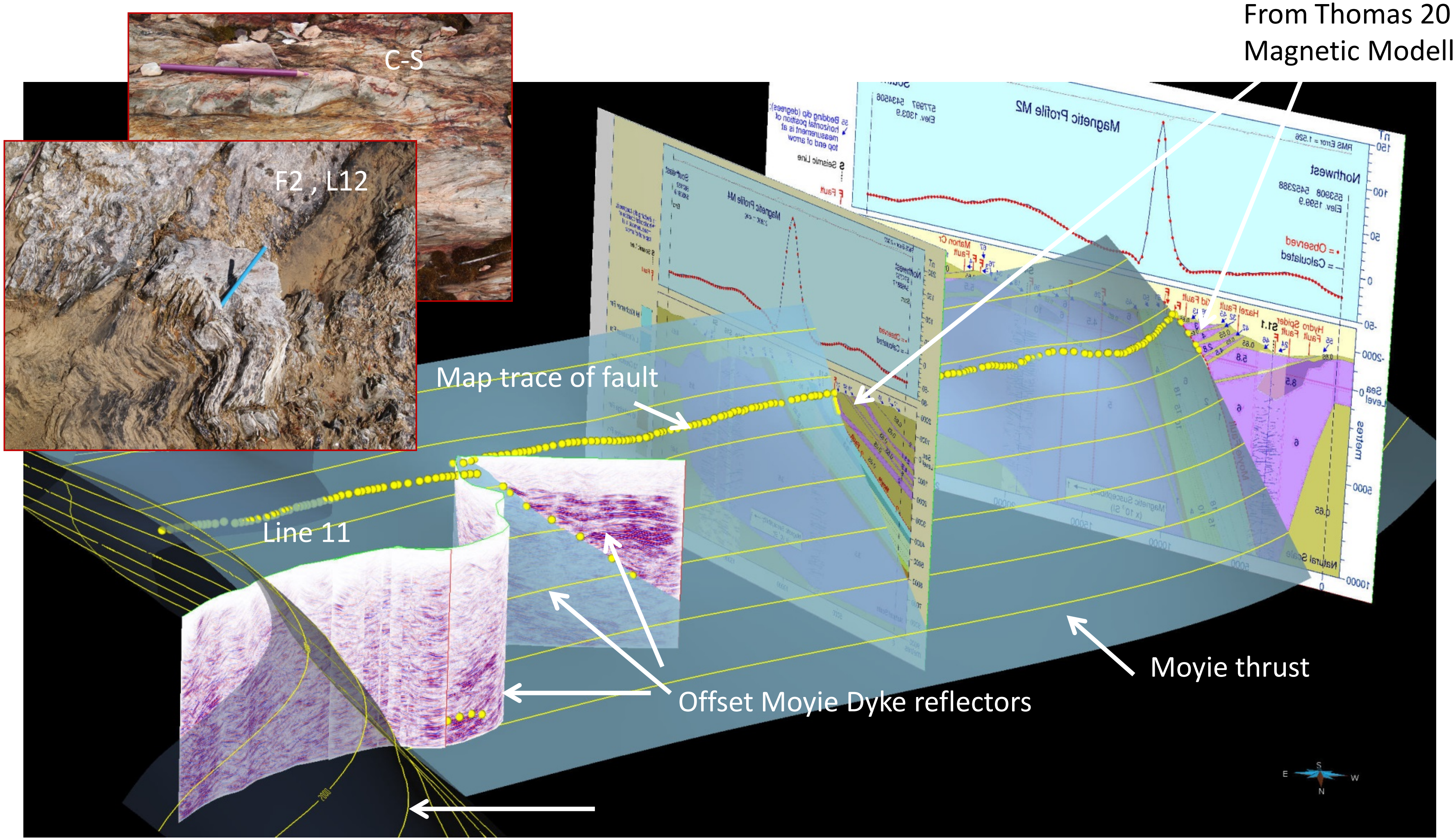






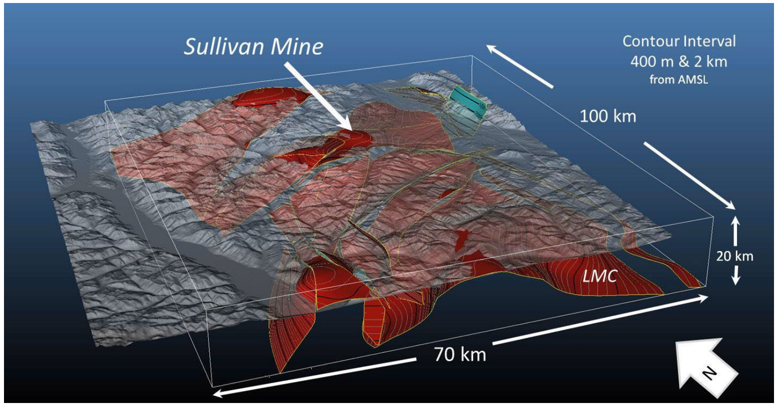
Multi-Parameter

Purcell 3D Faults

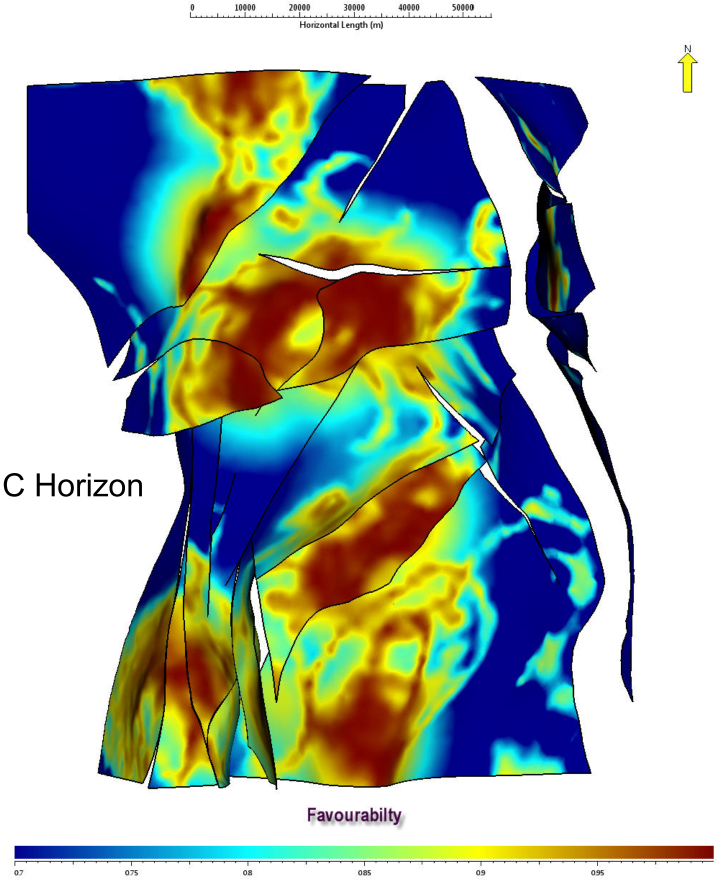


From Thomas 2013
Magnetic Modelling

Iterative

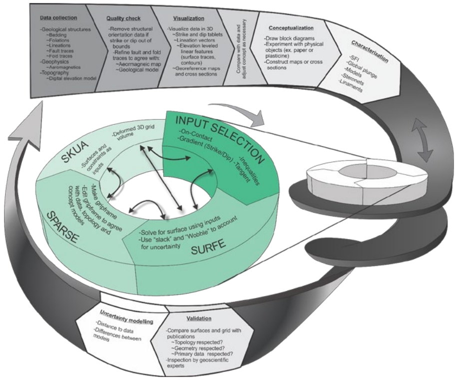


LMC Horizon

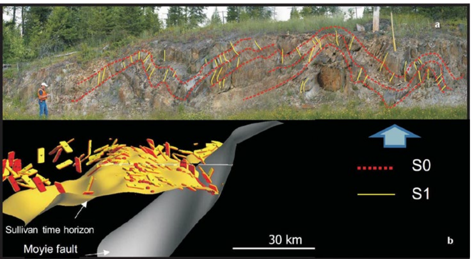


- Regional Uncertainty

Montsion 2017

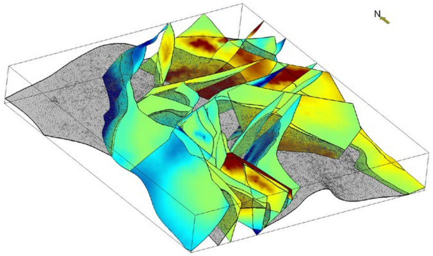


Structures

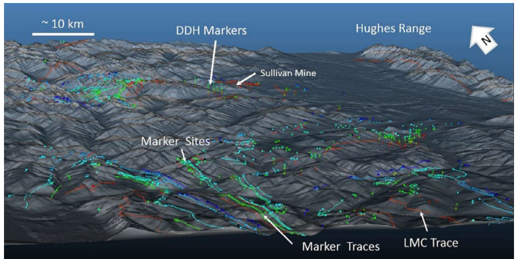


Stratigraphic Markers

Discontinuities



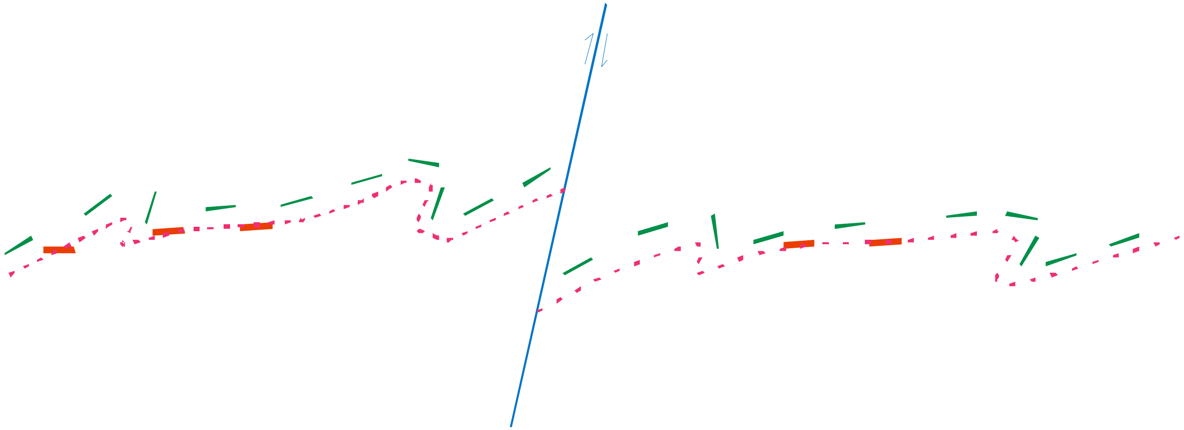
Spatial Integration

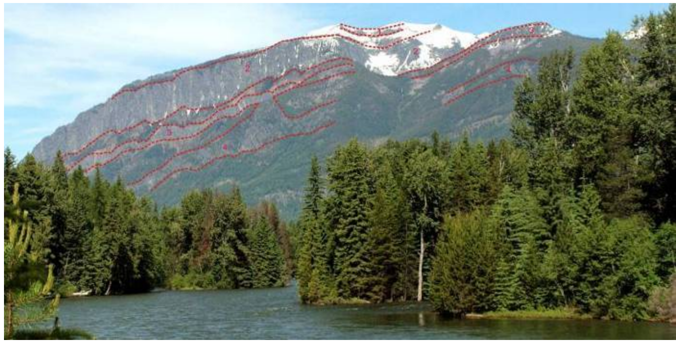


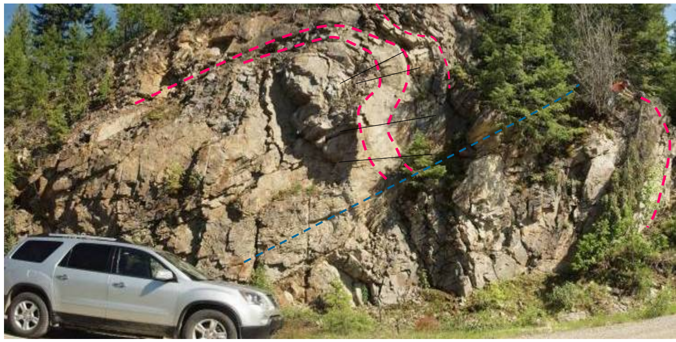
Regional 3D Modelling Challenge, Purcell anticlinorium

A) primary drill hole constraints

B) primary drill hole + secondary strike/dip constraints

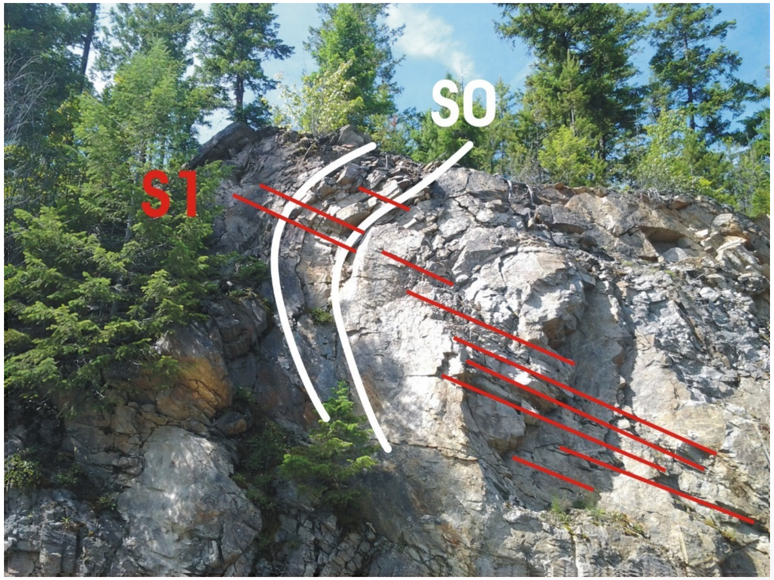






Spatial Continuity - Estimation

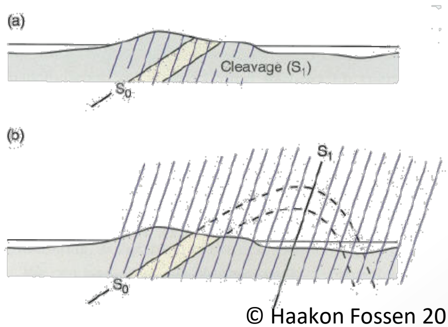
Orientation and Direction Data



Structural Observations

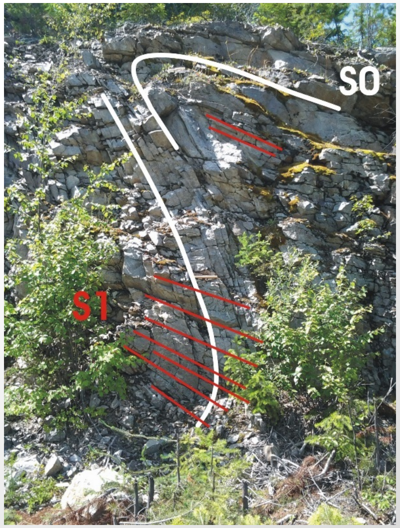
Knowledge

Structural style, fold parameters, etc.



© Haakon Fossen 2010

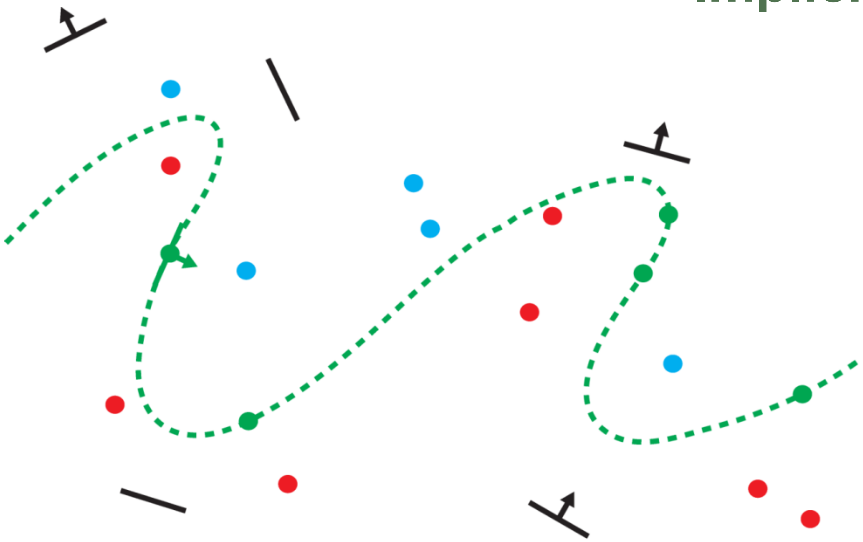
Data



Geologic constraints: types and abundance

Implicit Modelling Approach (SURFE)

Hillier, Schetselaar, deKemp, GSC, Mathematical Geosciences 2015



🟦 Rock Unit A

🟥 Rock Unit B

- - - - Contact (observed/inferred)

Surface is extracted by tracing equipotentials from a 3D scalar distance function

Constraint Types

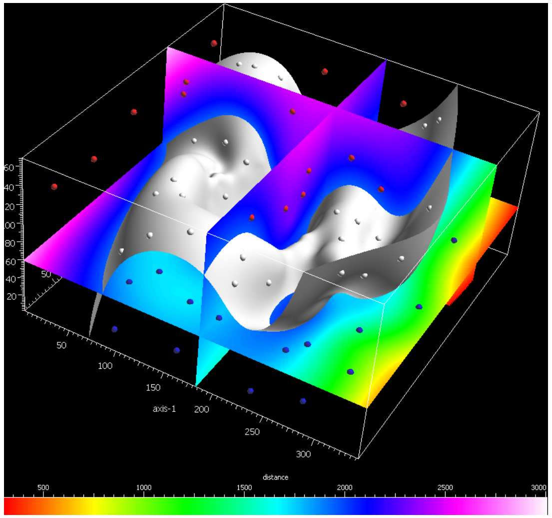
●, ● lithologic markers (inequality) → $f(\boldsymbol{x}) > 0, f(\boldsymbol{x}) < 0$

off-contact structural (gradient) → $\nabla f(\boldsymbol{x}) = \boldsymbol{n}$

lineations (tangent) → $\langle \nabla f(\boldsymbol{x}), \boldsymbol{t} \rangle = 0$

● on-contact (equality) → $f(\boldsymbol{x}) = 0$

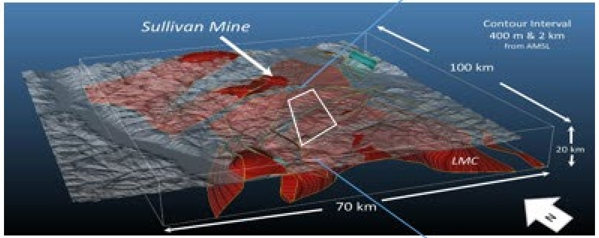
on-contact structural → $f(\boldsymbol{x}\ ) = 0, \nabla f(\boldsymbol{x}) = \boldsymbol{n}$



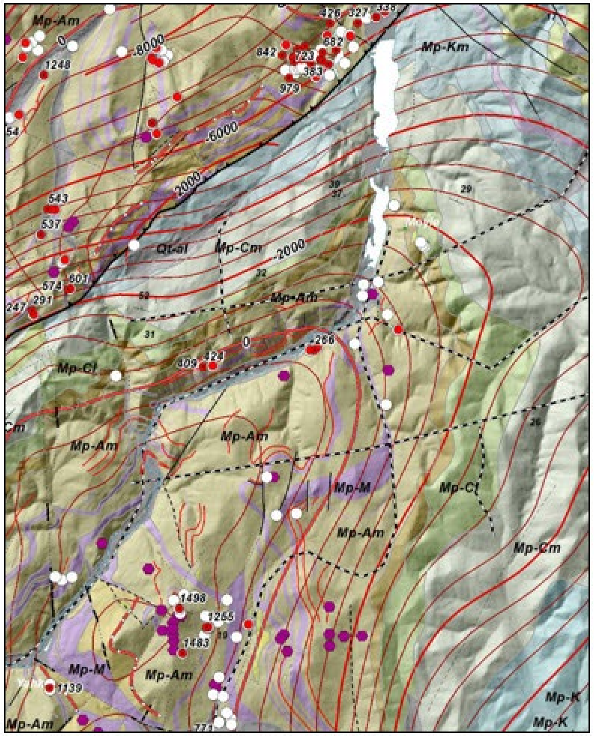
Predictive Region Model

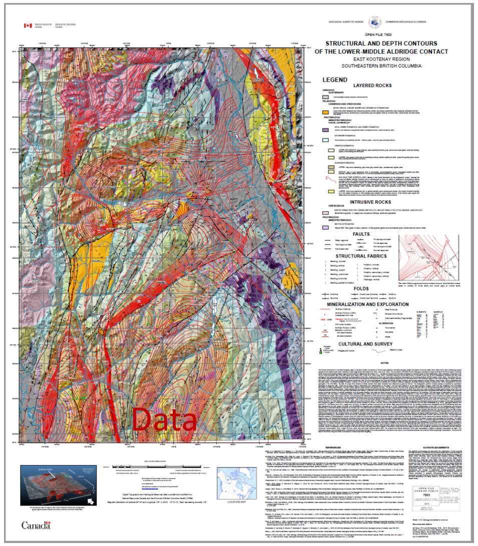
Purcell 3D

Model



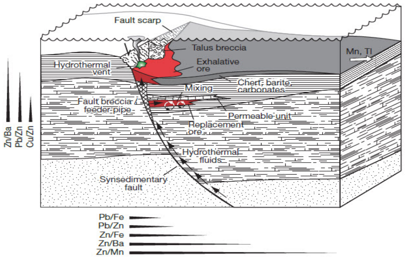
Map





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.

Knowledge

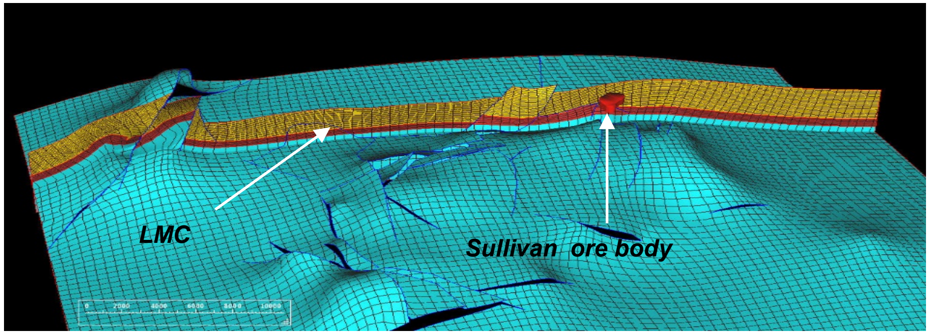


From J.J. Wilkinson 2014

Data

Folded, layered sulfides from the Sullivan mine. Scale in centimeters. (Image: NRC)

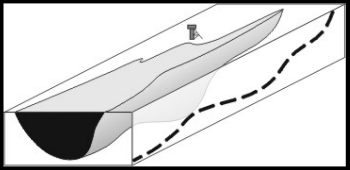
Data + Knowledge = Model



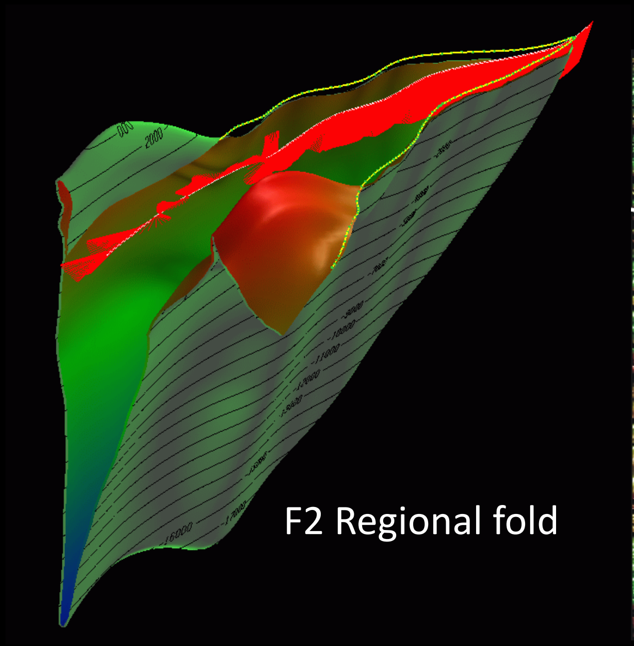
de Kemp et al. , 2016,Interpretation, Vol. 4, No. 3, p. SM33–SM50 http://dx.doi.org/10.1190/INT-2015-0191.1.

Propagation techniques

Regional (camp) Scale

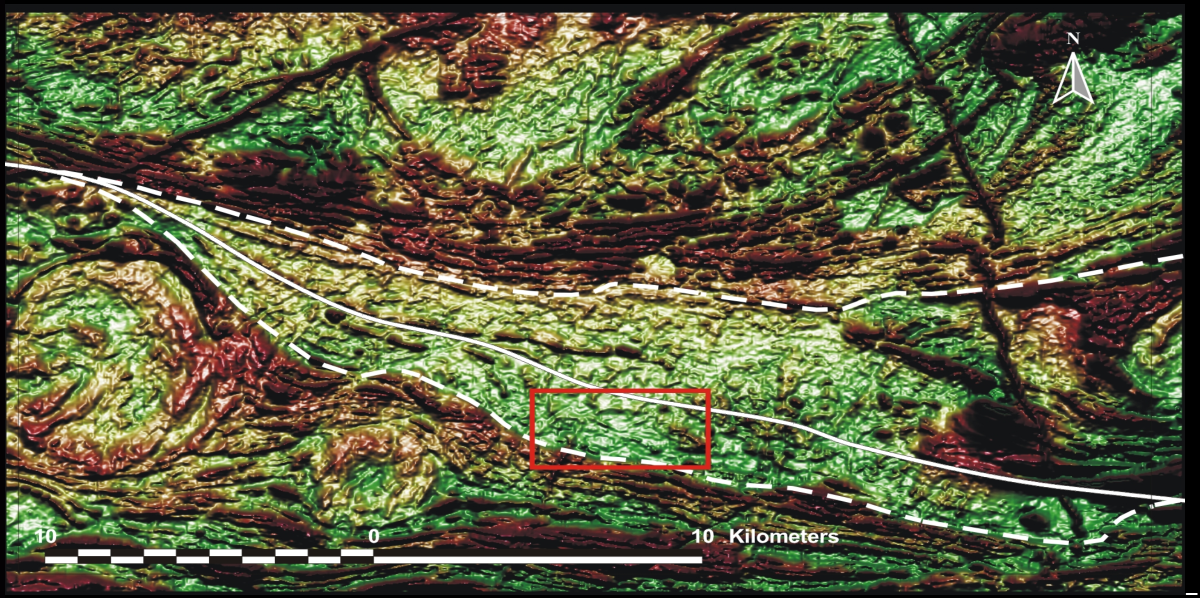


Vector field integration – field observations
Cross-section form lines for tie-lining
F2 Fold prediction ….



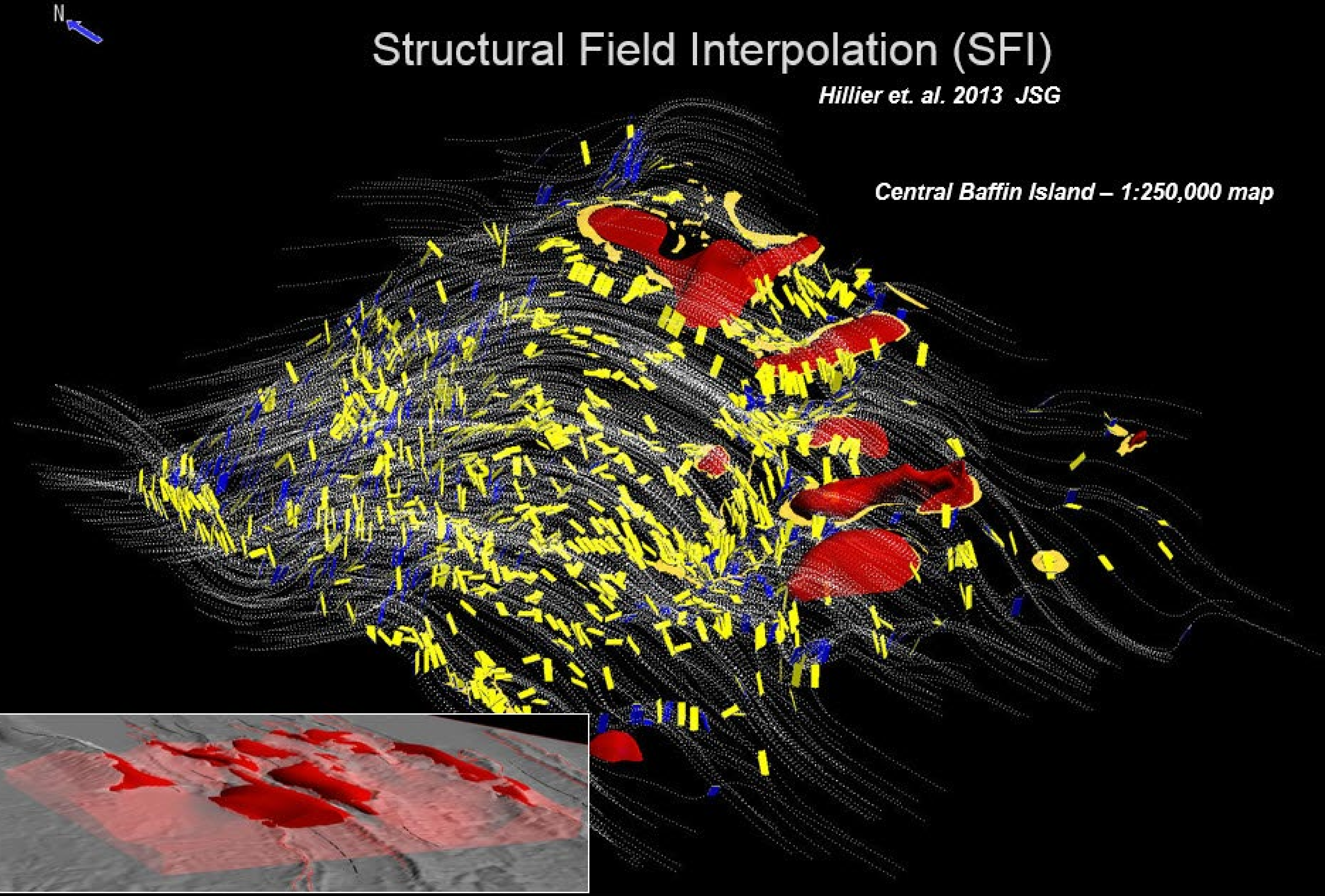
F2 Regional fold

Caopatina Formation – Abitibi Greenstone
de Kemp, 2000 (Enhanced Magnetics 100 m flight lines, 25 m grid)



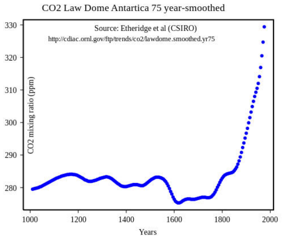
Structural Field Interpolation (SFI)

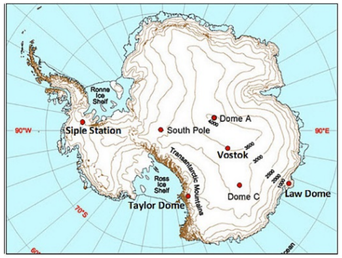
Hillier et. al. 2013 JSG

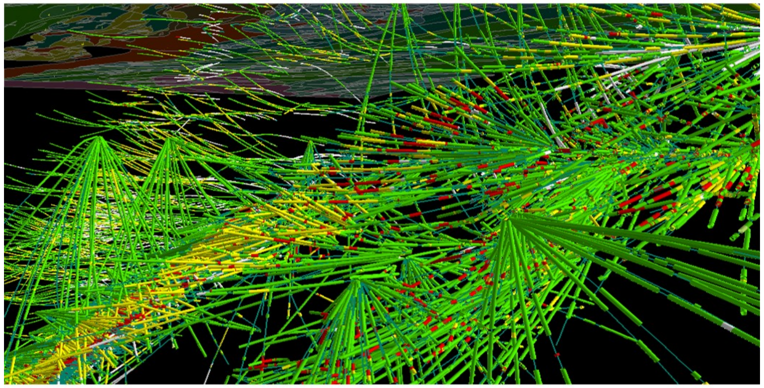


Greenfields

Data is precious… Knowledge is essential





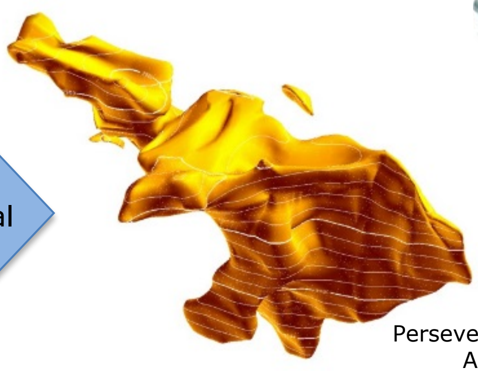


Dense Flin Flon lithostratigraphic drill core logs. Courtesy Ernst Schetselaar (GSC)

Dr. Kendrick Taylor (Desert Research Institute - Reno) examining Antarctic ice core. www.dri.edu

Global

Local



Courtesy CBGcorp

Perseverance VMS ore body
Abitibi, Quebec

Earth Model Space

Knowledge

Data

Reasonable Models ?

Geologic relationships

Folded gneiss. Teton Range, Wyoming. Courtesy of Marli Bryant Miller, Eugene, Oregon, marlimiller@earthlink.net Downloaded from http://marlimillerphoto.com/contact.html

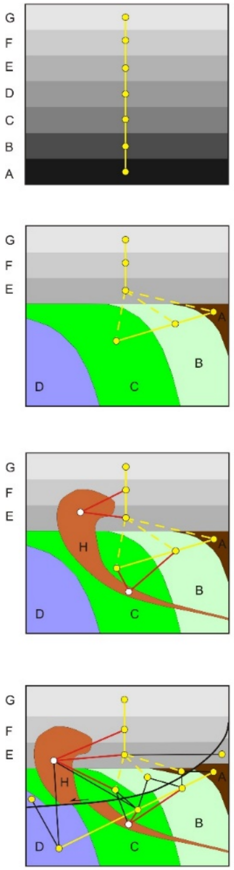
Geologic relationships and complexity

EXPLORATION 17
DMEC Decennial Mineral Exploration CONFERENCES

"Need to quantify complexity of the 3D geologic Model"

Pellerin et al. 2014

Geologic Topology Diagrams



Scenario 1

younger

		G	F	E	D	C	B	A
older	G	0	-1	0	0	0	0	0
	F	1	0	-1	0	0	0	0
	E	0	1	0	-1	0	0	0
	D	0	0	1	0	-1	0	0
	C	0	0	0	1	0	-1	0
	B	0	0	0	0	1	0	-1
	A	0	0	0	0	0	1	0

Scenario 2

younger

		G	F	E	D	C	B	A
older	G	0	-1	0	0	0	0	0
	F	1	0	-1	0	0	0	0
	E	0	1	0	0	-10	-10	-10
	D	0	0	0	0	-1	0	0
	C	0	0	10	1	0	-1	0
	B	0	0	10	0	1	0	-1
	A	0	0	10	0	0	1	0

Scenario 3

younger

		H	G	F	E	D	C	B	A
older	H	0	0	-20	-20	0	-20	-20	0
	G	0	0	-1	0	0	0	0	0
	F	20	1	0	-1	0	0	0	0
	E	20	0	1	0	0	-10	-10	-10
	D	0	0	0	0	0	-1	0	0
	C	20	0	0	10	1	0	-1	0
	B	20	0	0	10	0	1	0	-1
	A	0	0	0	10	0	0	1	0

Scenario 4

younger

		H	G	F	E	D	C	B	A
older	H	0	0	-20	-20	-30	-50	-20	0
	G	0	0	-1	0	0	0	0	0
	F	20	1	30	-1	0	0	0	0
	E	20	0	1	30	0	-10	-10	-40
	D	30	0	0	0	30	-31	0	0
	C	50	0	0	10	31	30	-1	0
	B	20	0	0	10	0	1	30	-1
	A	0	0	0	40	0	0	1	30

Feature Adjacency Matrices

Diagram Modified from Burns 1976, Theille 2016

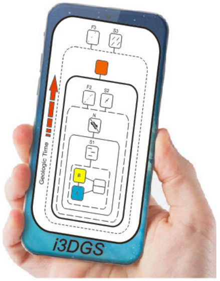
Complex Data Integration

Benefits to companies

- Reduces risk in mineral exploration.
- Enables synthesizing of multi-disciplinary knowledge.
- Maximizes return on expensive exploration data, (Legacy data).
- Offers a context for deeper geologic targeting.
- Provides more opportunities for predictive 3D mapping and targeting.
- Provides a more rigorous basis for exploration decision-making.
- Promotes and focuses teamwork and expertise.
- Consolidates corporate knowledge as an asset in a dynamic repository (evergreen strategy).
- Highlights data and interpretive uncertainties.
- Streamlines analysis of large data volumes (Big Data).

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)

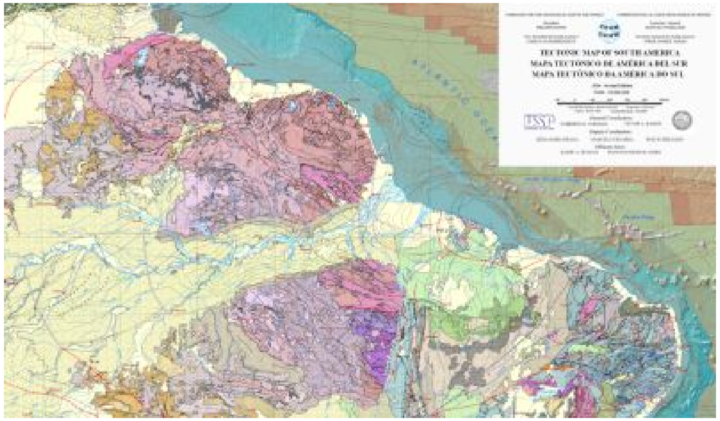


Summary

Onne Van Der Wall 2013
Courtesy of CNN

- Greenfields is where we need to go.
- Crew that stays in the harbor discovers nothing. The farther we sail the greater the reward!

> *"It's not that I'm so smart, it's just that I stay with problems longer."*
>
> *Albert Einstein*



Tectonics and
Metallogenesis of
NE South America
2 Day Conference

Paramaribo, Suriname
19th and 20th February 2019

Program

Summary

Onne Van Der Wall 2013
Courtesy of CNN

- Greenfields is where we need to go.
- There are abundant benefits with data integration.
- Complex geology and sparse data should not stop us.
    - Tools and active research going on **(ie. loop3d.org).**
- Invest in the infrastructure, staffing and technologies
    - Enhance your organization
- Needs collaboration – competition…**(ie. SAXI)**

Greenfields

- New approaches and technology is needed to reduce risk
- Key technologies:
  - Deep imaging – Seismic, MT, Gravity
  - Near surface – Magnetics, Gravity (FTG)
  - Structural Integration – Vector field visualization
  - GIS integration and reconciliation – (2D & 3D)
    - Geophysics – Geology
    - Geochemical – Geophysics
  - 3D Modelling –Geophysical Inversion, Implicit modelling
  - Uncertainty assessment and modelling
  - Knowledge and Data driven 3D simulation