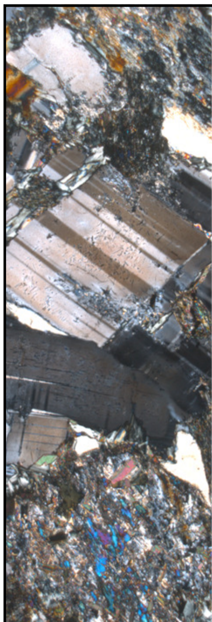

A Study of faults in the Superior Province of Ontario and Quebec using the Random Forest machine learning algorithm: Spatial relationship to Au mines

J.R. Harris[1*], M. Naghizadeh[1], J. Ayer[1], R Smith[1], D. Snyder[1], P. Behnia[1],H. Lui, M. Parsa[2] R. Sherlock[1,] M. Trevidi[3]

1. Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario, Canada

* Jeff Harris – corresponding author – 6 Sixth St., Fenelon Falls, ON, Canada, K0M 1N0

603jharris@gmail.com – 1-705-464-1562

2. Geological Survey of Canada
3. Laurentian University, Computing Science Dept.

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- **METAL EARTH – OBJECTIVES – Data Analytics**

  - how to integrate all collected and legacy data (2D & 3D) to assist in understanding fertile vs. non-fertile greenstone belts

  - create 2D and 3D mineral prospectivity models (MPM) from the data for each transect using machine learning languages

  Complete:

  Noranda – VMS (in review)
  Chibougamau – Au published
  Larder Lake – Au (in review)
  Sturgeon Lake – Au published (x2)
  Cobalt – Ag, Au
  Swayze – published (x2)

  Ongoing:

  Superior – fault study
  Rainy River
  Wabigoon vs. Abitibi

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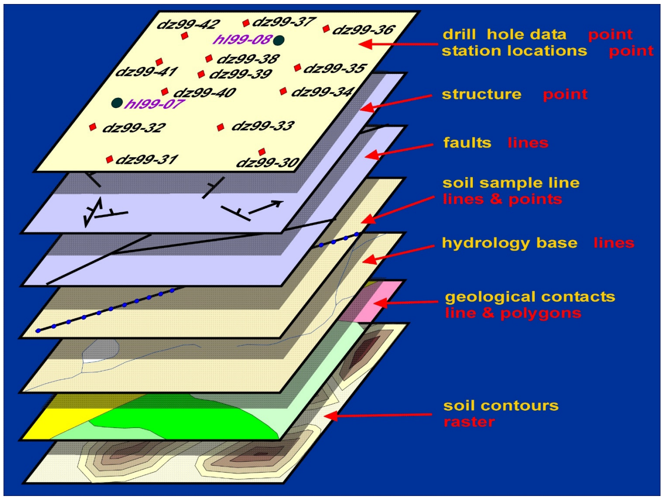
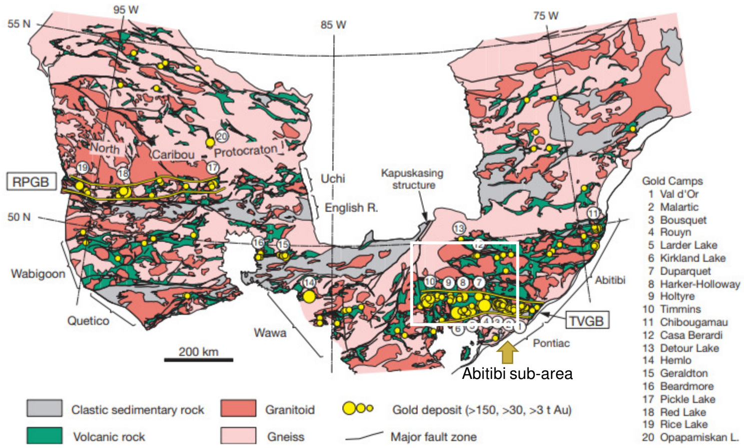
The Problem!



- How to integrate this data (**2D and 3D**) in a meaningful way?
- Mineral Prospectivity Mapping (MPM) – GIS + add-on software (ENMAP)

It is well known that EW trending faults are related to **orogenic Au** in many mining camps within the Superior geologic Province of Ontario and Quebec (Colvine, 1988; Robert et al., 2005; Poulsen, 2017; Dubé and Mercier-Langevin, 2020). For example, the major breaks; the Destor-Porcupine and Cadillac-Larder lake fault systems have acted as conduits for the transfer of Au-bearing hydrothermal fluids. Many authors (Poulson,2017; Dube et al, 2017) have observed in the field the relationship between orogenic Au and quartz veins and the major breaks and associated splay faults in the Abitibi region of the Superior Province.

General geology of the Superior Province



EXPLORATION MODEL - Mesothermal Au

Selection of evidence (data) from GIS database

Production of Evidence maps
(Binary, multi-class, continuous)

Choice of modelling method
(Data or knowledge-driven)
(or a combination)

Assignment of weights for evidence maps
Data-driven - (W+, W-, C, regression coefficients)
Knowledge-driven - subjective

Map

How well have we done?
….what is the uncertainty of this map?

Exploration (Deposit) Model

- most important part of the modeling process
- governs what evidence (predictor) maps will be used in the modeling process
- models based on knowledge, experience and empirical evidence
- Dynamic / volatile – “exceptions to the model”

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Table 2: Summary of mesothermal Au exploration criteria (compiled from Colvine et al., 1988; Colvine, 1983; Robert, 1990; Hodgson, 1993)

Lithology	Comments
	Lithology
Variable	Ultramafic, mafic and felsic volcanic and sedimentary rocks (See Table 5)
Felsic intrusions (QFP- Quartz feldspar porphyry))	Apparent association with late tectonic, felsic, especially quartz-bearing intrustions Source of Au-bearing hydrothermal fluids, sink for Au, or heat engine mobilizing Au-bearing fluids
	Structure
High strain (deformation zones)	Generally EW-trending (major “breaks”), 100’s km in length and several km’s in width Late tectonic event, transecting all lithologies Mostly simple shear - oblique transcurrent movement although late vertical movement also known Conduits for Au-bearing fluids
Smaller-scale splay faults	Generally oblique (low angle) to major deformation zones Dilational zones of enhanced permeability Occur within and outside major deformation zones
Lithological contacts	Conduits for Au-bearing fluids
	Alteration
Carbonatization	Dominant alteration style and widespread Replacement of magnesite, ankerite, dolomite, calcite Distinct from lower grade seafloor diagenesis where calcite, epidote, actinolite and zeolites are the major alteration minerals
Silicification	Quartz flooding (quartz veining - variable orientations)
Potassic alteration	Potassium metasomatism (Sericite and biotite growth)
Albitization	Metasomatism (Alkali feldspar growth)
Chloritization	Metasomatism (Chlorite growth)
Iron sulphides	Pyrite, pyrrhotite, arsenopyrite
	Geochemistry
Oxides and volatiles	Enrichment of CO_2, K_2O, S, H_2O, and Al_2O_3
Trace elments	Enrichment of Au, As, Sb, W, Mo, Ag, Cu, Zn, Pb

Exploration Criteria

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What about data preparation to create predictor (evidence) maps!

- Geo-referencing!
- Data quantity and quality!
- The GIS in concert with statistical and geo-statistical software is a very powerful tool for processing and preparing geoscience data for GIS modeling

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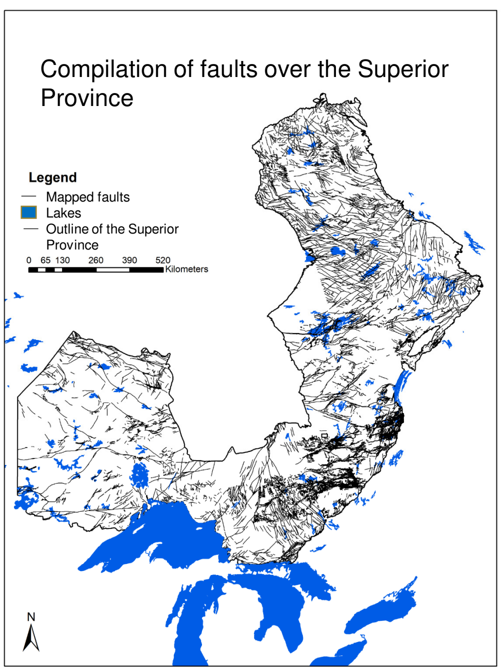
…our analysis is primarily on



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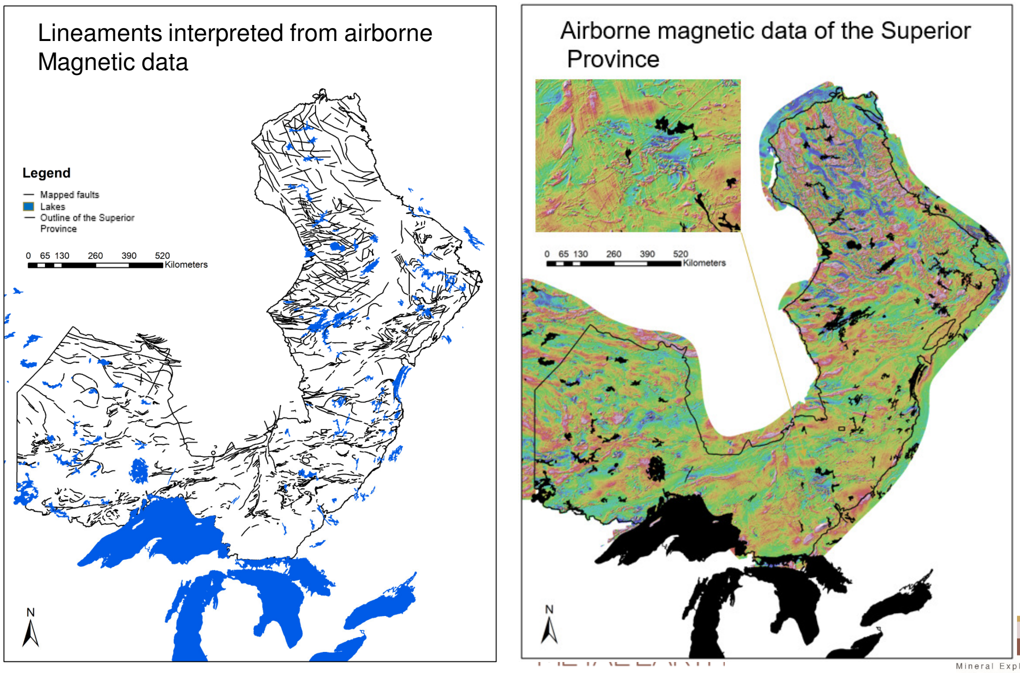

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Predictor maps

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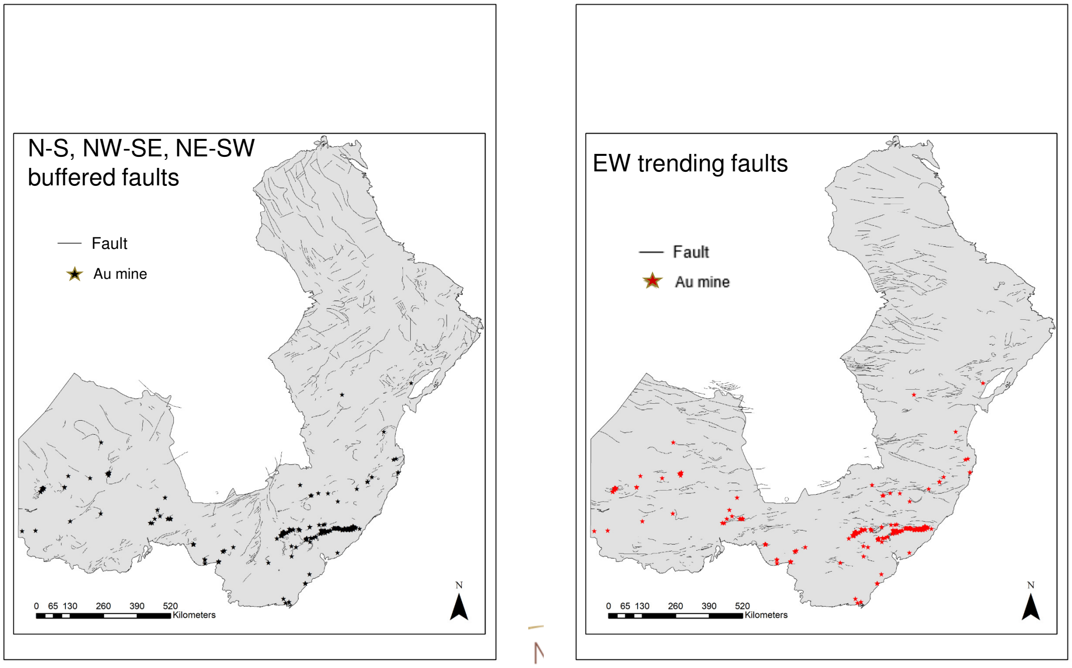
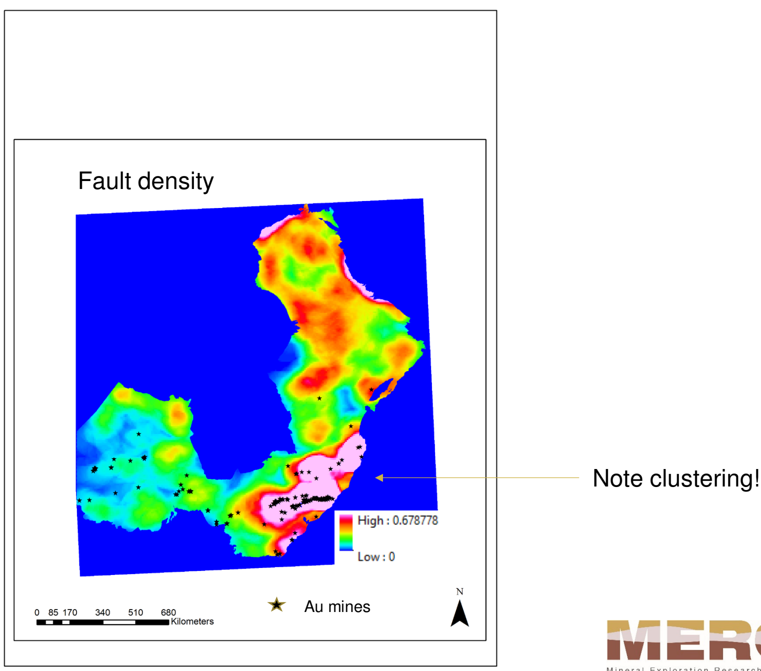
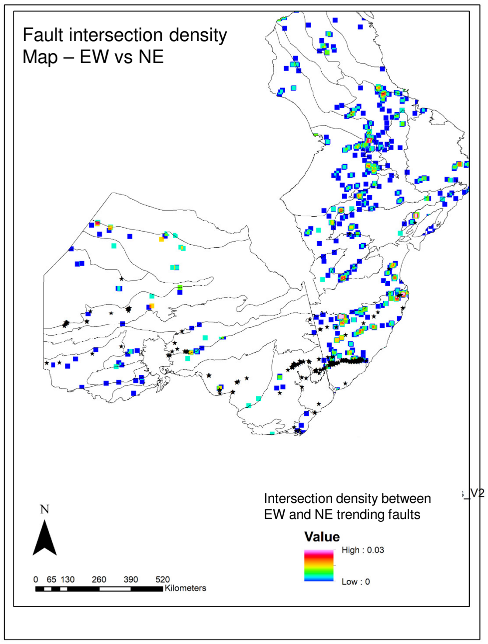
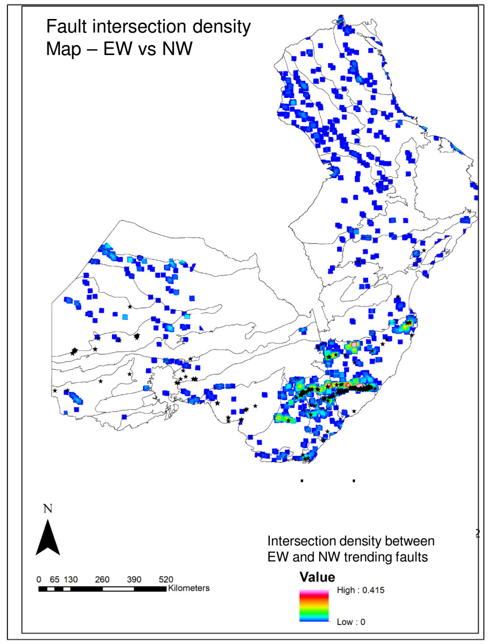

N-S, NW-SE, NE-SW
buffered faults
Fault
Au mine
0 65 130 260 390 520
Kilometers
N
EW trending faults
Fault
Au mine
0 65 130 260 390 520
Kilometers
N

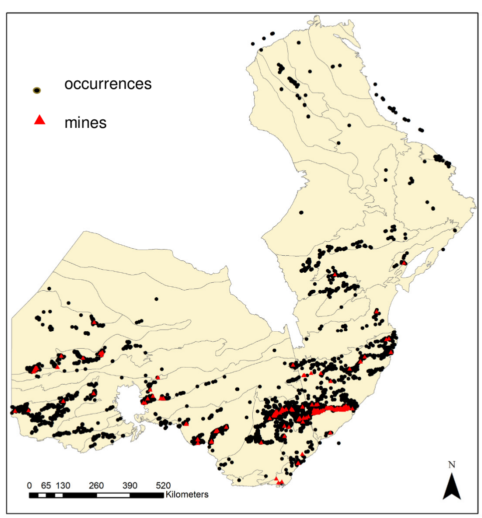

Fault density
Note clustering!
High : 0.678778
Low : 0
Au mines
0 85 170 340 510 680
Kilometers
N





-256 present and past producing mines
-4096 occurrences

Training Data – Au mines (present, past producing) and Au occurrences



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Modeling (Integration) Methods

- **Data-driven**

  use of a training dataset (mineral deposits) to drive the modeling process – importance of each evidence map determined statistically (i.e. – what is the spatial relationship between the deposits and the evidence map?)

- **Knowledge – driven**

  no training data – importance of each evidence map determined through exploration knowledge

- **Combined**

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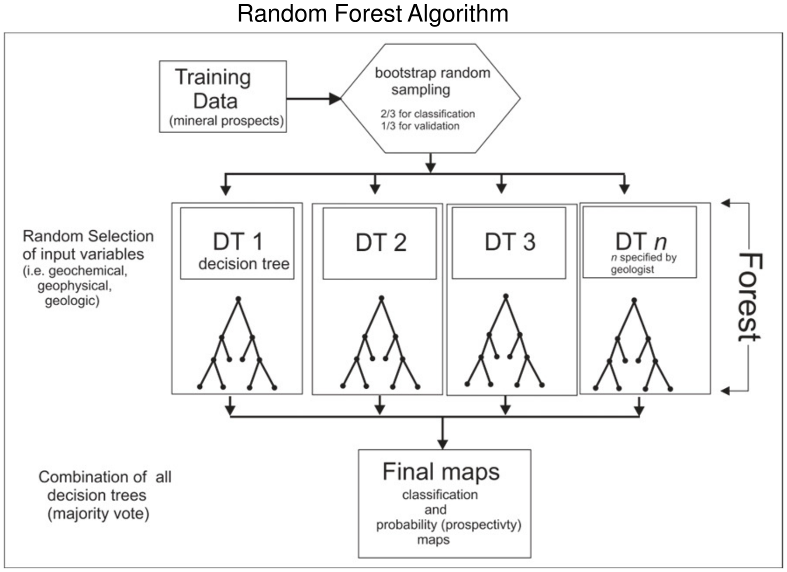
Random Forest Algorithm



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Knowledge driven - *Weighted Sum*

MPM = (pred A * W) + (pred B * W) +……..(pred N * W)

where:

pred = predictor (evidence) map

W = importance weight (1-10)

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Mineral Prospectivity Maps - MPMs

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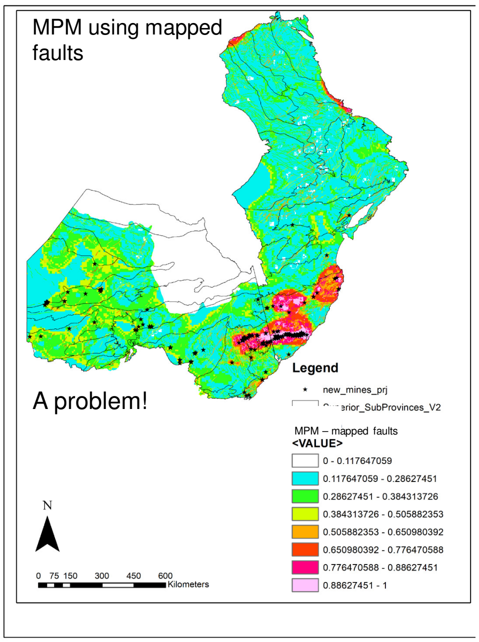
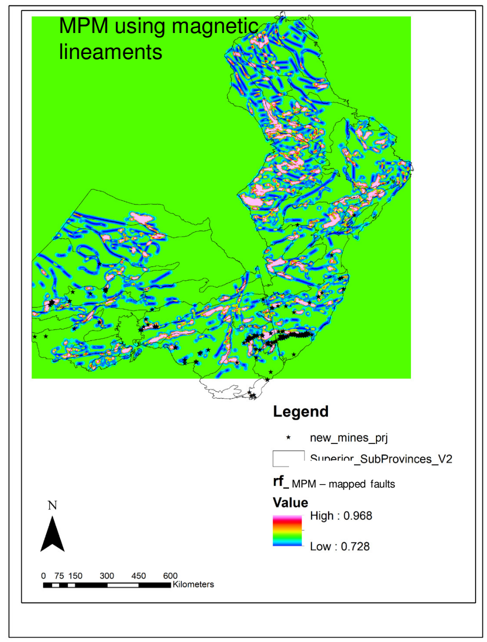
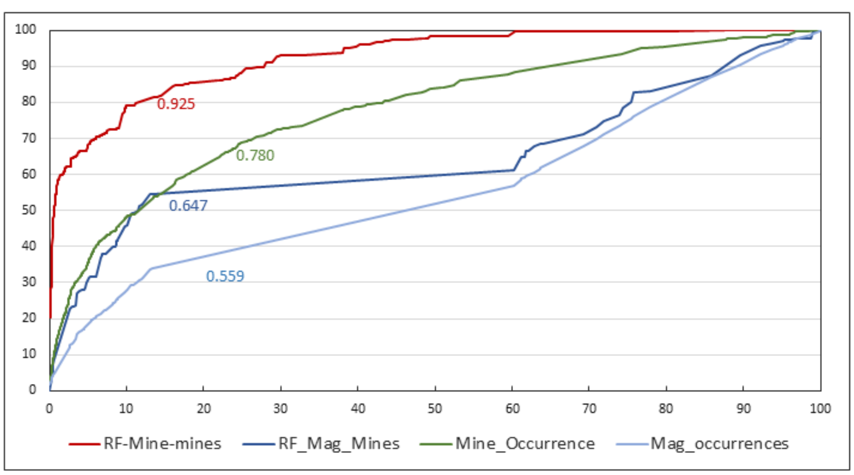




Validation

Efficiency of classification curves



Possible Solutions to Clustering Bias

- Randomly thin out faults in clustered zone
- Choose a sub-area of the Superior (Abitibi) where mapping effort was (is) more intense
- Use a knowledge based algorithm and down-weight fault density
- Use interpretation of faults based on high resolution magnetics

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Additional Predictor Maps added to the MPMs of the Abitibi sub-area

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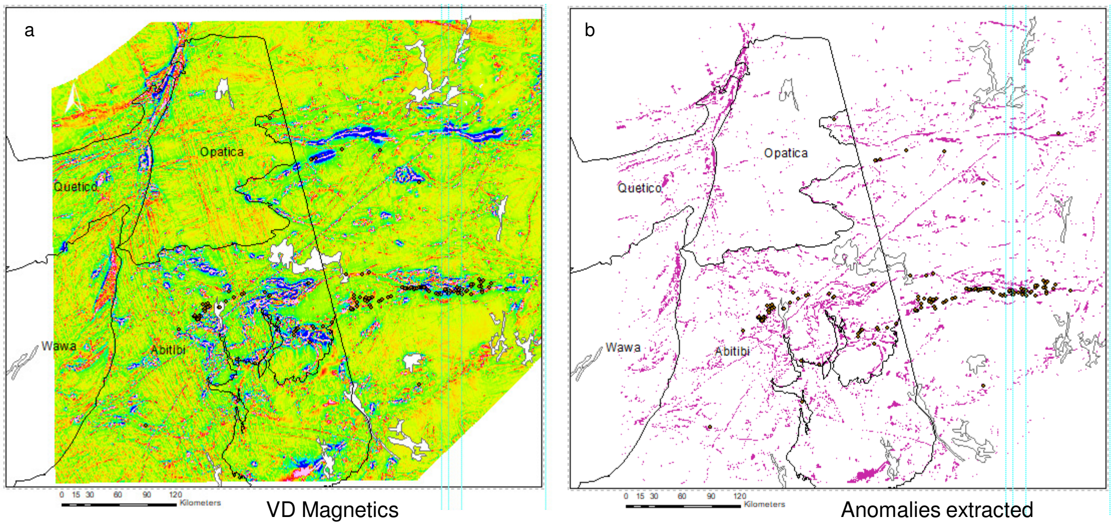

VD Magnetics

Anomalies extracted from the VD magnetic image (shown in a magenta colour)

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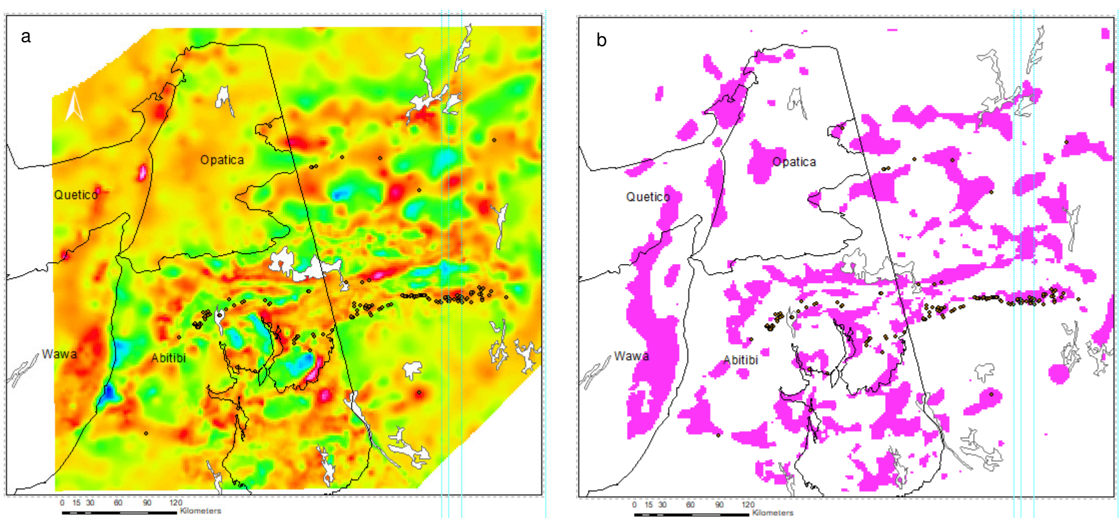

Vertical derivative - gravity

Density anomalies

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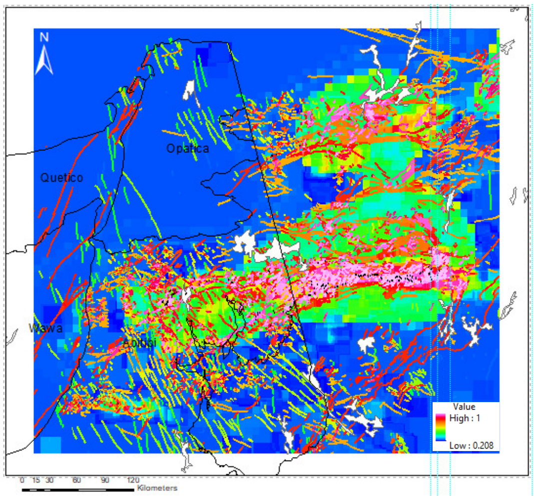
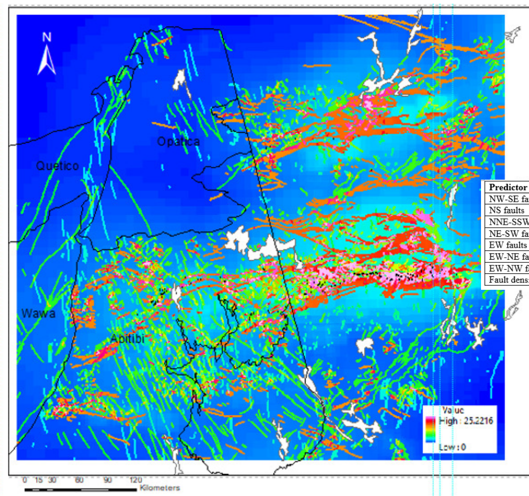
MPM – faults -Random Forest



MPM – faults - Weighted Sum



Predictor map	Weight (1 – 10)
NW-SE faults	4
NS faults	2
NNE-SSW faults	2
NE-SW faults	4
EW faults	10
EW-NE fault intersections	7
EW-NW fault intersections	7
Fault density	4

Correlation between these MPMs = 0.82!

MPM = (pred A * W) + (pred B * W) +……..(pred N * W)

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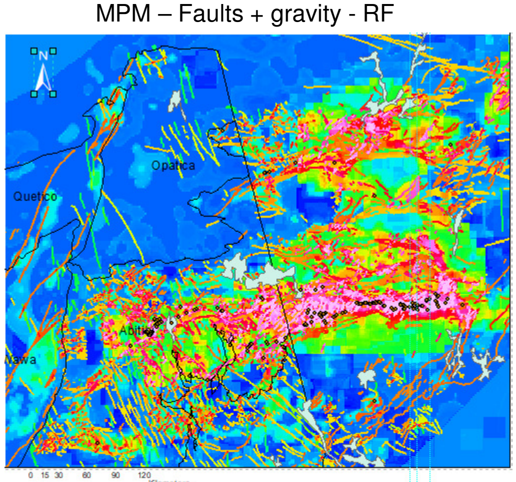
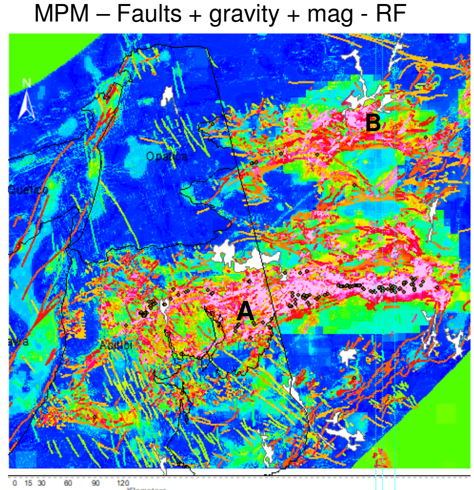
MPM – Faults + gravity - RF



MPM – Faults + gravity + mag - RF



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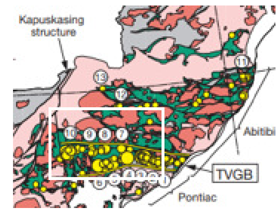
Best Predictors- Abitibi sub-area

Predictor map	RF importance sub area (no gravity or magnetics)	RF importance sub area (with gravity)	RF Importance sub-area (fault data and gravity and magnetic data)	Average score
NE-SW faults	1.3	1.22	1.24	1.25
EW faults	0.9	0.89	0.95	0.91
NW-SE faults	0.88	0.94	1.0	0.94
Fault density	0.53	.76	.7	0.66
EW-NW fault intersection	0.49	.58	.91	.66
NNE-SSW faults	0.29	0.32	.27	.29
EW-NE fault intersection	0.12	0.92	.33	.45
N-S faults	0.0	0.06	.06	.04
Gravity-VD-Raw		0.47	.42	0.44
Gravity- VD anomaly (high zones)		0.16	.1	0.13
Mag VD raw			.62	.62
Mag VD anomaly (lineaments)			.4	.4



Best predictors in red

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Validation Statistics

Correlation

	Faults (sub-area)	Faults + gravity	Faults + gravity + mag	Weight sum- faults
Faults RF- -subarea	1.0	.93	0.95	.77
Faults + gravity RF		1.0	0.93	.82
Faults = gravity + mag RF			1.0	.78
Weigh Sum -faults				1.0

Classification Accuracy

MPM	Overall Accuracy	Out-of-bag-accuracy (oob)
Faults+ gravity (sub-area)	96%	92%
Faults + gravity+ mag	98%	94%
Faults (sub-area)	95%	91%
Faults (entire area)	85%	83%
Mag Lineaments (entire area)	51%	52%

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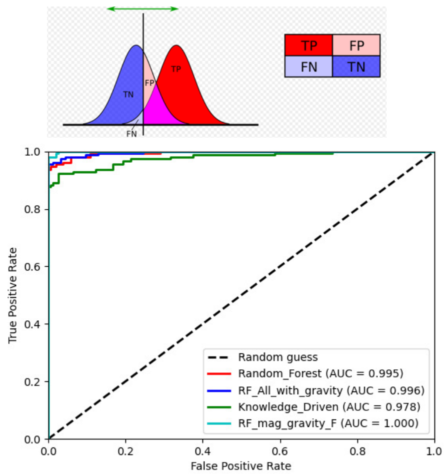
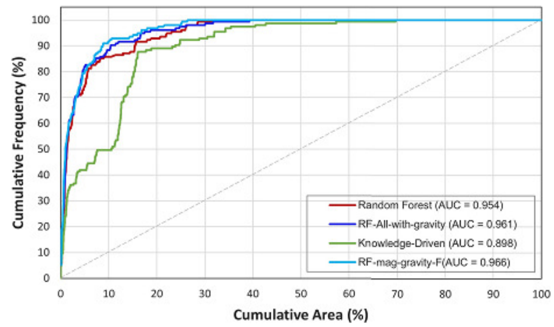
Validation

ROC curve



Where:
TPR = TP/TP+FN
FPR = FP/FP +TN



Efficiency of classification curve

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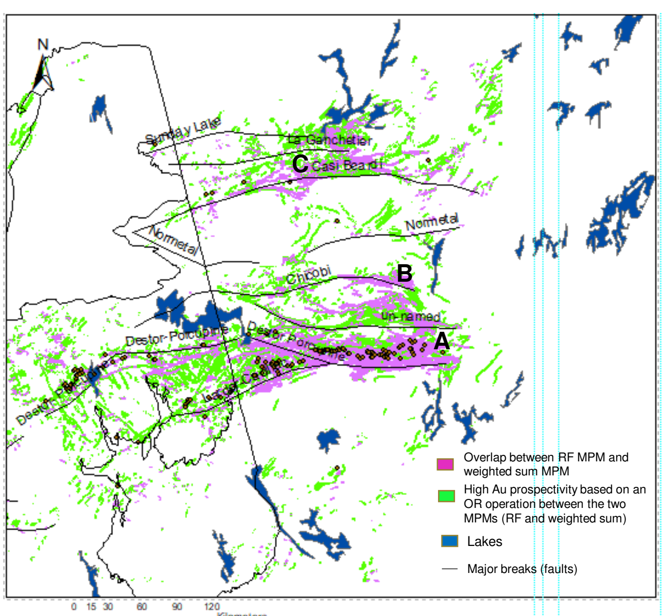

Top 15% of areas of highest Au prospectivity

RF MPM based on faults, gravity and magnetics and knowledge-based (weighted sum) algorithm

MPM – predicts the known Au mines very well but also reveals areas of high prospectivity where no mines are found (B and C)

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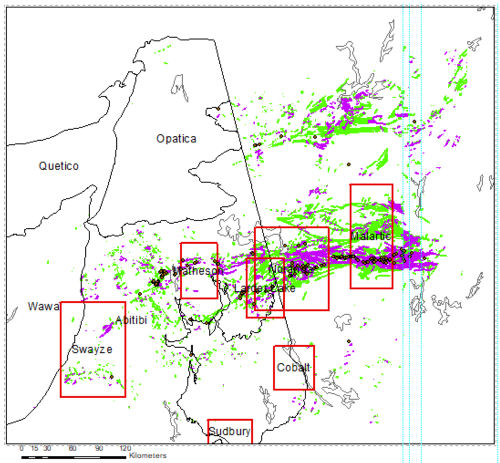
.....and what about the 3D characteristics of some of these faults?



Greenstone belts and zones of high potential for Au exploration

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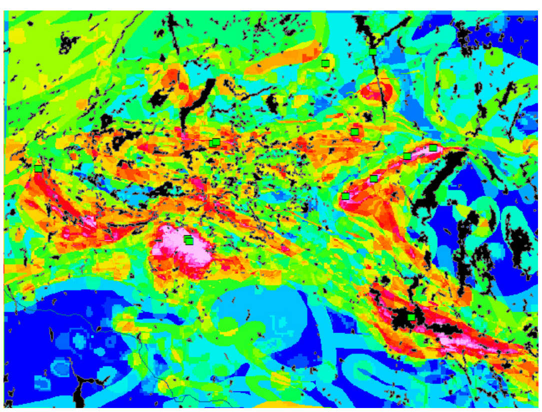
SOUTHERN SWAYZE – Orogenic Au

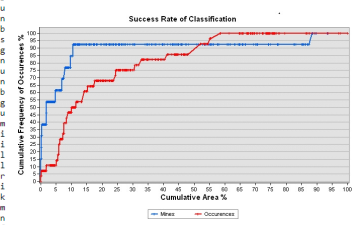


Mines + producers and past producers(13)

Discovery of new 10m oz Cote Au deposit !

Importance Values

Variable	Raw	Normalized	StdDev	Band Names
1	0.411	0.138	2.971	tr_hg
2	0.826	0.151	5.469	tr_au
3	0.156	0.061	2.579	tr_zn
4	0.851	0.173	4.913	tr_cu
5	0.679	0.151	4.486	ticp_zn
6	0.283	0.100	2.834	ticp_pb
7	0.106	0.040	2.654	ticp_cu
8	0.000	NaN	0.000	ticp_sb
9	0.010	0.009	1.004	ticp_au
10	0.043	0.038	1.157	au_grain
11	0.200	0.105	1.900	b_pb
12	0.000	NaN	0.000	b_as
13	0.000	NaN	0.000	b_hg
14	0.183	0.105	1.742	b_zn
15	0.074	0.041	1.820	b_cu
16	-0.029	-0.019	1.518	h_zn
17	-0.188	-0.100	1.872	h_pb
18	-0.015	-0.010	1.567	h_hg
19	-0.033	-0.012	2.859	h_cu
20	0.072	0.037	1.947	mag_anom
21	0.015	0.041	0.371	ccpi
22	-0.046	-0.070	0.656	epai
23	-0.039	-0.058	0.682	mol_n_al
24	0.000	NaN	0.000	mol_k_al
25	0.000	NaN	0.000	iser
26	0.357	0.142	2.520	ai
27	0.000	NaN	0.000	acnk
28	0.391	0.086	4.538	em_anom
29	2.053	0.265	7.744	mag_high_strain
30	0.124	0.046	2.673	if
31	0.091	0.026	3.444	fault contacts
32	1.963	0.210	9.346	contacts
33	0.452	0.075	6.015	geol_3
34	1.038	0.140	7.424	geol_2
35	0.213	0.056	3.805	geol_1



# class	(1)	(2)	Sum Ref.
(1) mines (m_rand_ras.dat) [Red] 13 points	12	1	13
(2) rand (m_rand_ras.dat) [Green] 13 points	1	12	13
Sum Est.	13	13	
User Accuracy	92	92	
Producer Accuracy	92	92	
F1 Accuracy	92	92	

Overall Accuracy: 92.31
Avg. F1 Accuracy: 92.31
Kappa Accuracy: 0.85

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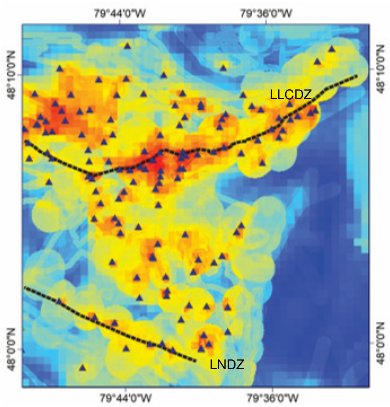
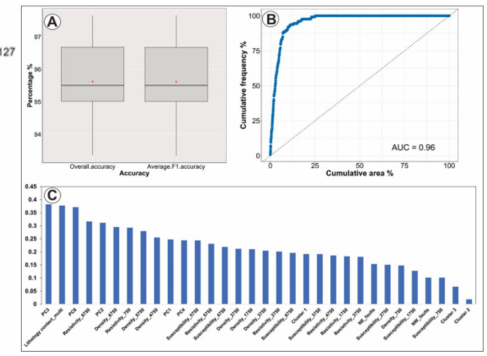
Larder Lake MPM – 0rogenic Au – from Lui et al



gold mineralization associated with the LLCDZ and the LNSZ are in general coeval and associated with a similar structural and stratigraphic framework



geochemical data using the PCA transformation (PC3 and PC8) and lithology contacts show the highest classification power

The area under curve (AUC) is 0.96 indicating that about 96% of all the deposits lie on the top 15% of high probability areas for the classification map

The overall accuracy for the ten times of RF classification was 95.63%, whereas the F1-score was 95.62%.

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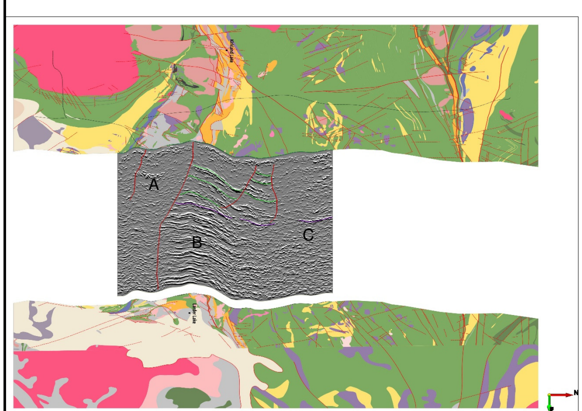
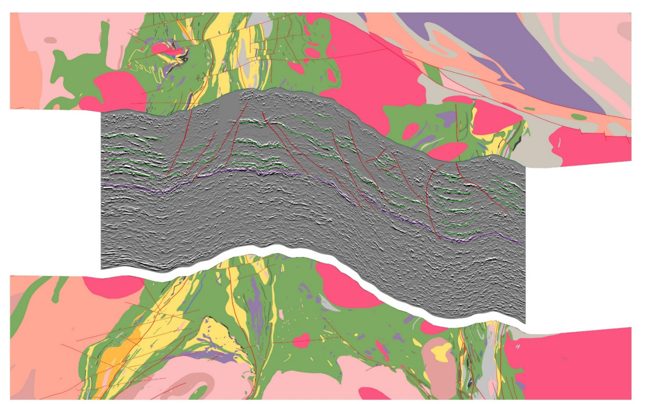


Larder Lake seismic profile with geology and seismic interpretation



Swayze seismic profile with geology and seismic interpretation

Interpreted faults

Bottom of upper crust (?)

Horizontal reflectors – lithological variations

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SUMMARY AND CONCLUSIONS

- We have produced two orogenic Au MPMs based on faults and magnetic lineaments for the entire Superior Province but have identified a data clustering issue that biases the final MPM.
  - *Solution*- create a sub-area and/or create a knowledge-driven model over an area of less clustered mapped faults (Abitibi-sub area) – these MPMs are more robust than the MPMs for the entire Superior Province
  - NE-SW, NW-SE, EW -trending faults, magnetic vertical derivative and EW-NW trending fault intersections have been confirmed statistically as strong predictors of orogenic Au mineralization
  - Although we have focused on faults, addition of other predictor maps including, lithological and geochemical data, would improve the perfomance of all 4 MPMs generated over the Abitibi sub-area – we can see how the performance of the MPMs increased with the addition of gravity and magnetic data
- Based on the newly collected seismic data **we speculate** that the Larder Lake greenstone belt is more fertile than the Swayze greenstone belt due in part to more deeply penetrating faults which provide conduits for Au-bearing fluids from the mantle. It also appears that the Swayze greenstone belt is more shallow than the Larder Lake greenstone belt and may represent a difference in geography with respect to plate tectonic activity.

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