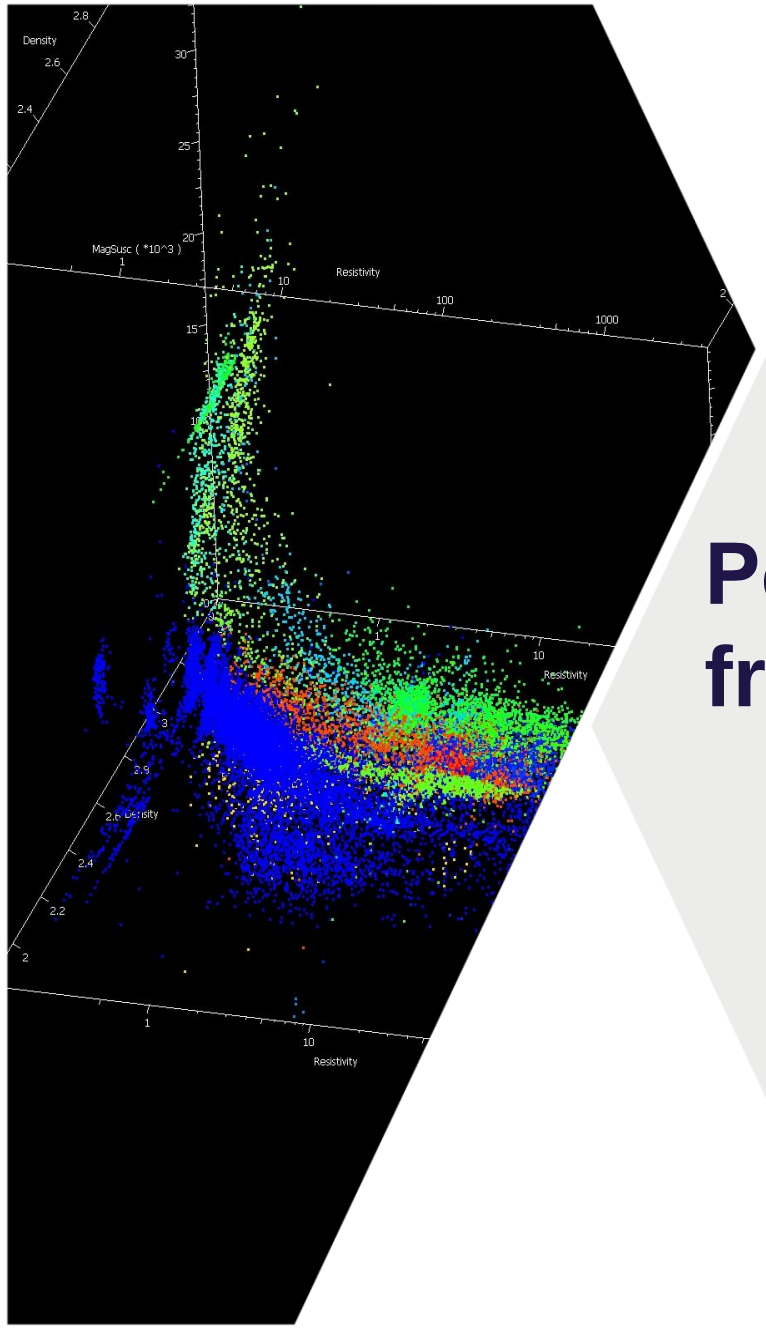


Petrophysical “Big Data” – case study from the Stavely Project, western Victoria

Phil Skladzien

4th September 2019, Perth

AEGC2019 Data to Discovery
Australasian Exploration Geoscience Conference
2-5 September 2019 • Perth, Western Australia
Incorporating the AIG, ASEG, PESA, and WABS

GEOLOGICAL SURVEY OF VICTORIA

VICTORIA State Government | Jobs, Precincts and Regions

Acknowledgements

Ross Cayley, Mark McLean

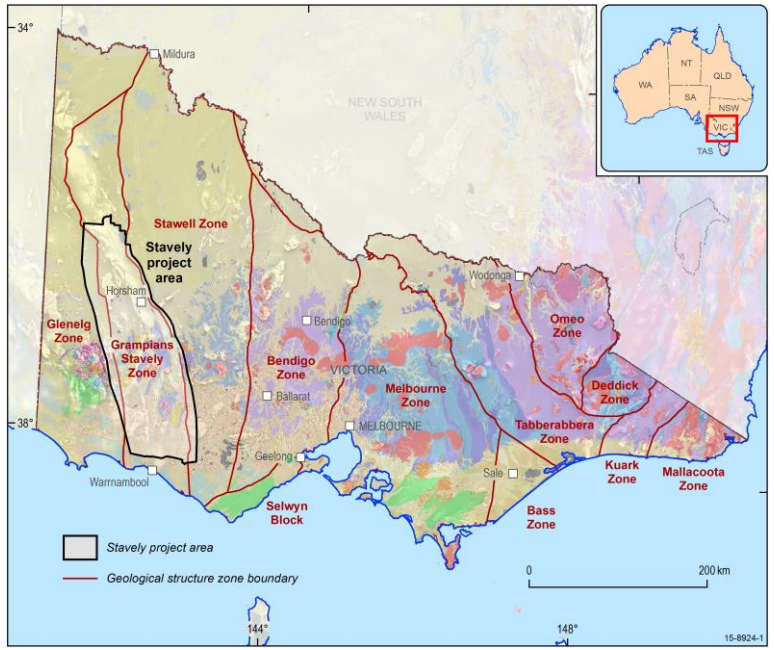
Philomena (Min) Manifold, David Belton, Scarlett Blewett, Alison Fairmaid and Dan Sandiford

Talk outline

- **The Stavely Project overview**
- Multi-Sensor Core Logger – data acquisition, validation and collation
- Data analysis and fusion – multivariate property data
- Modelling the Stavely Arc
- Conclusions

The Stavely Project

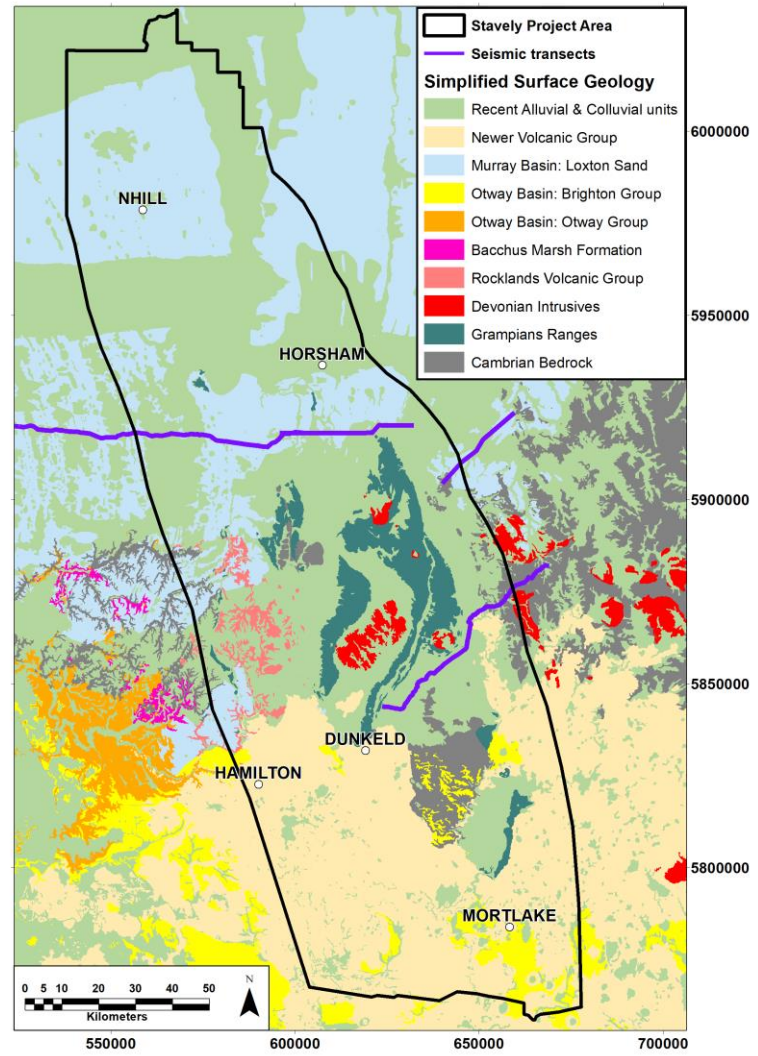
Collaborative project undertaken to better understand the Cambrian Stavely Arc in western Victoria.



Map extent, distribution and 3D geometry of arc related rocks under cover.

Only 3% of Cambrian basement exposed, but containing multiple prospects.

Catalyst was the 2009 deep crustal seismic reflection transect.



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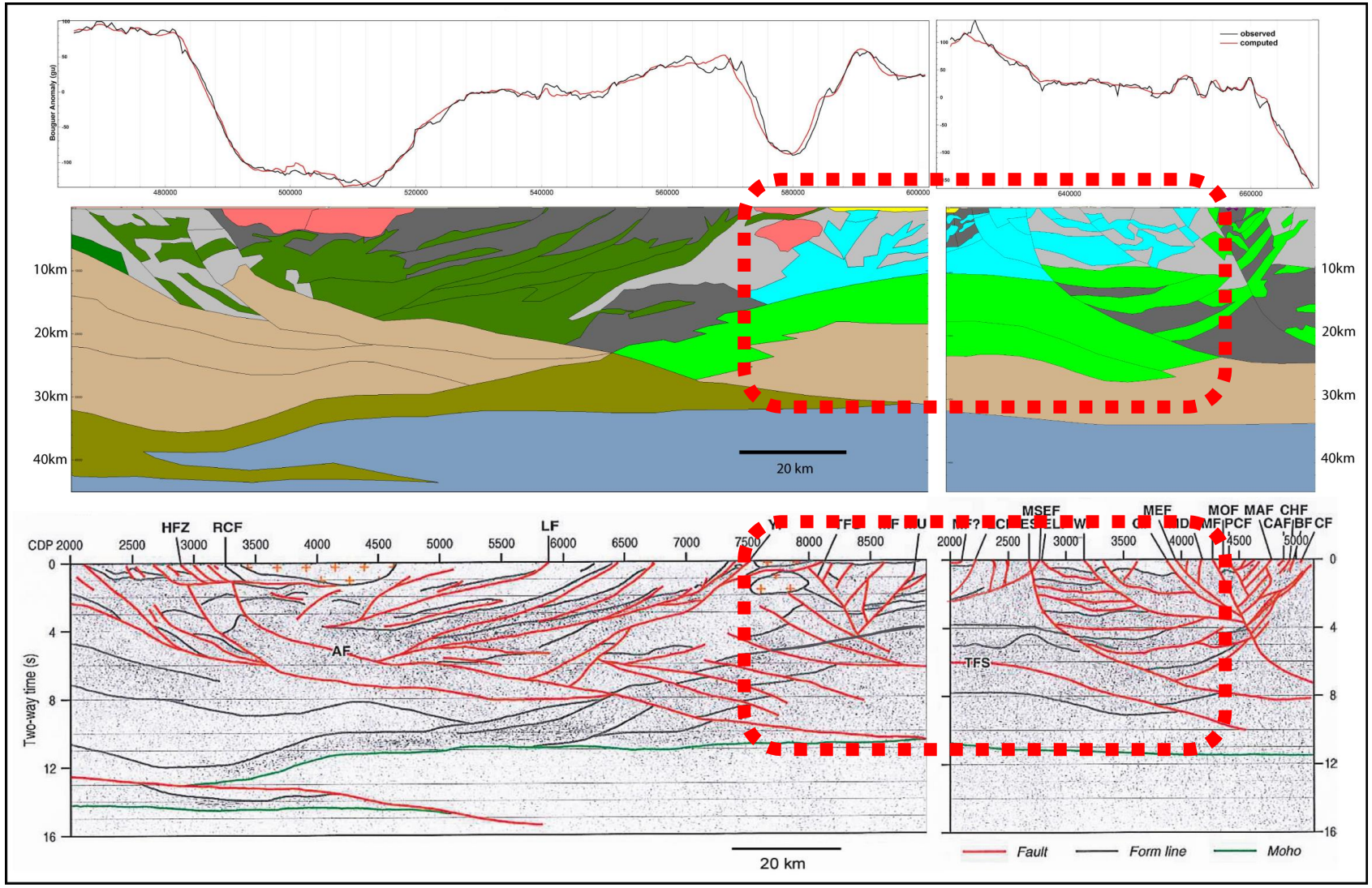
2009 Seismic Reflection Transects imaging the Cambrian aged Stavely Arc



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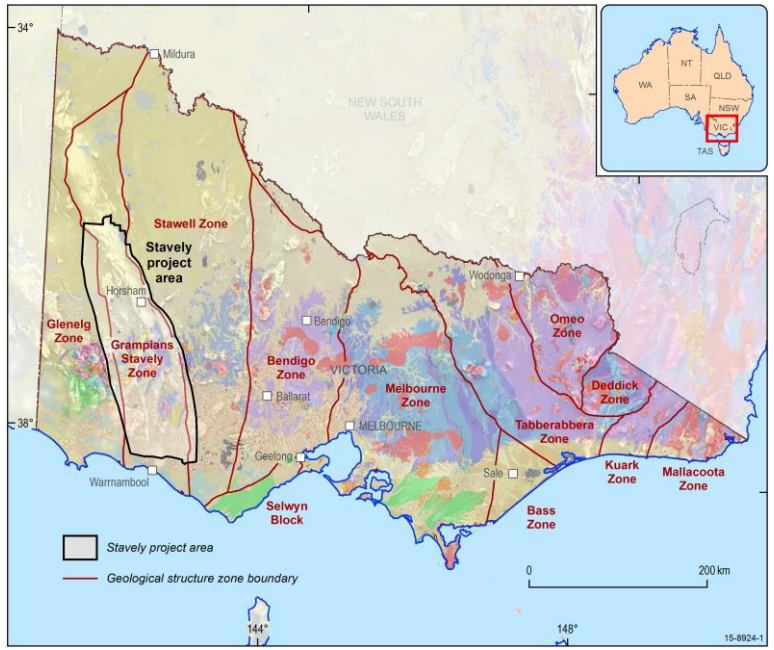

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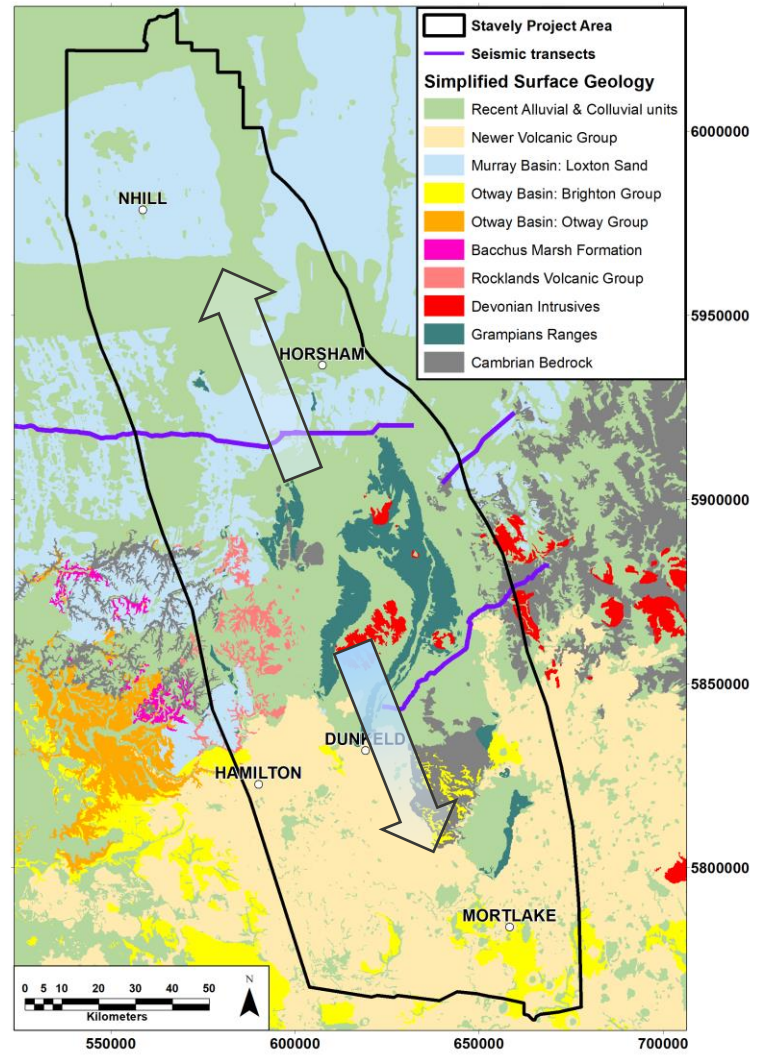

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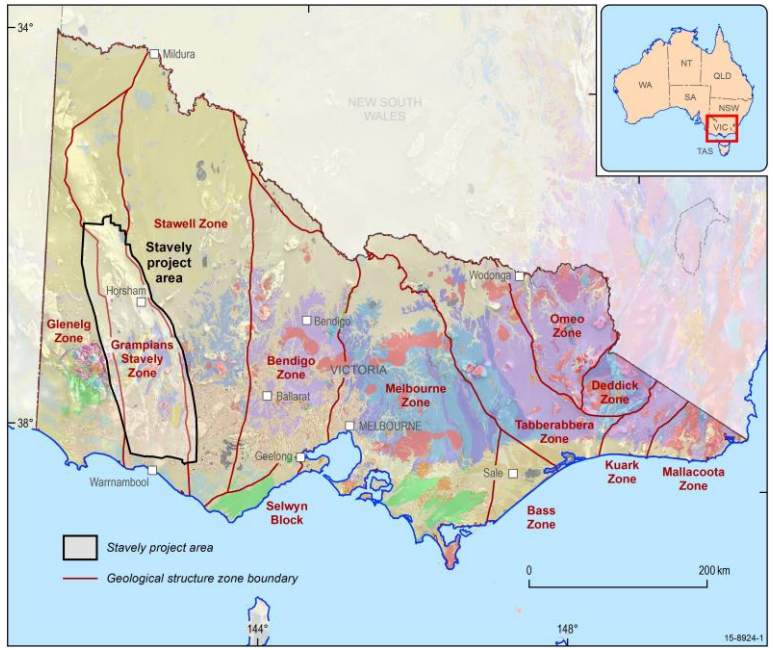

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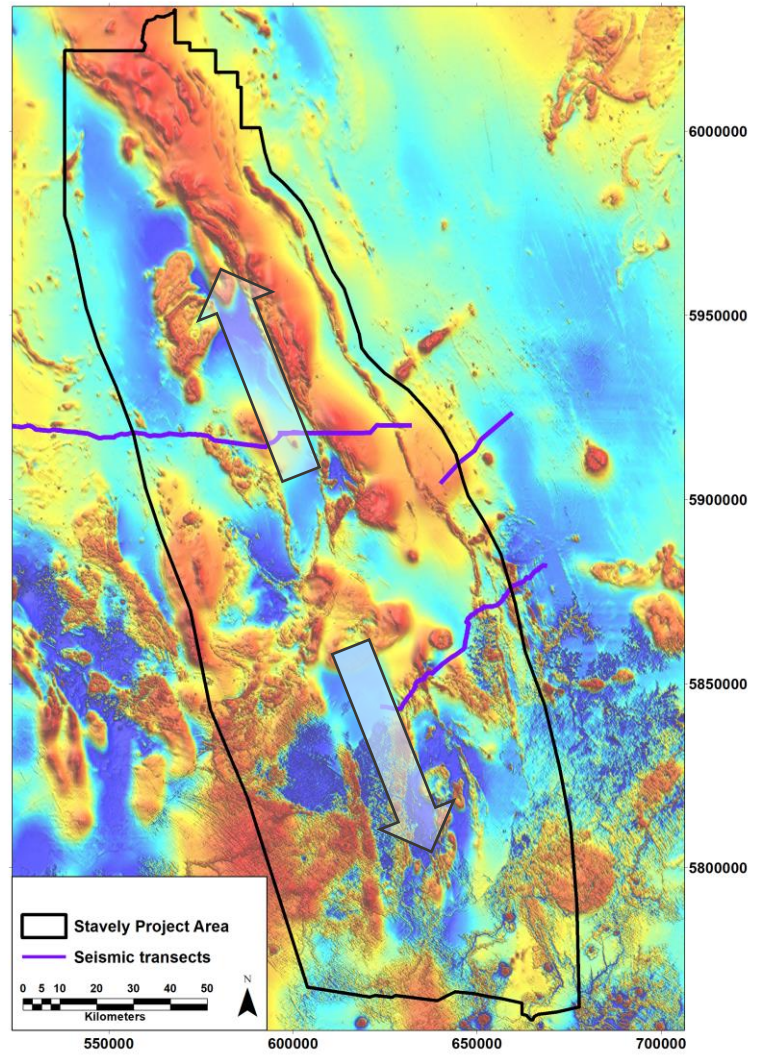

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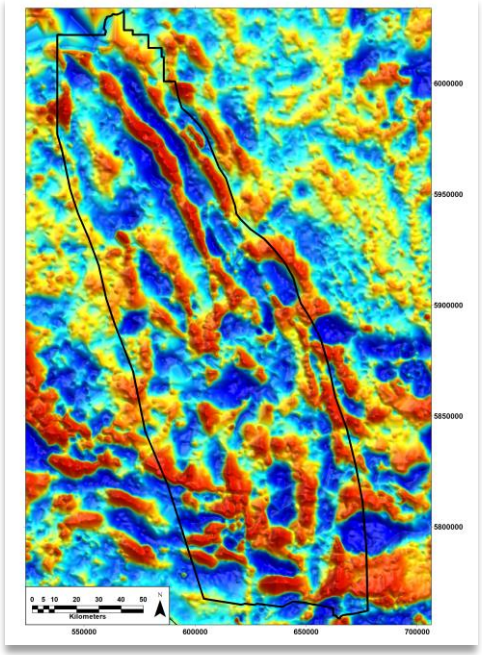
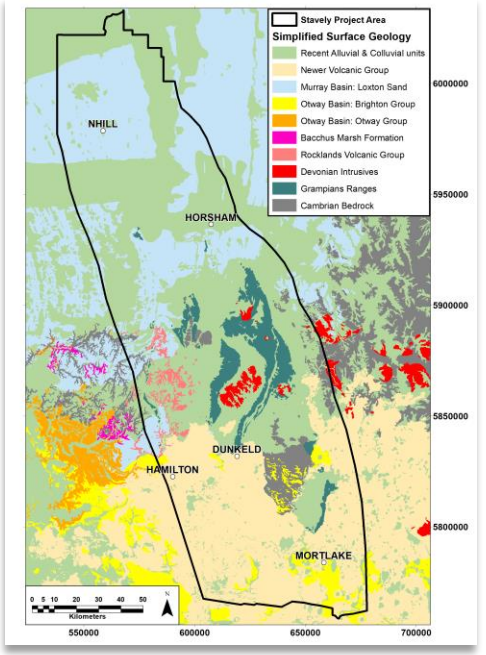
The missing (or under-utilised) link….

Geophysical Data

Geology (geological model)



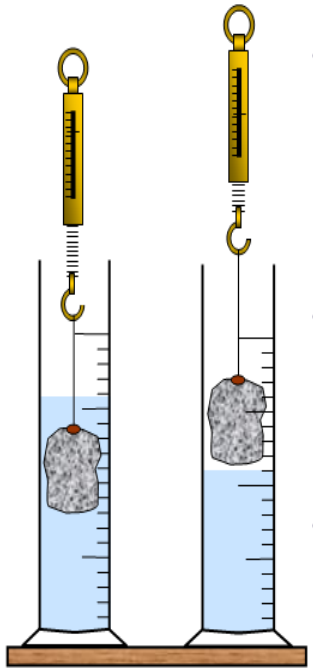
Physical rock properties

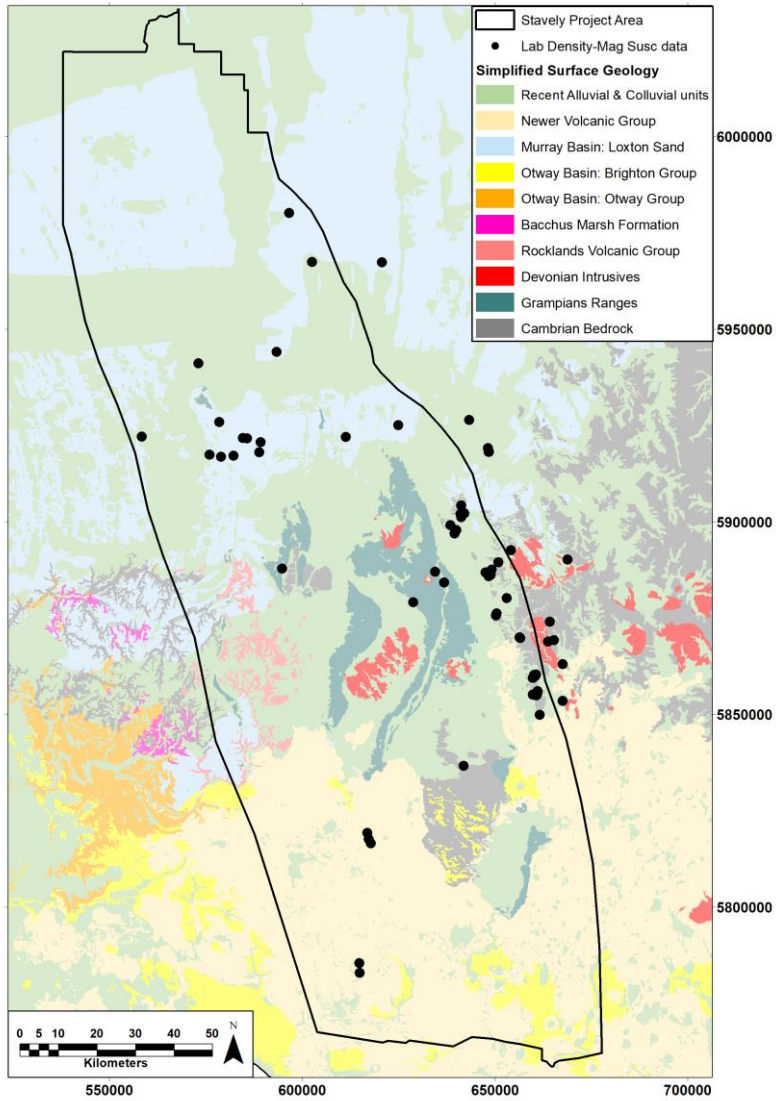


Traditional laboratory petrophysical data

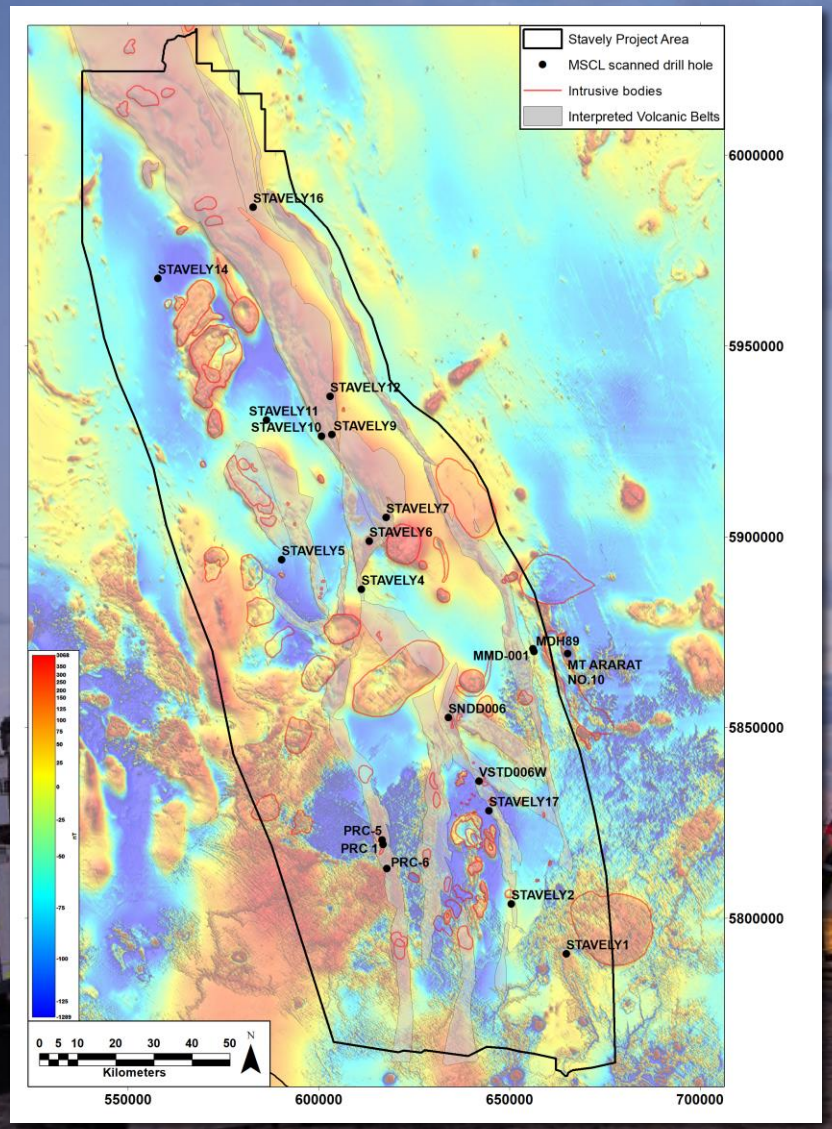
Project area contained:

- 194 density measurements
- Hand held magnetic susceptibility measurements on outcrop
- Limited core basement sample measurements
- Multiple properties rarely acquired on same sample





Stavely Project drilling



- 14 Stavely stratigraphic drill holes completed in 2014/15 – sonic and diamond core tails
- 8 historical company drill holes in Willaura area – diamond core stored at GSV Core Library
- Hylogger
- Multi-Sensor Core Logger
- Wireline logging (Stavely drill holes)
- Geochronology
- Geochemistry

Talk outline

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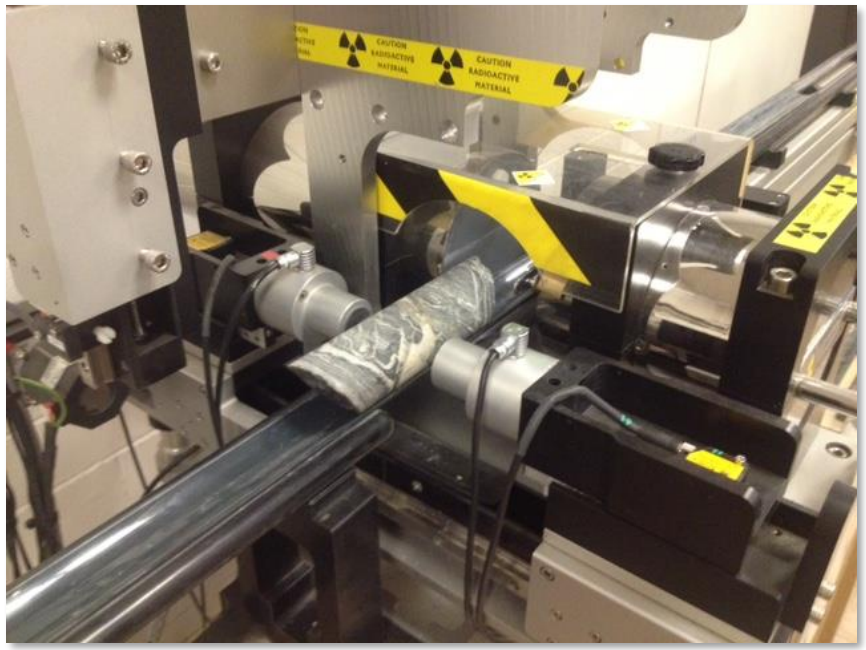
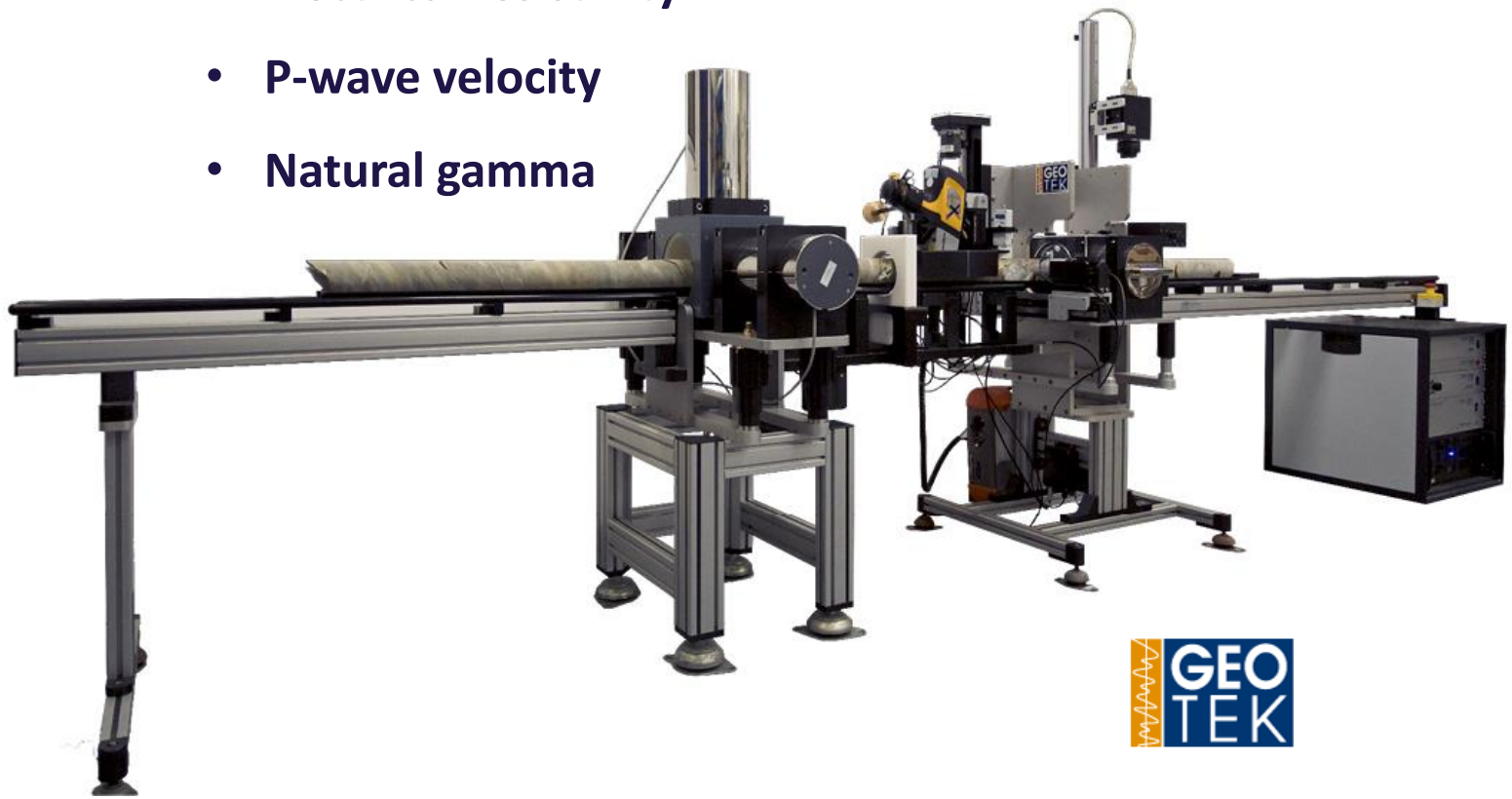
Geotek Multi-Sensor Core Logger (MSCL)

Physical rock properties measured:

- Magnetic susceptibility
- Gamma density (Bulk density)
- Electrical resistivity
- P-wave velocity
- Natural gamma





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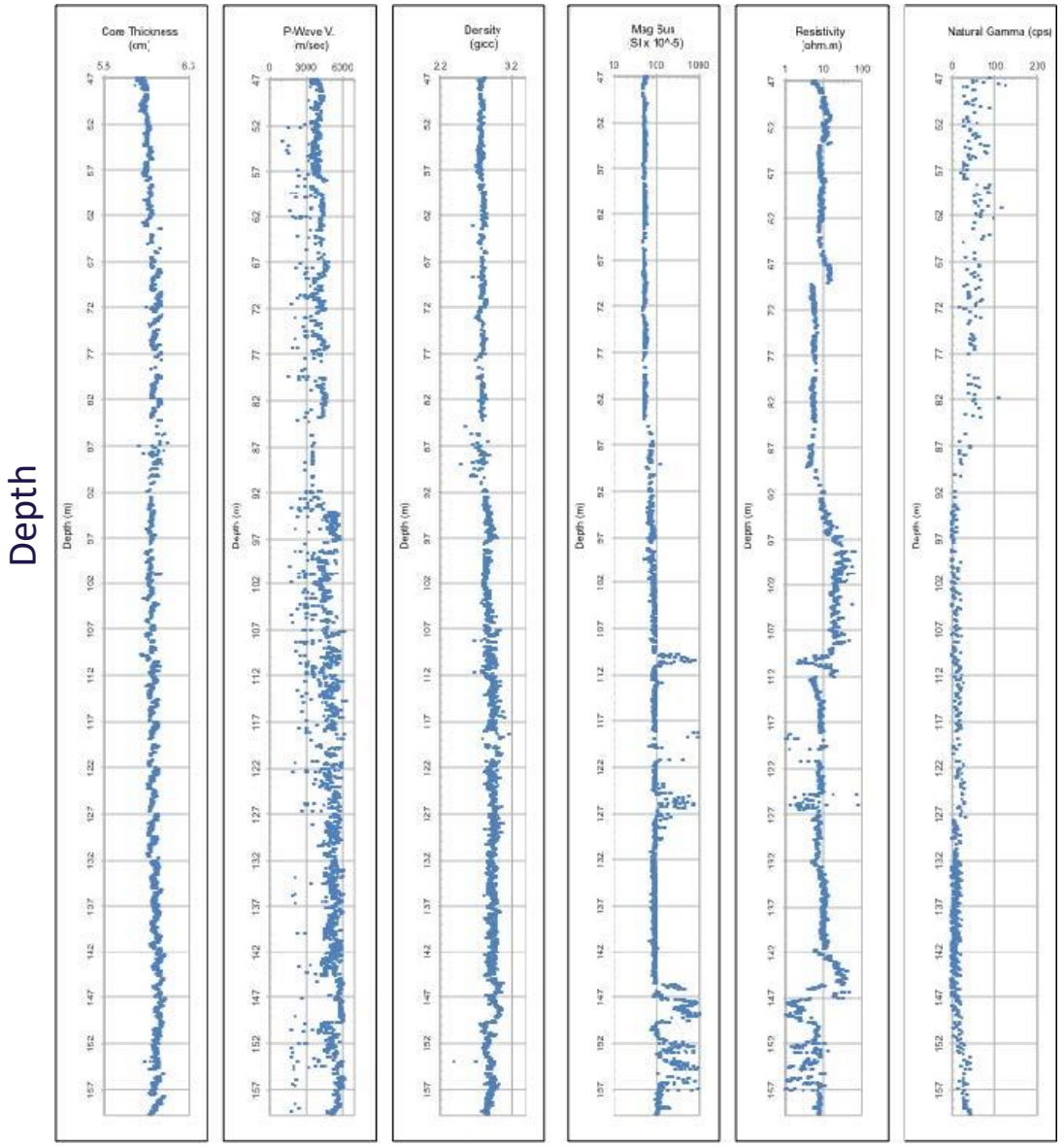
Stavely MSCL Data

- 21 drill holes scanned in Stavely Project area
- 1,940 m of diamond core scanned
- 259,040 total measurements for five properties
- 2 cm measurement resolution:
  - *Density*
  - *Magnetic susceptibility*
  - *Electrical resistivity*
  - *P-wave velocity*
- 2 – 10 cm measurement resolution:
  - *Natural gamma*

Drill hole Stavely02 (47 – 159 m)



Data Validation and Analysis

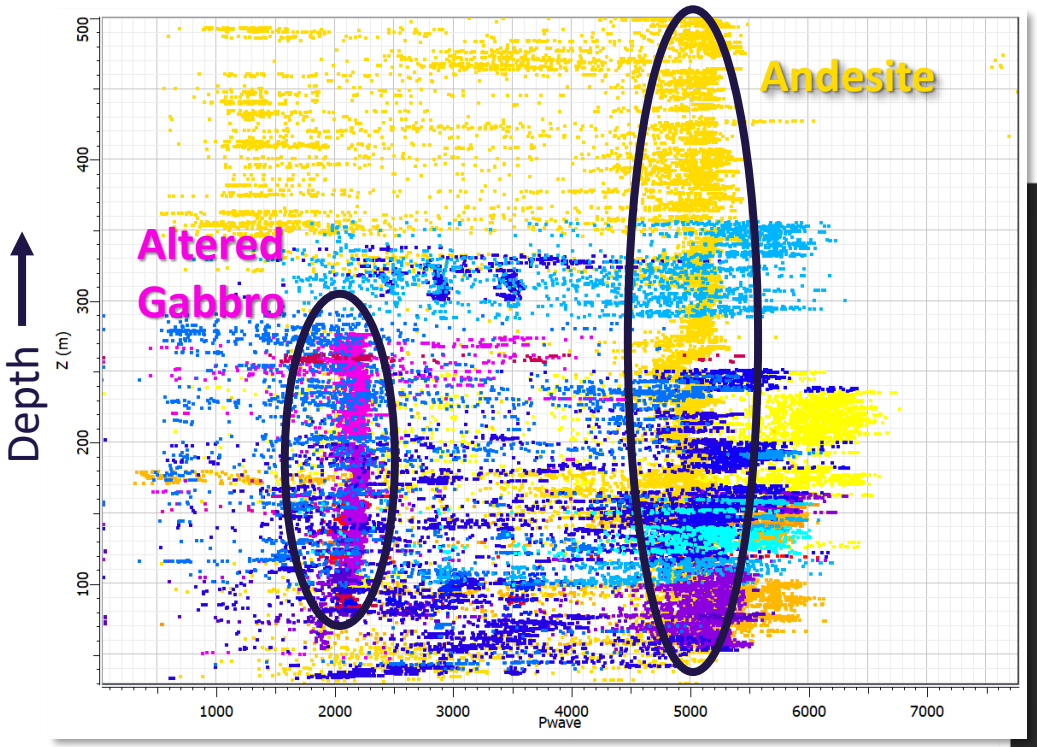
- Assign lithology and stratigraphy to measurements
- QC and validate data – from a total of 259,040 measurements a final dataset of 216,699 measurements was derived.
- Summary statistics run on lithologies and stratigraphy for all five individual properties.
- **Cover:** 6 stratigraphic units; 11 lithological units
- **Basement:** 12 stratigraphic units; 29 lithological units

Stratigraphy	Density (g/cm³)							
	Median	Percentile 25%	Percentile 75%	Min	Max	Mean	Std Dev	Samples
Cover Units								
Grampians Group	2.78	2.77	2.80	2.65	2.86	2.78	0.028	783
Otway Basin (all samples)	1.81	1.76	1.86	1.57	2.70	1.85	0.190	366
Crayfish Group (Otway Basin)	1.71	1.63	1.76	1.57	1.87	1.72	0.108	8
Heytesbury Group (Otway Basin)	1.80	1.76	1.83	1.58	2.17	1.80	0.077	265
Wangerrip Group (Otway Basin)	1.91	1.82	2.00	1.60	2.70	1.99	0.312	93
Newer Volcanic Group	2.68	2.58	2.72	1.94	2.81	2.64	0.122	423
Cambrian Bedrock								
Grampians-Stavely Zone								
Bushy Creek Suite	2.58	2.50	2.63	2.19	2.78	2.57	0.105	288
Glenthompson Sandstone	2.75	2.69	2.79	1.17	3.63	2.73	0.114	5955
MSVC (all)	2.78	2.63	2.97	1.82	3.47	2.79	0.204	33671
MSVC (excluding andesite)	2.97	2.87	3.06	1.84	3.47	2.97	0.127	16517
MSVC (excluding andesite & qtz diorite)	2.99	2.92	3.07	1.84	3.47	2.99	0.124	13813
MSVC (excluding qtz diorite)	2.73	2.63	2.98	1.82	3.47	2.79	0.210	30967
Nargoon Group	2.72	2.41	2.81	1.41	2.96	2.57	0.316	2210
Stawell Zone								
Moornambool Metamorphic Complex (all)	2.99	2.90	3.10	2.17	3.47	3.00	0.116	7157
Carrolls Amphibolite (MMC)	3.10	3.05	3.15	2.17	3.47	3.09	0.099	3258
Lexington Schist (MMC)	2.90	2.87	2.93	2.76	3.20	2.90	0.059	2194
Magdala Volcanics	2.95	2.91	2.99	2.85	3.08	2.95	0.054	175

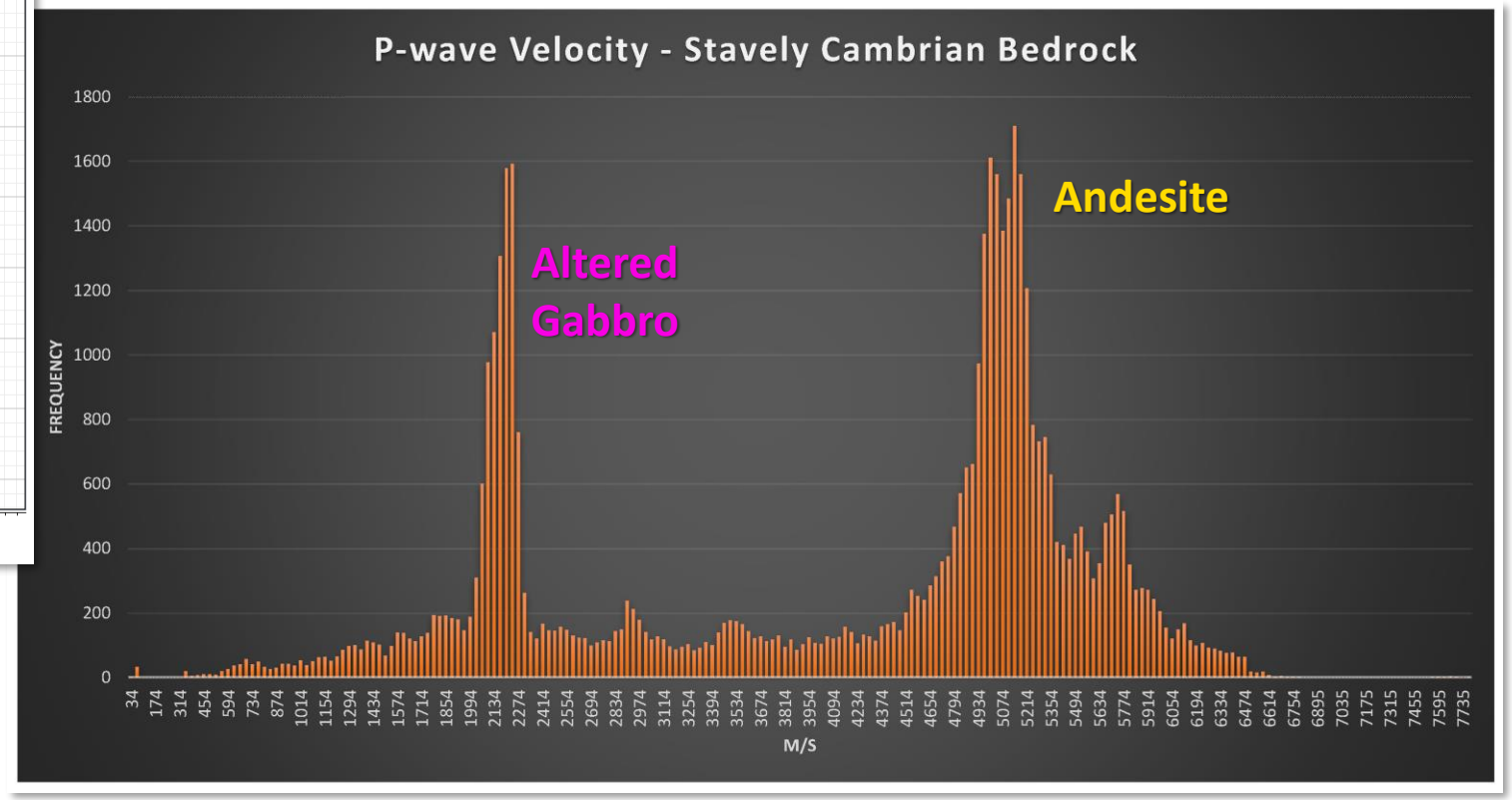
Lithology	Density (g/cm³)							
	Median	Percentile 25%	Percentile 75%	Min	Max	Mean	Std Dev	Samples
Cover Units								
Basalt (Newer Volcanic Group)	2.68	2.58	2.72	1.94	2.81	2.64	0.122	423
Clay (Otway Basin)	1.82	1.63	2.66	1.62	2.70	2.07	0.504	13
Coal (Otway Basin)	2.62	2.61	2.65	2.61	2.66	2.63	0.022	5
Conglomerate (Grampians Group)	2.79	2.77	2.80	2.71	2.82	2.78	0.021	65
Gravel (Otway Basin)	1.71	1.63	1.76	1.57	1.87	1.72	0.108	8
Marl (Otway Basin)	1.81	1.78	1.83	1.71	1.93	1.81	0.041	146
Sand (Otway Basin)	1.97	1.92	2.63	1.82	2.69	2.15	0.344	17
Sandstone (all)	2.78	2.75	2.80	1.58	2.86	2.64	0.350	837
Sandstone (Grampians Group)	2.78	2.77	2.80	2.65	2.86	2.78	0.029	718
Sandstone (Otway Basin)	1.77	1.72	1.82	1.58	2.17	1.79	0.104	119
Silt (Otway Basin)	1.88	1.82	1.93	1.60	2.04	1.87	0.102	58
Cambrian Bedrock								
Grampians-Stavely Zone								
Andesite	2.63	2.61	2.66	1.82	3.45	2.63	0.101	17154
Basalt	2.95	2.90	3.00	2.07	3.30	2.94	0.093	1937
Breccia	2.92	2.89	2.95	2.39	3.01	2.91	0.064	247
Cataclastite	3.20	3.15	3.23	3.01	3.36	3.19	0.077	33
Diorite	3.08	2.96	3.12	2.95	3.21	3.06	0.077	13
Dolerite	3.08	3.03	3.11	2.79	3.47	3.07	0.072	804
Dyke-felsic	2.90	2.88	3.12	2.87	3.14	3.00	0.124	10
Dyke-mafic	2.79	2.75	2.81	2.70	2.85	2.78	0.040	18
Fault-breccia	2.76	2.70	2.80	2.49	2.88	2.75	0.076	63
Gabbro-all	3.07	3.01	3.12	2.42	3.36	3.06	0.083	5590
Gabbro-olivine	3.13	3.10	3.16	2.65	3.36	3.12	0.068	2116
Gabbro-pyroxene	3.03	2.99	3.07	2.42	3.33	3.03	0.074	3474
Granophyre	2.91	2.87	2.96	2.78	3.19	2.92	0.065	432
Lamprophyre	2.90	2.87	2.93	2.71	2.99	2.90	0.044	176
Mudstone	1.99	1.78	2.13	1.70	2.20	1.98	0.166	24
Porphyry	2.58	2.50	2.63	2.19	2.78	2.57	0.105	288
Quartz-diorite	2.84	2.82	2.86	2.24	3.22	2.86	0.081	2704
Quartz-dolerite	3.00	2.93	3.06	2.65	3.32	2.99	0.101	820
Sandstone	2.72	2.61	2.77	1.17	3.63	2.65	0.222	5366
Serpentinite	2.67	2.59	2.73	1.91	2.90	2.65	0.110	418
Siltstone	2.79	2.75	2.82	1.30	2.96	2.77	0.114	2775
Volcanic-breccia	2.93	2.88	2.98	2.08	3.19	2.93	0.082	2566
Volcaniclastic-all	2.92	2.88	2.95	2.76	3.07	2.92	0.051	855
Volcaniclastic-rock	2.88	2.86	2.91	2.78	3.01	2.89	0.038	126
Volcaniclastic-sandstone	2.92	2.89	2.96	2.76	3.07	2.92	0.052	729
Stawell Zone								
Amphibolite	3.10	3.05	3.15	2.17	3.47	3.09	0.099	3258
Basalt	2.95	2.91	2.99	2.85	3.08	2.95	0.054	175
Schist	2.90	2.87	2.93	2.76	3.20	2.90	0.059	2194
Tuff	2.92	2.88	2.96	2.83	3.09	2.92	0.052	177

A couple of things to consider…. Sampling (lithological) bias

Over representation of measurements from single or limited lithology.

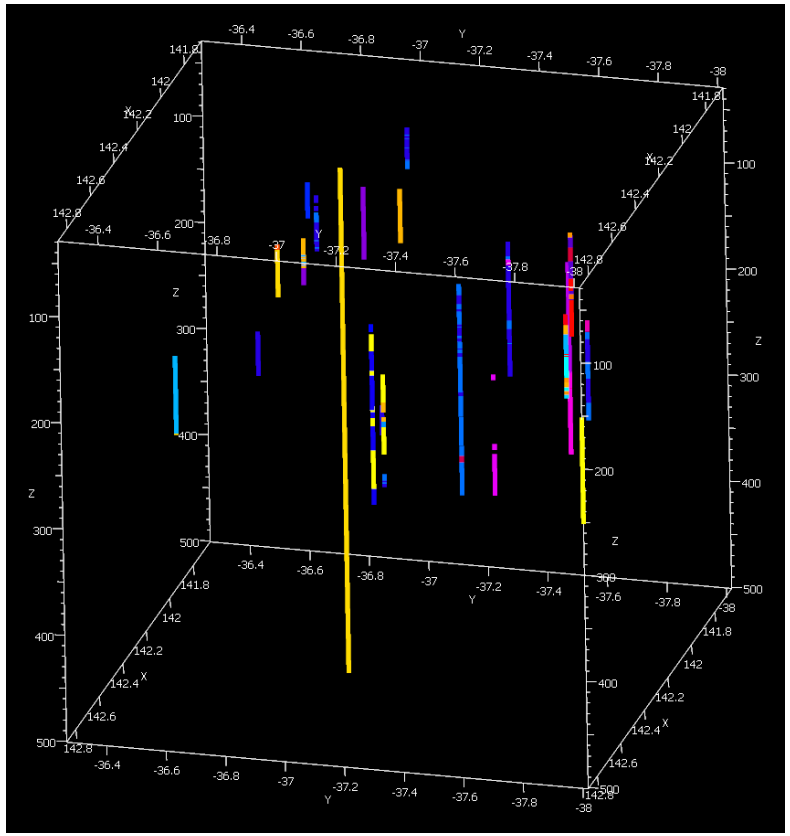


Colours represent lithology

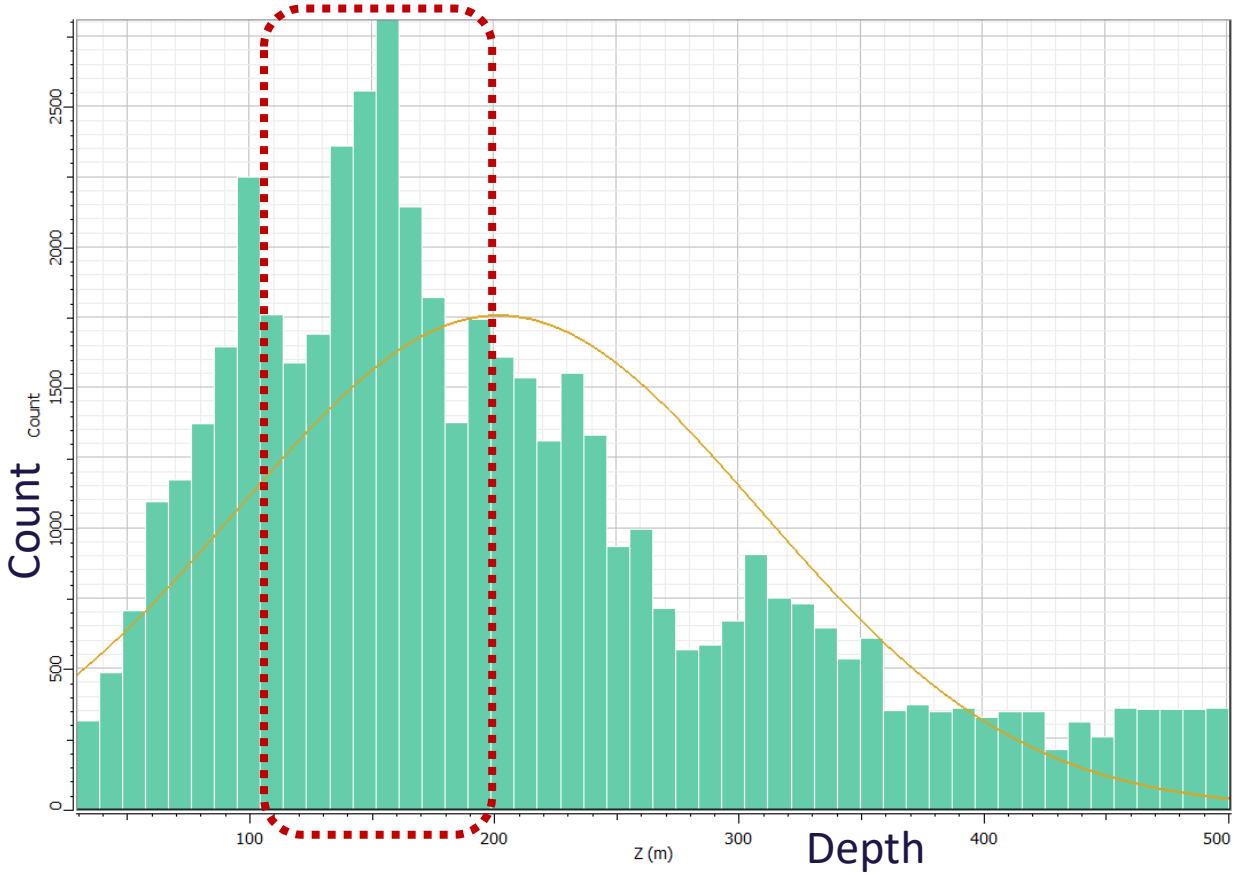


A couple of things to consider….. Spatial bias

Limited **geographical** locations (drill holes)



Over-representation of measurements from confined **depth** range.



"If you don't reveal some insights soon, I'm going to be forced to slice, dice, and drill!"

Talk outline

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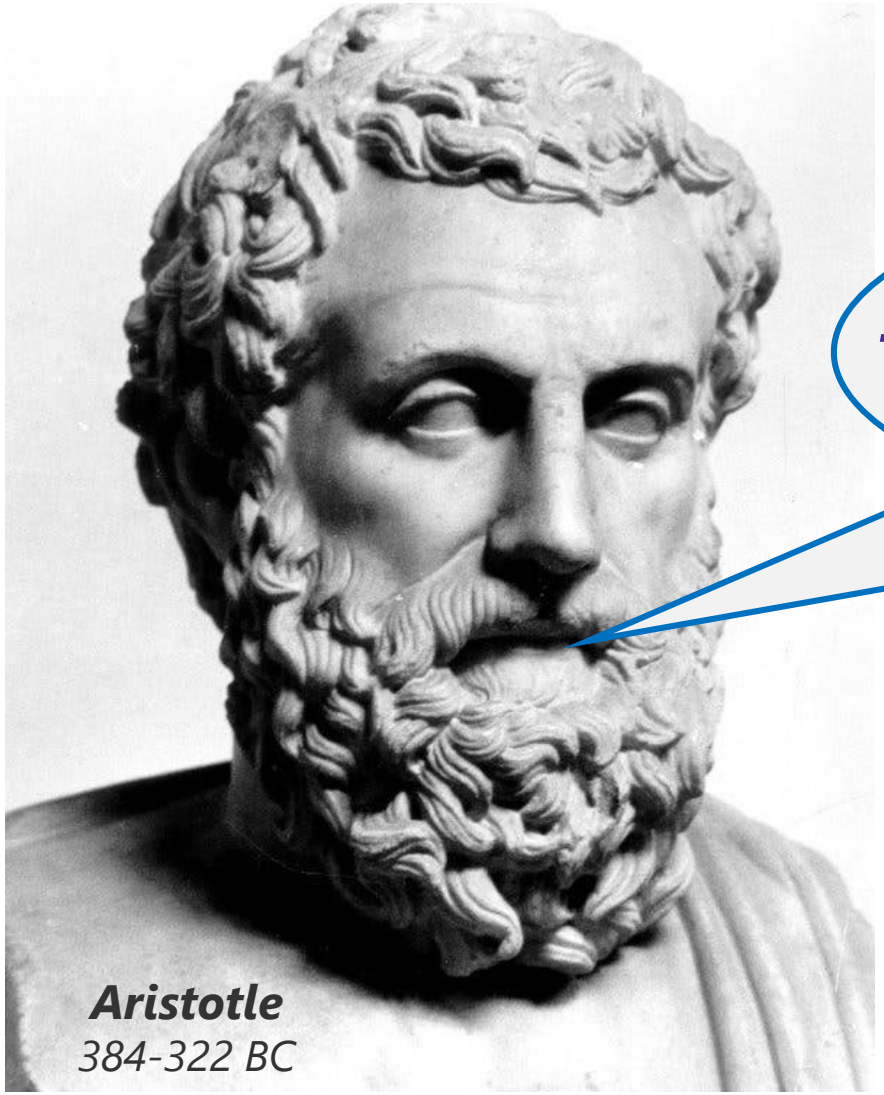
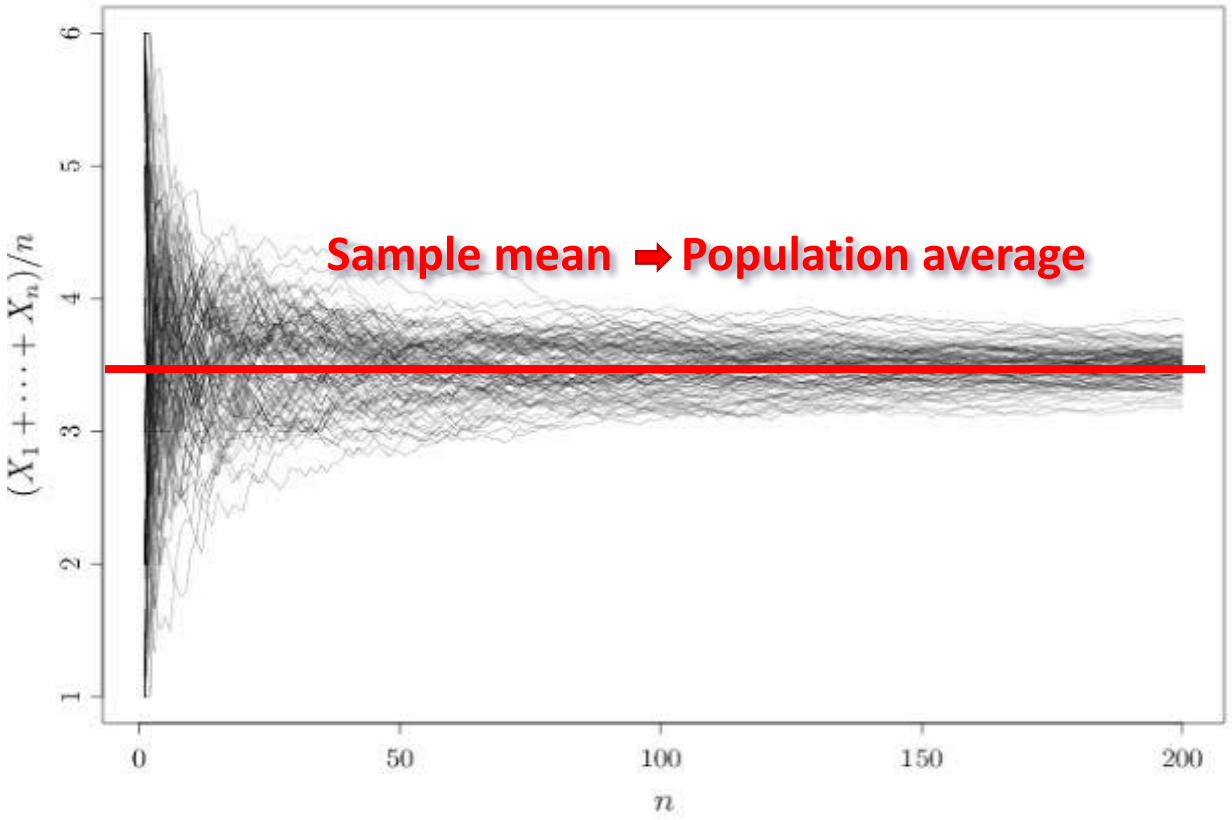


The whole is greater than the sum of its parts!

“**Data fusion** is the process of integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by any individual data source.”

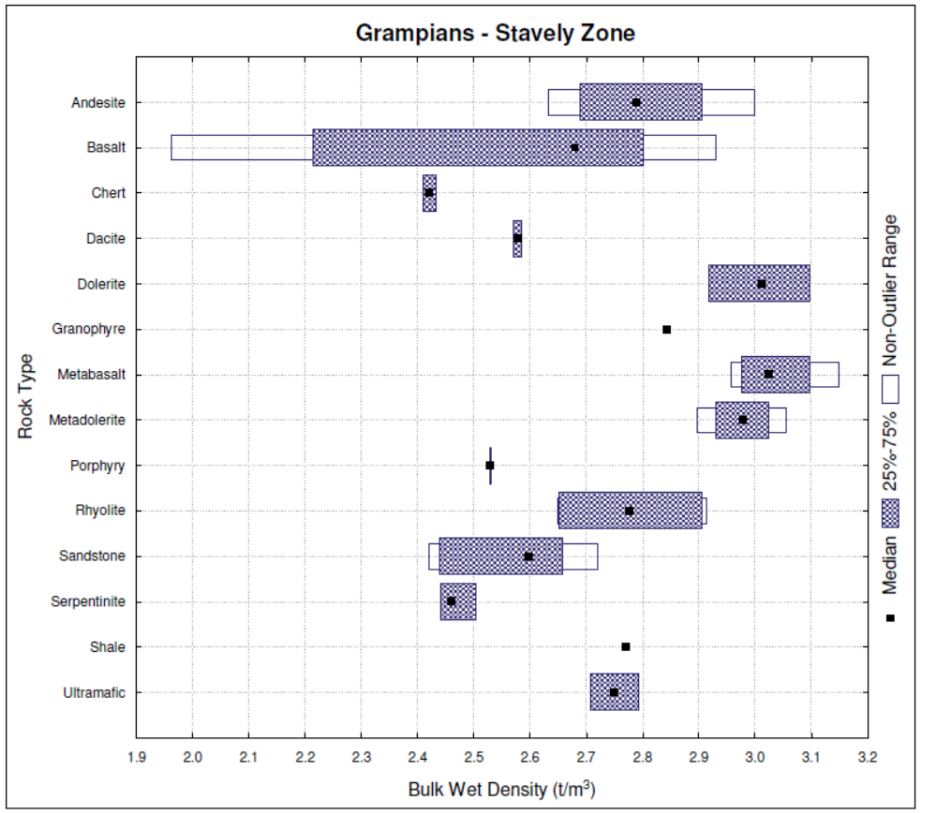
Haghighat el al., 2016.

Single Property - Mean and Range



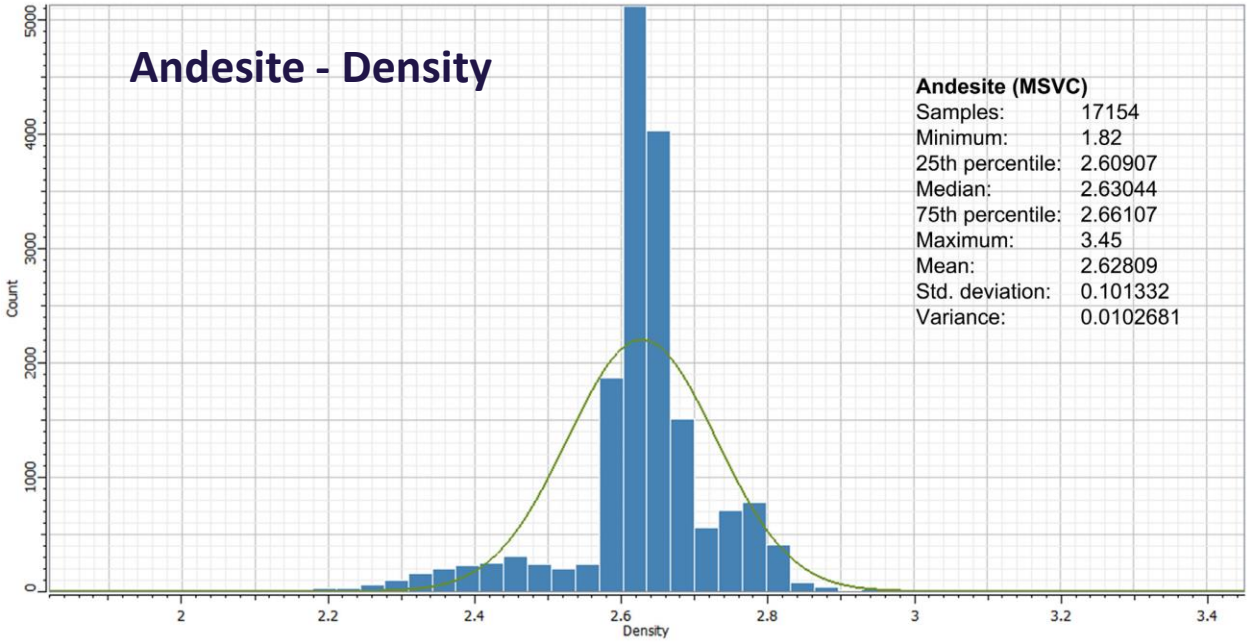
***Law of large numbers**…as a sample size grows, its mean gets closer to the average of the whole population.*

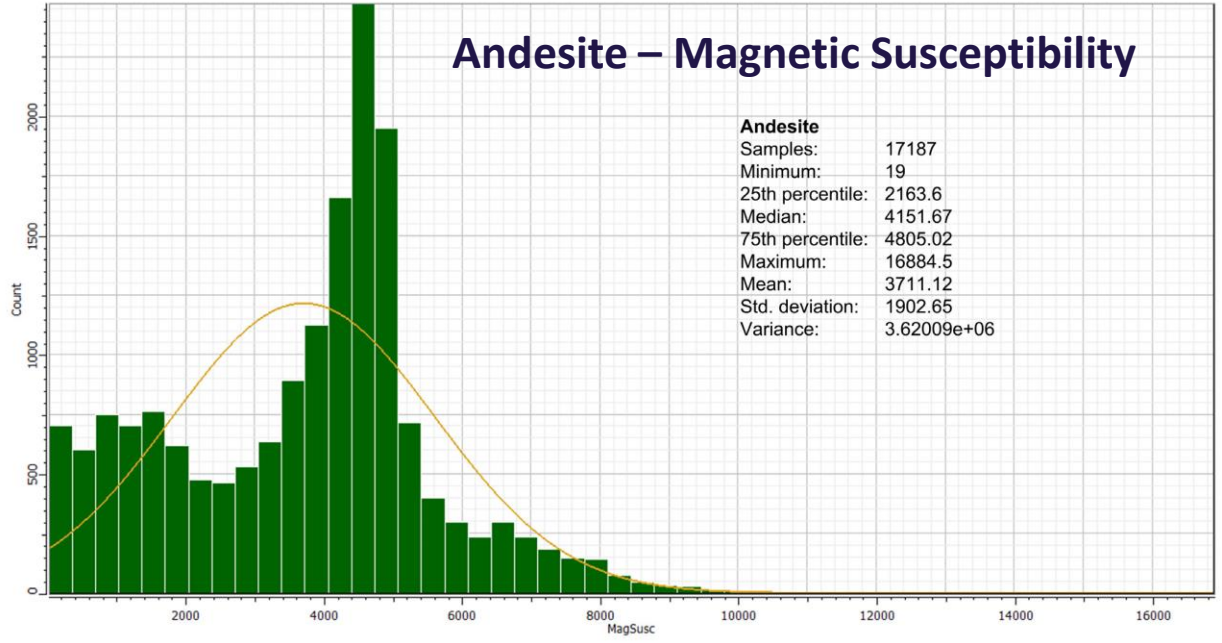
- Rock property data typically displayed as box plot
- Single representative mean/median value with range
- Lacking geological context



Single Property - Probability Distribution

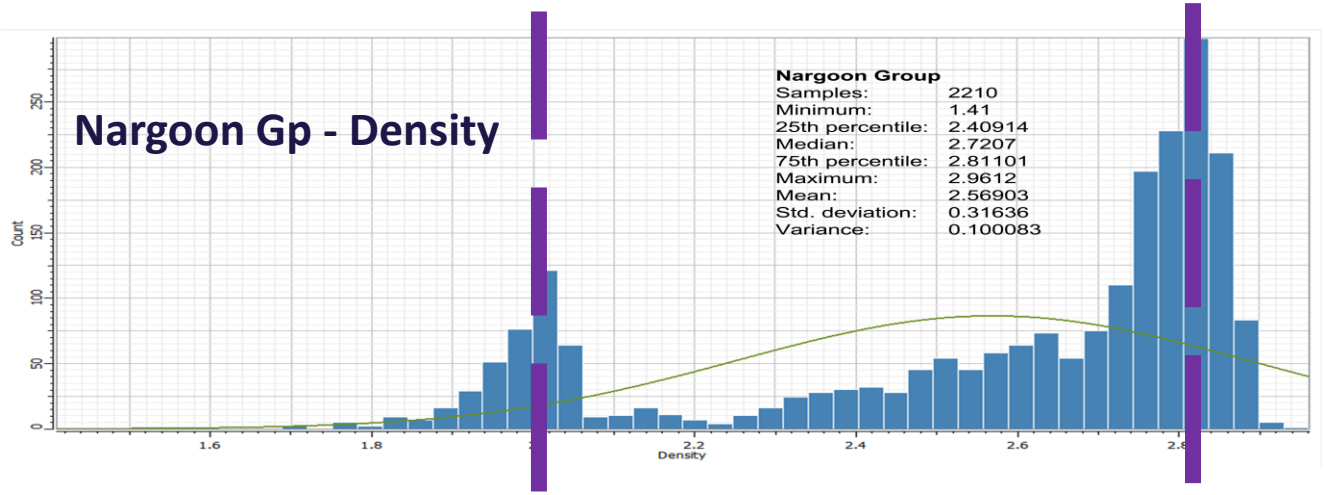
- Better definition of property value distribution
  > (multi) bi-modal; skewness etc.
- Particularly when describing a stratigraphic unit comprising multiple lithologies
- Large sample size acquired by MSCL is ideal
- Limited geological context

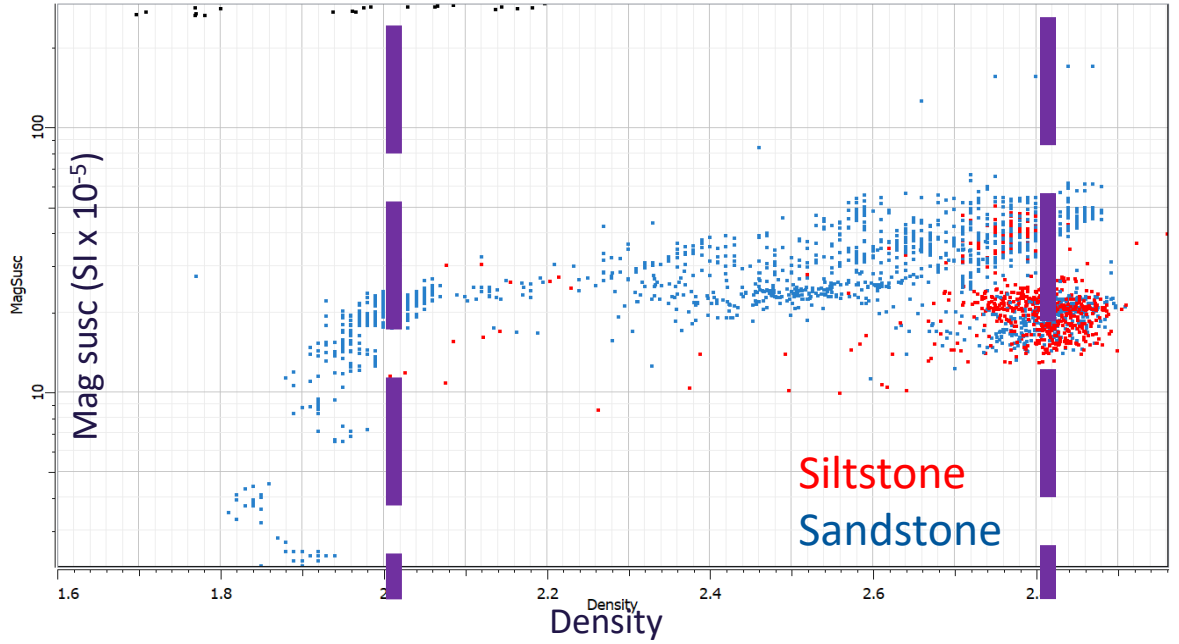




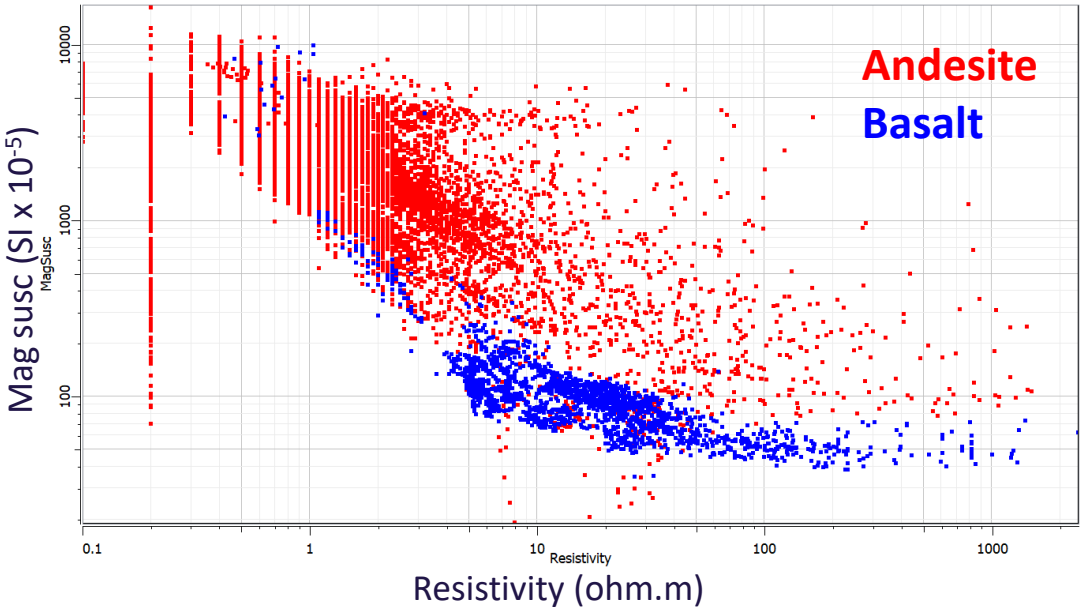
Multivariate Data Fusion – Geological Differentiation

- Coincident multiple property data acquired MSCL scanning enables multivariate data fusion
- Spatially coincident multi-property data provide additional information
- Allows lithology / stratigraphy differentiation

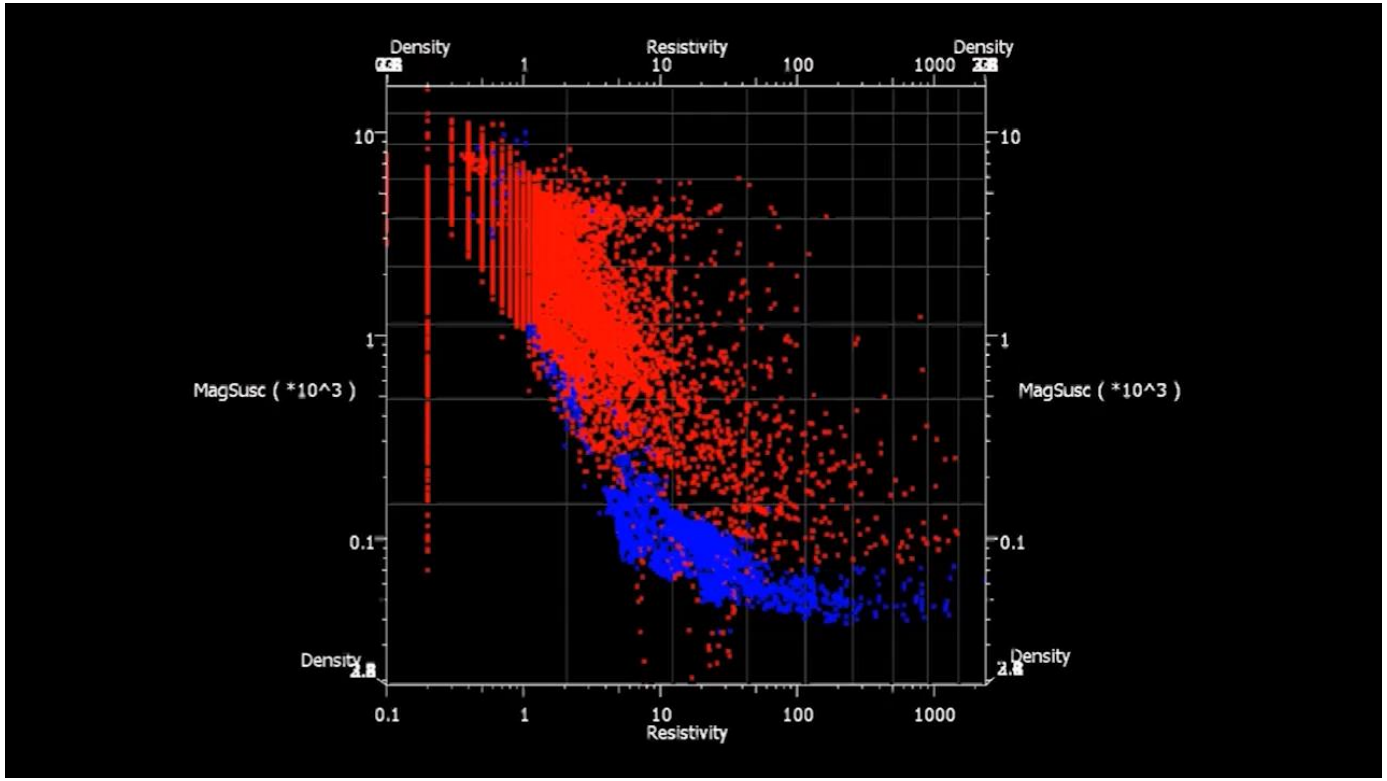




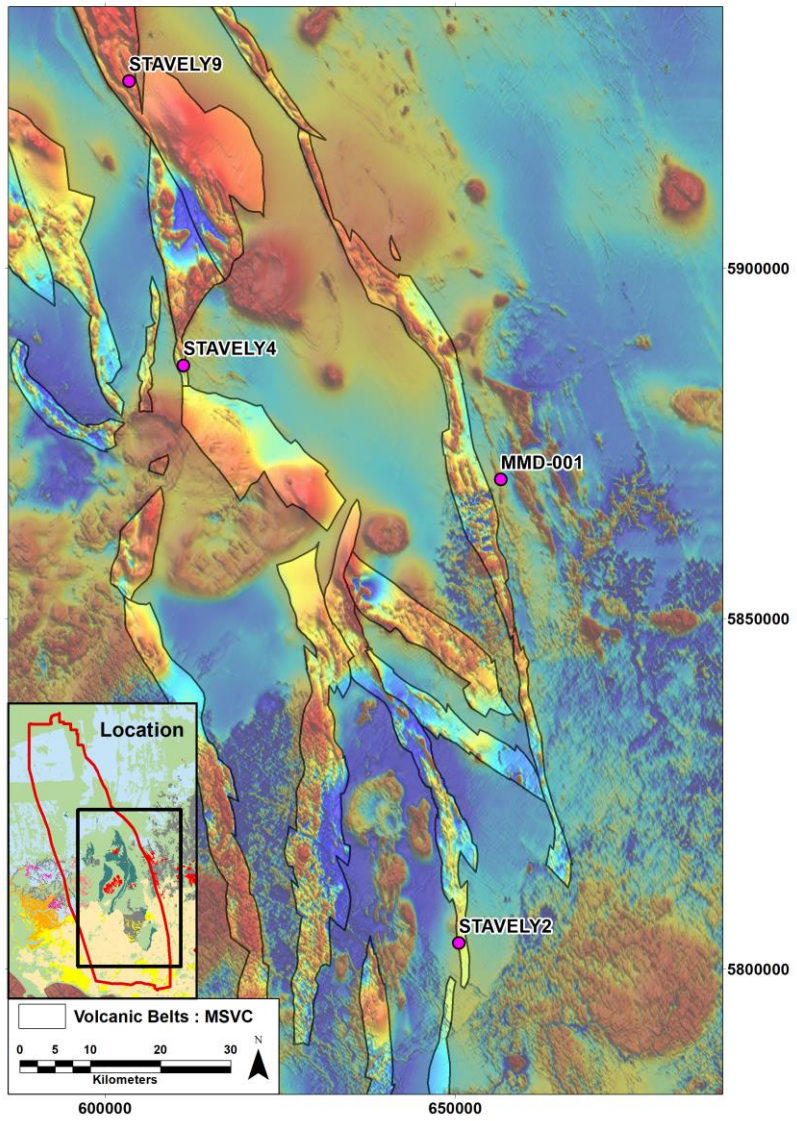
Multivariate Data Fusion – Geological Differentiation

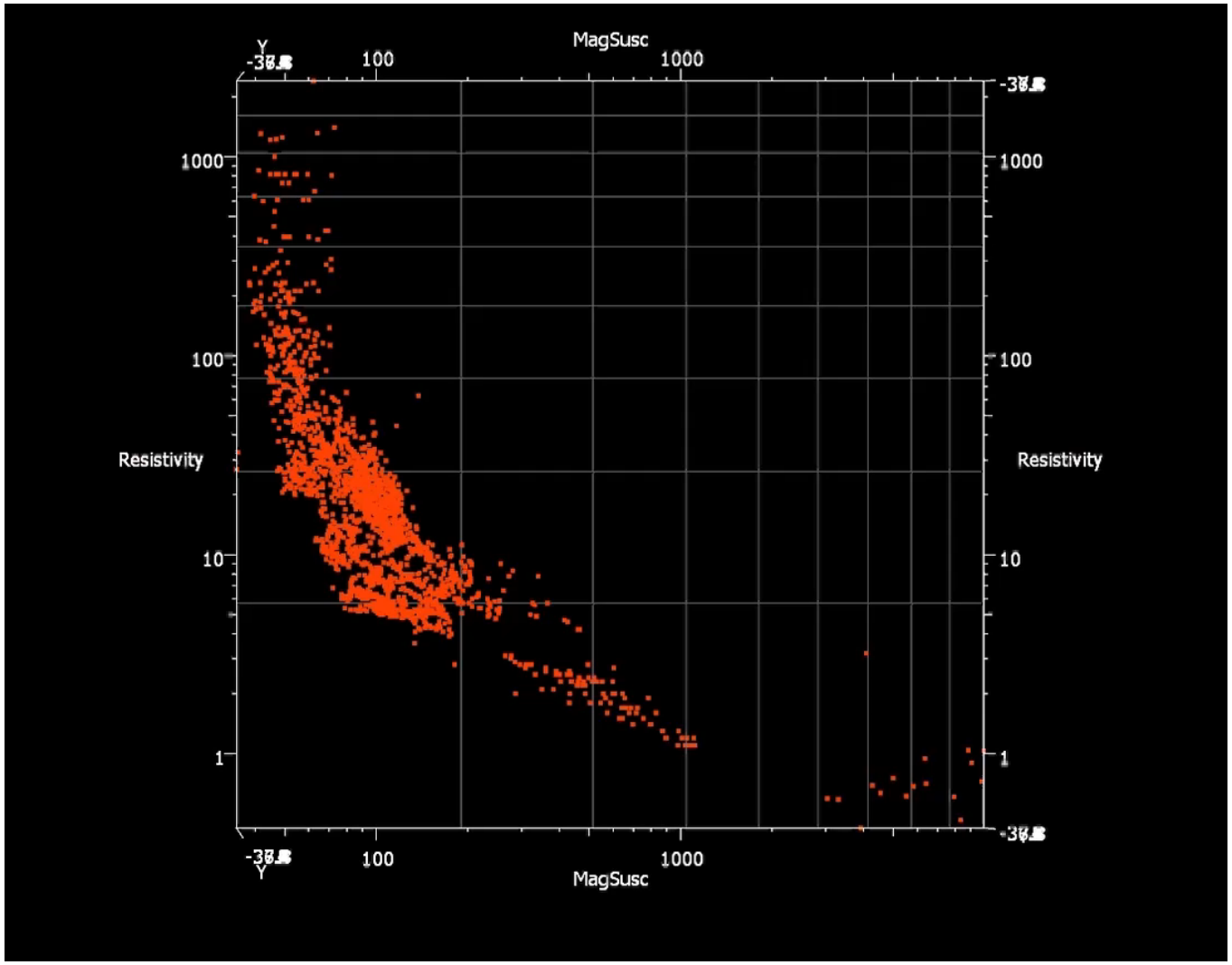


Overlap of properties in cross-plot from different lithologies.

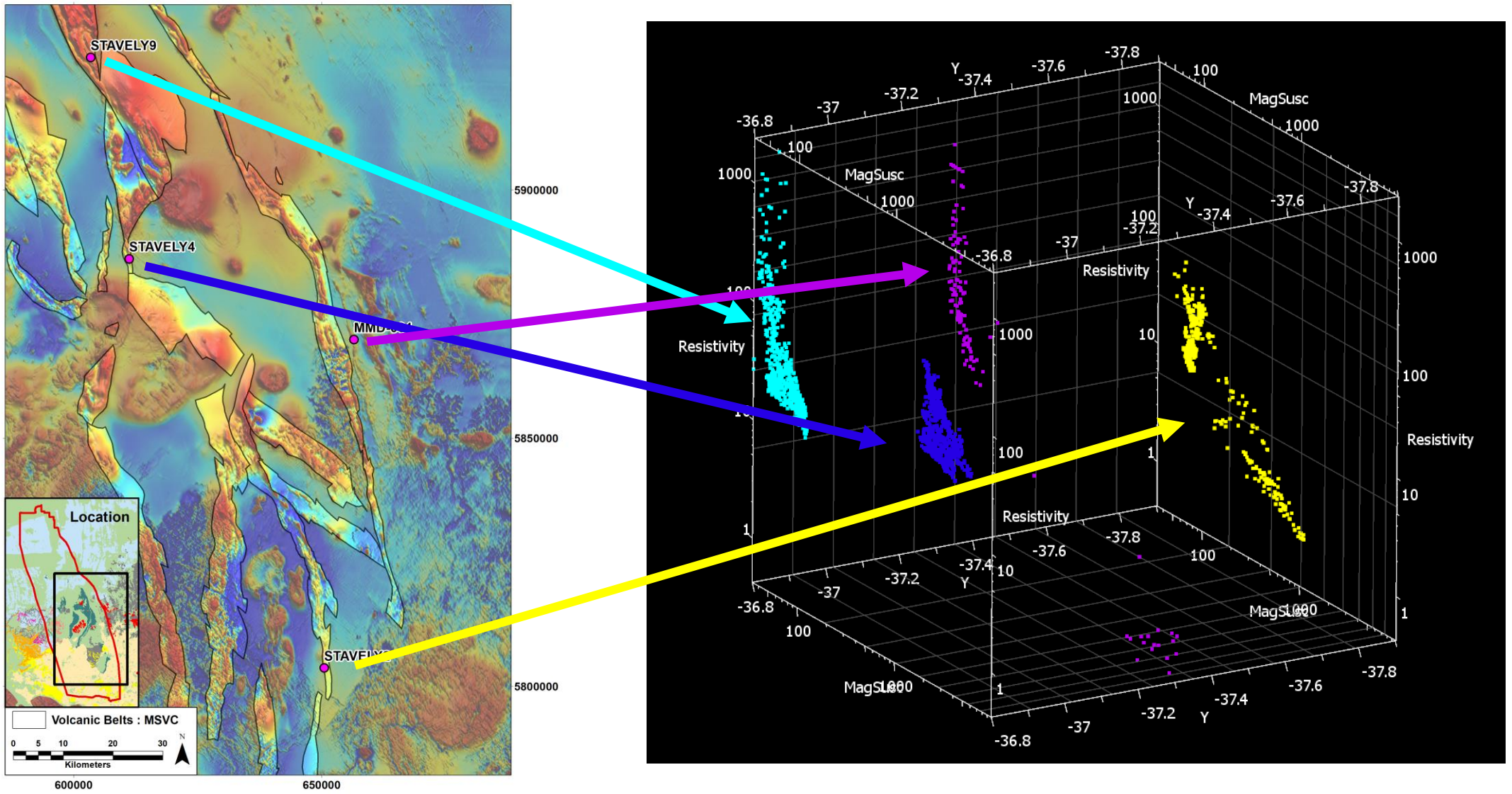


Multivariate Data Fusion – Spatial Correlations: Basalt





Multivariate Data Fusion – Spatial Correlations: Basalt

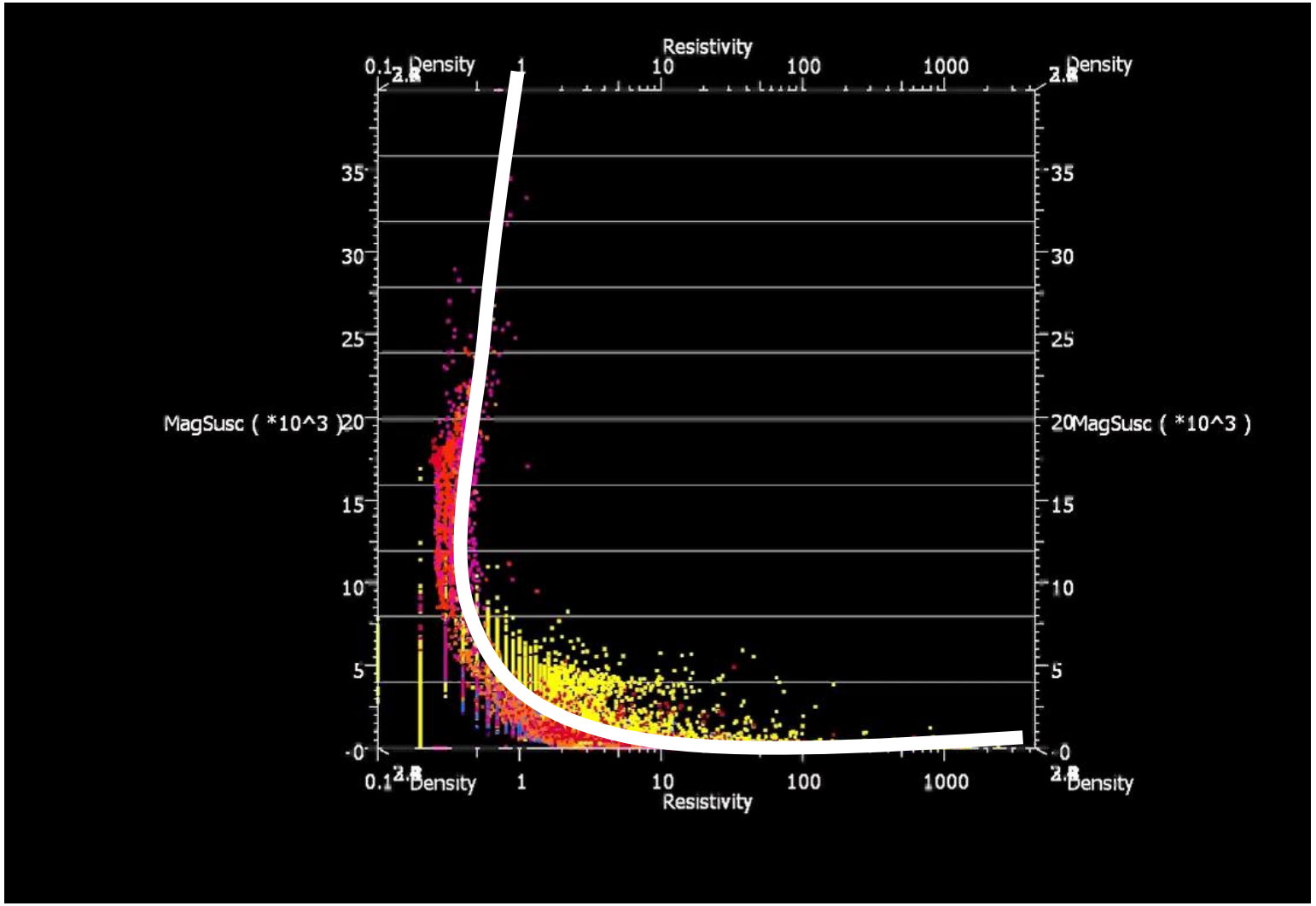


Multivariate Data Fusion – Trends

Mount Stavely Volcanic Complex

- Mag Susc vs Resistivity trend reversal
  - Potentially indicating multiple processes controlling the relationship between properties?

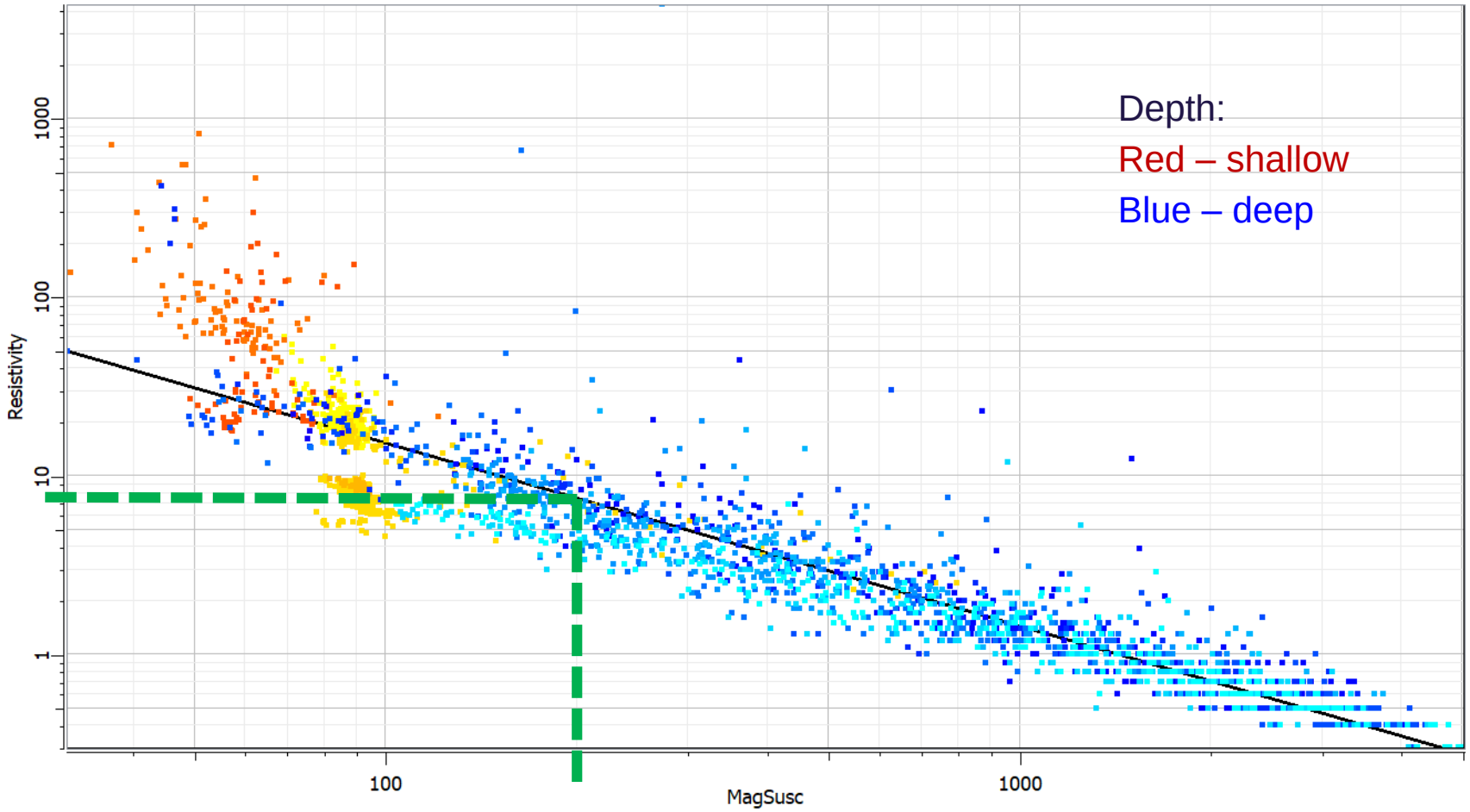
Colours represent lithology



Multivariate Data Fusion – Property Estimations

Volcanic breccia (MSVC)

- Estimation property using relationship to another known property
- Probabilistic vs Deterministic approach

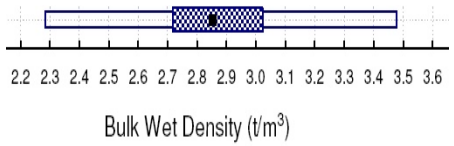


Increasing geological information

Better correlation between geophysics and geology

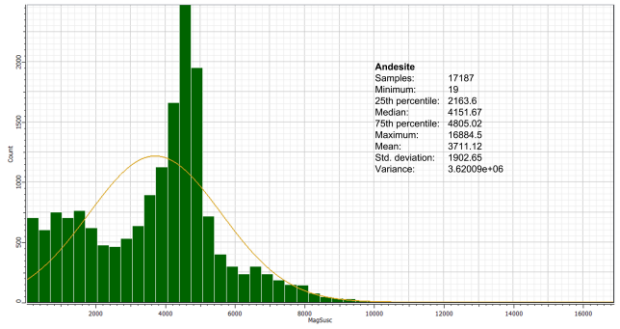
Single property

Mean and range



Box plot

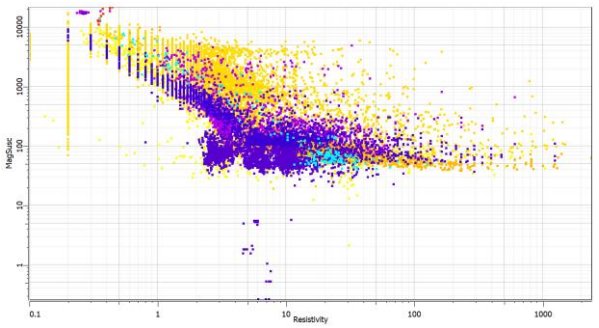
Probability distribution



Frequency histogram

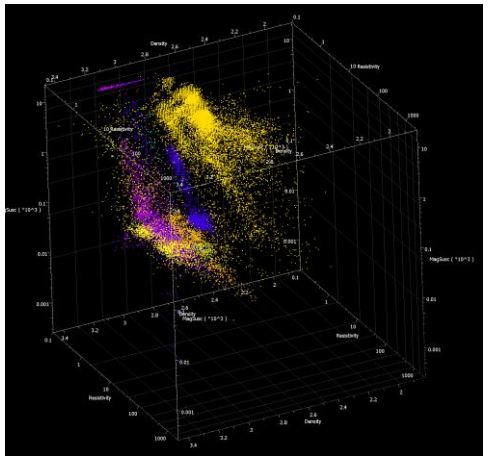
Multivariate Data Fusion

Spatial distribution



2D multivariate cross-plot

Geological differentiation

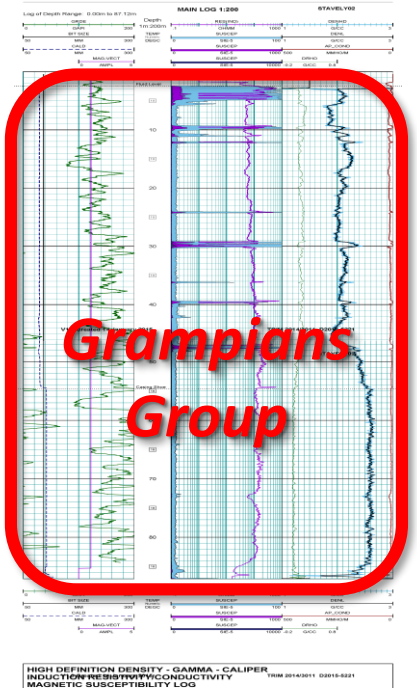


3D multivariate scatter plot

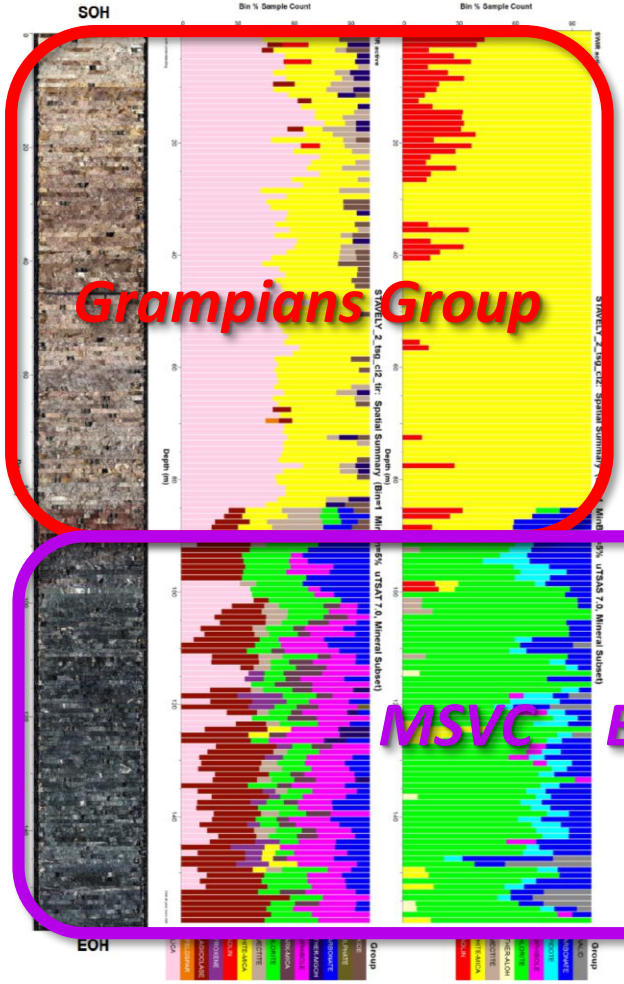
Integration with Complimentary Geological Datasets

Drill Hole Stavely02

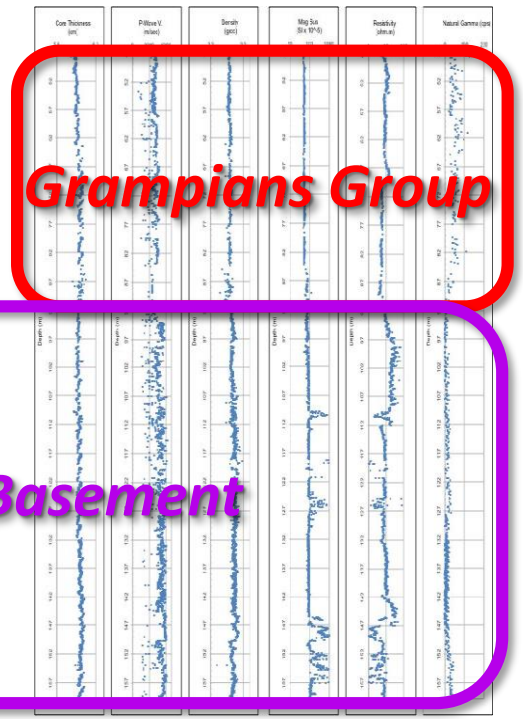
Wireline logs

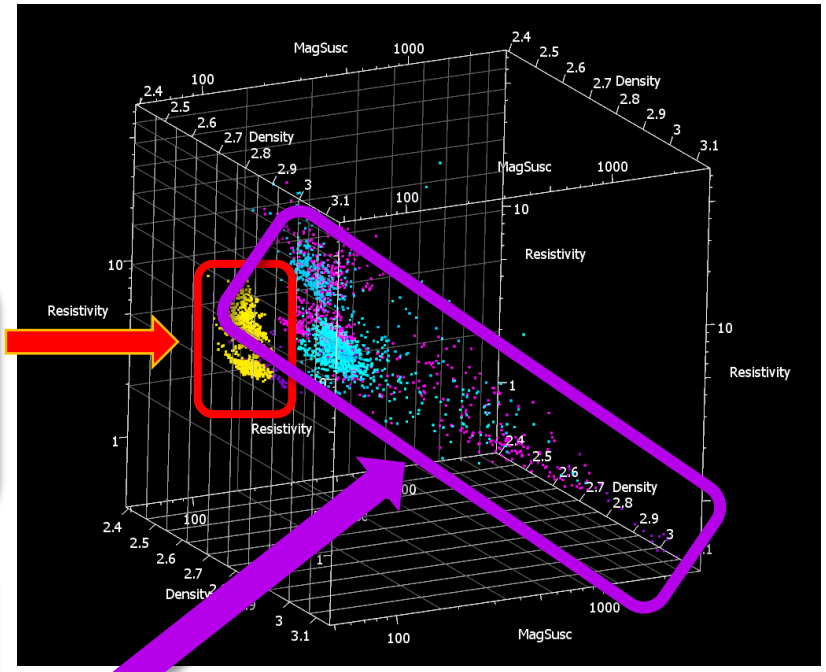


Hylogger



Multi Sensor Core Logger





Colours represent lithology

+Mineralogical data

+Geochemical data

+XRF/XRD

Talk outline

- The Stavely Project overview
- Multi-Sensor Core Logger – data acquisition, validation and collation
- Data analysis and fusion – multivariate property data
- **Modelling the Stavely Arc**
- Conclusions

Petrophysical data applications

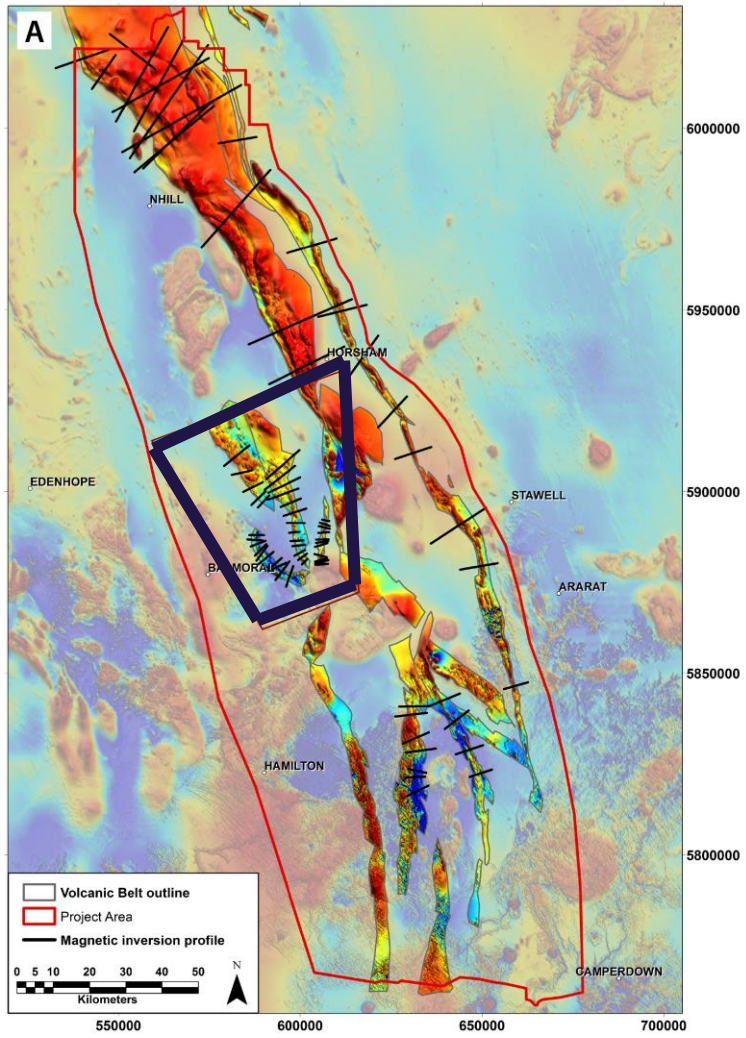
- Geological - geophysical correlation
- Constraints for inversion/forward modelling
- Anomaly drill test confirmation
- Refine data interpretation
- Baseline physical property values
- Identification of anomalous zones – e.g. alteration
- Geophysical survey planning
- Geophysical feasibility studies

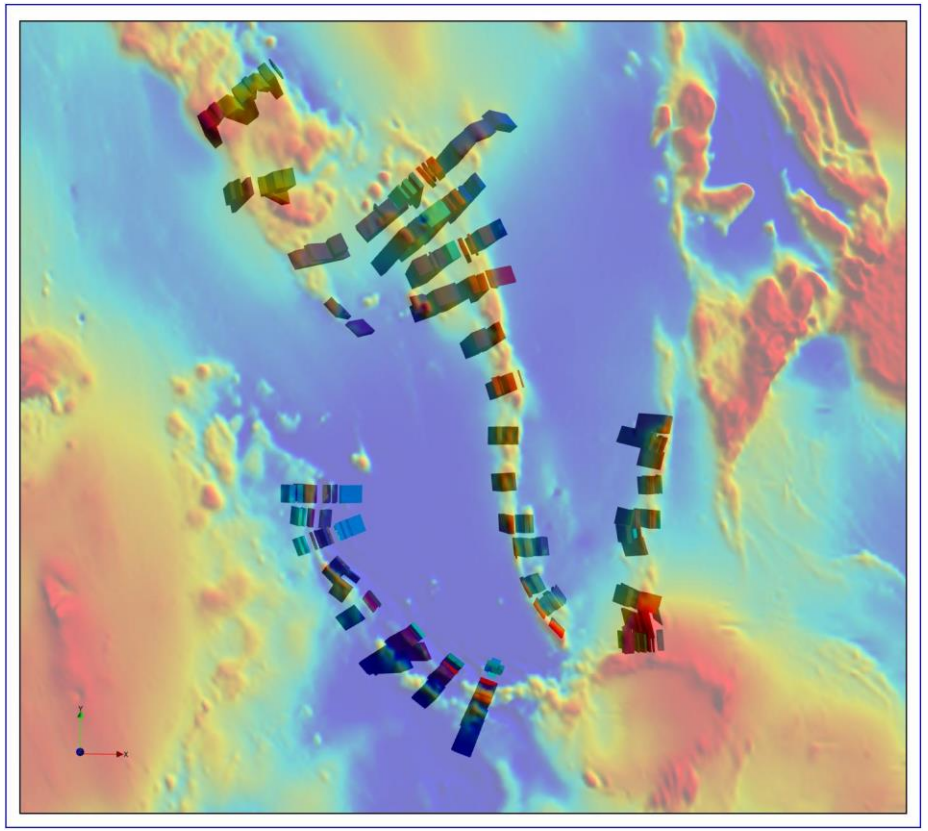
Petrophysical data applications

Value add to expensive geophysical datasets

- ***Geological - geophysical correlation***
- ***Constraints for inversion/forward modelling***
- **Anomaly drill test confirmation**
- **Refine data interpretation**
- **Baseline physical property values**
- **Identification of anomalous zones – e.g. alteration**
- **Geophysical survey planning**
- **Geophysical feasibility studies**

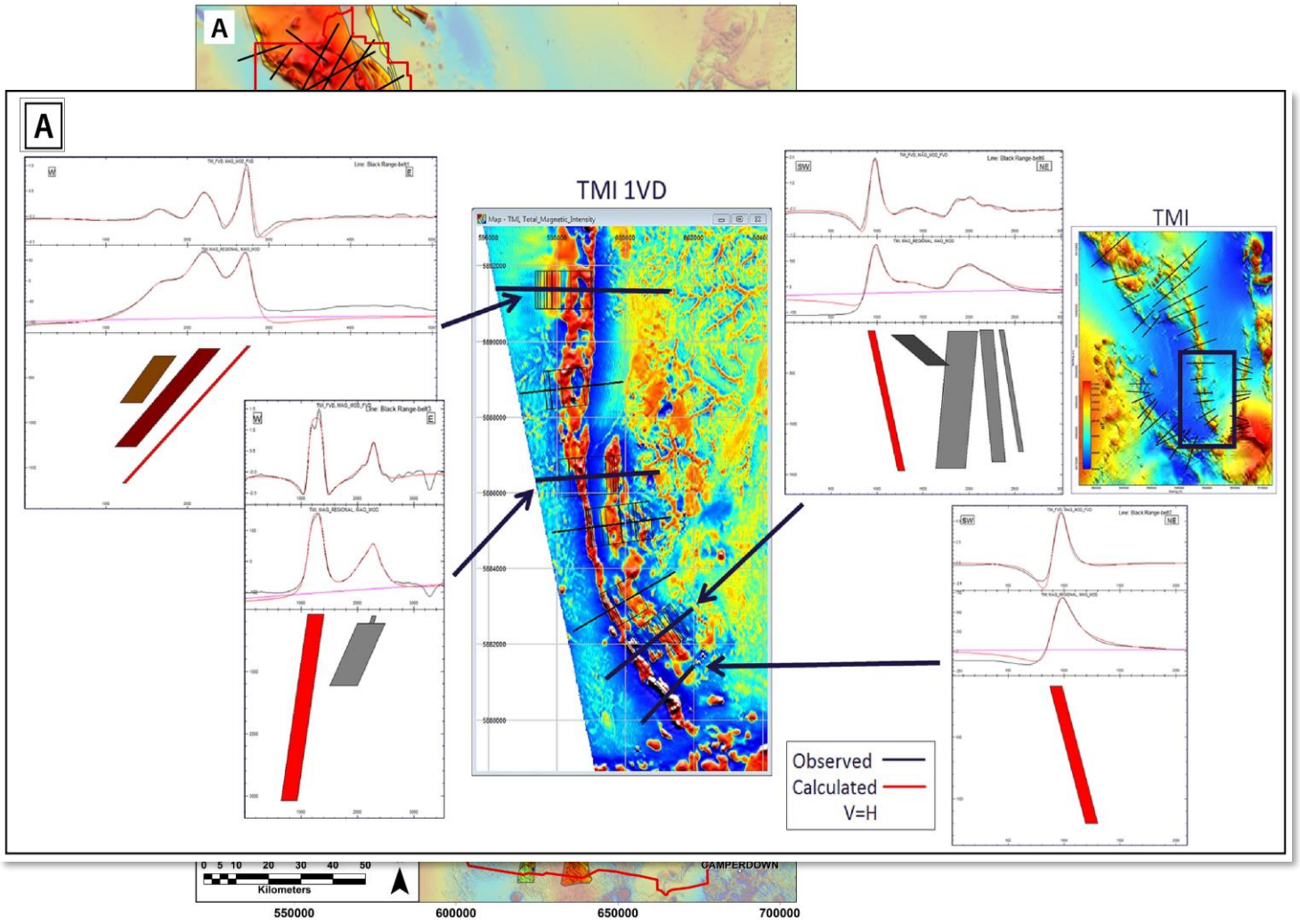
Magnetic Inversion Modelling

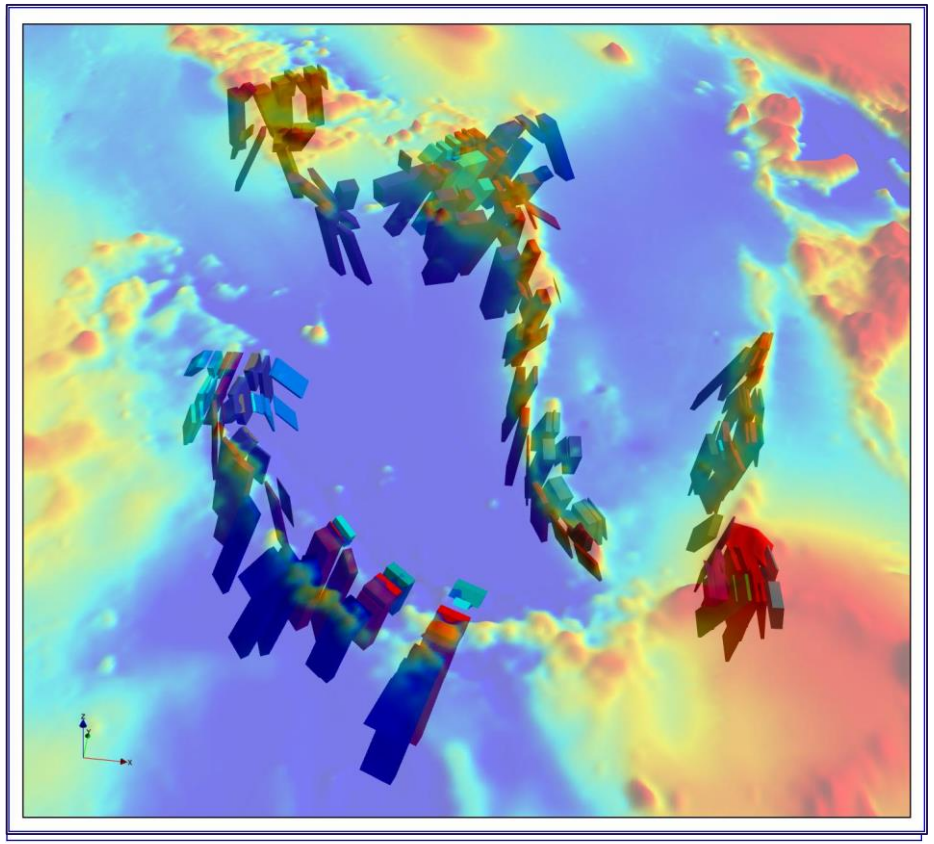




Black Range region

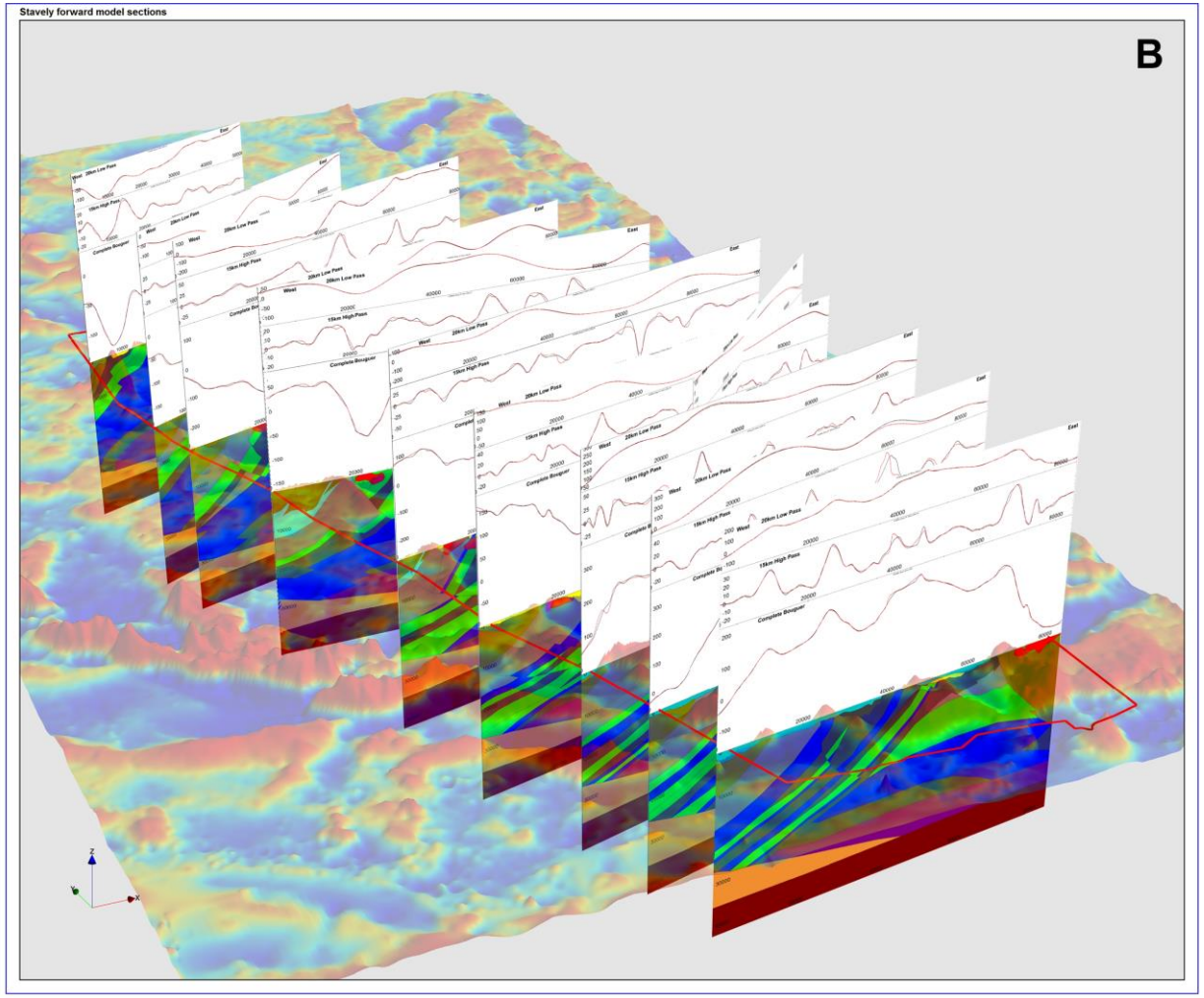
Magnetic Inversion Modelling

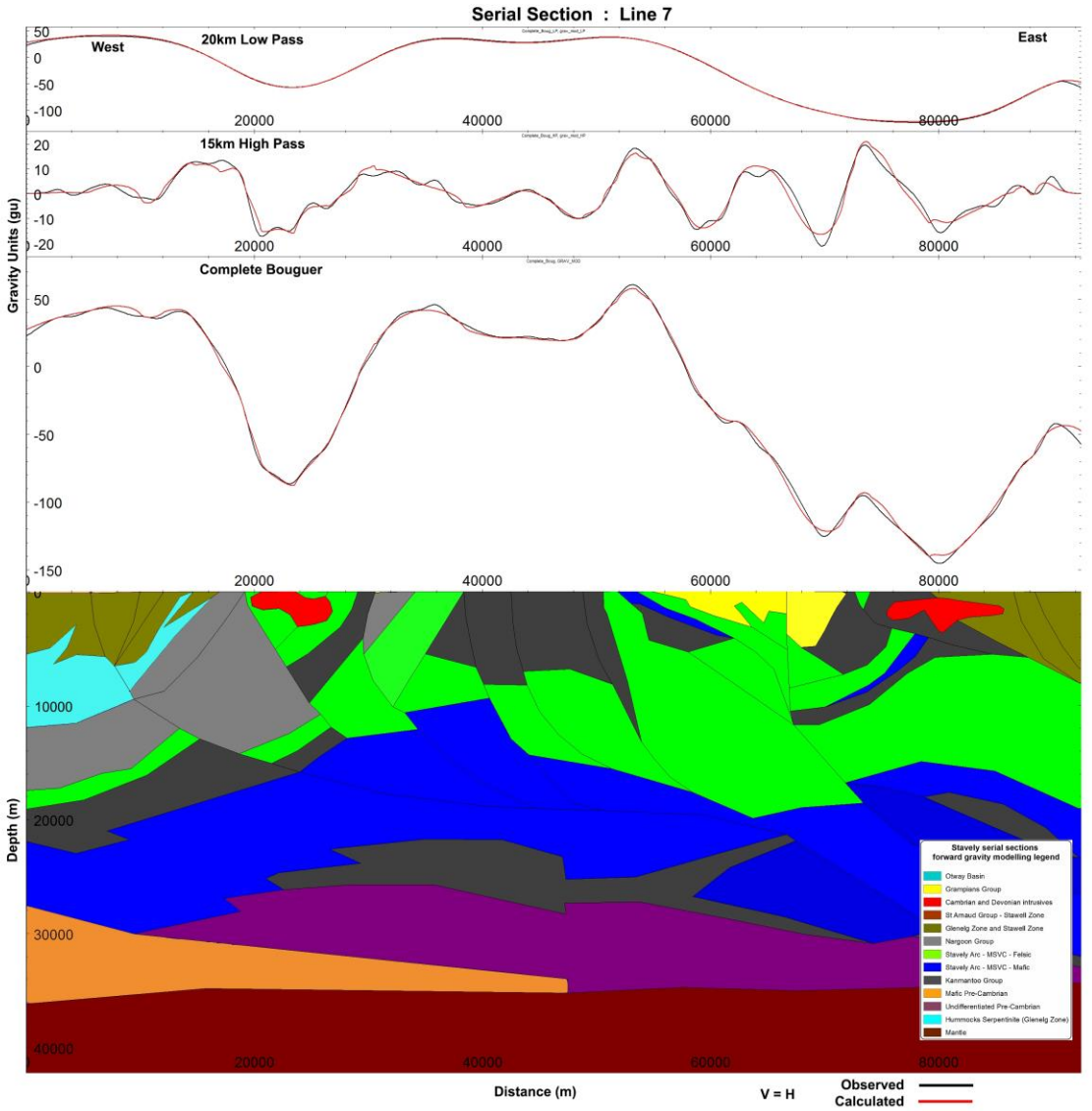




Black Range region

Gravity Forward Modelling





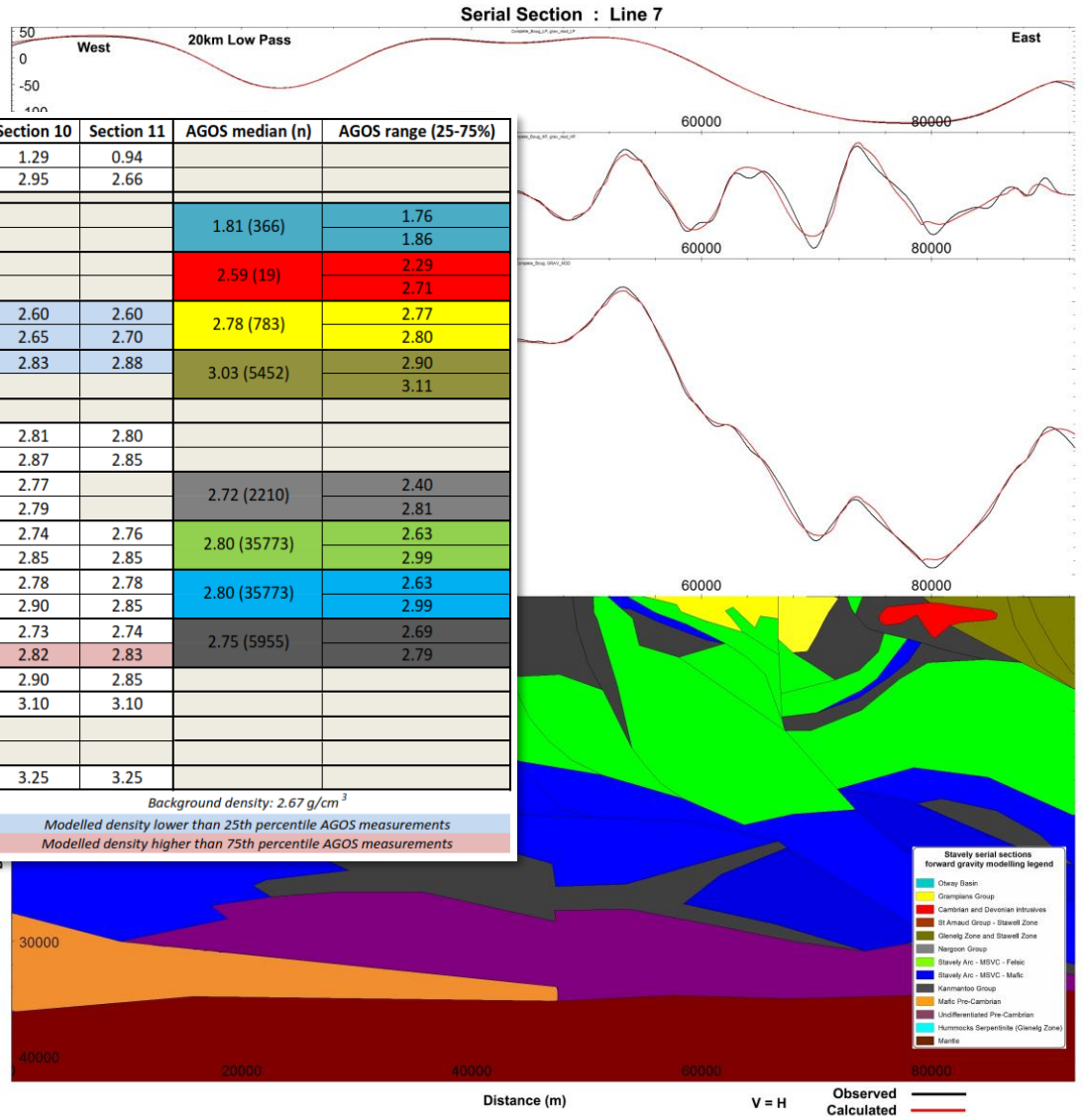
Gravity Forward Modelling

Forward gravity model densities	(g/cm^3)	Section 1	Section 2	Section 3	Section 4	Section 5 (AR1)	Section 6	Section 7 (SD1)	Section 8	Section 9	Section 10	Section 11	AGOS median (n)	AGOS range (25-75%)
RMS of modelled to observed profile	TC_Boug	0.73	4.35	1.91	0.81	2.13	1.25	1.16	2.34	2.33	1.29	0.94		
	HP15	3.41	8.69	4.12	2.05	9.11	4.07	4.45	2.31	3.31	2.95	2.66		
Otway Basin	Min	2.50	2.40	2.50									1.81 (366)	1.76
	Max	2.55	2.50											1.86
Intrusives	Min	2.62	2.60	2.75	2.50	2.65	2.45	2.65	2.60	2.61			2.59 (19)	2.29
	Max		2.67		2.76		2.66		2.75	2.64				2.71
Grampians Group	Min	2.60	2.64	2.60	2.62	2.67	2.63	2.65	2.65	2.65	2.60	2.60	2.78 (783)	2.77
	Max			2.76	2.65	2.75	2.68	2.68	2.68		2.65	2.70		2.80
Moornambool Metamorphic Complex	Min	2.68	2.76	2.79	2.82	2.79	2.73	2.79	2.78	2.69	2.83	2.88	3.03 (5452)	2.90
	Max	2.79	2.78	2.86	2.91	2.88	2.80	2.85	2.80	2.77				3.11
St Arnaud Group						2.79	2.68							
Glenelg River Metamorphic Complex	Min	2.77	2.69	2.70	2.84		2.78	2.77	2.81	2.76	2.81	2.80		
	Max			2.72			2.80	2.80		2.81	2.87	2.85		
Nargoon Group	Min	2.72	2.70	2.70	2.75	2.75	2.73	2.72	2.73	2.70	2.77		2.72 (2210)	2.40
	Max	2.73	2.82	2.80	2.78		2.77	2.77	2.80	2.76	2.79			2.81
MSVC felsic	Min	2.77	2.76	2.75	2.62	2.71	2.72	2.70	2.75	2.75	2.74	2.76	2.80 (35773)	2.63
	Max	2.83	2.90	2.84	2.89	2.83	2.83	2.83	2.85	2.85	2.85	2.85		2.99
MSVC mafic	Min	2.71	2.78	2.85	2.78	2.65	2.76	2.83	2.76	2.77	2.78	2.78	2.80 (35773)	2.63
	Max	2.85	2.95	2.95	2.90	3.00	2.90	3.05	3.00	2.90	2.90	2.85		2.99
Kanmantoo Group	Min	2.72	2.70	2.73	2.75	2.77	2.72	2.73	2.72	2.68	2.73	2.74	2.75 (5955)	2.69
	Max	2.85	2.79	2.81	2.83	2.85	2.85	2.85	2.85	2.83	2.82	2.83		2.79
Mafic Pre-Cambrian		2.90	2.95	2.90	2.90	3.10	2.90	3.00	3.00	2.90	2.90	2.85		
Undifferentiated Pre-Cambrian		3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10		
Hummocks Serpentinite	Min						2.80	2.83	2.91					
	Max							2.84	3.00					
Mantle		3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25		

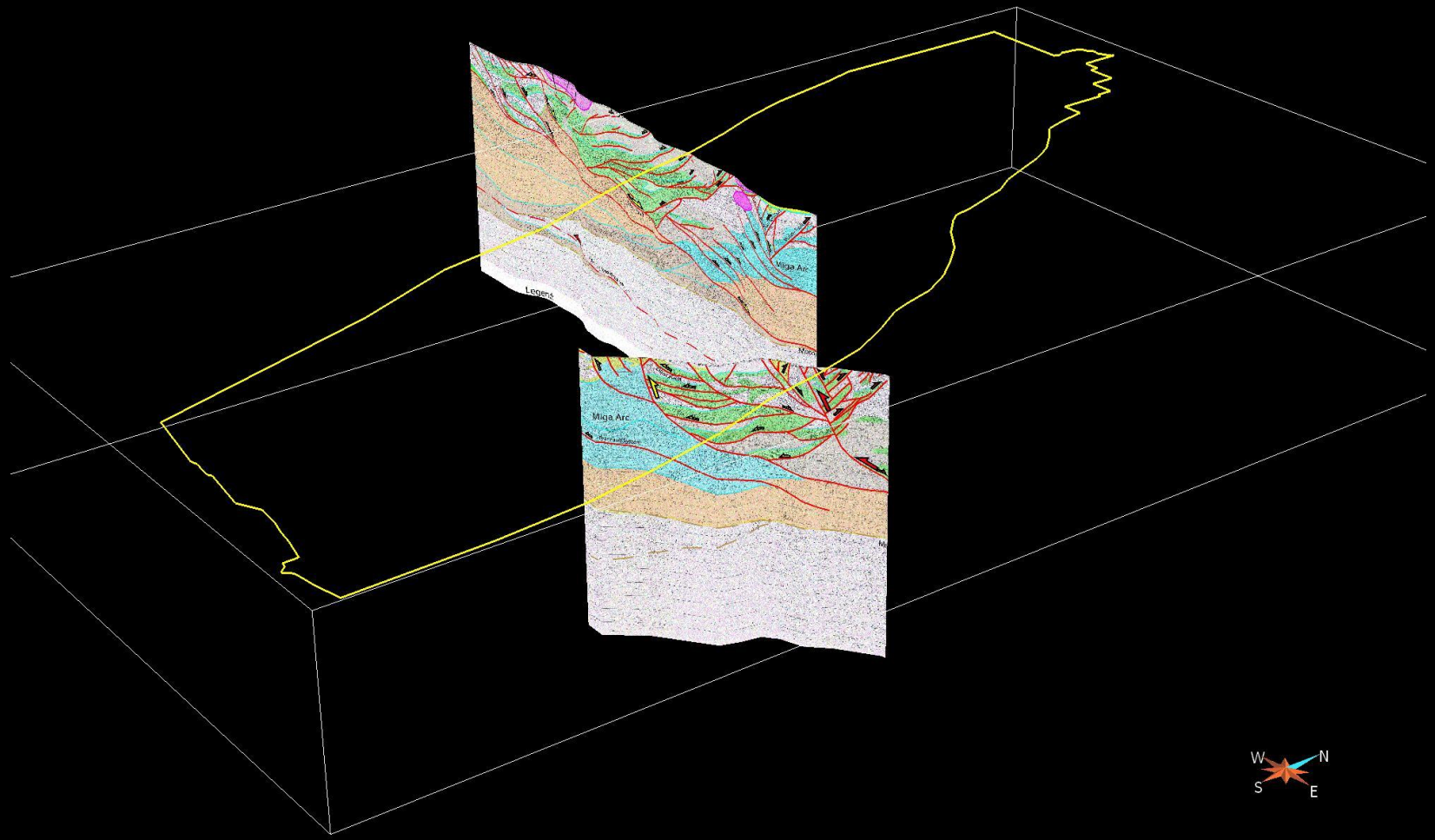
Background density: 2.67 g/cm³

Modelled density lower than 25th percentile AGOS measurements

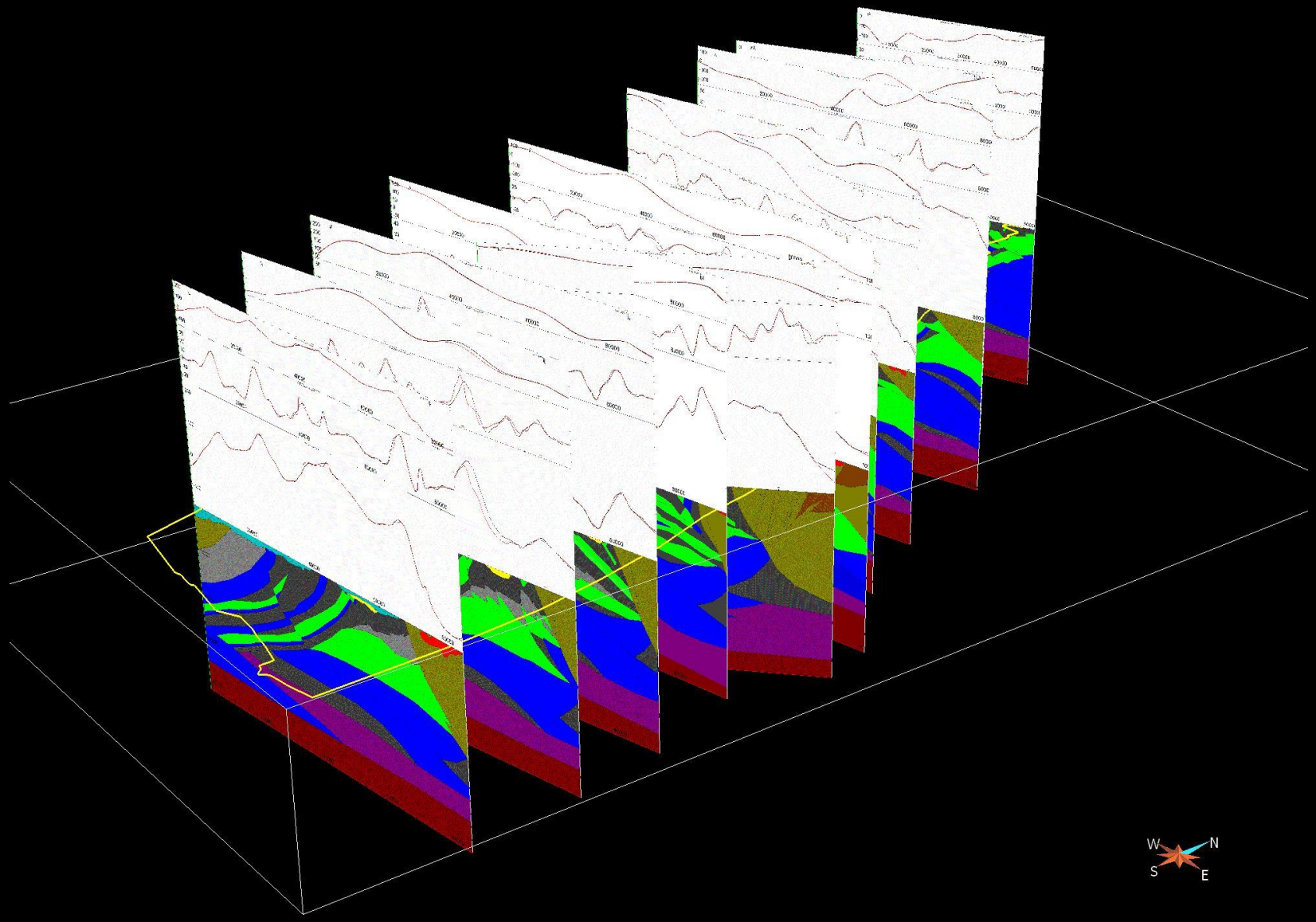
Modelled density higher than 75th percentile AGOS measurements



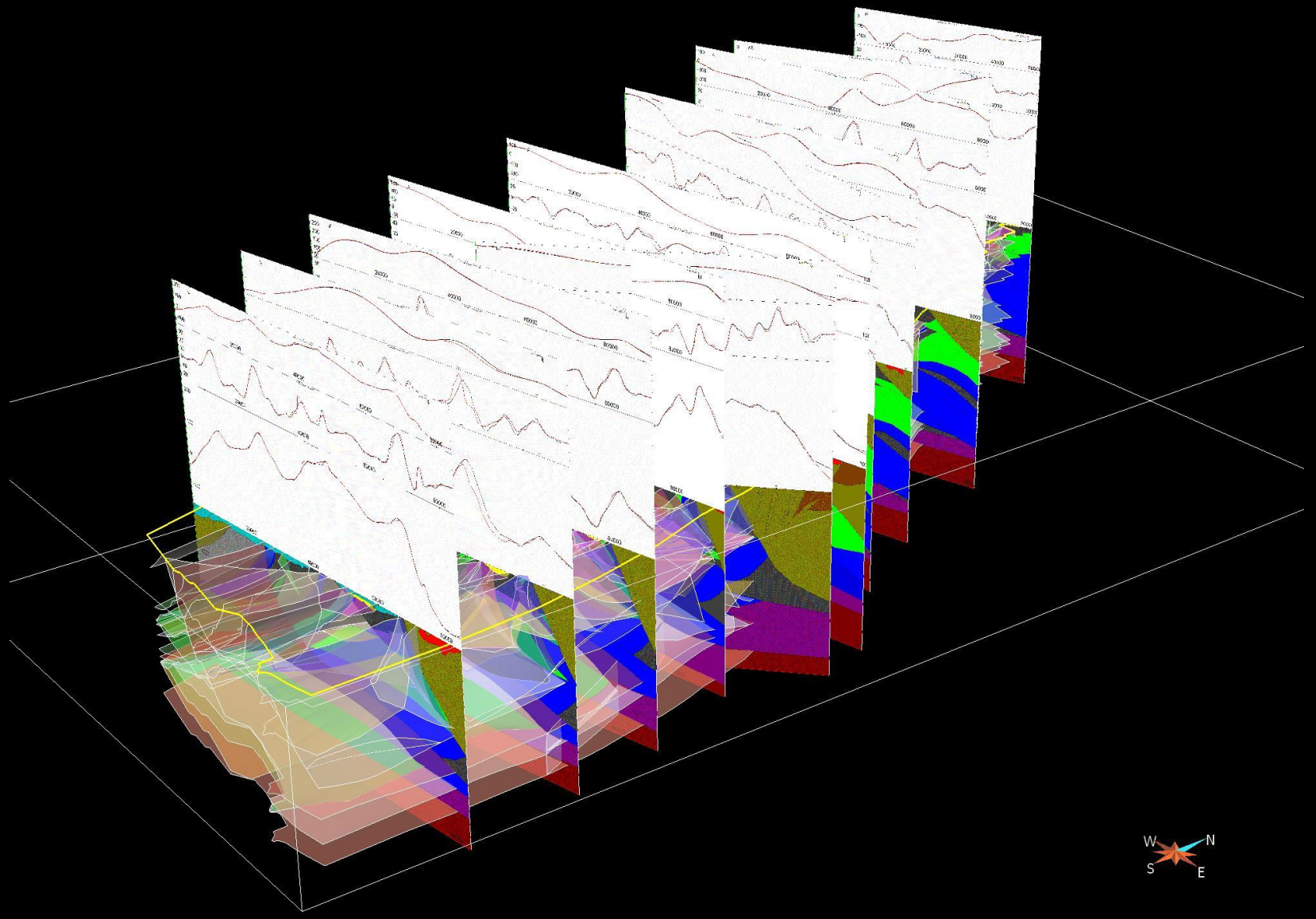
3D model – seismic sections



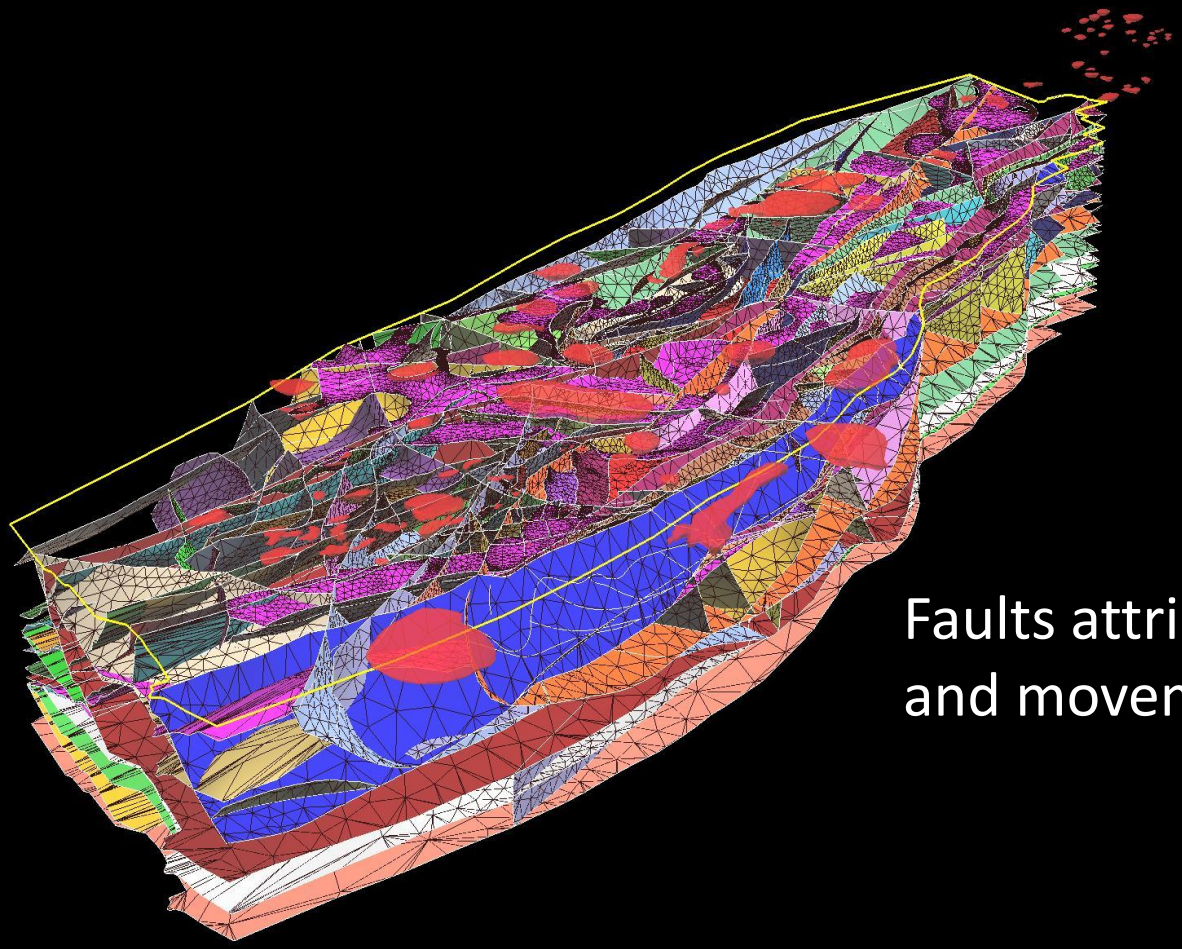
3D model – forward modelled serial cross-sections



3D model – build fault surfaces



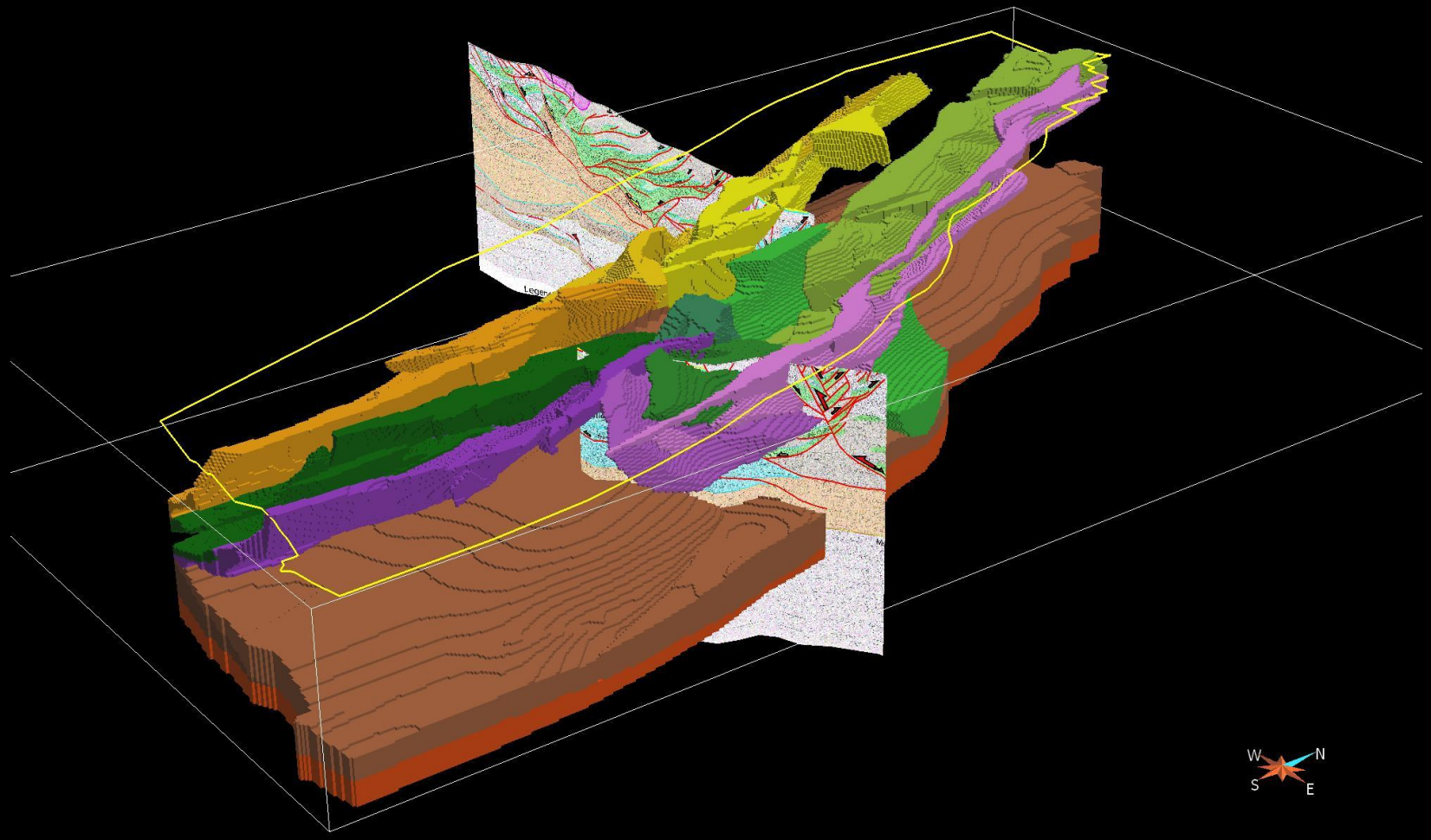
3D model – fault surfaces and intrusives



Faults attributed with timing and movement sense

3D model – voxet model

Volumes representing Stavely Arc volcanic belts



Conclusions

- Acquire more multi-property datasets
  > core held in core libraries = millions (+) of potential rock property determinations!

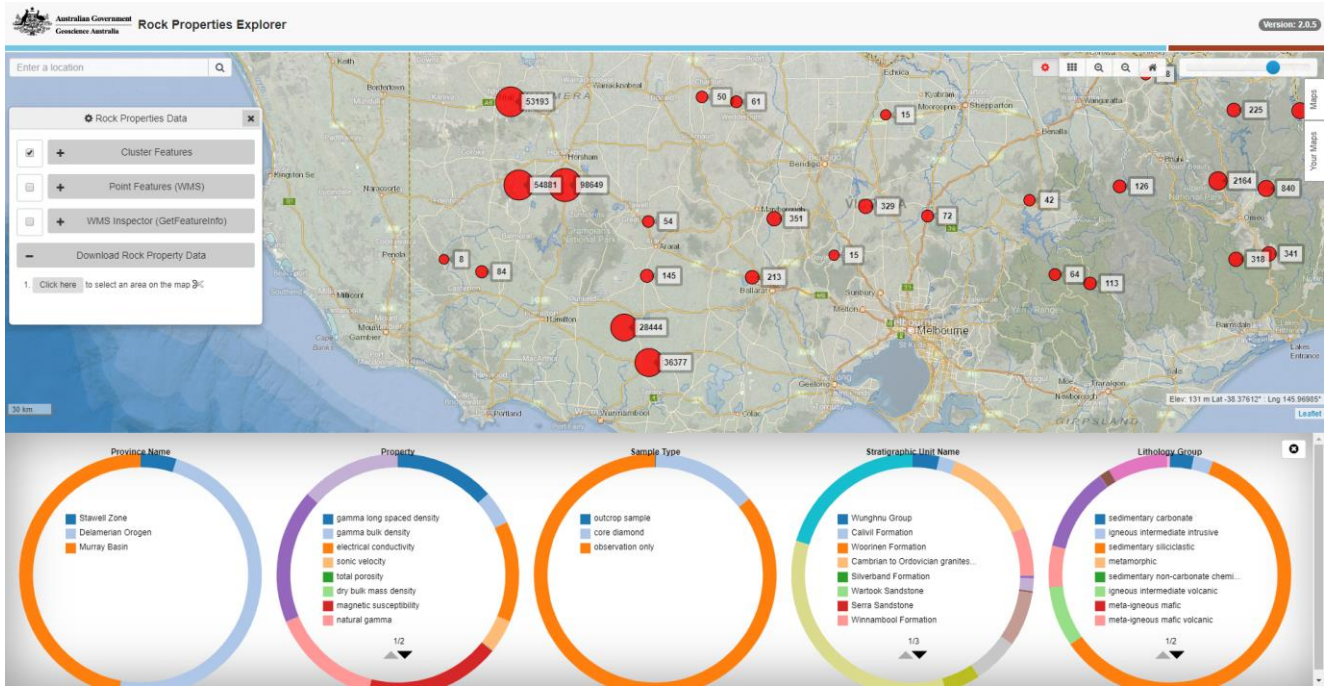
- Move beyond *mean and range* property descriptions

- Think about the geological environment and what it means for petrophysical data
  > Integrate with complimentary geological datasets

- Machine learning / AI……???

http://earthresources.efirst.com.au/product.asp?pID=1167&cID=64&c=22328

Geoscience Australia's Rock Property Explorer portal



http://www.ga.gov.au/explorer-web/rock-properties.html