Learning from Mining: Applications to Unconventional Reservoirs*

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Abstract

Production from unconventional reservoirs is a relatively recent phenomenon. In contrast, mining dates back thousands of years, and as a result has gone through many of the teething problems that are now facing the oil industry. In addition, the hands on nature of mining has provided unique insights into the behaviour of rocks under stress, and the architecture of depositional systems.

Examples that will be presented include a Portland Stone mine in the United Kingdom, which is mining building stone using a room and pillar system, the only mine of this type in the country. The mine has accessed natural fractures in the subsurface, as well as complex depositional patterns highlighted by chert replacement, that have necessitated novel mining approaches that can readily be applied to unconventional production.

Another mine under the spotlight will be St. Helena Gold Mine in the Free State of South Africa. A unique data set has been collected from the Leader Reef Zone of the Witwatersrand Supergroup, exposed close to one kilometre underground. A total of 156 sections, ranging from less than 1 metre to around 3 metres in thickness, were measured through this stratigraphic horizon. The dimensions of the entire study area were around 120 metres by 150 metres. These sections were used to construct a complex 3-dimensional depositional model, which was then populated by a proxy for reservoir porosity. The resulting model of porosity distribution allows wells to be placed with maximum efficiency in a braided river depositional system. The methodology can be directly applied to other depositional settings.

Even mines focusing on igneous rocks and their associated minerals can yield important data on fracture distribution and fault behaviour. Examples from chromitite and vanadium mines in Mpumalunga, mining within the Bushveld Complex in South Africa, demonstrate how even relatively small scale faulting can prove disastrous to horizontal well paths, while slumping and the development of pot holes can actually enhance potential production. The encroachment of gabbro in such subsurface deposits bears many similarities to secondary cementation of reservoirs, with consequent potential as an analogue to silica and calcite cements.

In addition to structural and sedimentological interpretation, economic aspects of mining can also provide guidance when assessing new unconventional targets for exploration potential. Models will be presented that demonstrate how mining models can be applied in the subsurface. Current economic analyses focus on spreadsheets, but kriging and other statistical tactics can enhance results and the under-standing of production potential. Overall it is clear that we have barely scratched the surface of a valuable and de-tailed database with the potential for huge synergies with the energy industry.

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Learning from Mining: Applications to Unconventional Reservoirs

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Introduction

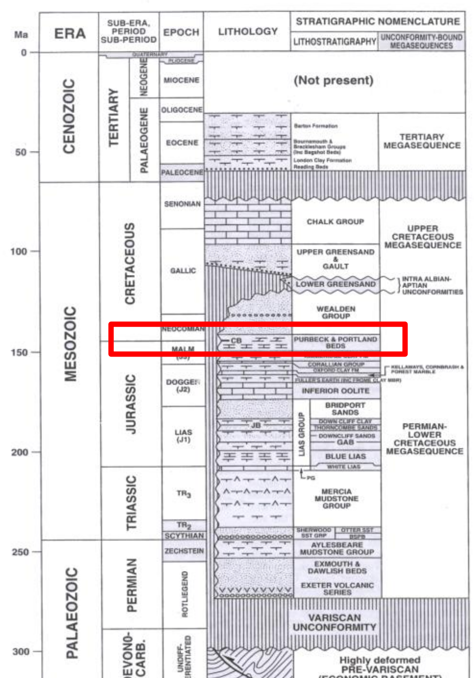
- Mining dates back thousands of years and has built on this pedigree
- The ability to get "inside the rocks “ means that detailed geology can be undertaken
- The range of deposits has led to a wide variety of potential learnings, from both sedimentary and igneous rocks.
- Today we will look at:
    - A building stone mine in Portland, UK
    - A gold mine in South Africa
    - The untapped power of kriging
    - A platinum mine in South Africa

Grimes Graves, Norfolk: flint mining complex dating back to the Neolithic, around 3000 BC, with 433 mineshafts, pits and quarries

Cementing a friendship: The Isle of Portland

Underground mine on Portland

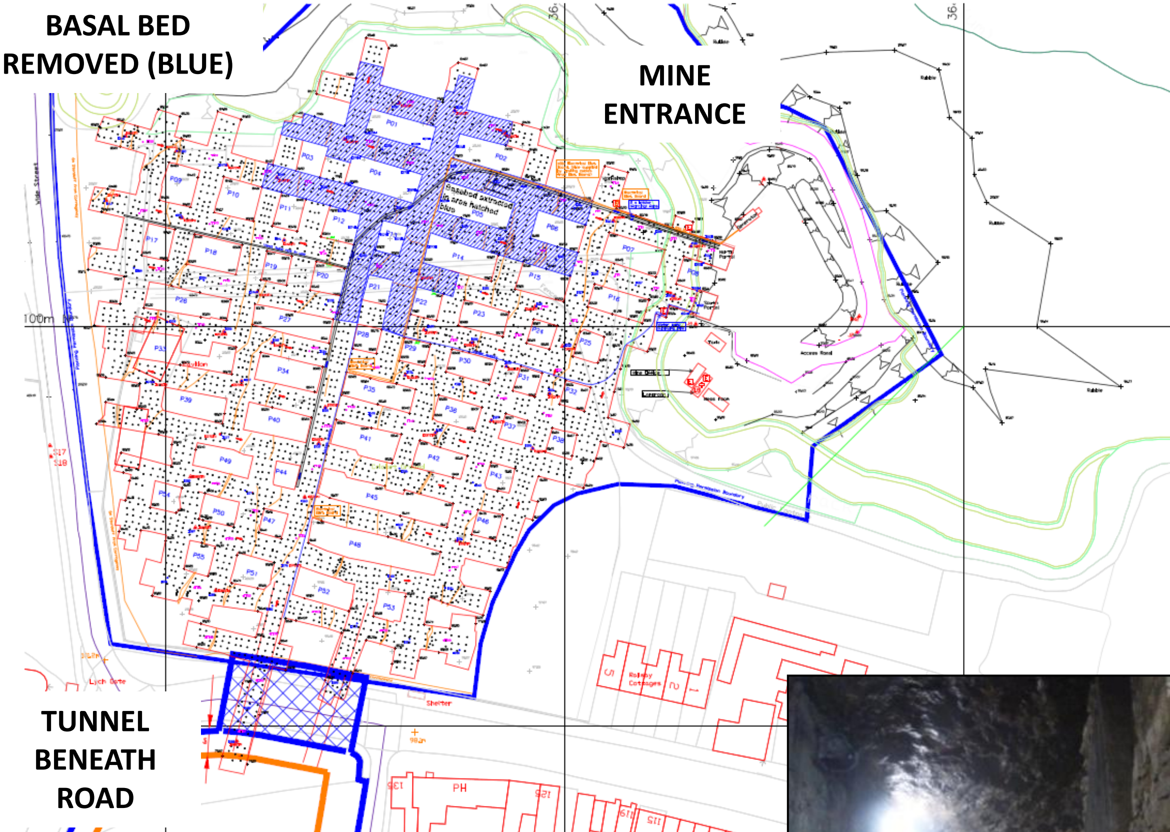
- Mining Portland Limestone
- History of usage in London – Christopher Wren & St. Paul's
- Extensive opencast mining across the Isle of Portland
- Now mining underground due to:
    - Overburden
    - Environmental issues
    - Positive economics



Church constructed of Portland Stone.

Mine planning: New Mine

- Initial pilot project at another mine
- Lessons re block orientation applied in first commercial mine
- Room and pillar system, with 6 m gridding
- Individual blocks sell for $15,000



Challenges for underground mining

- Fractures are open and may reach a metre in dilation.
- Relate to Alpine orogeny, which formed an anticline across the island.
- Now mining to keep fractures in pillars.
- Fractures only extend around 4 m into hangingwall.

- Subterranean channels are occasionally encountered in the mine.
- Would act as thief zones in a well.

Challenges for underground mining

- Patch reef development.
- Cross-beds cemented by flint.
- Hangingwall is a dirt bed, exposure surface:
  - No karstification
  - Tree boles
  - Fairly secure when rock bolted

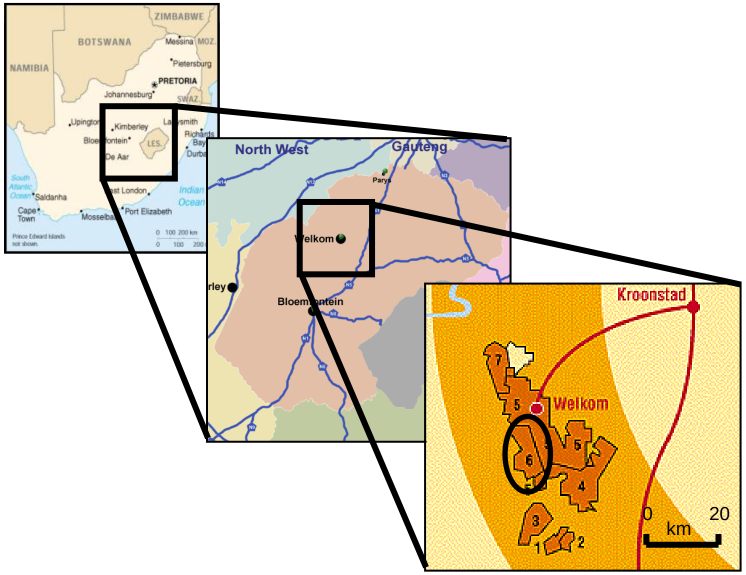
Overall lessons:

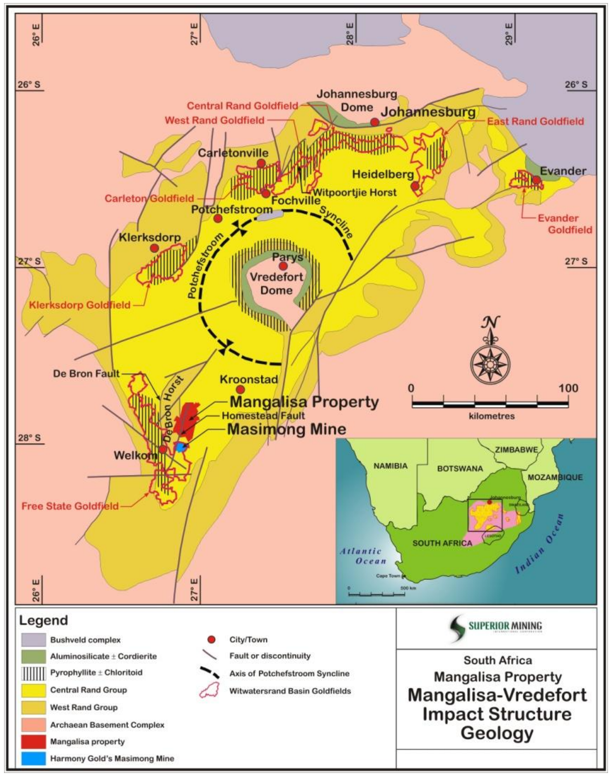
- Fractures are sparse and large.
- No evidence of fracture propagation, even when exposed – may be due to homogeneous groundmass.
- Orientation does not directly match regional fault strike.
- No cementation observed, despite limestone.
- Cross-beds provide baffles or barriers to flow.
- Patch reefs also act as baffles.
- Potential for caves to act as thief zones.

Rivers of Gold

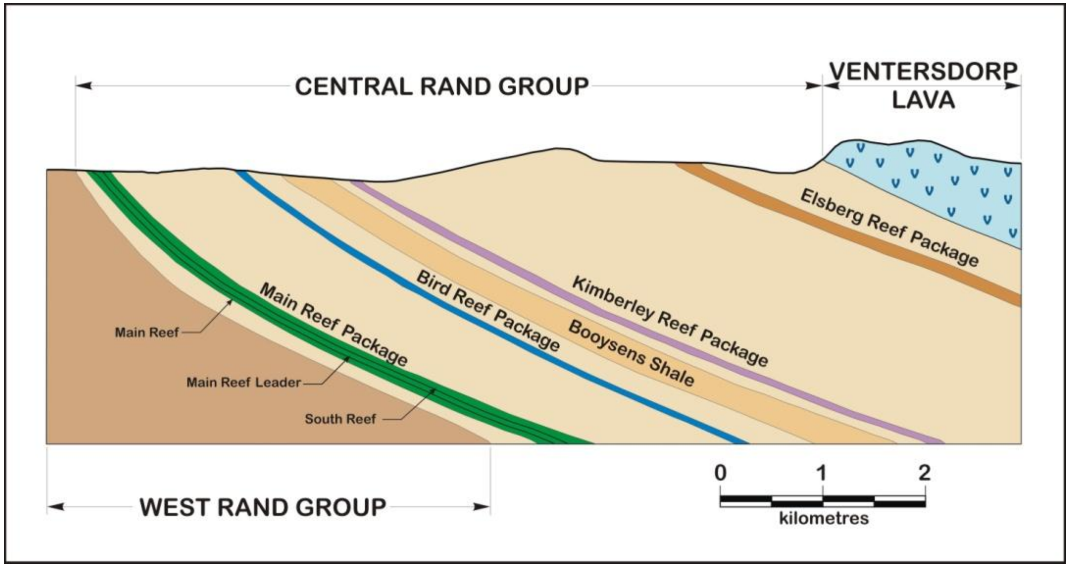
Rivers of gold

- St Helena Gold Mine is located in the Free State, RSA
- Mining lease granted in 1941
- Produced the first bar of Free State Gold in 1953
- Welkom produced 21% of world's gold

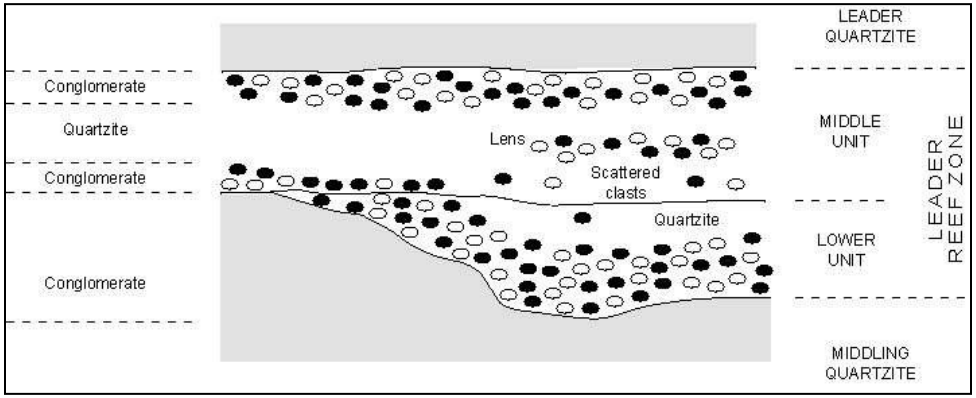




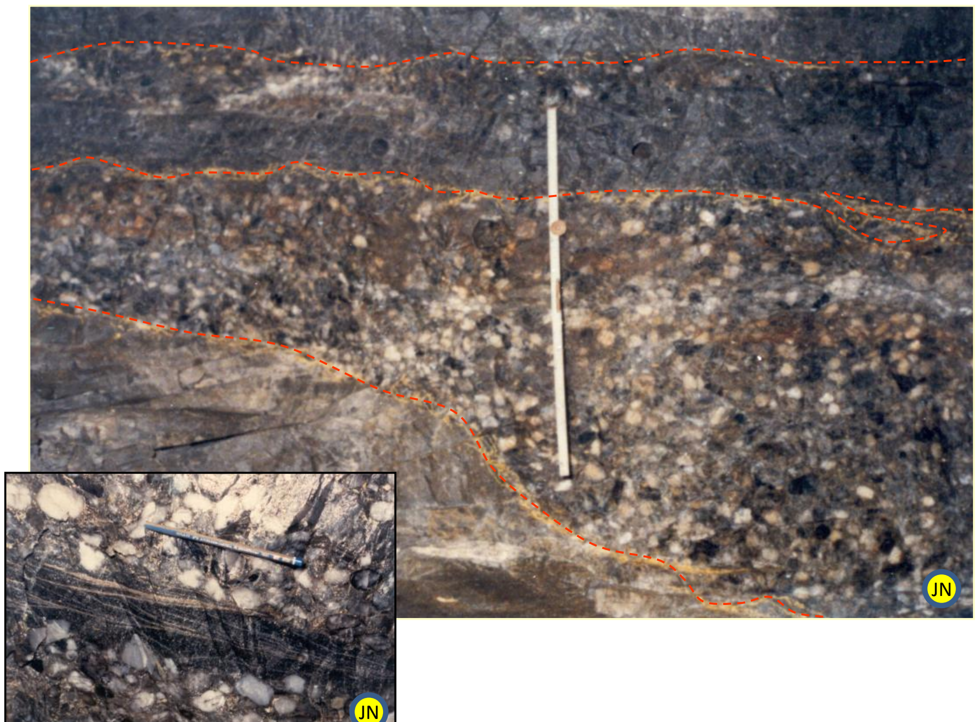
Vredefort Dome is a meteor impact



Depositional system



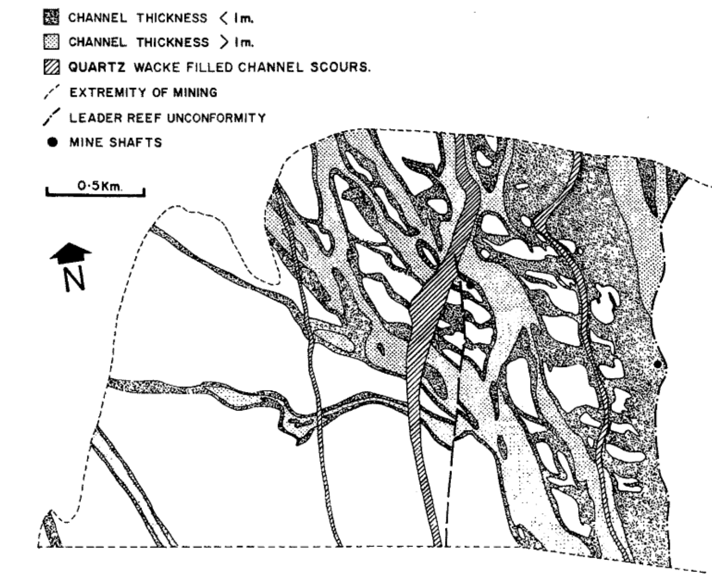
- Leader Reef, 2.9 BB years old.
- Deposited in alluvial fans and braided rivers in Witwatersrand Basin.
- Lower Unit more channelized.
- Upper unit sheet-like.
- Dominated by conglomerates with some quartzite (heavily metamorphosed).



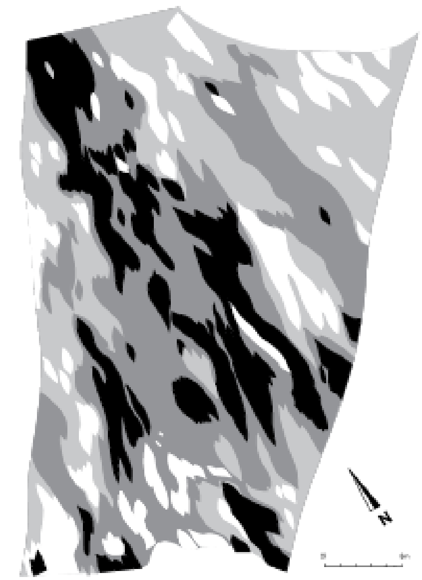
Braided rivers in New Zealand

Enrichment by bitumen migration

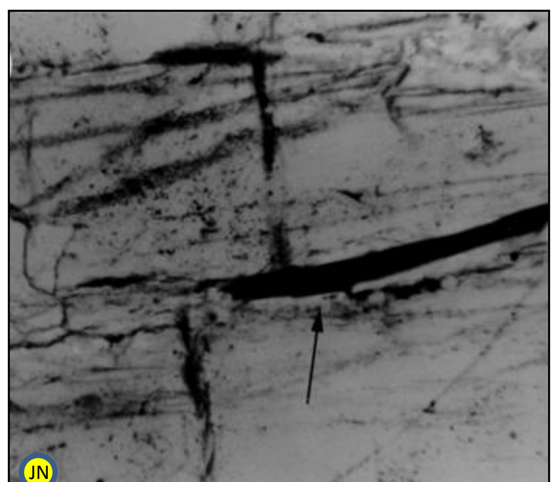
- The seam and flyspeck carbon of the Witwatersrand reefs is classified as a pyrobitumen.
- Defined as migrated bituminous material altered by the action of heat (Jacob 1993).
- Immature algal kerogen is the source rock.
- Gold values may reach > 10 kg/tonne in the carbon seams.
- Armed guards on stopes.

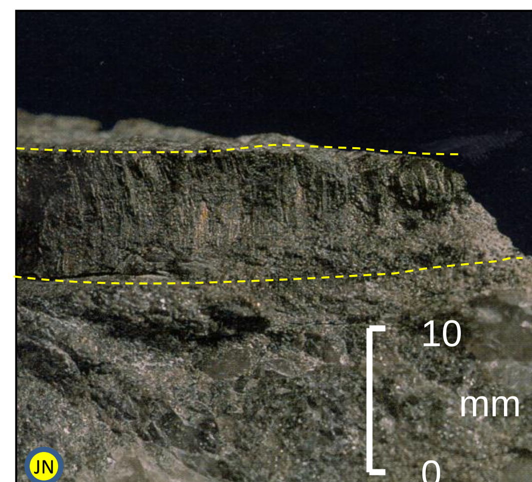


Channel map, Klerksdorp

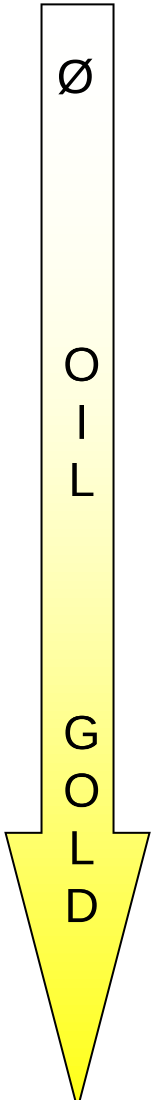


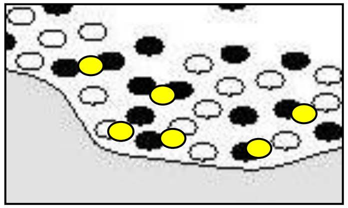
Kerogen values, Klerksdorp





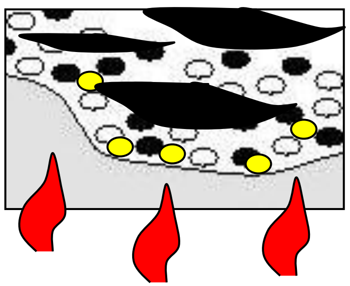
The model and the model





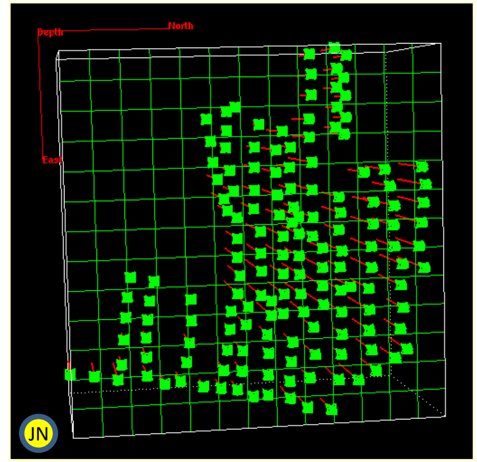
1. Deposit conglomerate, and some gold

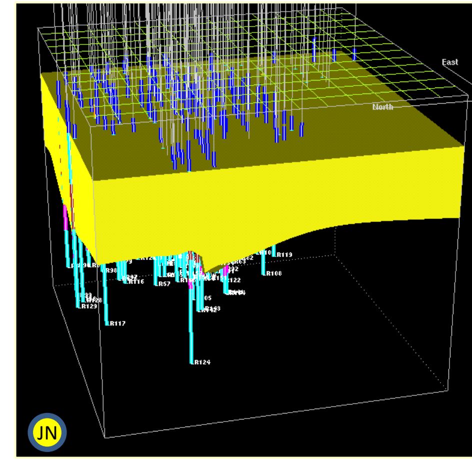
2. Add oil

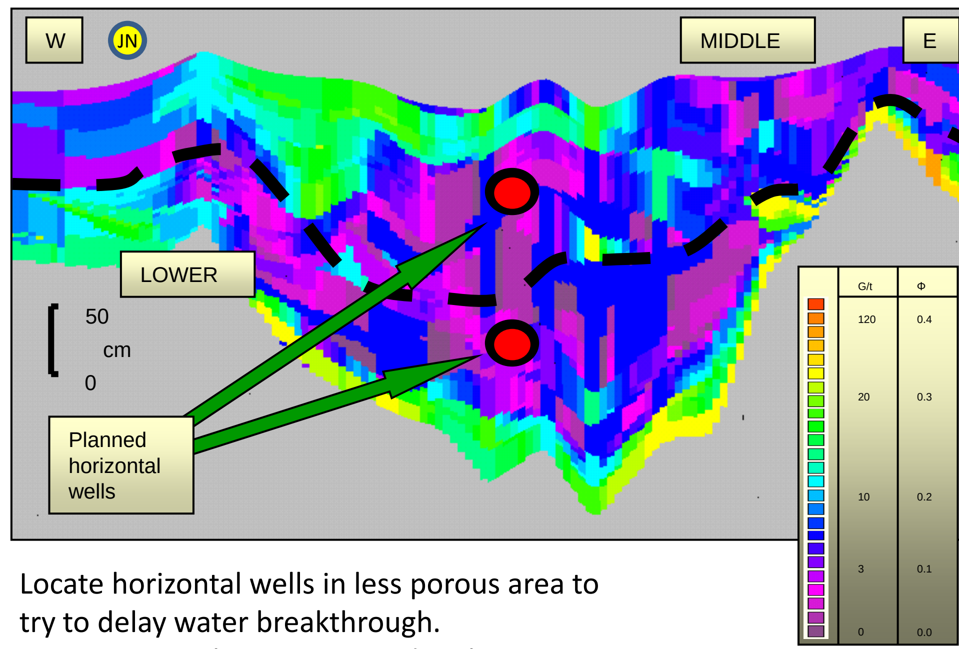


3. Metamorphose oil to carbon

4. Add gold-rich pore waters and form amalgam with carbon

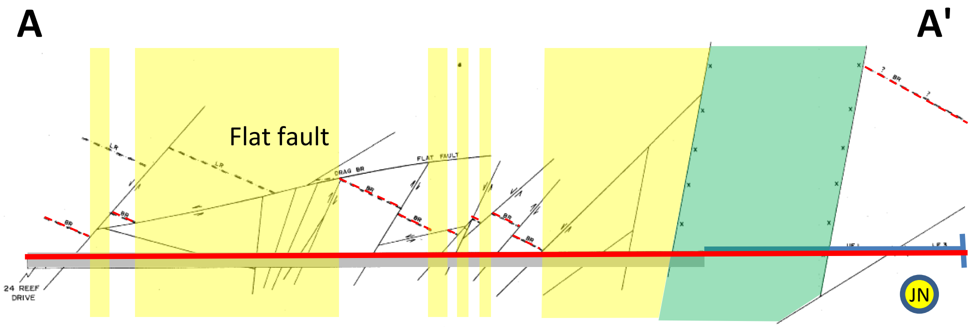




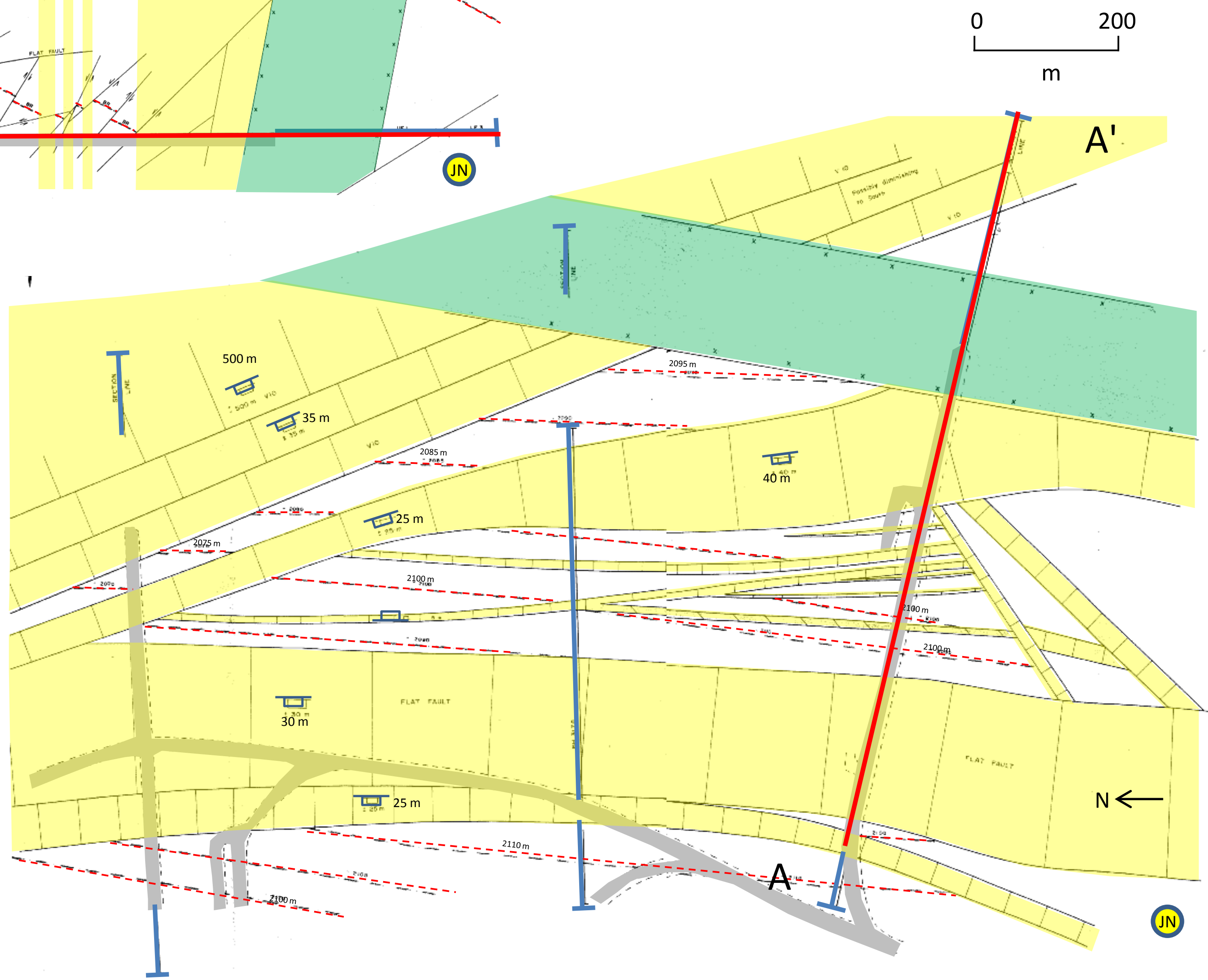


Locate horizontal wells in less porous area to try to delay water breakthrough.
Cross-section shows porosity distribution.

Structural complexity

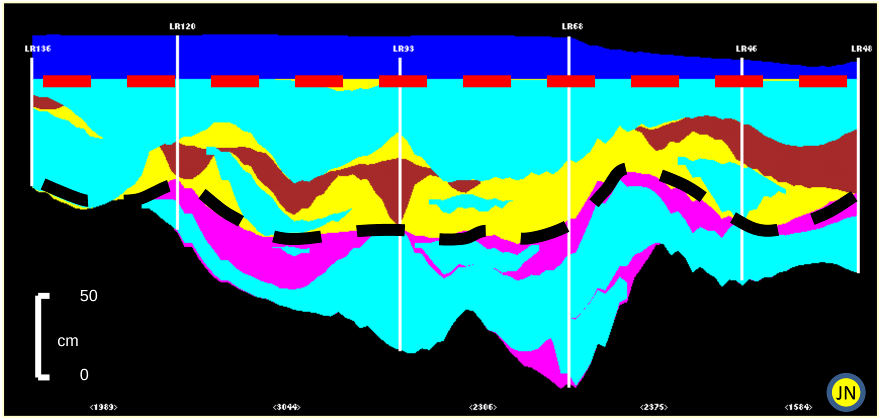


- Complex faulting can be mapped out.
- Gives feel for how fault systems interact.
- Highlights drag, gouge, fracture networks.

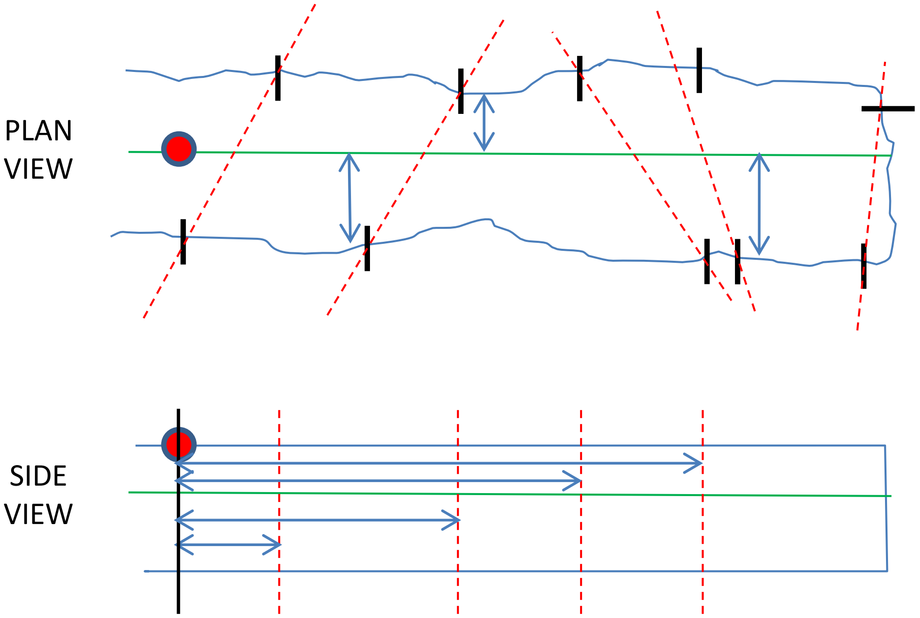


Lessons from the Leader Reef

- Mines provide an amazing 3D data set.
- Can map out facies properties in sections to build up a 3D model of porosity, etc.
- In this example gold provides a proxy for oil saturation.
- Structural characteristics can also be mapped out:
    - Faults
    - Fractures
    - Drag and fault gouge
- Following an earthquake, we were able to visually inspect the 30 cm fissure that had opened up
- Work with rock mechanics to learn additional information

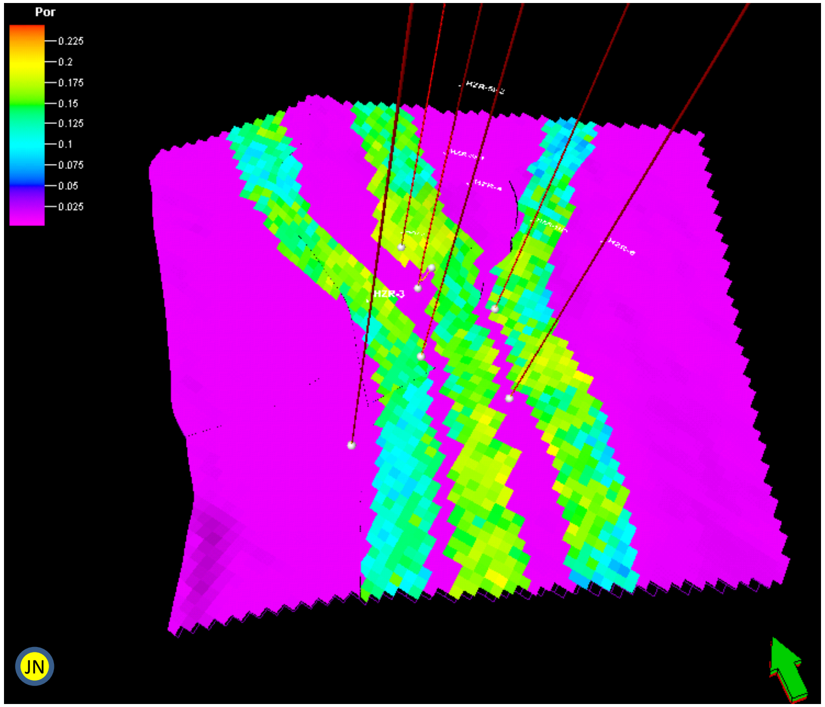


By facies



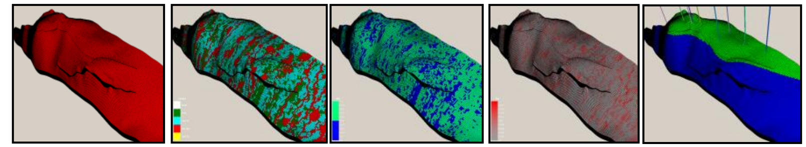
How faults are mapped underground

Advances in Kriging

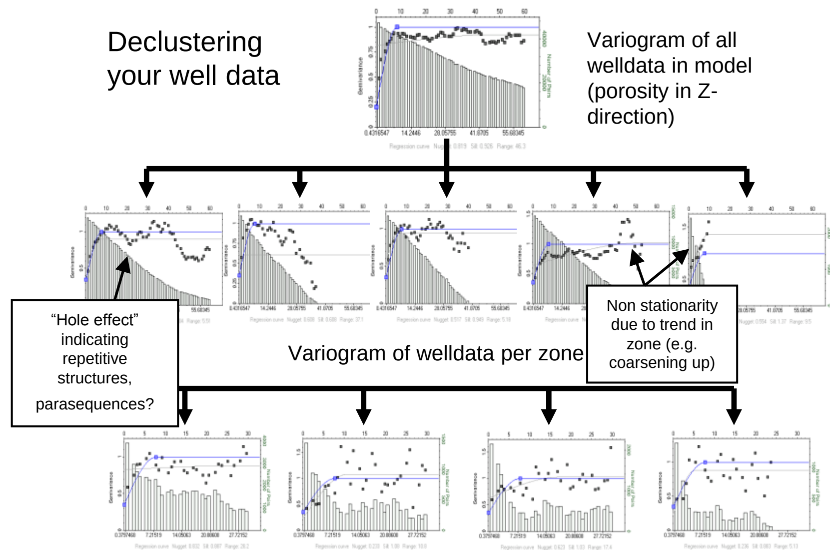


Geostatistics and Kriging

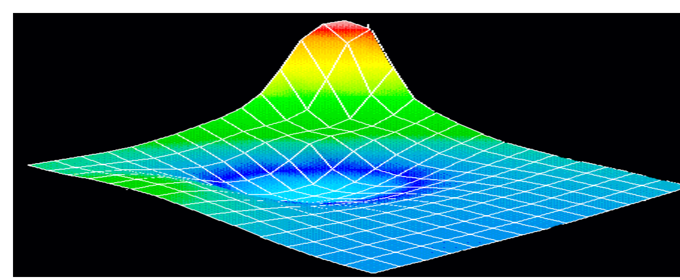
- Named in honour of Danie Krige (1919-2013).
- Study the gathered data to establish the predictability of values from place to place.
- Results in a graph known as a semi-variogram.
- This models the difference between values depending on the distance and difference between them.
- Kriging then uses a weighted average of neighbouring samples to estimate the unknowns at given locations: weightings are optimized using:
  - the semi-variogram model
  - the sample locations
  - all relevant inter-relationships between known and unknown values
- The technique also provides a standard error to quantify confidence levels.



Structure Facies N:G Porosity OWC



Variogram of welldata per facies in zone



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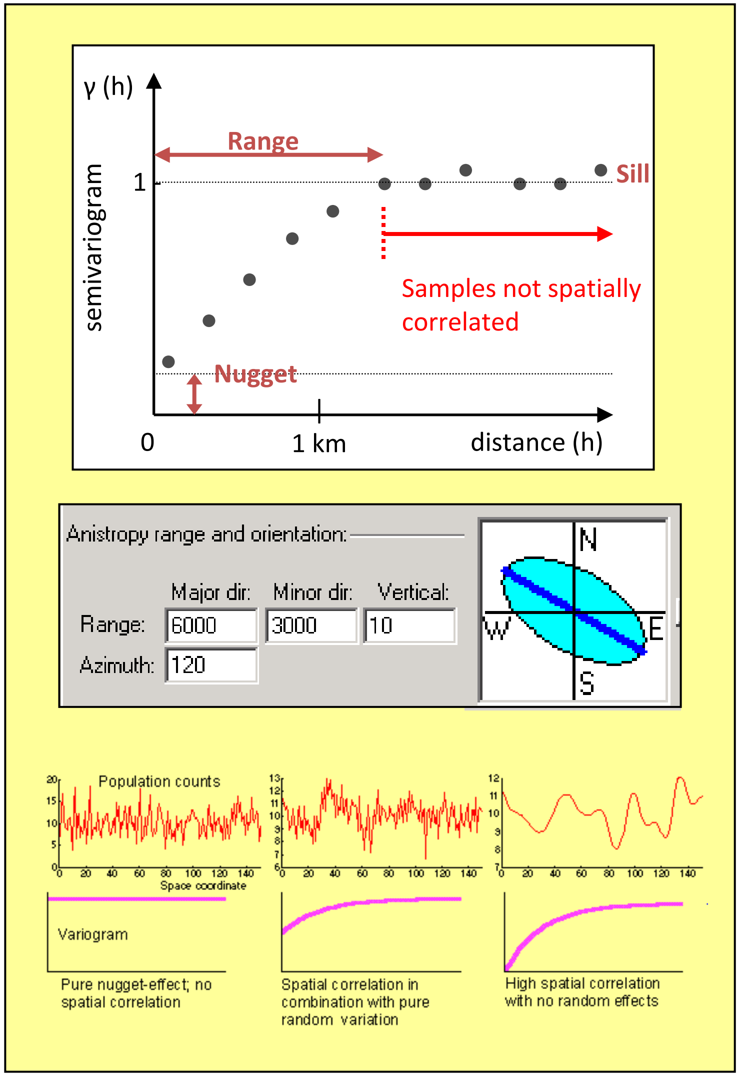
Variograms

- A graphical representation of the roughness of a dataset.
- Compares experimental variogram from data with mathematical function variogram, looking for the best curve fit.
- Typical variogram has 4 characteristics:
  - Range = distance between samples where variogram appears to level off.
  - Sill = level where no further correlation between pairs of samples
  - Nugget = expected variance between closely spaced samples (gold has high nuggety factor)
  - Azimuth = direction in which data will be stretched



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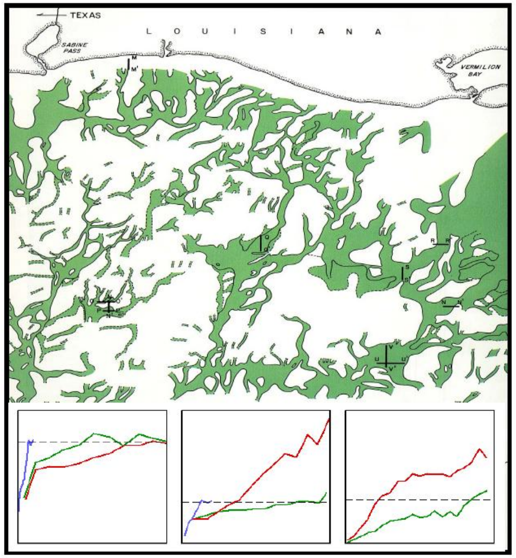
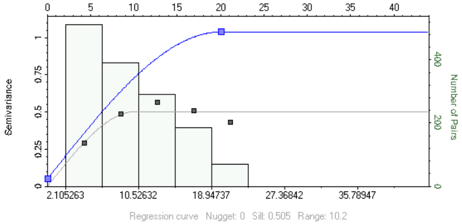
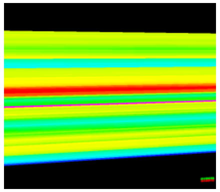
Use of variograms

- Using variograms to assess reservoir geobody orientations.
- Also use them to pick parasequences.
- Factorial co-kriging (Uni. of Adelaide), which allows the use of data sets at different scales to build semi-variograms to predict data values, then use factorial co-kriging to model.

Directional variograms in a channel environment (Rambert 2015)

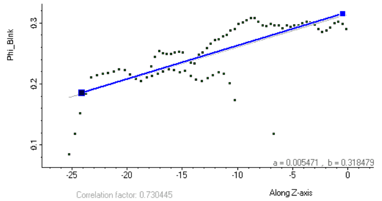




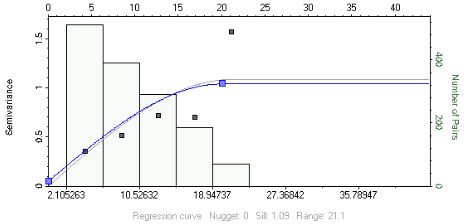


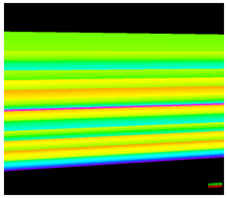
Sill of variogram in Z-direction is not between 0.8 and 1.2 after the normal score transformation

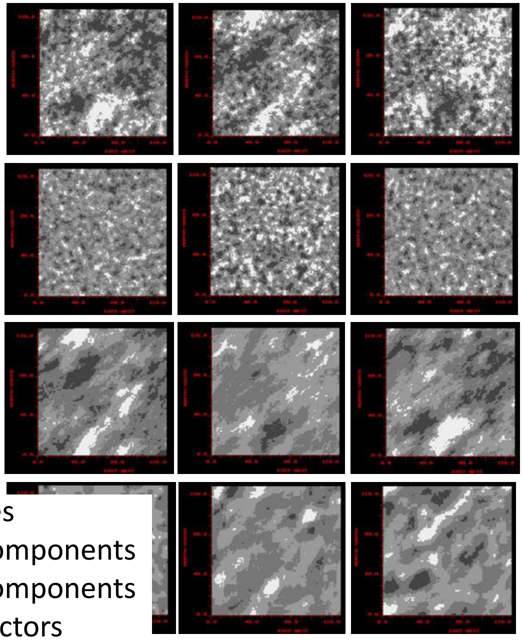
By searching for a (1D) trend in your zones….



Sill of variogram is now 1.0
Model shows parasequence sets





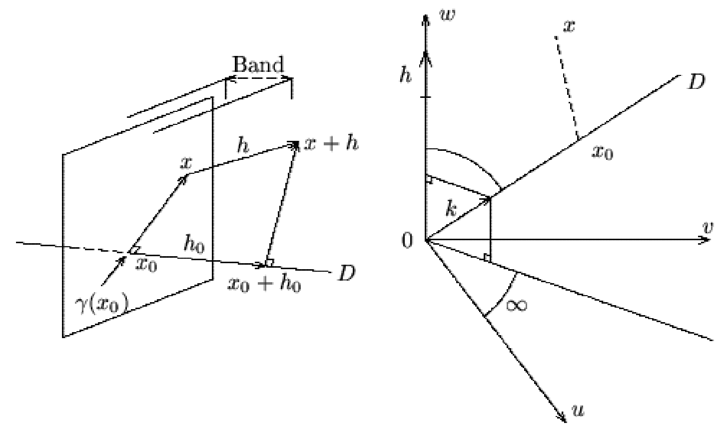


Factorial co-kriging:

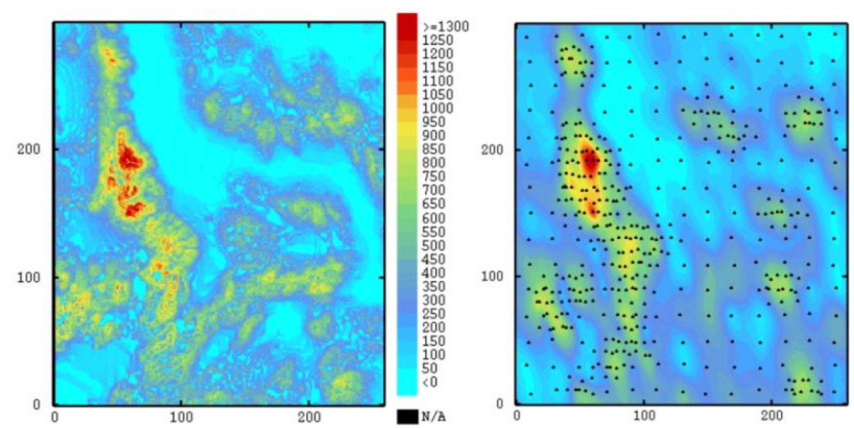
- Three spatial variables
- Short range spatial components
- Long range, spatial components
- Long range, spatial factors

Types of kriging

- Various types of kriging: universal, ordinary, simple, co-kriging.
- For non linear problems use other types of kriging e.g. Multiple Indicator Kriging.
- Co-kriging has power to incorporate other variables to steer interpolation.
- Oil industry has only scratched the surface.
- When you need to assess the uncertainty attached to the prediction of a variable, you can use Geostatistical Simulations. These generate a series of equiprobable realistic outcomes, each honouring the input data (Monte Carlo style):
  - Examples are Sequential Gaussian Simulations (SGS) and Turning Bands (TB). Many other methods
- **Kriging strives for accuracy.**
- **SGS strives for reality.**



Turning bands forms a 3D simulation via a series of 1D simulations along individual lines which have an intermediate co-variance (Journel 1974)



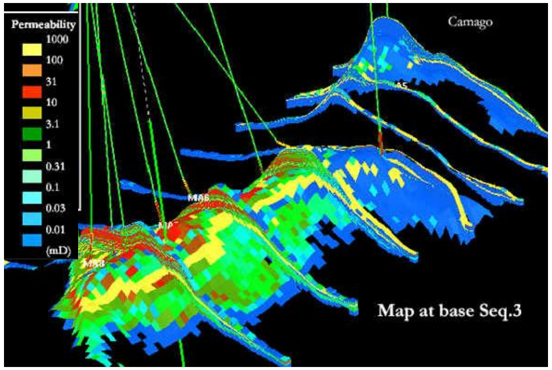
Kriging smooths reality

Lessons from modelling mine reserves

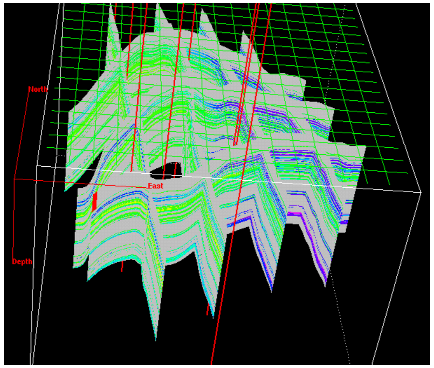
- Need to work more closely with mining specialists.
- Decluster data then use variograms to assess heterogeneity.
- Simple kriging may only be a starting point.
- Fractures can be modelled as easily as facies.

Modelling HC reservoirs

- Subdivide those variables that are facies dependant and those that are not e.g. fractures.
- Carbonates and clastics model differently (see table for suggested inputs).



Miocene Malapaya reefs, Philippines



Miocene lower shoreface, Sakhalin

	Patchy facies	Facies belts
CO3	Reef	Platform
Clastic	Channel	Shoreface
Inter well spacing	Range < well spacing	Range > well spacing
Infield	SGS	Kriging
Nugget	Most CO3s variable at small scale	Most clastics predictable at small scale
Trends	Not in CO3s, yes in clastics	Yes in CO3s and clastics

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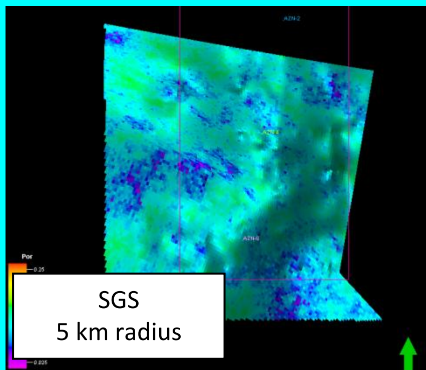
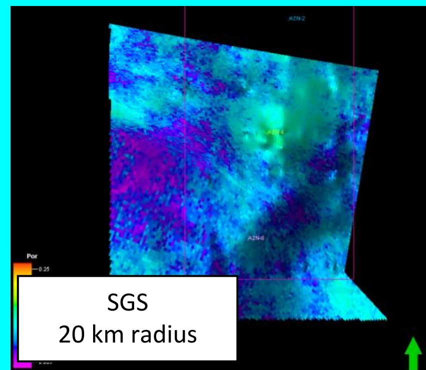
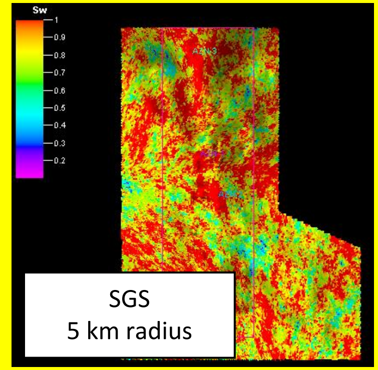
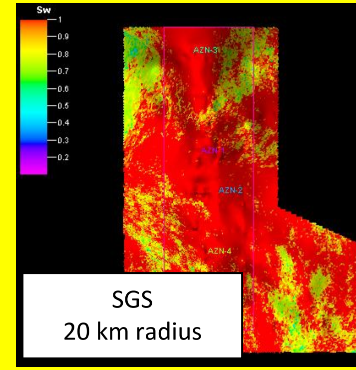
Using the appropriate interpolation methodology







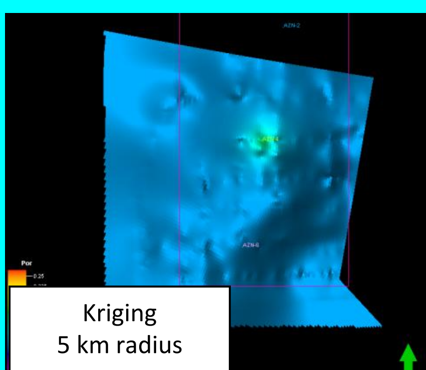


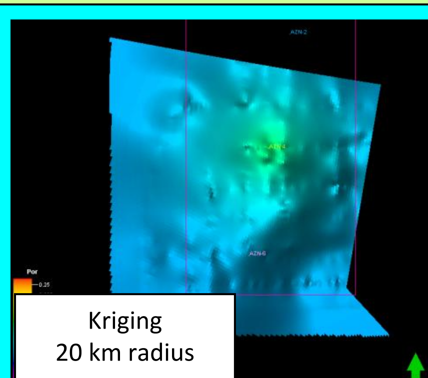
RADIUS

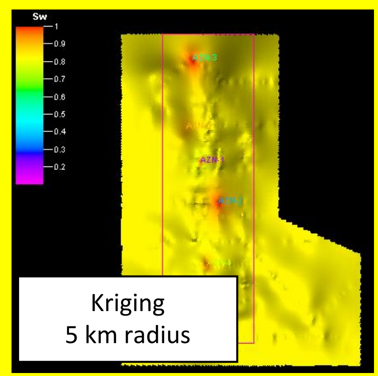
Not surprisingly, the larger the search radius, within which the interpolation algorithm can search for, and use, other wells, the smoother the overall pattern. Note that with a wide well spacing, as in this example, the change of radius makes less difference.

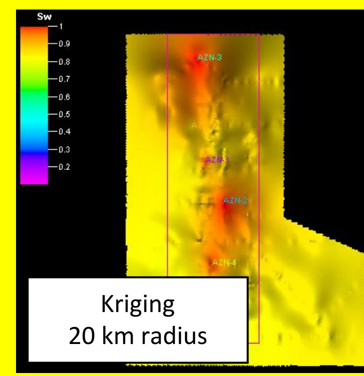
RADIUS AND TREND

The examples to the left have had no trend applied to the interpolation (Fahliyan platform carbonate), while those to the right (Burgan shoreface sands) have had a NW trend applied. Note how this has affected the SGS interpolation.









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Mining methodology -> Oil and Gas

Exploration:

- Use ESDA (Exploratory Spatial Data Analysis) to find potential outliers and define groups of correlated variables.
- Variography is used as a guide for optimizing drilling patterns
- Kriging is used to build first stage block model and estimate resources.
- Sampling strategies can be tested based on reducing uncertainties.
- Facies simulations can be used to build a geological framework.

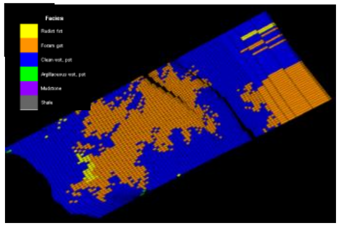
Appraisal:

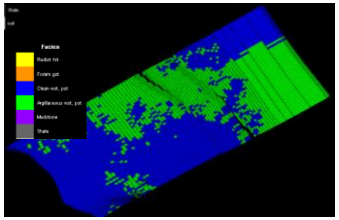
- Update ESDA and spatial modelling.
- Use non linear methods to evaluate resources.
- Use confidence levels to set proven, probable, possible reserves.

Production:

- Update ESDA and spatial modelling.
- Use production to ground truth and refine models.

Facies model 1
High connectivity good quality facies
Restricted volume poor quality facies

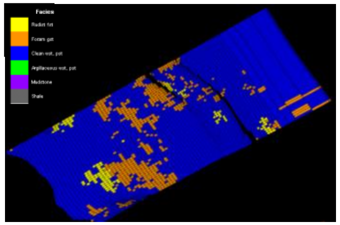


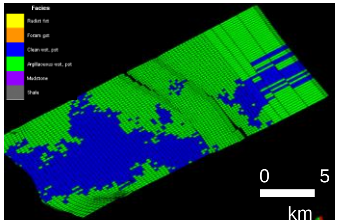


Facies model 2
Low connectivity good quality facies
Increased volume poor quality facies

Scenarios capture uncertainty for models.

Each model concentrates on one facies only.



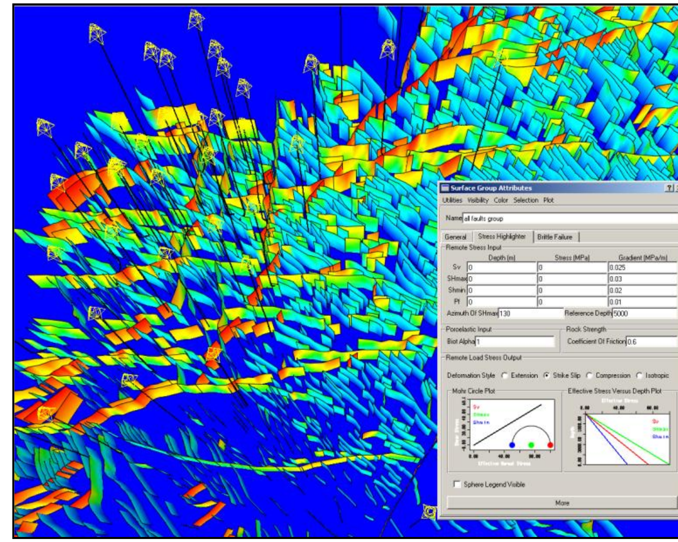


Rambert 2015

Fractured dreams

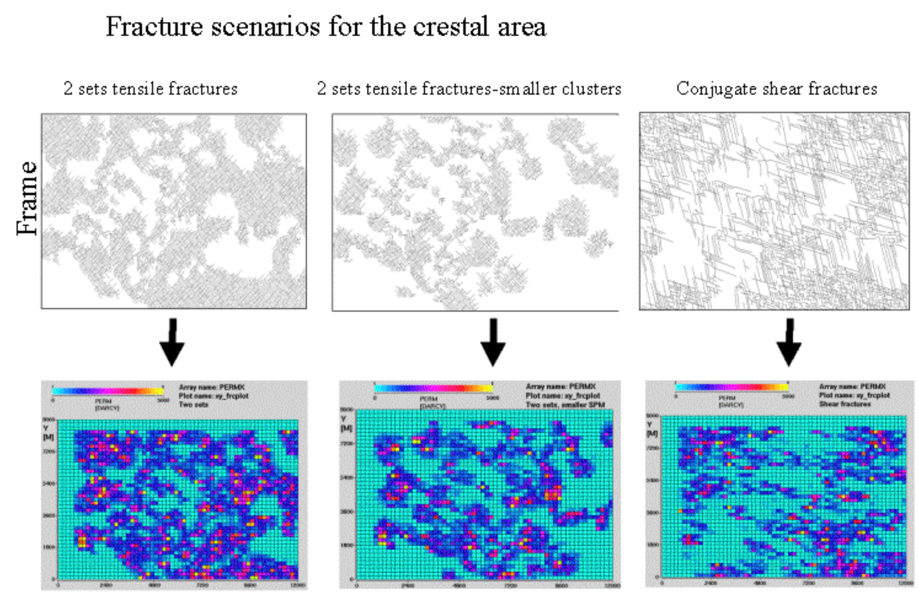
Fracture modelling

- Data analysis:
  - Stereonet analysis
  - Brittle failure analysis
  - Stress calculations and highlighter
  - Curvature calculation
  - Analogue data and concepts
  - Fracture spacing statistics
  - Fracture growth module
  - Fault damage zone – distance to fault



Applications to hydrocarbons:

- Data analysis as above.
- Consider dual porosity systems.
  - Matrix vs. fractures
- Model your fracture system.



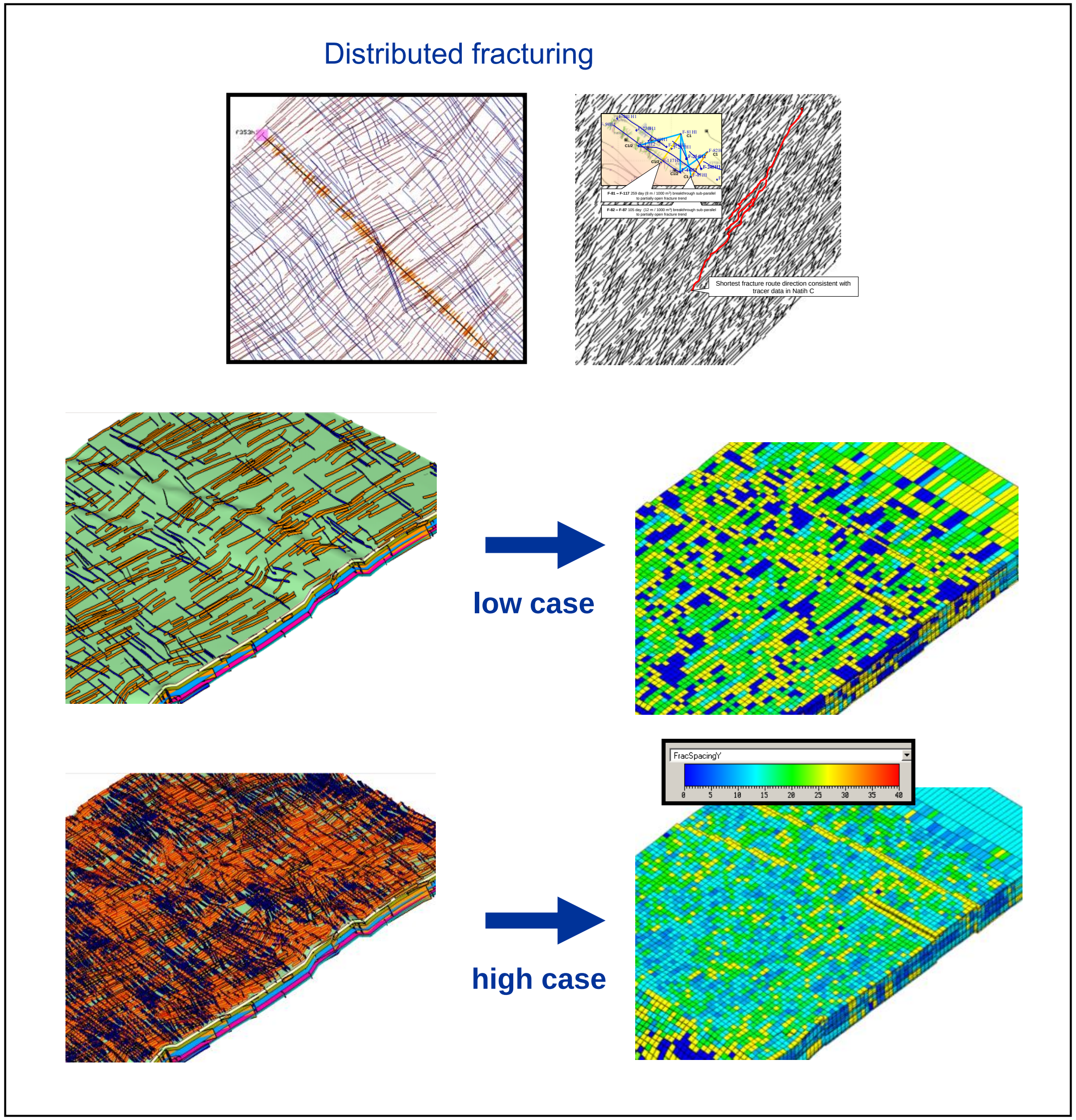
Noad et al SPE Beirut 2004

Fracture modelling

- Unlike facies modelling, fracture and diagenetic modelling are not facies specific.

Workflow:

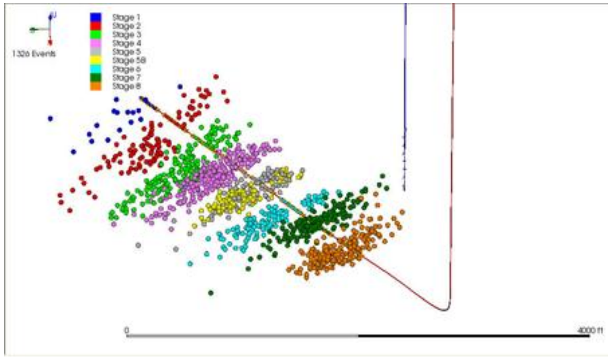
- Build a fracture model based on outcrop, FMI and other data.
- Sample model to populate each cell and layer of the model.
- Apply a template to concentrate fractures around faults interpreted from seismic.

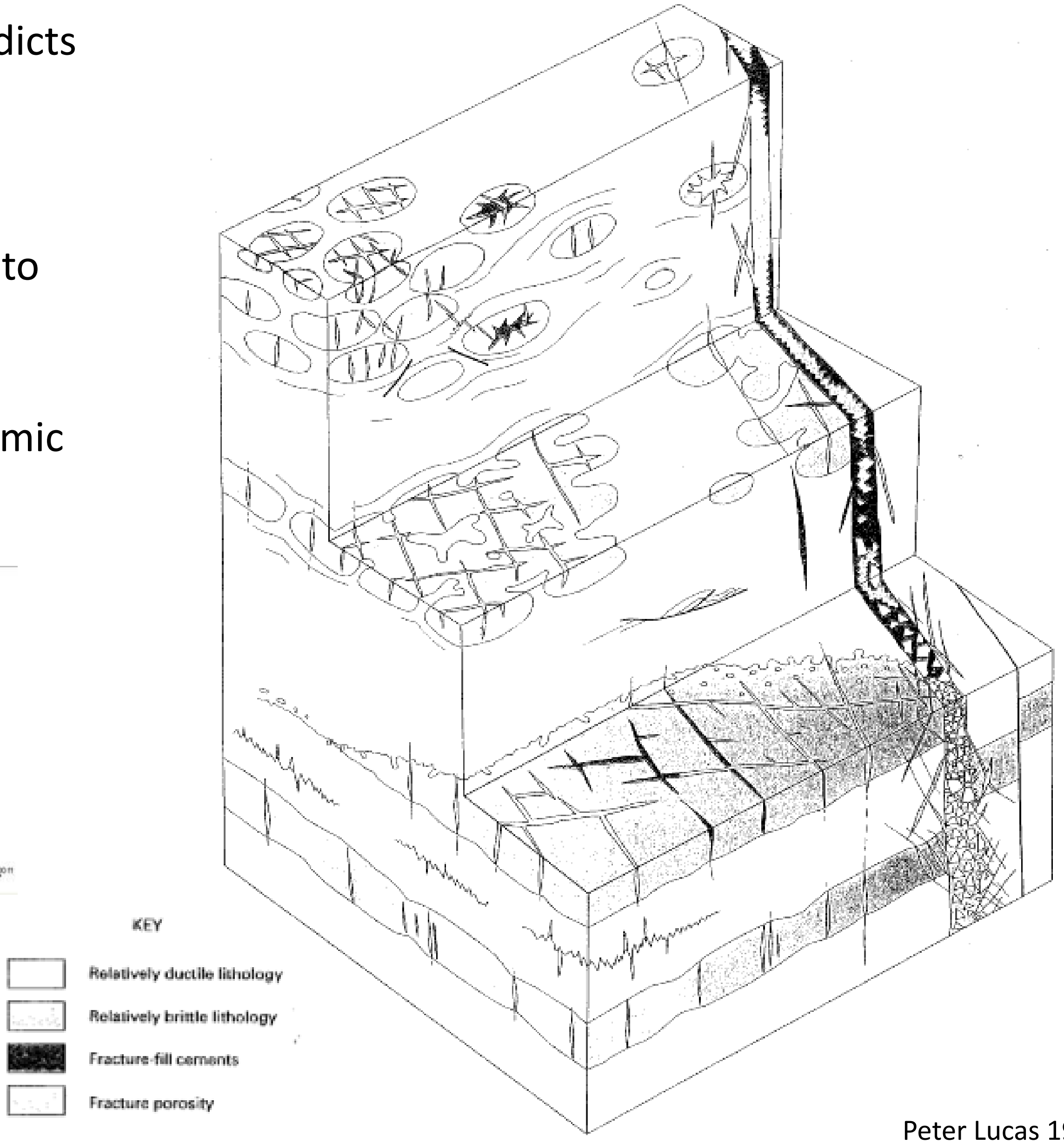


Noad et al SPE Beirut 2004

Summarising mining fracture data

- Model developed that predicts fracture type based on lithology for microporous reservoirs.
- Allows rheology to be tied to fractures.
- Can be applied to interpretation of microseismic data.



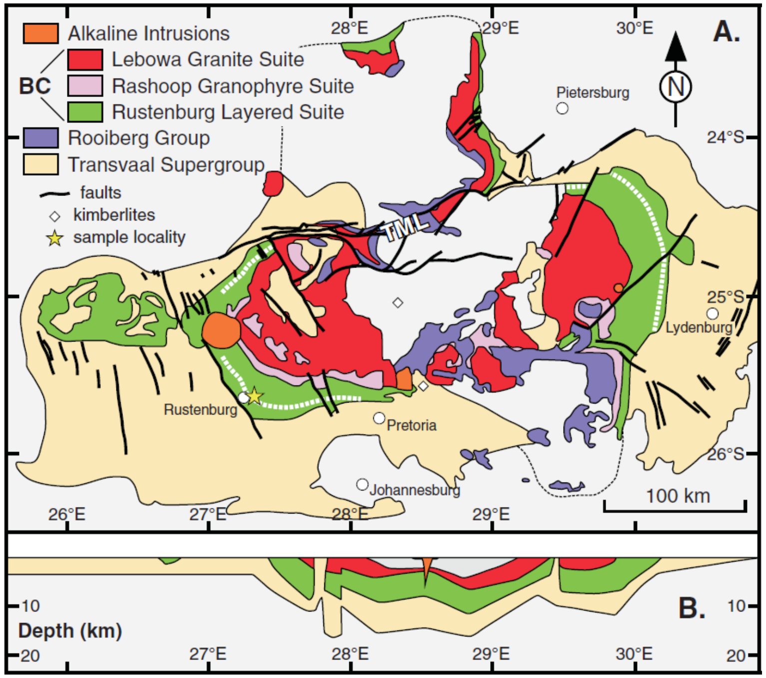


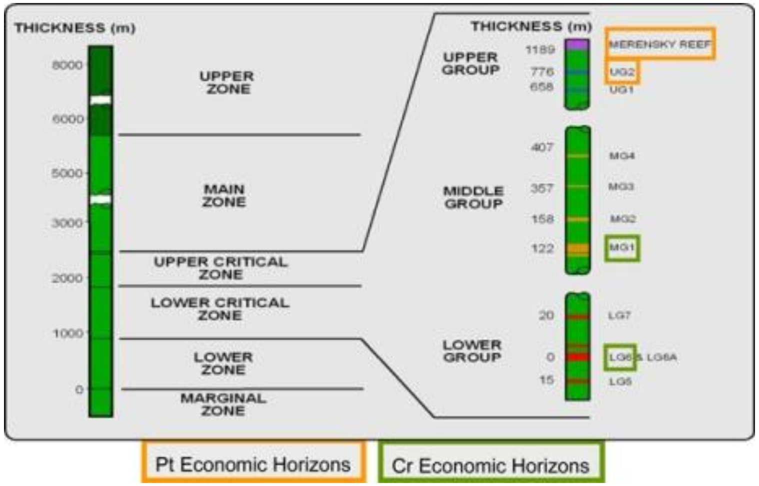
Peter Lucas 1997

Platinum Monde

The Bushveld Complex of South Africa

- Largest layered intrusion known on Earth, 2.2 BYO.
- Includes platinum group metals (PGMs), chromitite, vanadium, etc.
- PGMs hosted in chromitite seams or pyroxenite.
- Geological disruptions:
  - Dykes
  - Faults and joints
  - Pegmatoids
  - Domes and Potholes
- PGM split in UG2 reef is Pt 43%, Pd 48%, Rh 7%, Au 2%.
- Typically 5.8 to 9.3 g/t in eastern Bushveld.

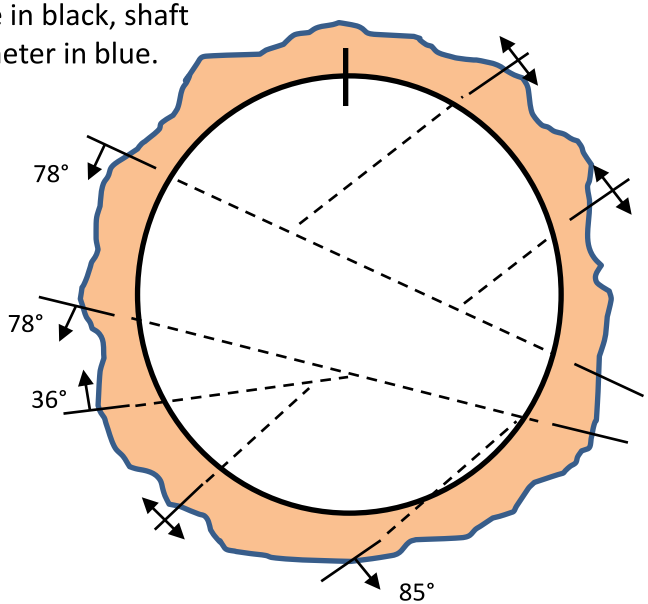


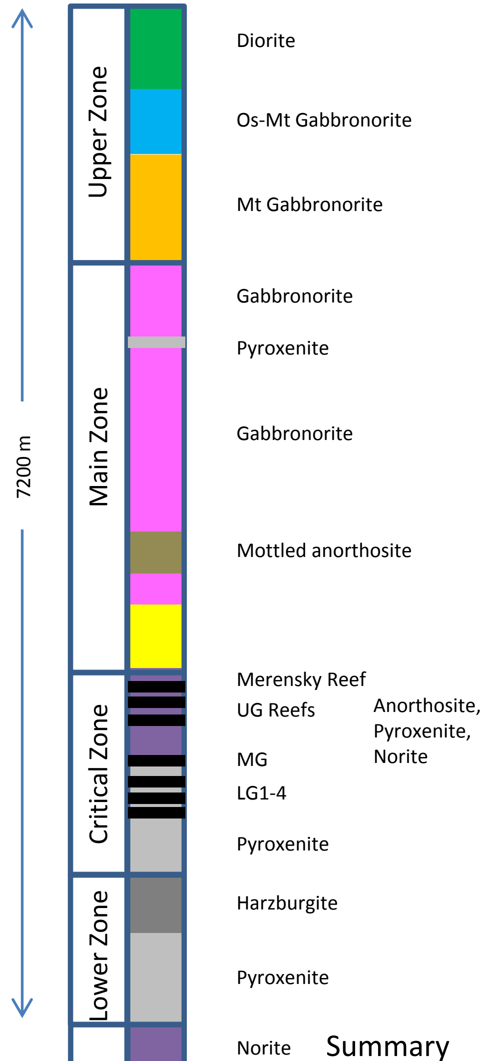


Shaft sinking data – prime data set

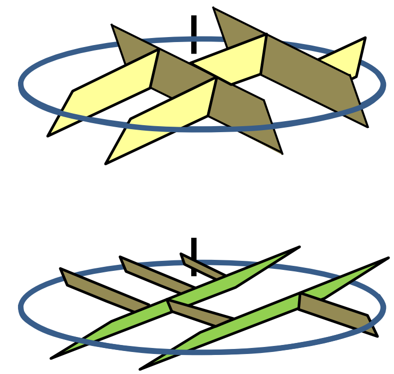
- Shaft logged every 4 m vertically.
- Picks up all fractures, though throws typically unknown.
- Orientation based on inner frame: 8 m diameter.
- Cement poured outside the frame.

Shaft being sunk. Metal frame in black, shaft perimeter in blue.

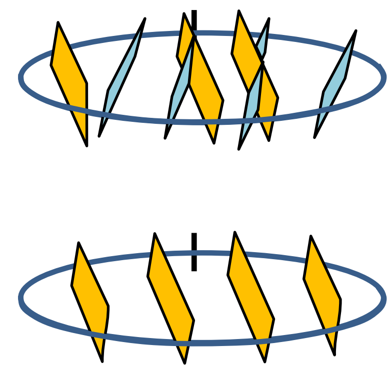




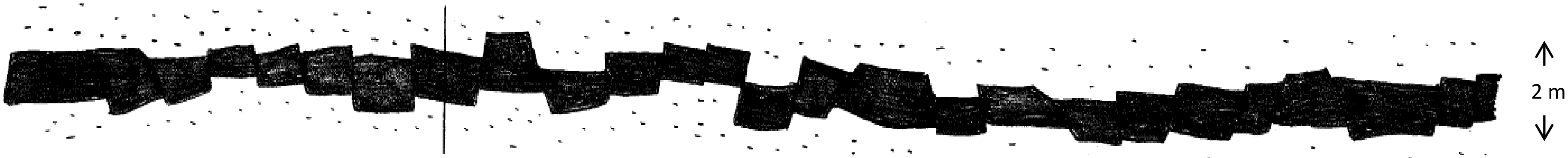
Summary stratigraphy of the Bushveld Complex.

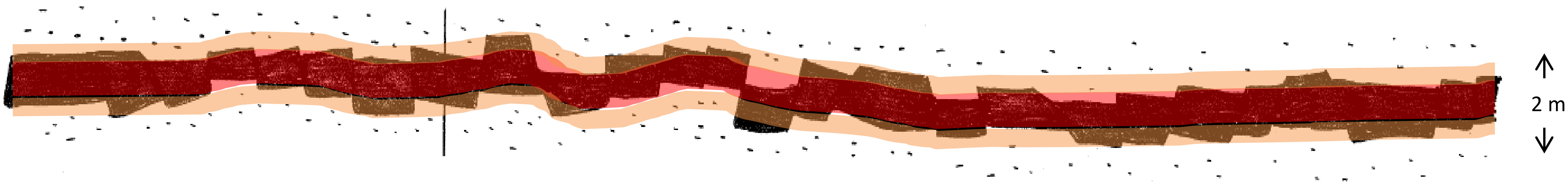


The fracture patterns vary widely at different levels. Detailed logging allows the fractures to be plotted over significant vertical distance.

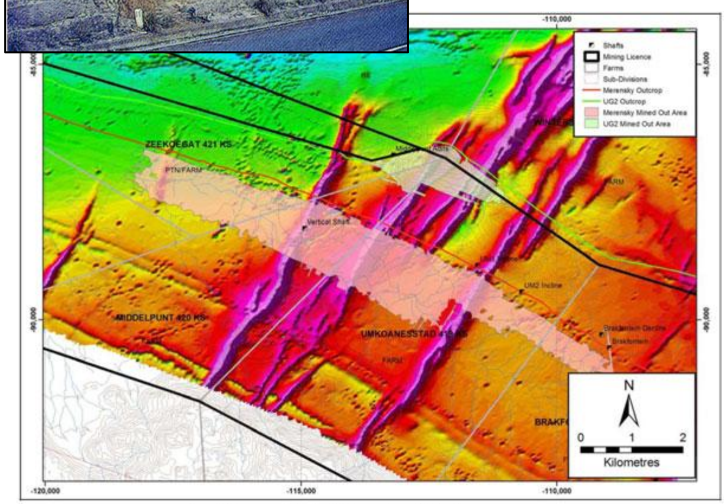


UG2 reef intersection – Death of a Mine





Dolerite dykes typically pick out faulting. These are carefully mapped out and can often be tied to regional structural fabrics.



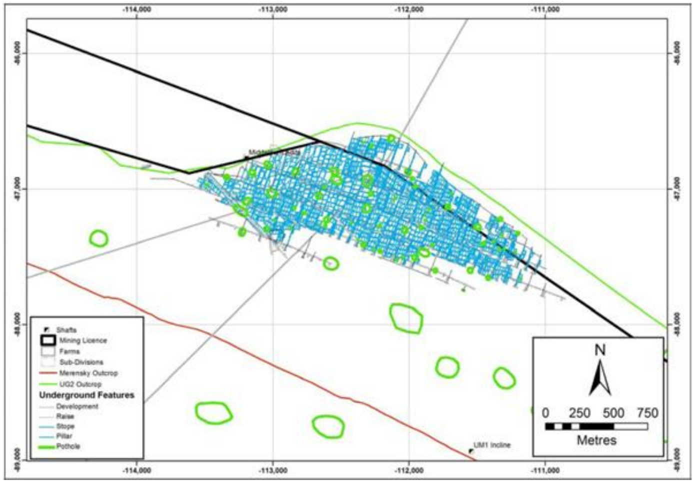
Purple lineaments indicate the location of intrusives

- Shaft intersection of the UG2 at a Bushveld mine
- Made up of microfaulted blocks of chromitite.
- Economic impact is to dilute the ore by around 40%, because of increased stope width required.
- Could not tell from vertical exploration wells.

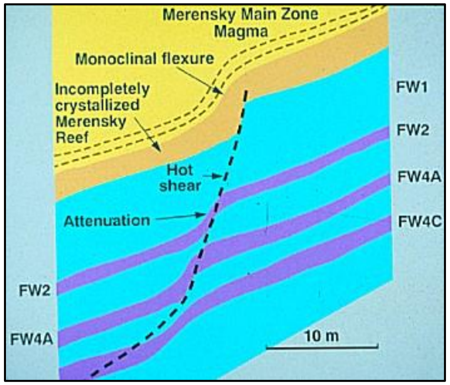
Potholing

http://www.sec.gov/

- Potholes lead to 15% loss of UG2 and 25% loss of Merensky Reef
- Behave as sags, and provide analogue for slump margins.
- Typically circular to elliptical, may be funnel shaped. Updip flank vertical, downdip horizontal. Base coincides with marker horizon.
- Potholes may be sites of non deposition, as opposed to resorption of cumulate. Locally high concentrations of volatiles lowered temperatures and suppressed crystallization.
- Also possibly due to contaminated magma.
- May relate to underlying anticlines in basement.
- Careful study of margins shows sag/drag mode.



Potholes on Middelpunt Hill UG2 horizon



Pegmatoid growth

- Definition: holocrystalline, intrusive igneous rock with crystals > 2.5 cm.
- Iron rich, ultramafic pegmatites composed of olivine intrude the Critical Zone cumulates.
- Behave as a “cancer “, growing and replacing chromitites and other minerals.
- Super heated liquids drive reactions.
- Series of bulk exchange vectors required i.e. intra- and inter-crystalline cation exchanges.
- Solve the vectors using simplest solution.
- Possible implications for cement growth, and for in situ replacement by minerals.

Pegmatitic, feldspathic, pyroxenite, Merensky Reef

Petrified wood: silica in groundwater, sourced mainly from volcanic ash, initially reacts with cellulose, and then the silica gradually alters to opal.

Secondary gypsum after anhydrite after primary gypsum, Lower Purbeck Formation, Dorset (Ian West).

Learning from chrome

- Unique opportunity in a sinking shaft: like a giant well bore.
- Allows evaluation of:
    - Change in fracture patterns with depth.
    - Change in fracture patterns with rheology.
    - Relation between fracture development and regional geological trends.
- Also can provide additional data on structural controls on reservoir development.

Pneumatic shaft jumbo

- Potholes provide window into sag/slump mechanisms.
- Overall geometry may be replicated in sedimentary environments.
- Pegmatites can provide data on cation exchange, which is applicable to in situ replacement by minerals.

LG6 chromitite seams; these can be traced for 400 km across the Bushveld Complex.

So what nuggets of knowledge did we glean?

Conclusions - sedimentary

- Mines provide a unique opportunity to get “inside“ the rocks.
- Mining of sedimentary deposits underground (or in quarries) provides an opportunity to sample them for properties, and to use these to construct detailed 3-D models as templates.
- Even igneous rocks can provide lessons on slumping and replacement/cementation.

- Kriging was invented in the mining industry.
- Mining uses many types of kriging, which have not yet been used to model hydrocarbon distributions.
- Opportunity to improve economics.

Blackhawk coal seam at Castle Gate, Utah

Syncrude Mine

Exposed face at Syncrude Mine

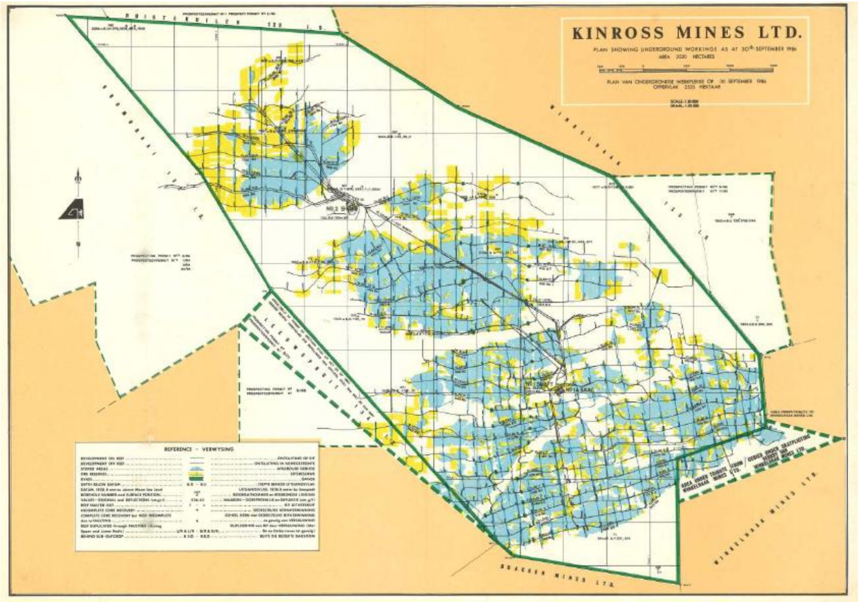
Conclusions - structural

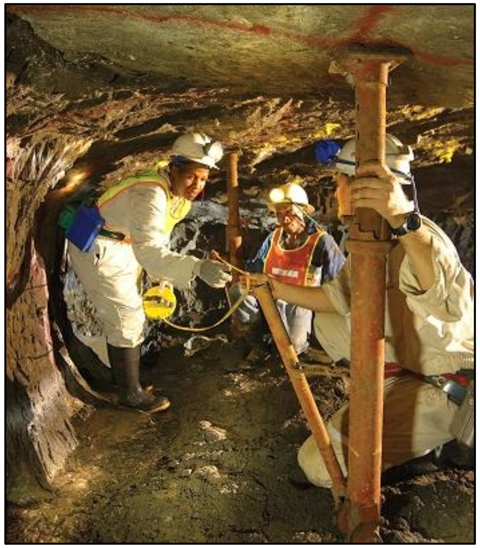
- Fracture propagation is worked on by rock (geo)mechanics – consult them.
- Fracture modelling is far more advanced in rock mechanics.
- Ancient gold mines can be structurally complex, which may provide detailed information on structural evolution.
- Shafts provide a giant well bore to examine for “super FMI “ data.
- Possible to test impact of:
    - Depth
    - Change in rheology

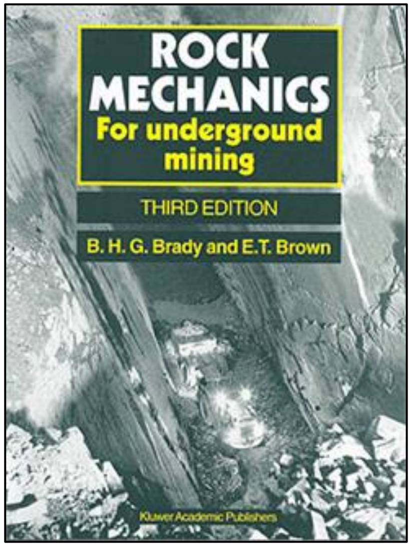
  on fracture propagation.

And as we saw in Bushveld Mine:

- Exploration can go horribly wrong!







LOOK FOR THE LIGHT AT THE END OF THE TUNNEL!