Using a Petroleum Systems approach to improve exploration outcomes for sediment-hosted copper deposits

Jane Cunneen and Graham Banks

Basin Scope Consulting Pty Ltd. jane@basinscope.com.au
School of Earth and Planetary Sciences, Curtin University

Route 2 Reserves route2reserves@gmail.com
Southern Geoscience Consultants www.sgc.com.au

Introduction

Jane Cunneen (B.Sc., Ph.D, UWA)

Basin Scope Consulting

- Specialist in the structural and tectonic evolution of sedimentary basins.

Ph.D (UWA) Tectonics Centre

GSWA: Basins group

Consulting to petroleum industry

IOC/UNESCO Tsunami Unit

Research Fellow, Curtin University (Chevron-funded)

Graham Banks, B.Sc., Ph.D

Route To Reserves (Vancouver and Copenhagen)

- Impartial advice to spectrum of exploration stakeholders.
- Nation-scale strategy to prioritising drilling locations.
- Probability of success, uncertainty, risk and value of exploration.

Southern Geoscience Consultants (Perth, Toronto and Vancouver)

- Principal Geologist (Americas).
- Geophysics and exploration consulting services.
- Mineral exploration and environmental sectors.

11 years: basin screening, petroleum system, play analysis, prospect generation, portfolio analysis, drilling.

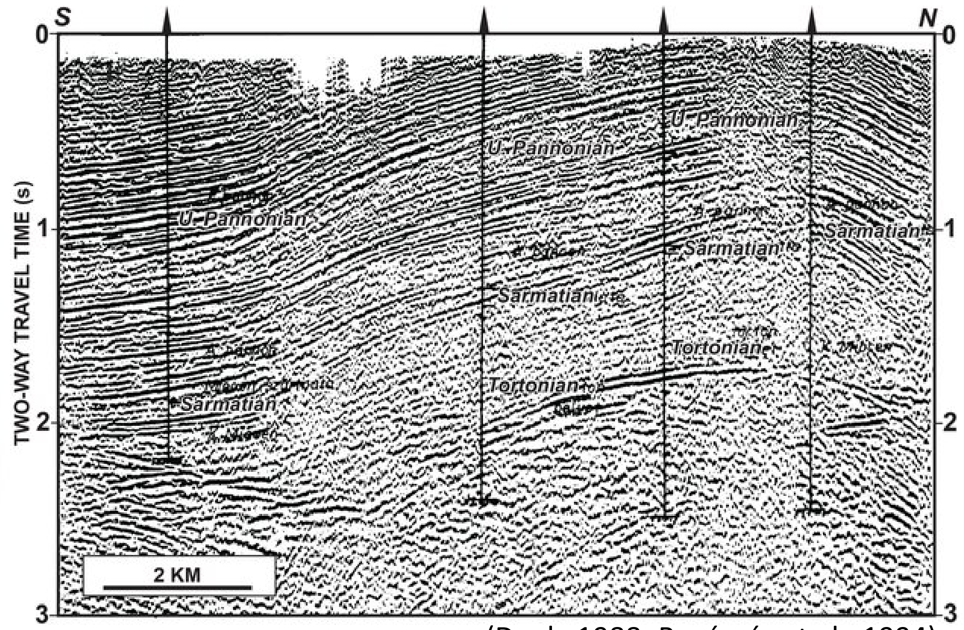
4 years: basin screening, mineral system, play analysis, prospect generation, portfolio analysis, drilling

Petroleum exploration was there until the 1990s

Focused on prospect scale. Drilled the anomalies.

Destroyed billions $ of value.

Vintage 2D reflection seismic, Budafa Field



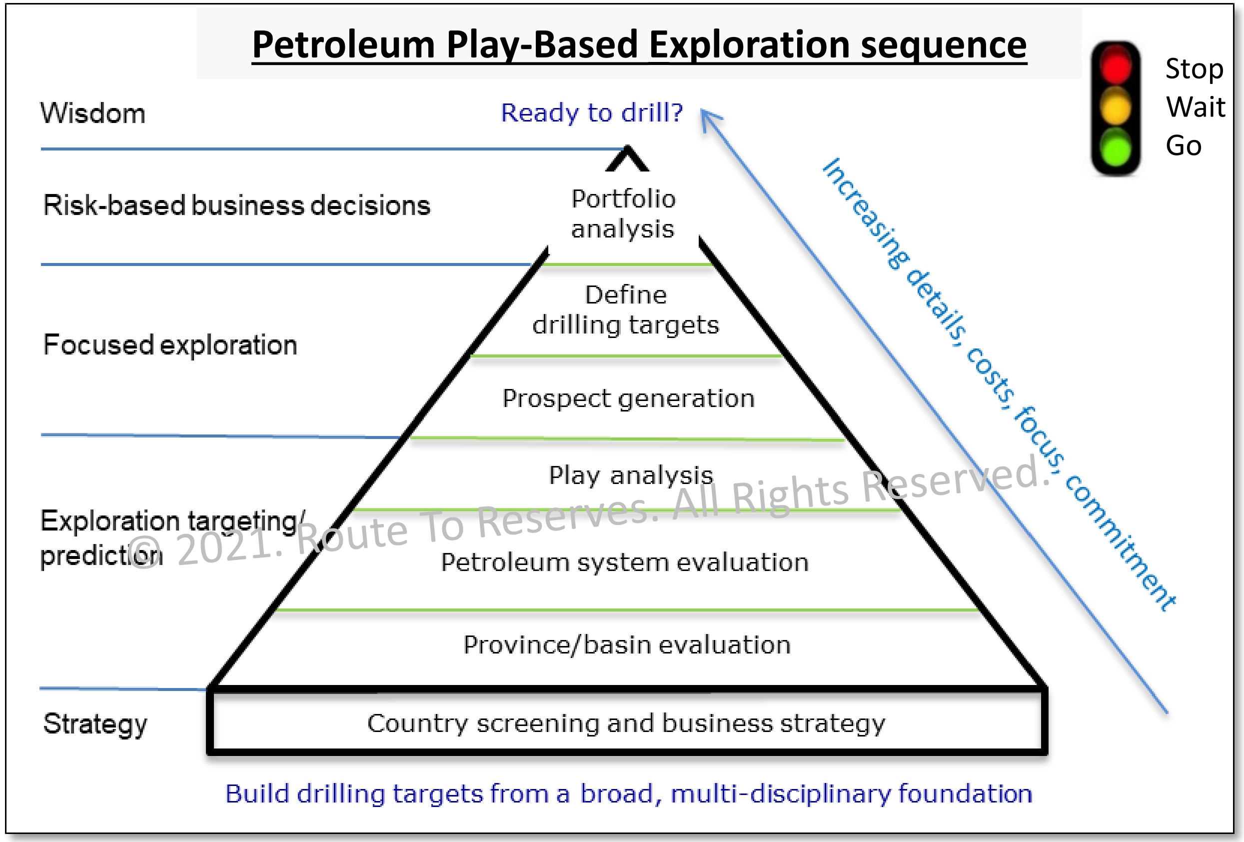
(Dank, 1988; Pogácsás et al., 1994).

Executives demanded a new approach from Exploration teams

Exploration Reset: regional geology and chance of success

Put a petroleum system and its plays at the core of the exploration business.

= Play-Based Exploration.



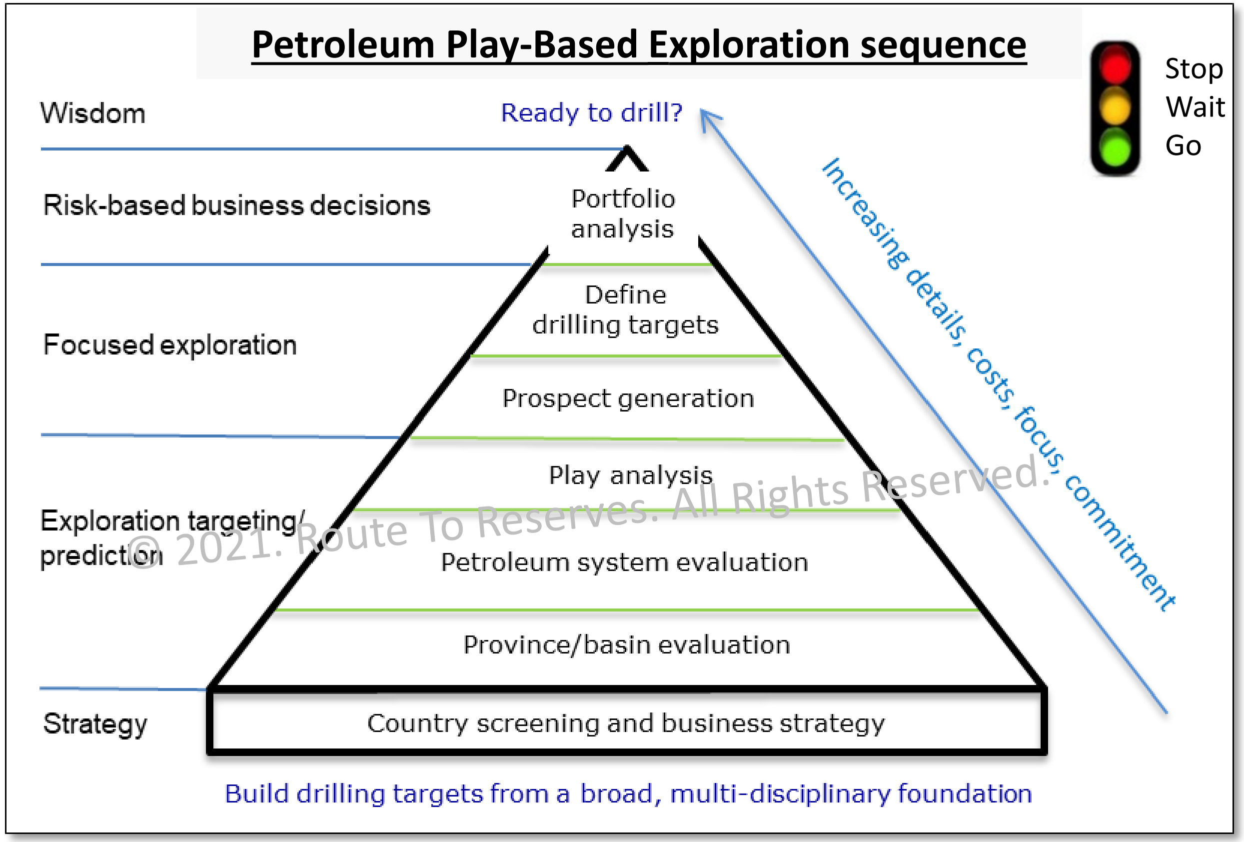
A petroleum system evaluation

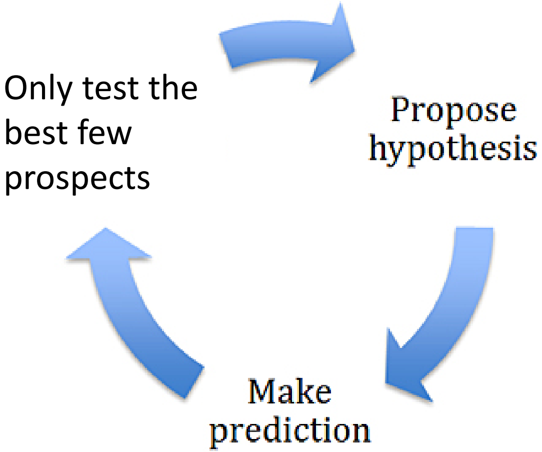
Standardized globally across departments, jurisdictions, JV partners

Sequence of geoscience-business analyses

Series of “What if Nature did…?” predictions through progressively smaller scales.

Start with possible source quality and its possible yield at >10,000 km^2.





*Rarely ‘see’ petroleum on seismic.

**Prospects are kms deep, often below the ocean floor.

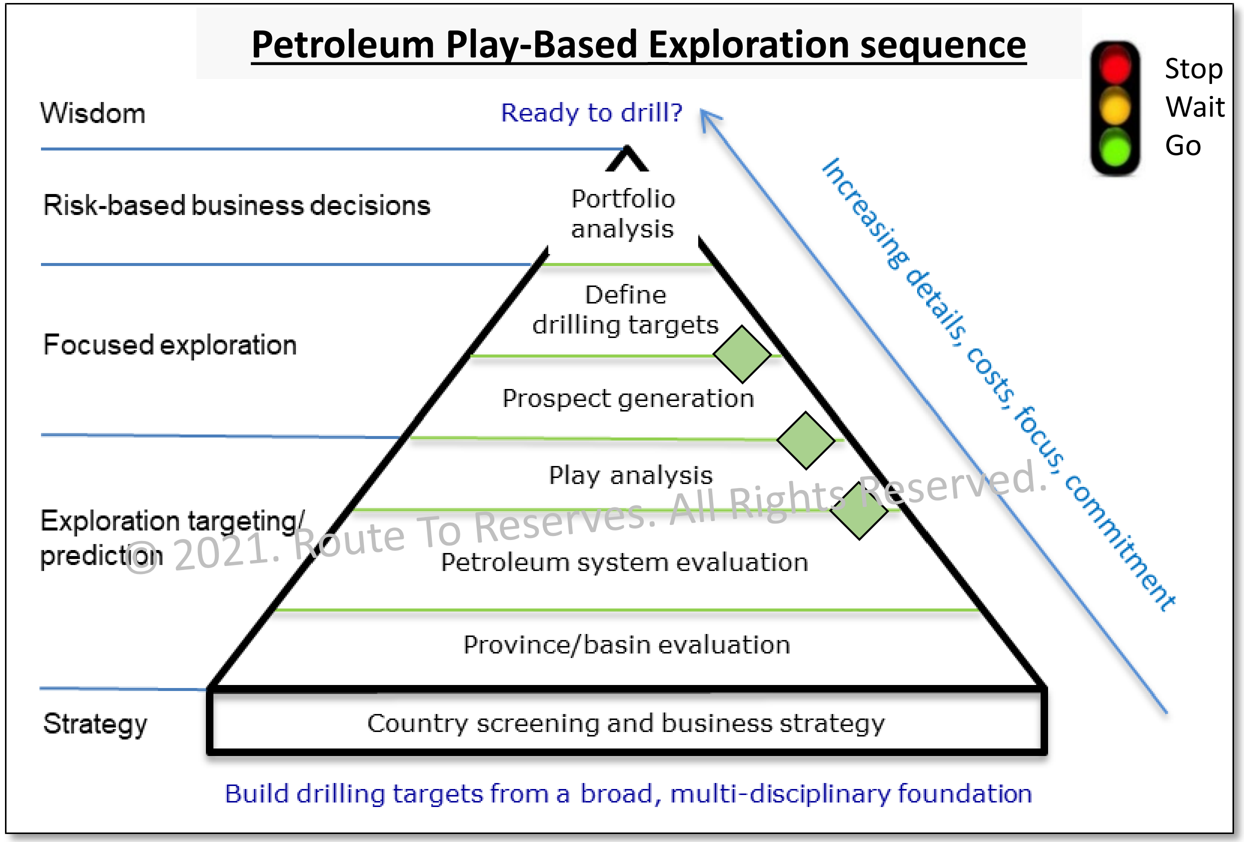
**Uncertainty ranges and confidence levels stated.

Geoscientists “follow the molecules” to predict* possible permeability: “If molecules exist…”**

System to play to prospect to portfolio predictions

Geologists explain regional models to strategists in economic forecasting terms.

◇ = 3 pre-drill decision points to: proceed, deal or [quickly, easily, cheaply] divest.



Few prospects get drilled: 4D geological hypothesis and risked resource must be convincing

Plays, probability of success, uncertainty, risk

2 km ocean. Boreholes to 5.7 km deep. Rarely ‘see’ petroleum on seismic. No surface evidence.

So, geoscientists report petroleum system, play and prospect models in forecasting metrics.

4.13 RISKS AND PROBABILITY OF SUCCESS

Prepared According To
National Instrument 51-101

This is a frontier exploration project that carries an exploratory risk profile. The risk for this project is still very high even though 3D seismic has been acquired and analyzed. The modeling, such as the inversion and interval velocity work, that has been done mitigates some of the risk of finding reservoir quality rock. Until a well is drilled that confirms the presence of hydrocarbons in commercial quantities, the models cannot be proven. The estimated Probability of Success (POS) for this project is on the order of 7.8% to as high as 57.6% for the Turonian targets, not an unusual risk profile for frontier exploration projects around the world. These risk profiles are based on the multiple geological uncertainties that are associated with these plays and that are

Gustavson Associates (2012)

So investors can estimate value of frontier region opportunities at early-stage

A petroleum systems approach to mineral exploration

Advantages:

- Exploring undercover
- Focus on source rock quality and distribution
- Scale: Basin-wide rather than deposit models
- Essential components and critical moment
- Play-based exploration with a sequence of decision gates
- Predictive approach: process oriented
- Strong understanding of regional geology, rather than relying on direct detection. *Get more out of existing data*, save on drilling costs etc.
- Use petroleum industry examples for mineral system elements

Components of a Petroleum System

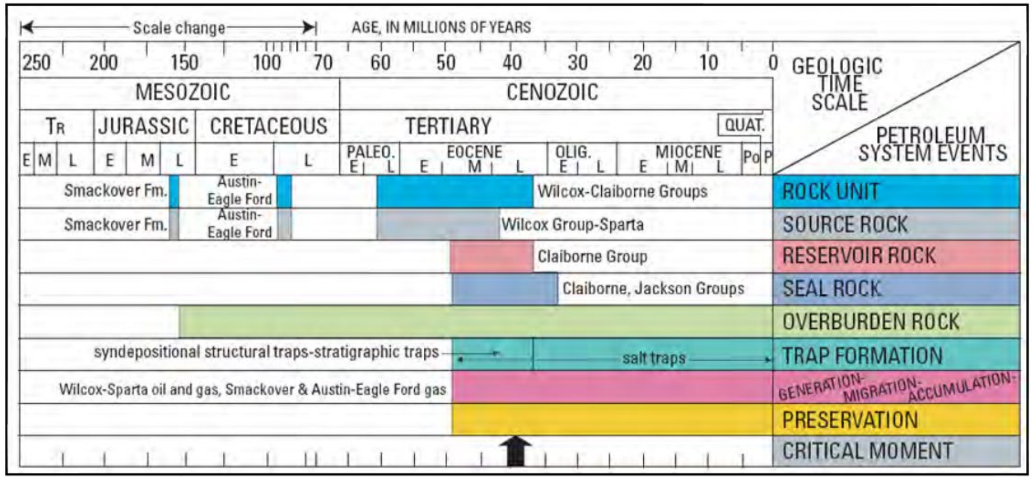
The essential elements and processes for oil and gas accumulations to occur

“The genetic relationship between a pod of active ***source rock*** and the resulting oil and gas accumulations” (Magoon & Dow, 1994).

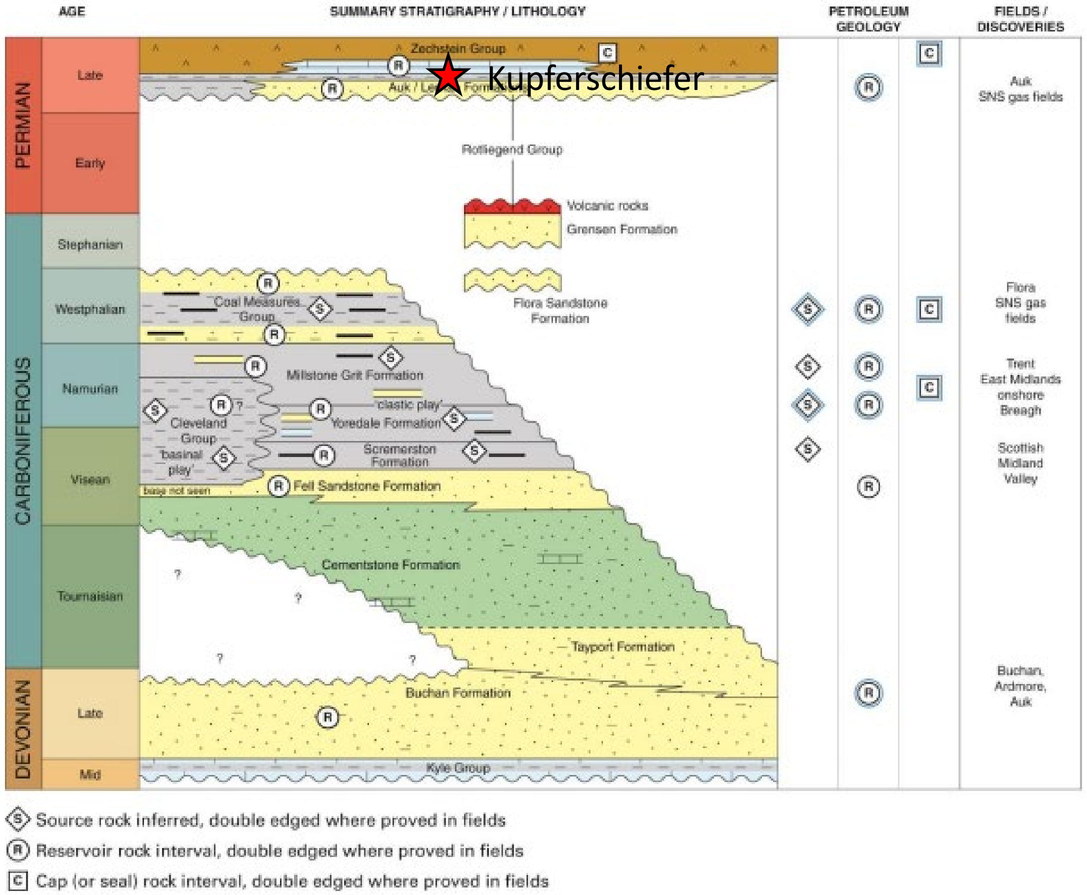
- Source, reservoir and seal rock
- Formation of traps (structures)
- Generation and migration of hydrocarbons
- Preservation of accumulation

TIMING is critical!

If events occur out of order then the system process fails….



https://core.ac.uk/download/pdf/96704773.pdf



Petroleum Systems Charts

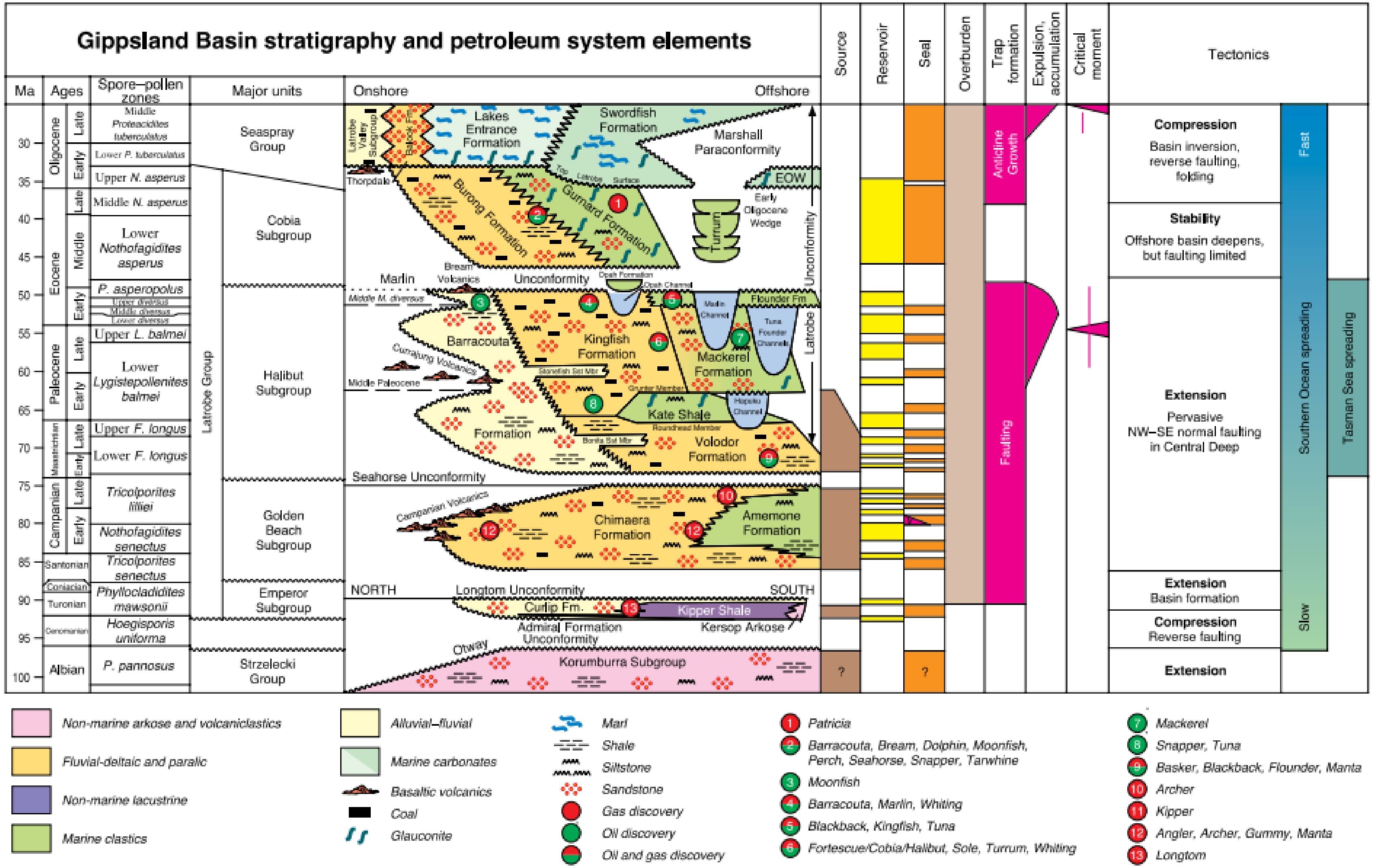


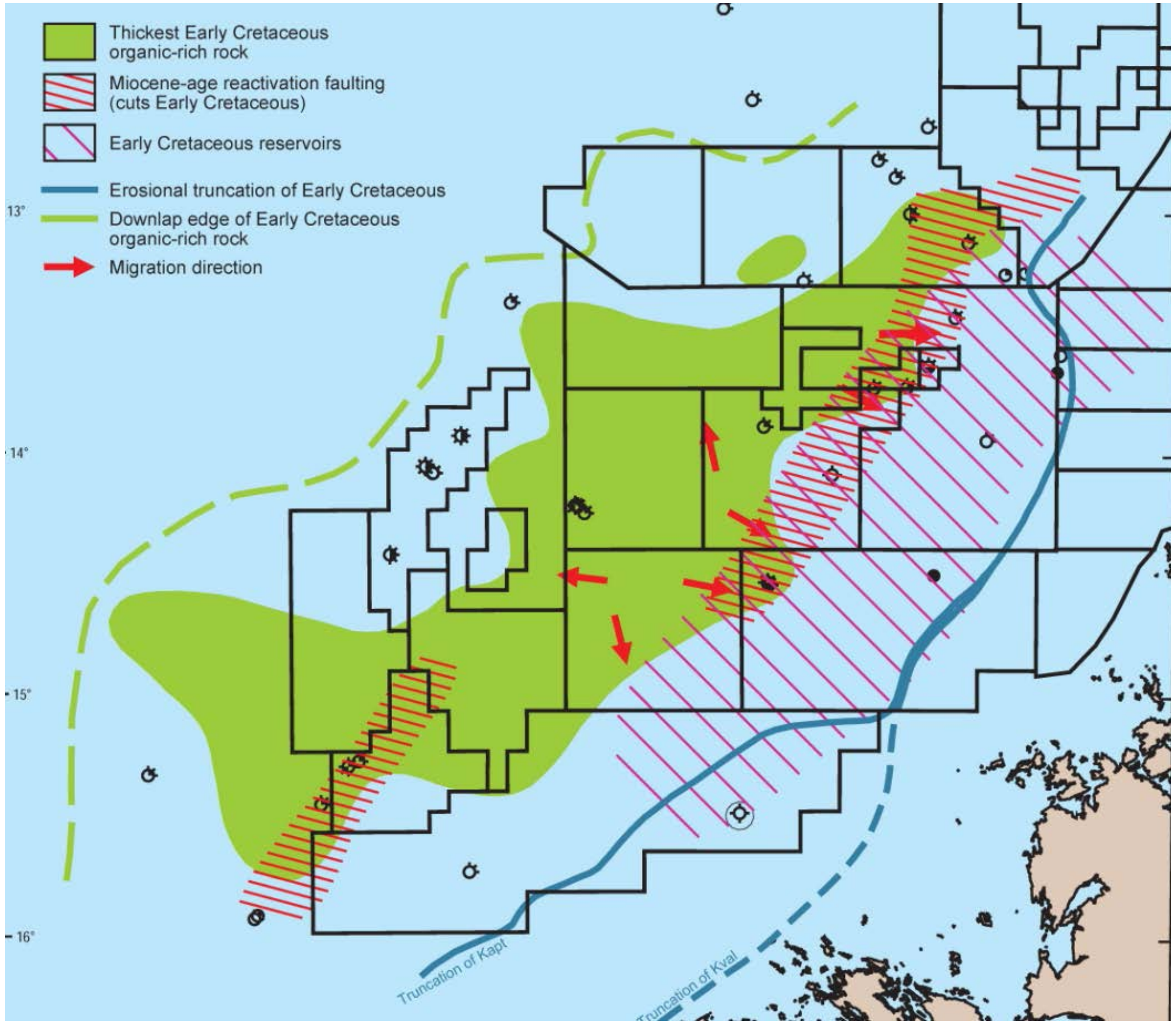
Figure 4.18: Gippsland Basin stratigraphic chart, showing sedimentary units, petroleum system elements and tectonic events. (Source: modified from Bernecker et al., 2006)

This shows a petroleum system in TIME; now let us look at one in SPACE

http://press-files.anu.edu.au/downloads/press/p194981/pdf/chapter-4.pdf

Mapping Petroleum Systems

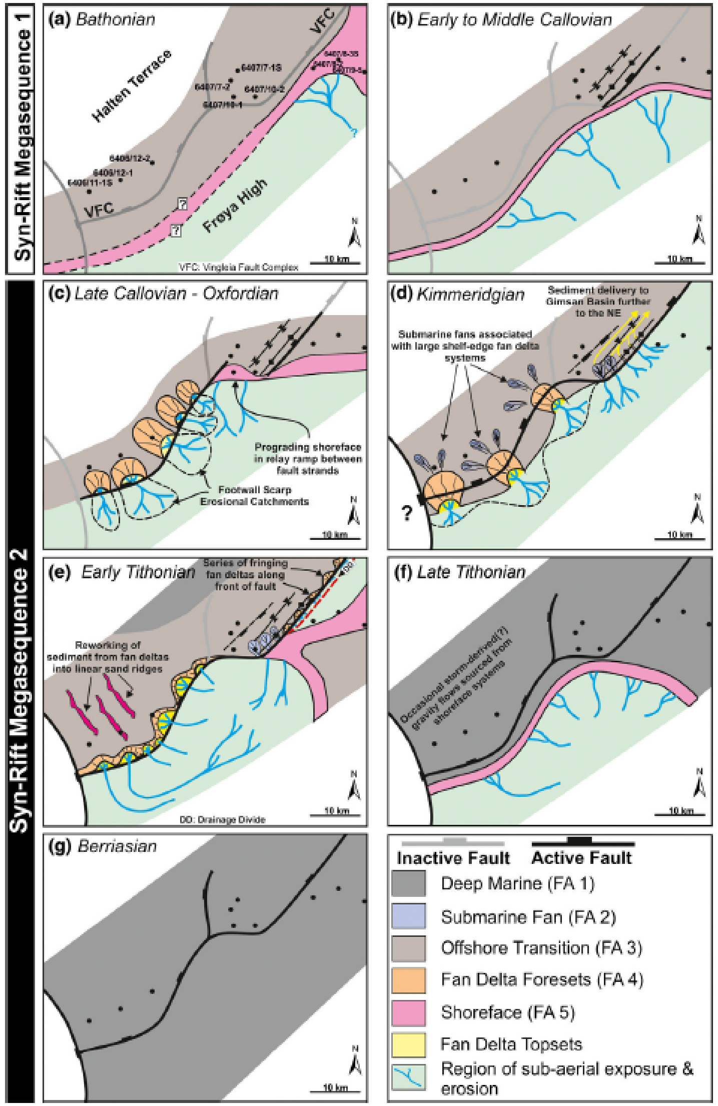
BASIN SCOPE CONSULTING



(Blevin et al., 1998)

- Palaeogeographic maps
- Source
- Reservoir
- Seal
- Traps

Now let us look at CONFIDENCE

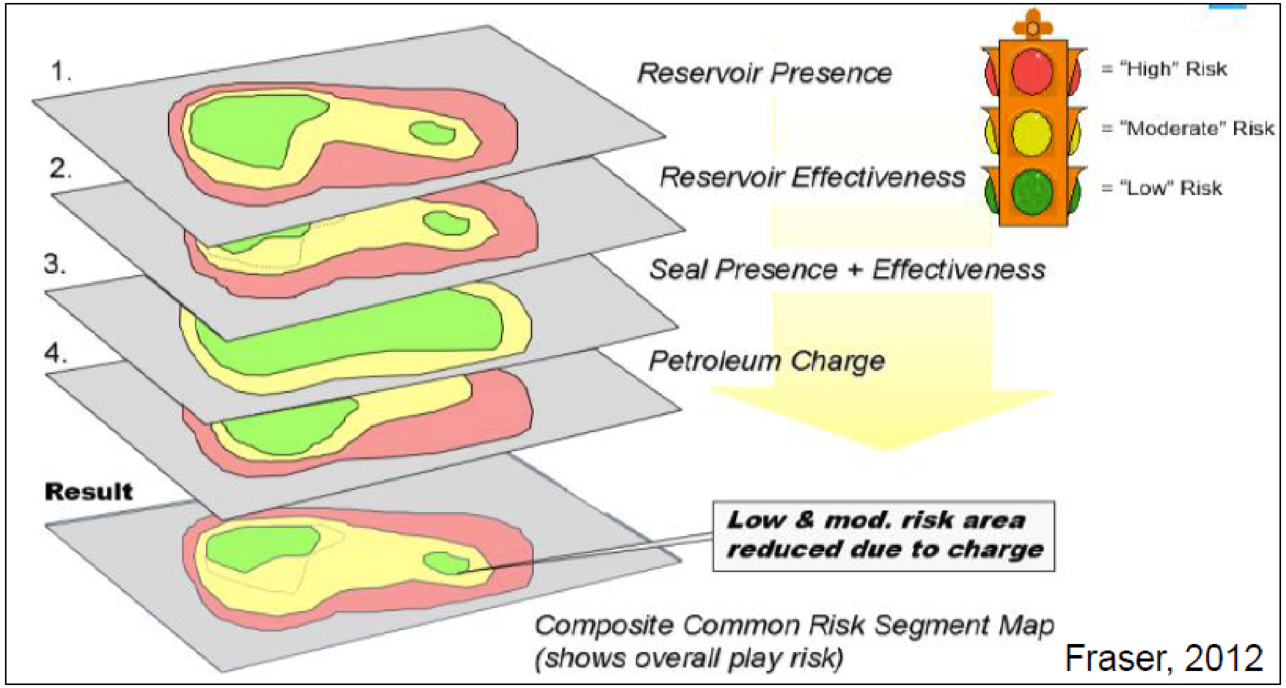


(Elliott et al., 2015, Basin Research)

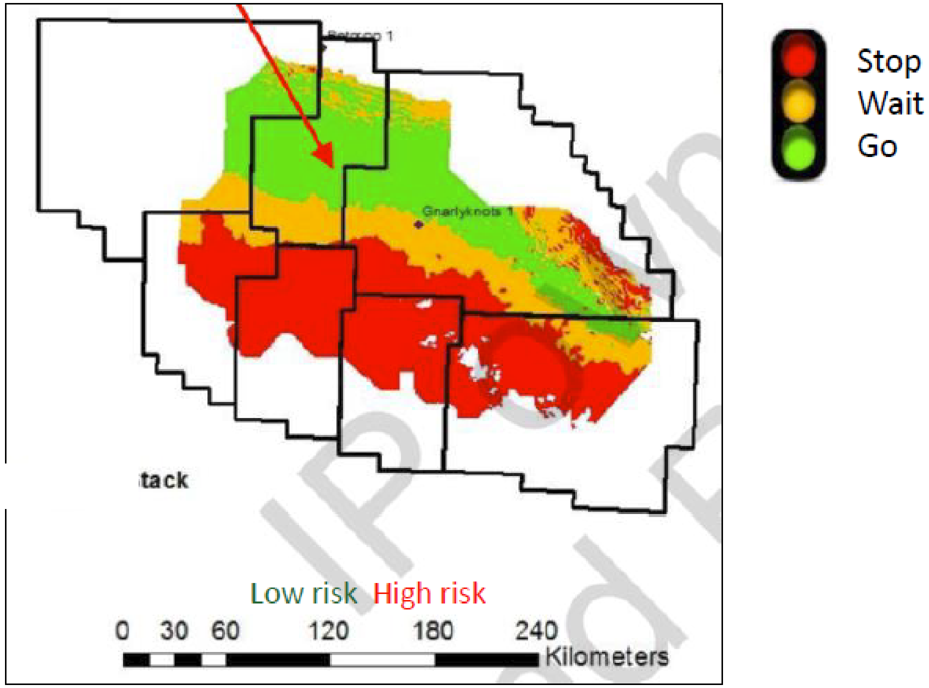
Composite risk maps

- Confidence in likelihood of each critical component being high quality
- Similarities with mineral prospectivity mapping, but also quantifies uncertainty
- Incorporates reservoir quality, seal effectiveness etc. as standard practice.

Map and stack key risks to build a pre-drill, composite risk map



Composite Geological "Risk" map



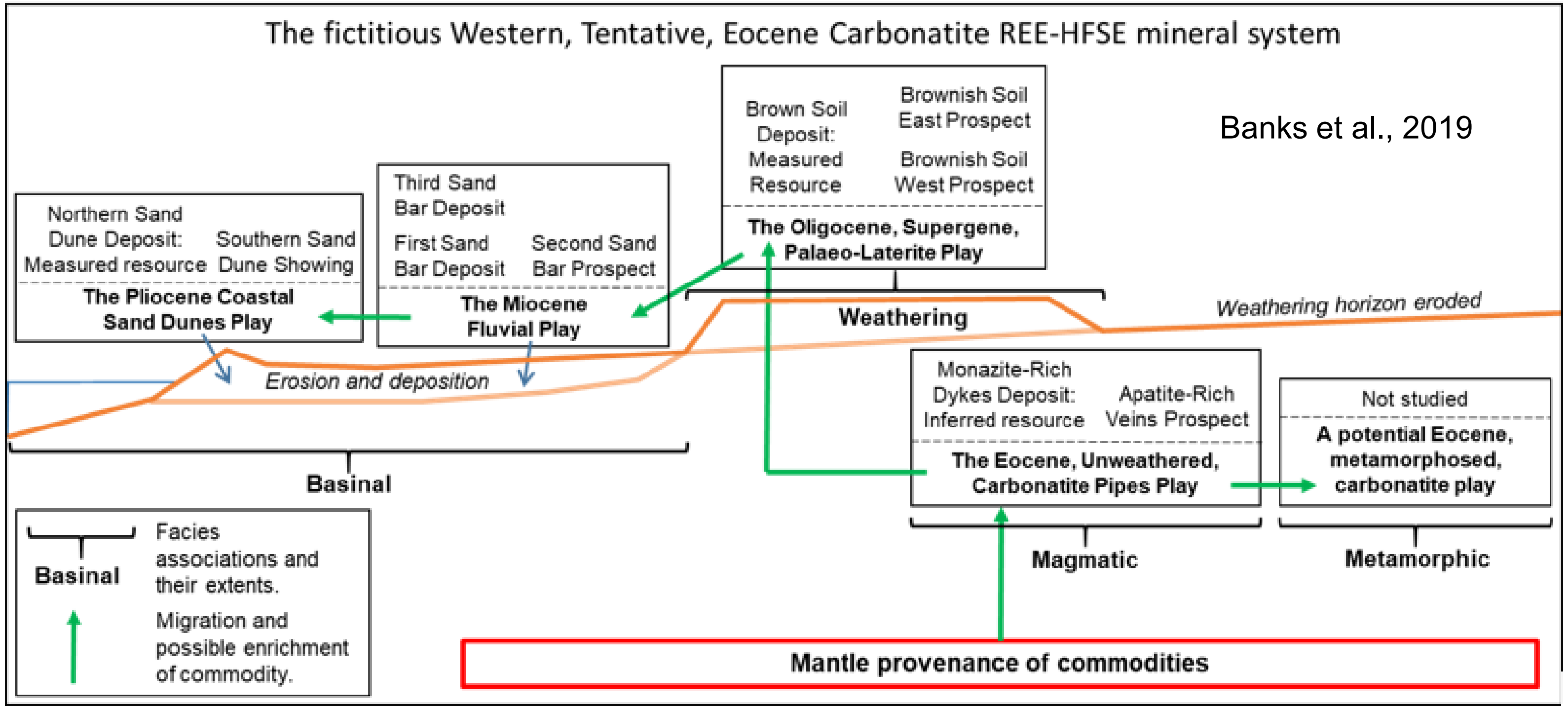
Longley and Brown, 2016

A mineral system presented in petroleum system style

All genetically linked resources, deposits, occurrences from commodity source/event.

4D model: mantle source to all the known mineral occurrences.

Play: a 'branch' with genetically related prospects/discoveries in a specific time interval



Play-Based Exploration:

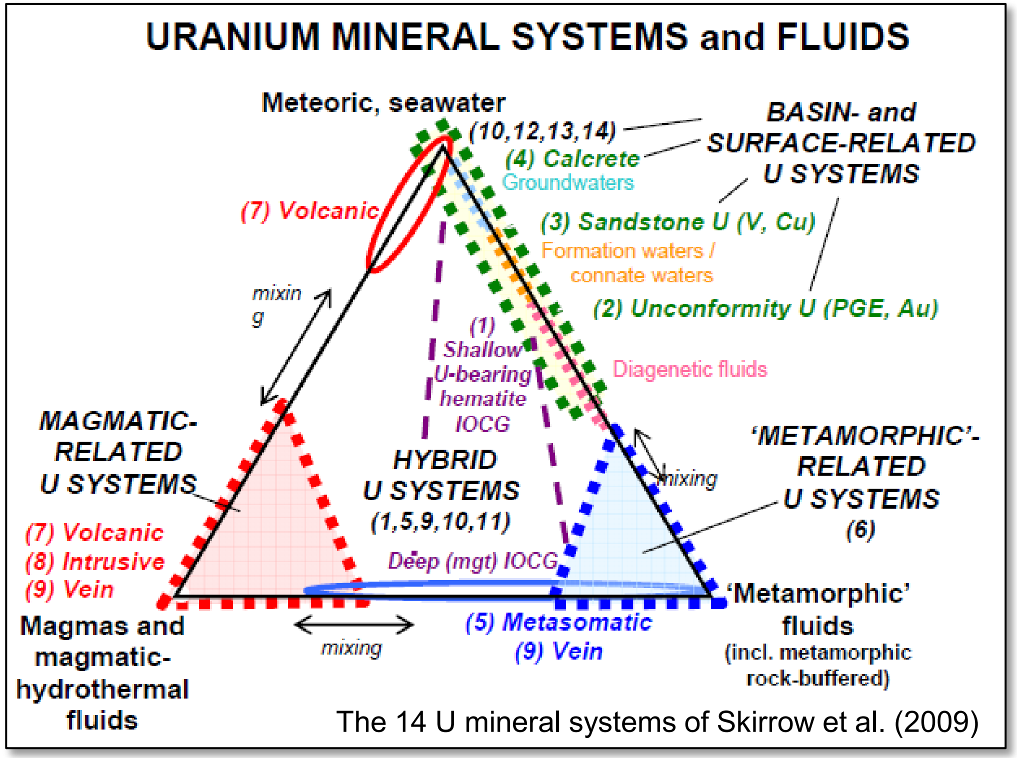
- To discover a family of deposits.

Calibrate:

- Prospect chance of success to play maps.
- Prospect resource estimate to play's deposit size distribution.

Plays as branches of a mineral system

"Mineral systems more diverse and complex than petroleum systems" Wyborn et al. (1994)



The 14 U mineral systems of Skirrow et al. (2009)

Deposit Profile Name	Alternate Names
Sediment-hosted Cu-Ag-Co	Sediment-hosted stratiform Cu
Volcanic redbed Cu	Basaltic Cu
Carbonate-hosted Cu±Pb±Zn	Kipushi Cu-Pb-Zn
Besshi massive sulphide Cu-Zn	Kieslager
Cyprus massive sulphide Cu (Zn)	
Noranda/Kuroko massive sulphide Cu-Pb-Zn	
Alkalic porphyry Cu-Au	Diorite porphyry copper
Porphyry Cu ± Mo ± Au	Calcalkaline porphyry

Lefebure and Jones (2020)

Are some mineral systems only mineral plays? Would simplify mineral system catalogues.

Implications for categorising sediment-hosted and porphyry copper systems?

Detailed Components of a Petroleum System evaluation

Petroleum system scale

- Estimate the source extent, richness, maturity and yield potential. “If it exists, how much/many/deep…?”
- Charge. Where would the petroleum have migrated towards, if it was generated? What mass?

Continue, pause or stop?

Play scale

- Estimate the regional reservoir’s range of likelihood and quality. “If it exists, how thick/deep/porous…?”
- Estimate the regional top seal’s range of likelihood and quality. . “If it exists, how thick/deep/impermeable…?”
- Screening economics.

Continue, pause or stop?

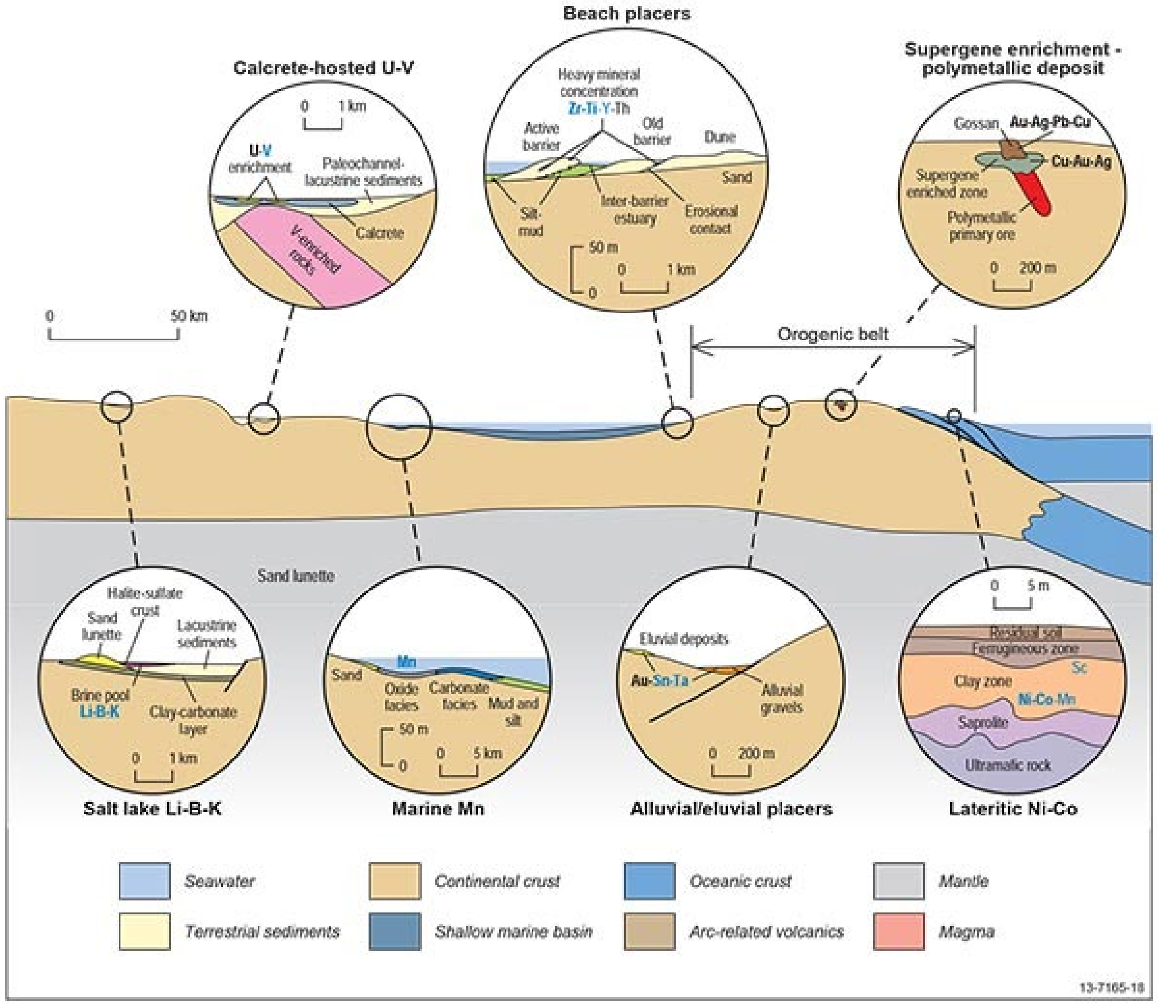
Prospect scale

- Quantity the chance, risk, uncertainty range of confidence for trap, contained reservoir, access to charge.
- Probability of preservation of accumulation.
- Detailed Expected Value, engineering, drilling, economics planning.

Most prospects don’t justify drilling. Divest instead.

Petroleum Systems approach applied to Sed-hosted Cu systems

- Fluid pathways are key: source, reservoir, seal, migration, trap, timing
- Similar elements: organic-rich source rocks (petroleum) can be reducing layers (copper).
- Evaporites can be seals (petroleum), provide brines (copper)
- Faults as fluid pathways, rock porosity important for reservoirs (petroleum) and fluid pathways (copper)
- Tectonic events
- Petroleum geology examples to look at mineral system

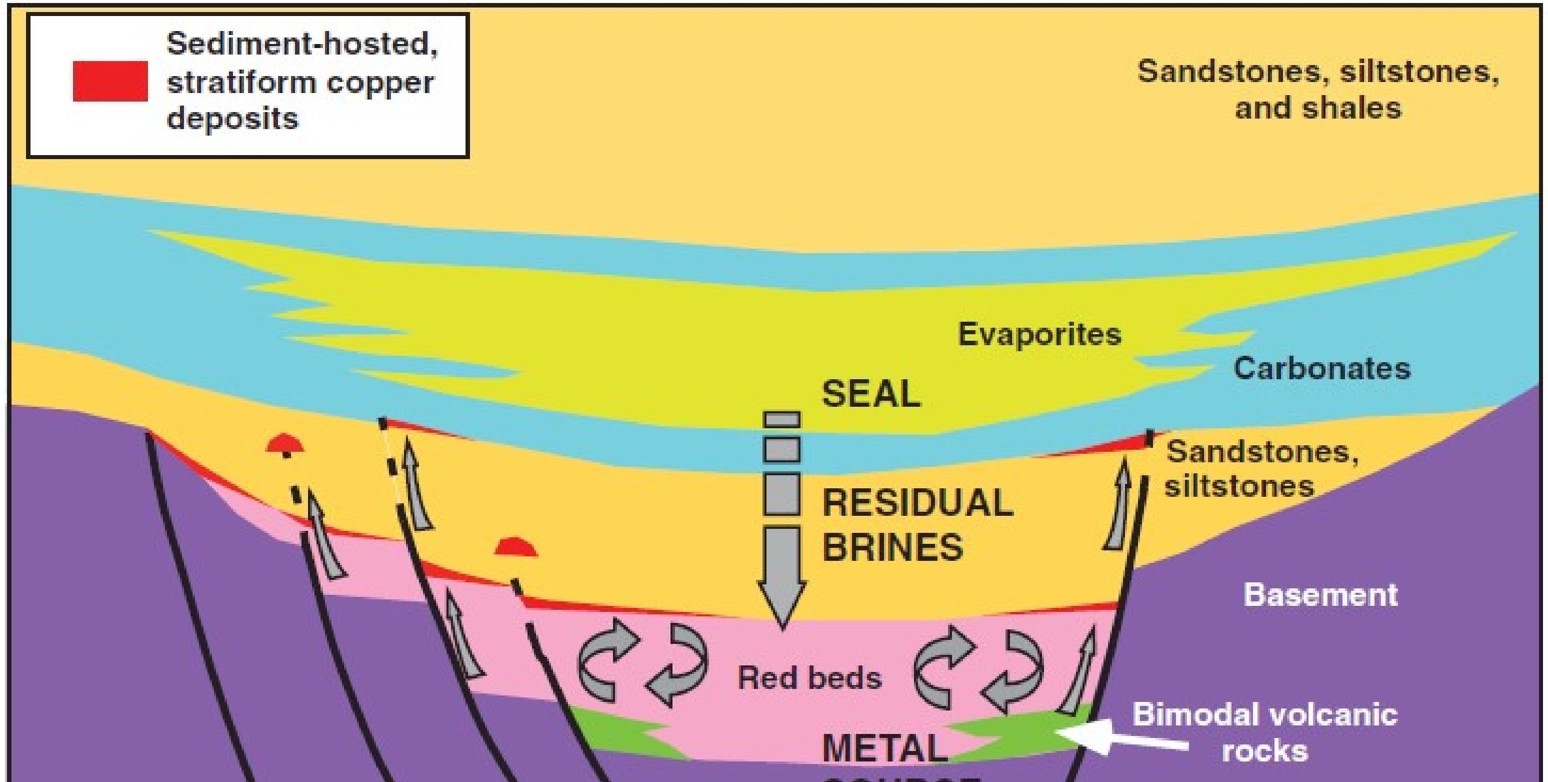


https://www.ga.gov.au/data-pubs/data-and-publications-search/publications/critical-commodities-for-a-high-tech-world/surficial-mineral-systems

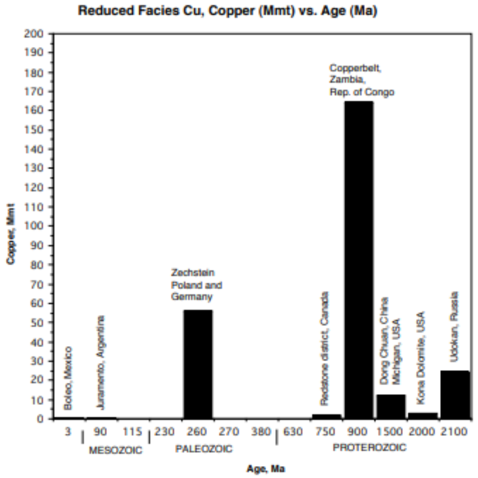
Key features of sediment-hosted Cu deposits (Hitzman, 2010)

BASIN SCOPE CONSULTING

- Model describes giant deposits in Europe (Kupferscheifer) and Africa (CACB)
- Failed rift – restricted basins
- Redbeds and volcanics (source)
- Evaporites/brines
- Organic-rich shales/carbonates
- Glacial sediments (Sulphur)
- Tectonic events – fluid movement



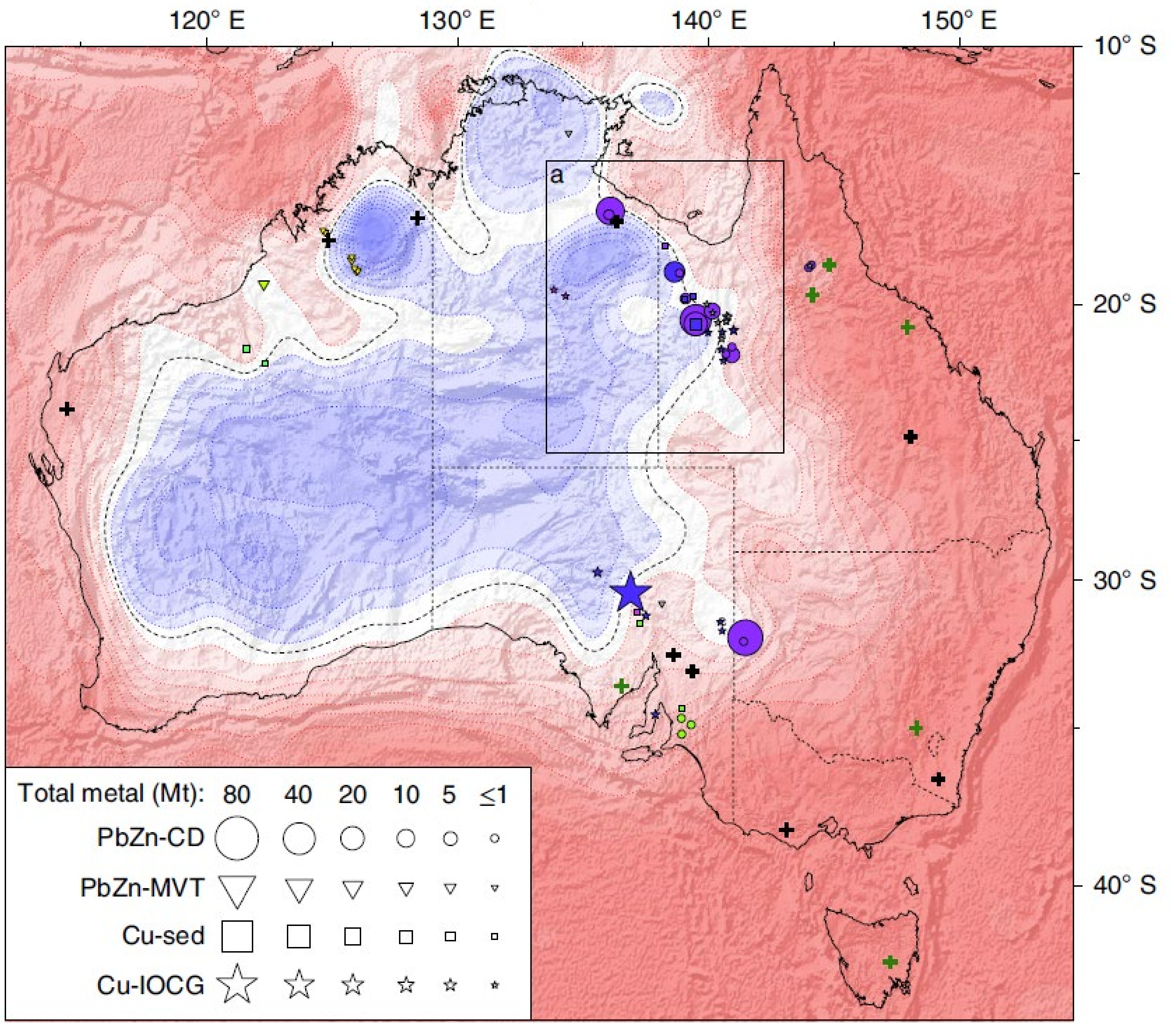
(Hitzman, 2010)



- Rodinia breakup: Neoproterozoic (CACB)
- Pangea breakup: Late Paleozoic (Zechstein)

Basin screening: Geodynamic setting

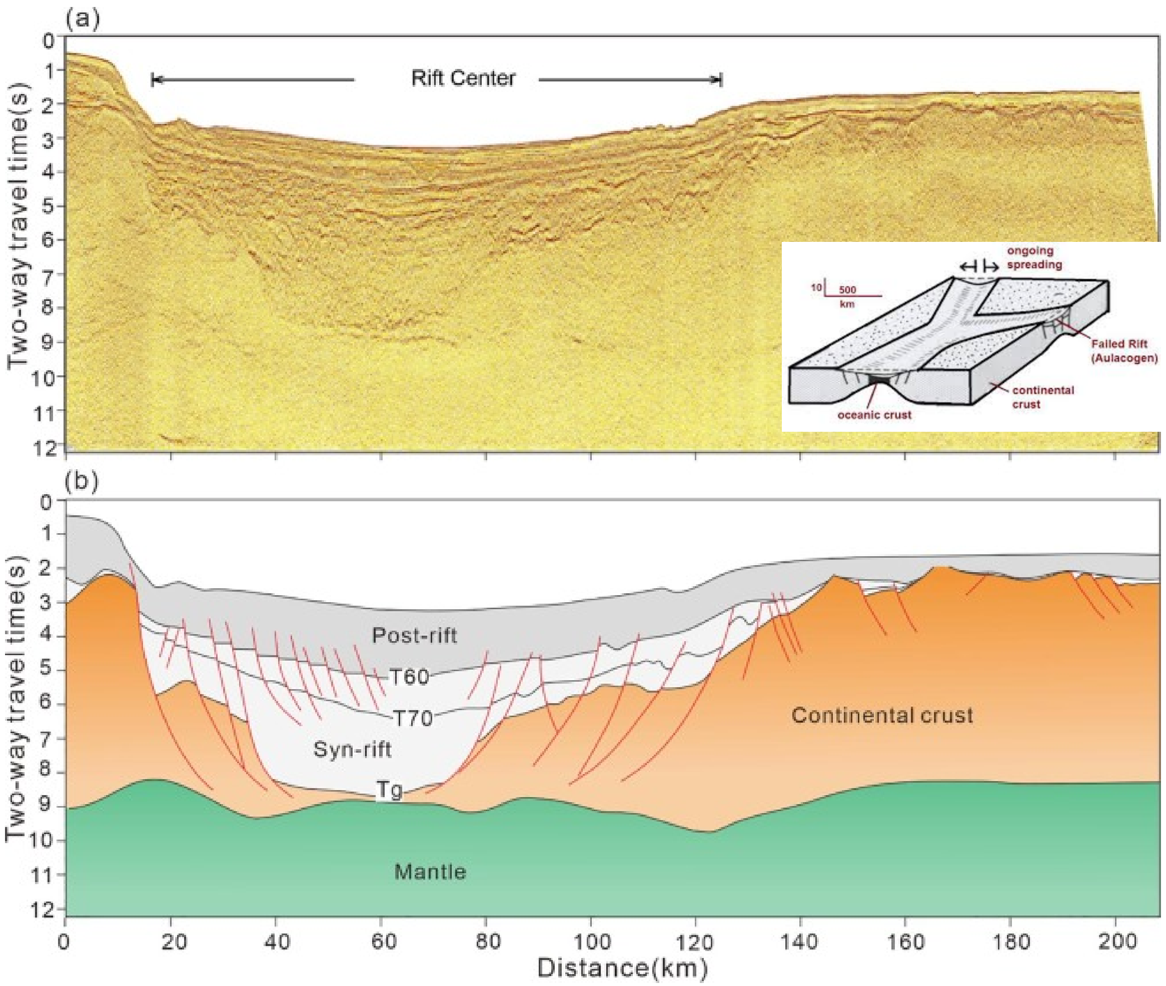
- Distribution of sediment-hosted and IOCG base metals as a function of Australian lithospheric thickness (Hoggard et al., 2020)
- Link to geodynamics – craton edges undergo repeated rifting and amalgamation with supercontinent cycles
- This is where you would expect to see high heat flow (source), high fluid flow, and failed rift systems
- Ideal environment to produce key elements for sed-hosted copper



(Hoggard et al., 2020, Nature)

Basin screening: Basin types

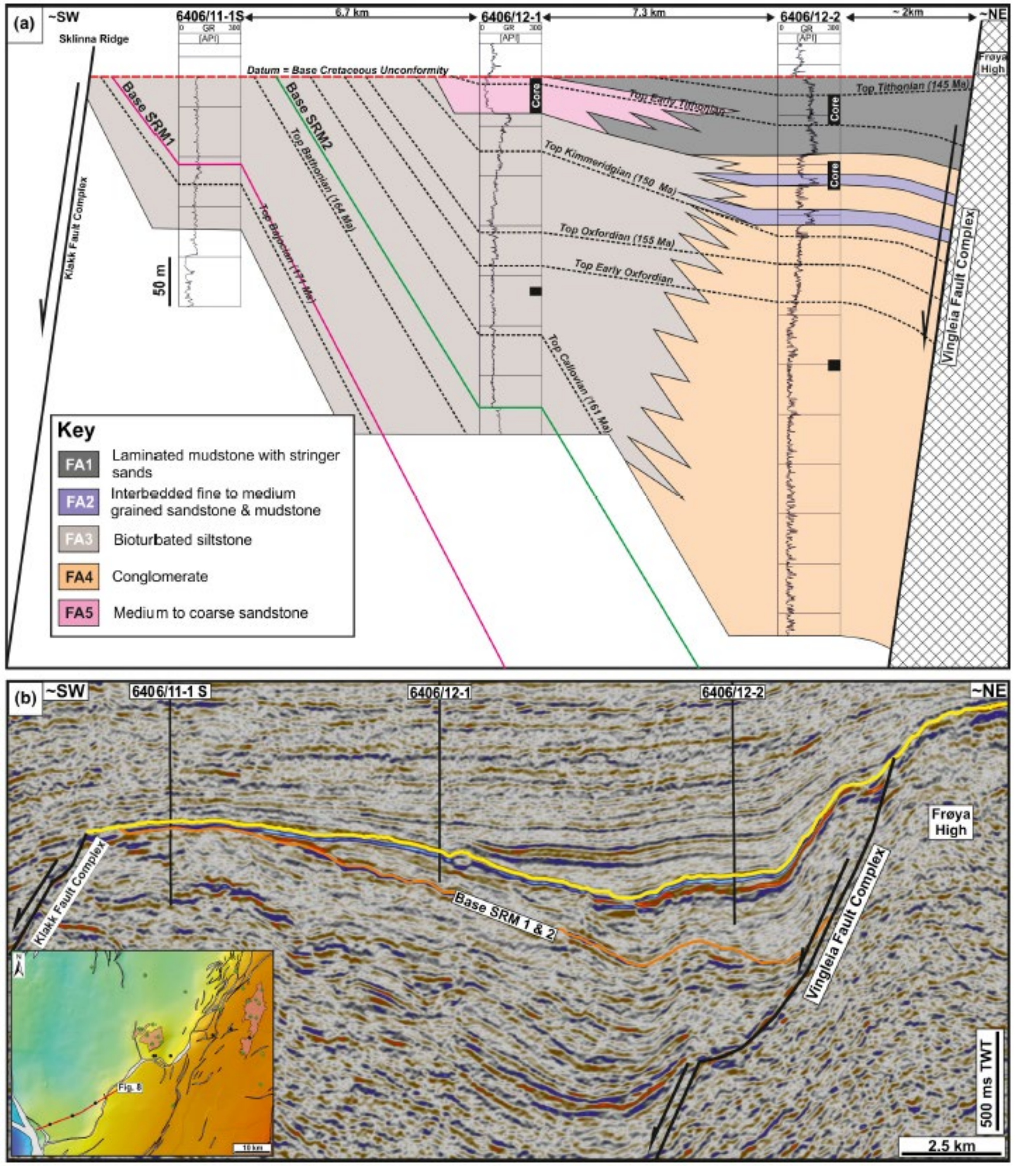
- Failed rifts and intracratonic basins most prospective for sed-hosted Cu (but think about other restricted basin types)
- Can form long, narrow basins (failed rift) or broad shallow ones (intracratonic)
- Extension and subsidence but does not progress to continental breakup and ocean spreading.
- Often contain bimodal volcanics (source)
- Increased heat flow during rifting, followed by thermal subsidence
- Critical features: large enough to contain large volumes of fluid, but closed so the fluid can circulate
- Basin fill influenced by: Shape, Sediment supply, Depositional environment (climate, eustacy), Subsidence rates, Geothermal gradients



(Yi et al., 2020, Journal of Asian Earth Sciences)

Petroleum System: Stratigraphic architecture

BASIN SCOPE CONSULTING



(From Elliott et al., 2015, Basin Research)

- Non-marine rift basins typically begin with <u>basin-wide fluvial deposits</u> (red beds?) overlain by deepening-upward <u>lacustrine succession</u> (reductant surface?)
- These are overlain by gradual shallowing-upward lacustrine and fluvial successions
- Periodic marine incursions - <u>evaporites</u>
- Lateral facies changes – need sequence stratigraphic correlations. Lateral variation in rock type, plus porosity and permeability
- Can be challenging from drill hole only (1D) – improved with seismic data

Petroleum System: Evaporites

- Occur in restricted shallow marine or sabkha environment (early rift sequence)
- Mobile in the subsurface. Presence and absence visible in seismic data
- Traps and seals (petroleum)
- Brine source, trap (minerals)

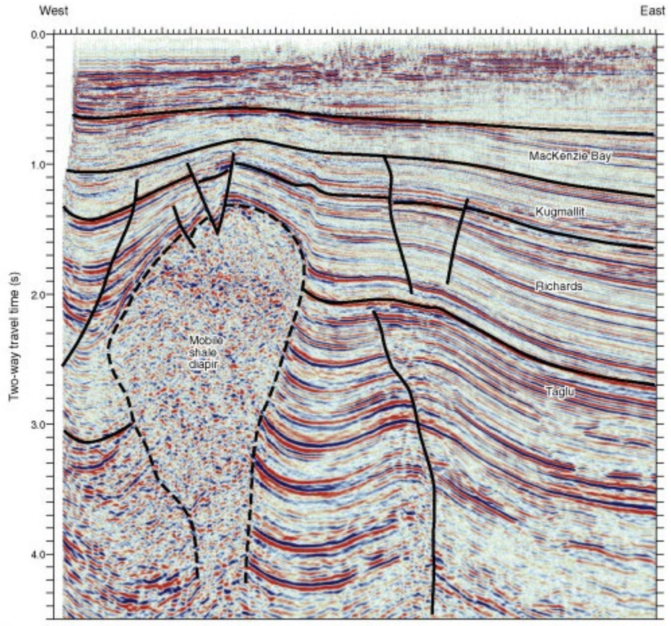
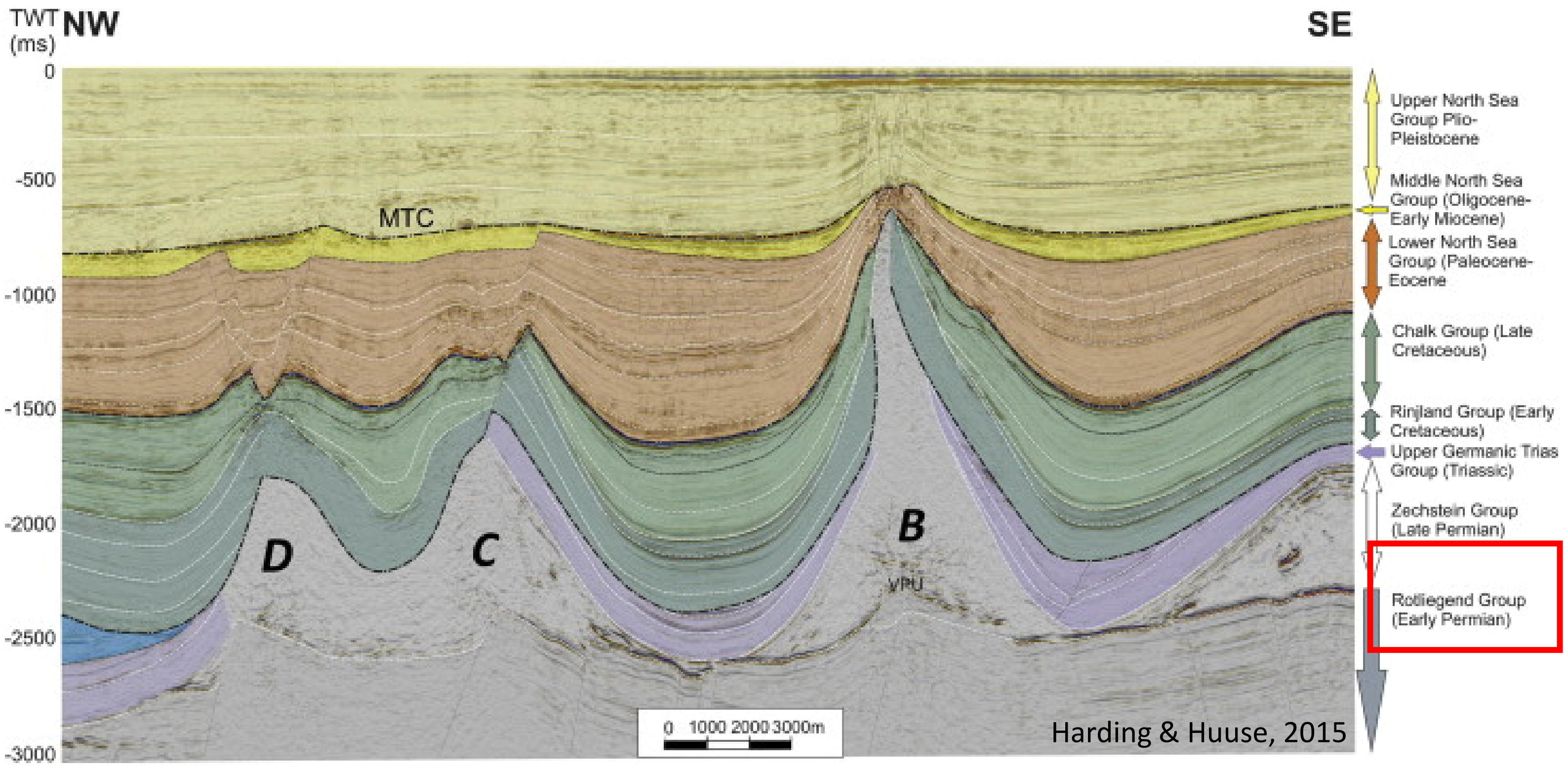


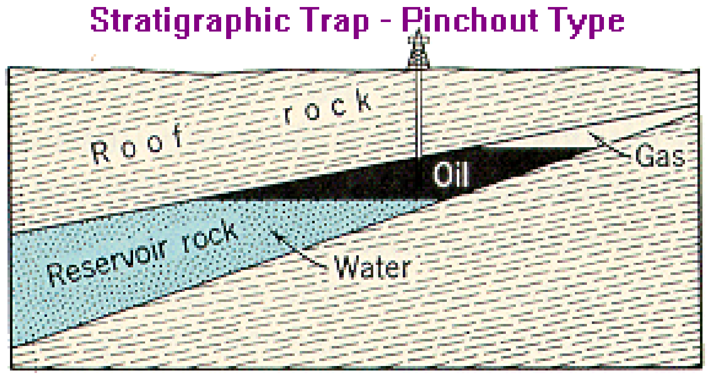
Image courtesy of G. Isley, Devon, Canada

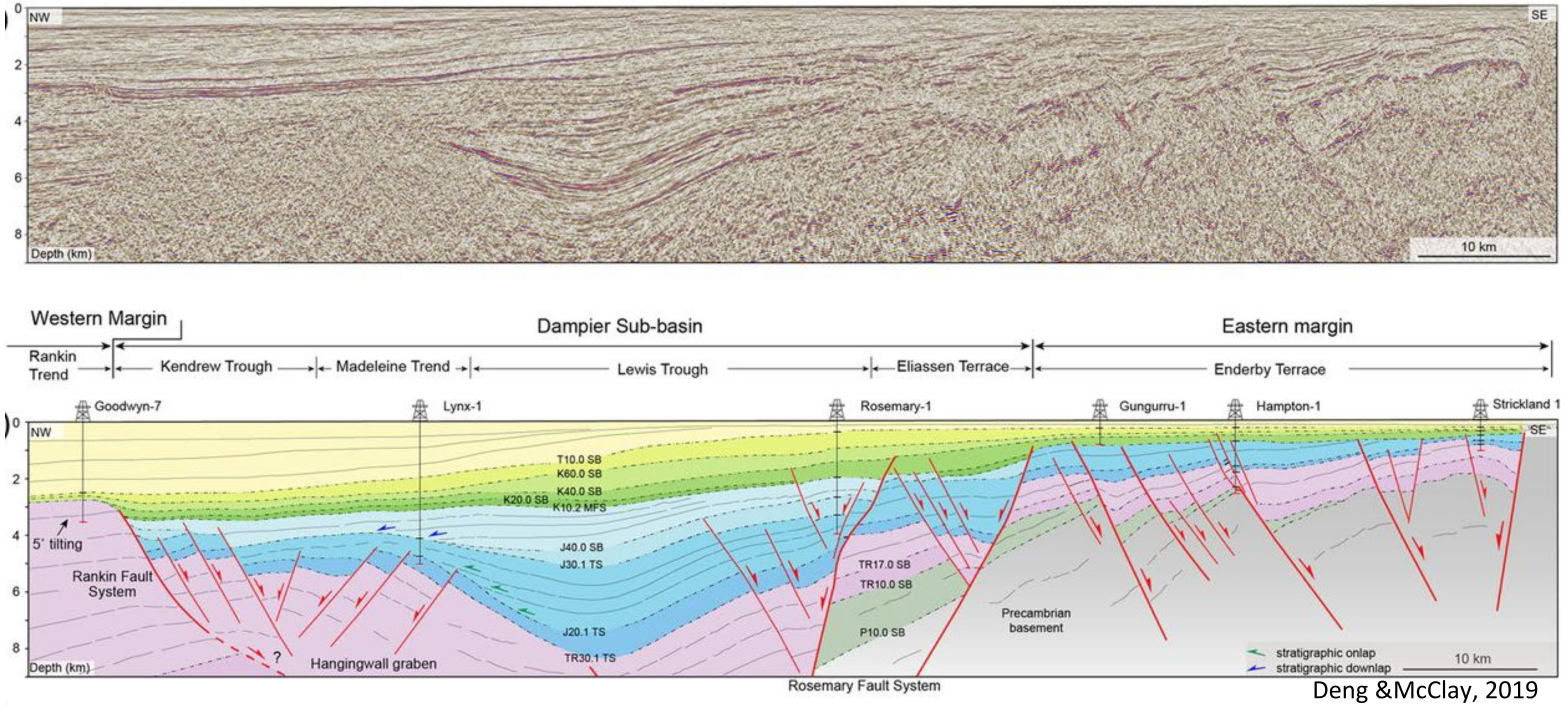


Harding & Huuse, 2015

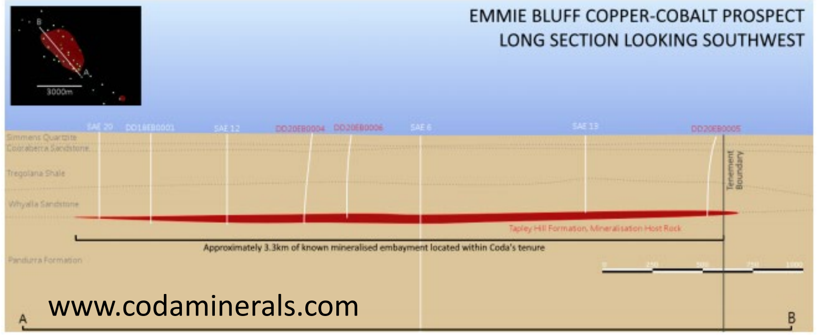
Petroleum System: Fluid pathways

- Fracture permeability– sub-vertical fluid movement on faults, fractures, karst
- <u>Matrix permeability</u>: Tabular deposits (e.g. Kupferscheifer, Emmie Bluff) suggest permeability in underlying layers to give mineralizing fluids maximum access to reducing layer
- Stratigraphic pinchouts – fluid overpressure aids precipitation?



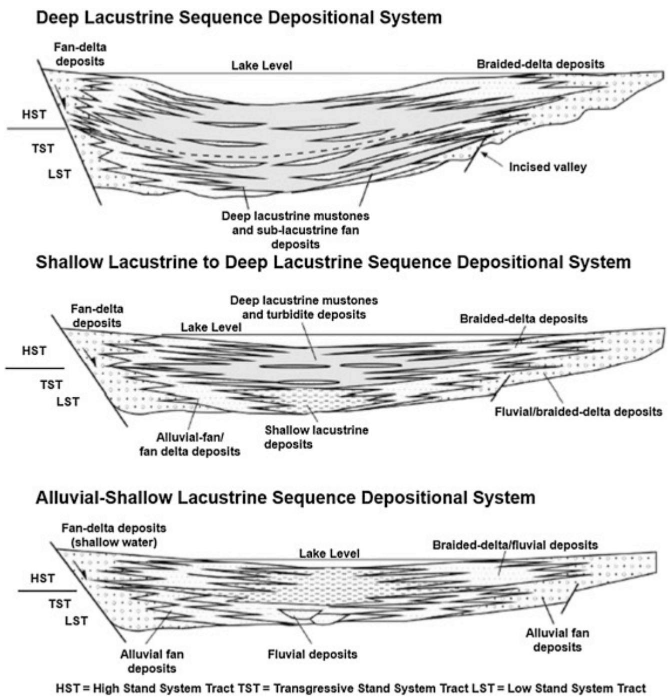


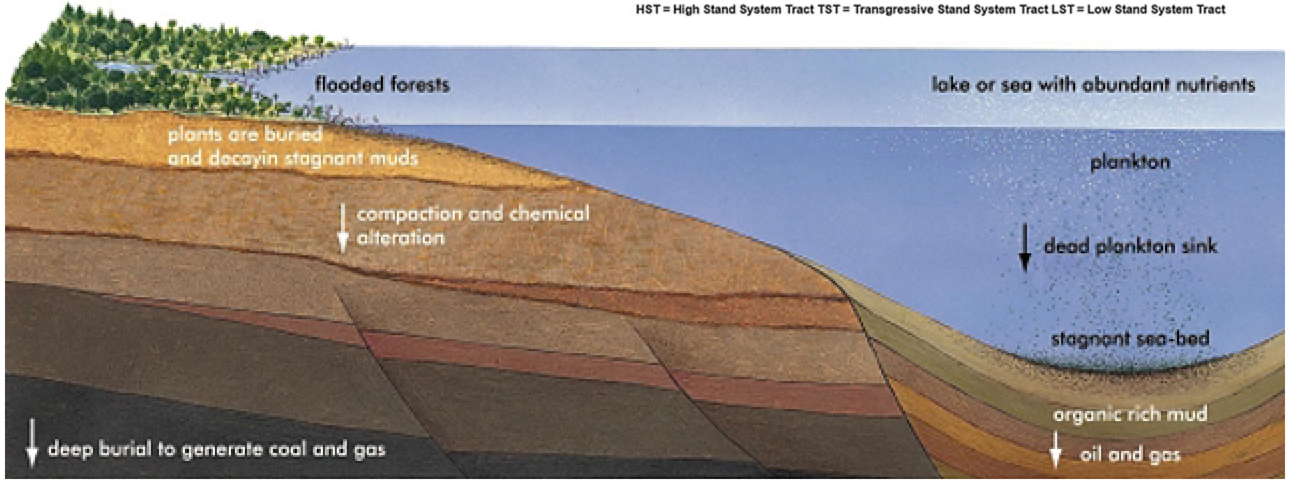
Deng &McClay, 2019



Petroleum System: Host rocks (reducing)

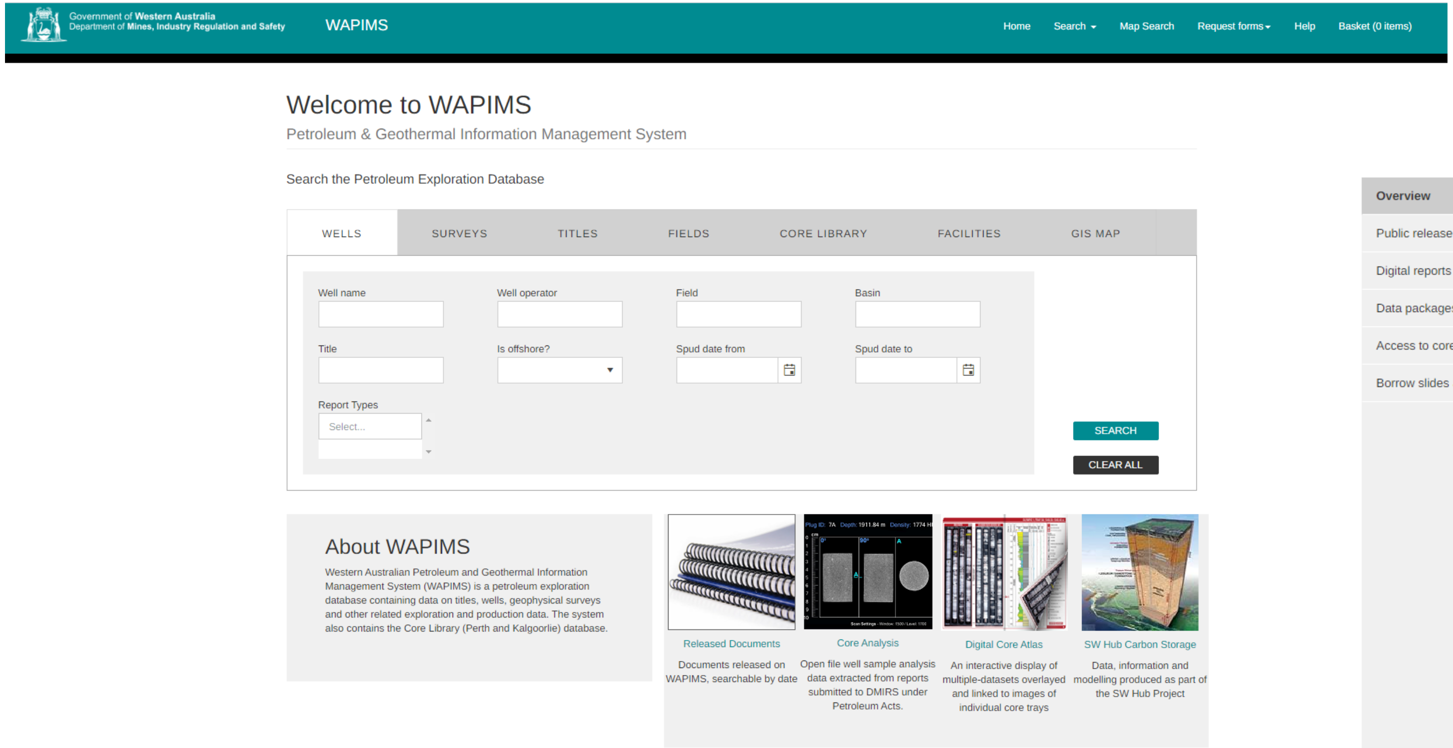
- Reduced facies, organic content, carbonates
- Depositional environment – sequence stratigraphy. Low sedimentation rate: ocean, lagoon, lake, low-sand rivers
- Early rift sequences: lacustrine, early marine incursions, open marine anoxic settings
- Link to petroleum source rocks

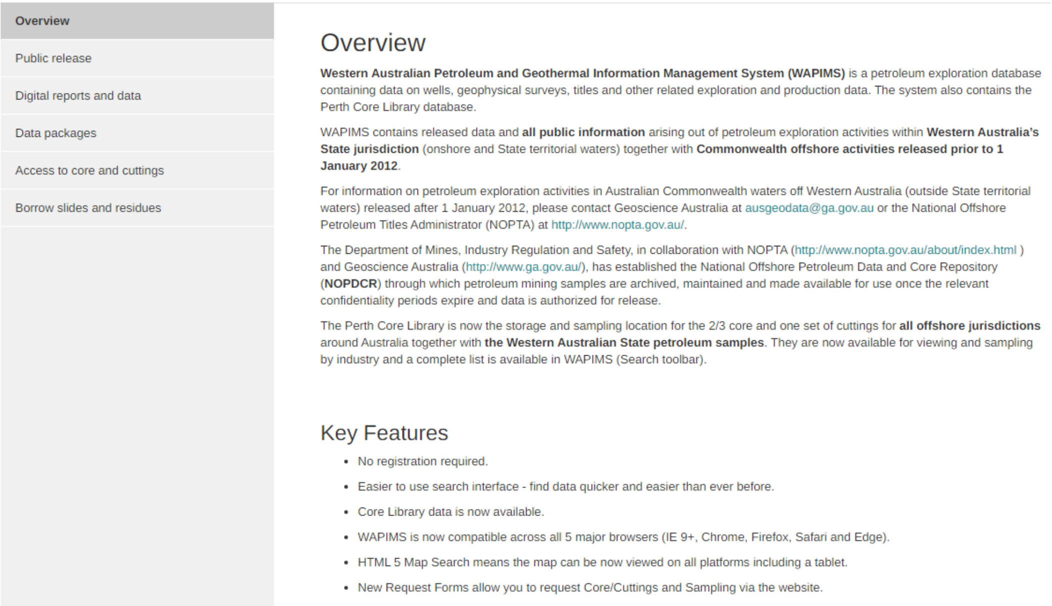




Petroleum data sources

- Potential fields: GADDS
- Seismic, Wells, reports: NOPIMS/WAPIMS
  https://wapims.dmp.wa.gov.au/WAPIMS/



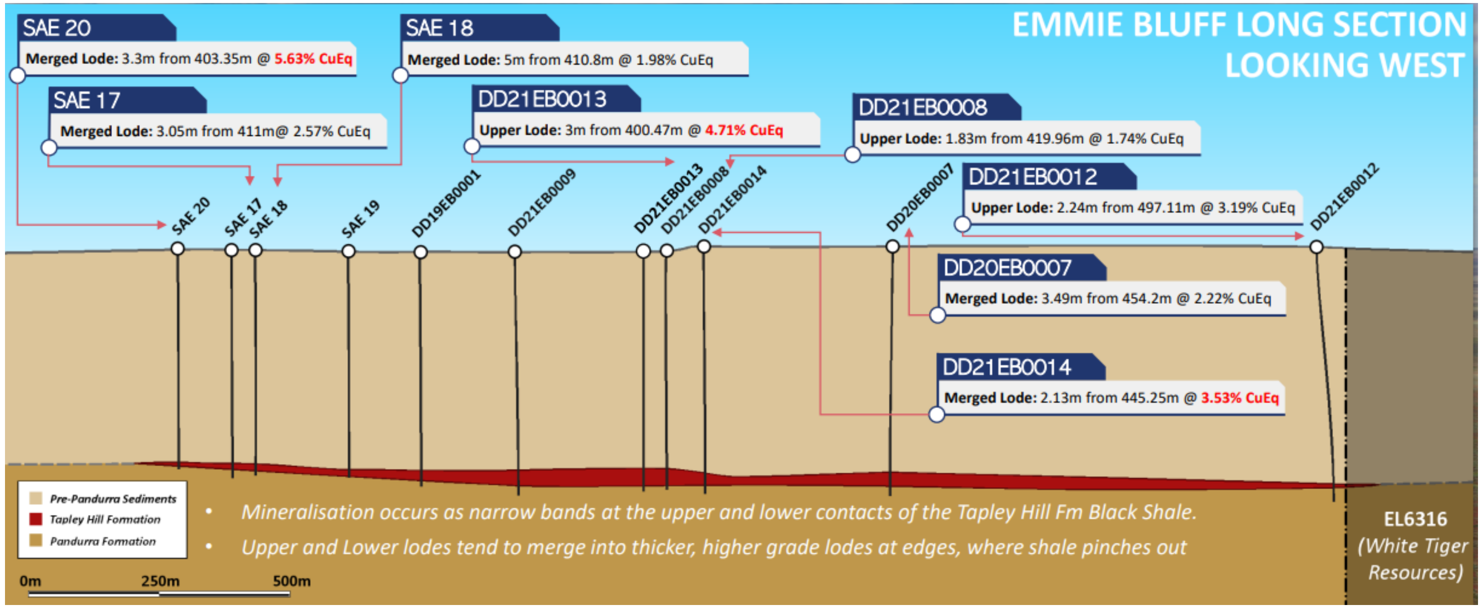


Case study 1: Emmie Bluff shale-hosted copper deposit

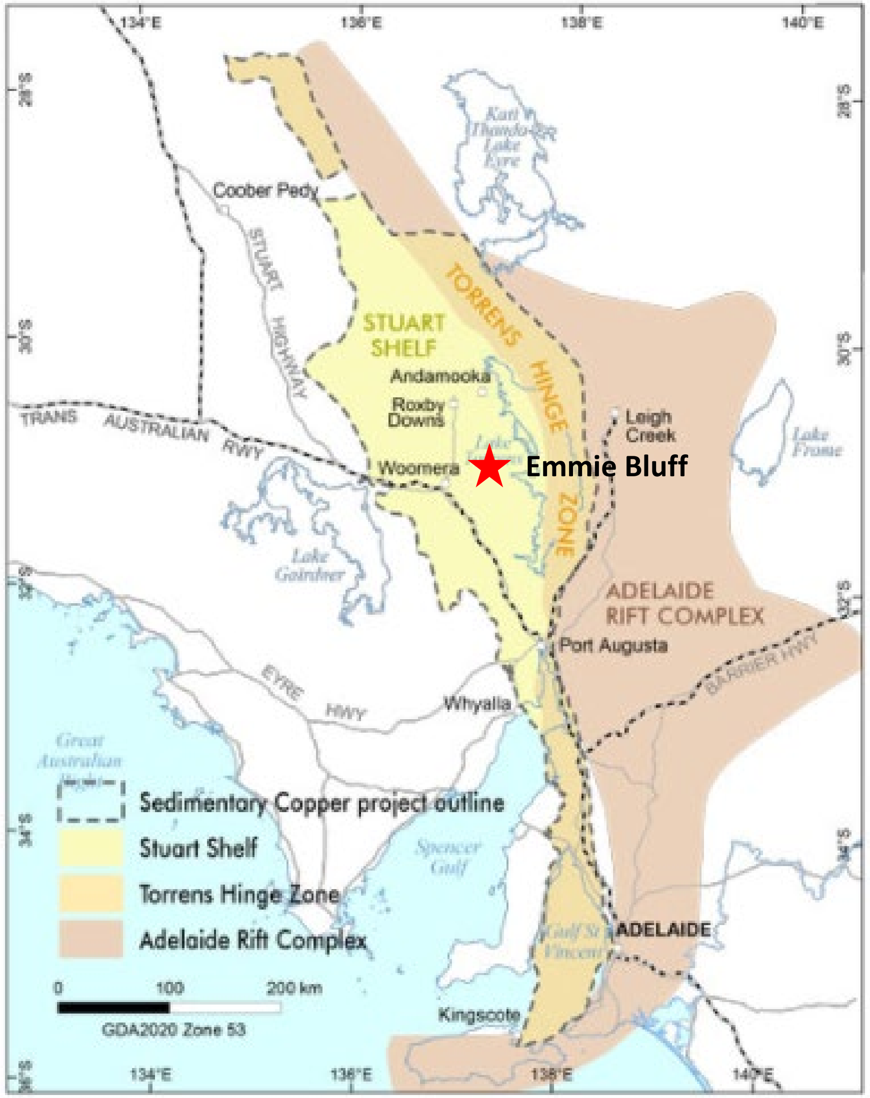
BASIN SCOPE CONSULTING

Existing discovery: classic example

- Stuart Shelf, South Australia, Current study by GSSA and CSIRO: basin architecture
- Historic deposit, mineralization in Neoproterozoic Tapley Hill Formation: Overlies known IOCG deposit (source?). Mineralized at top and bottom of shale layer
- Open marine depositional environment with localized shallow water facies. Rift shoulder.

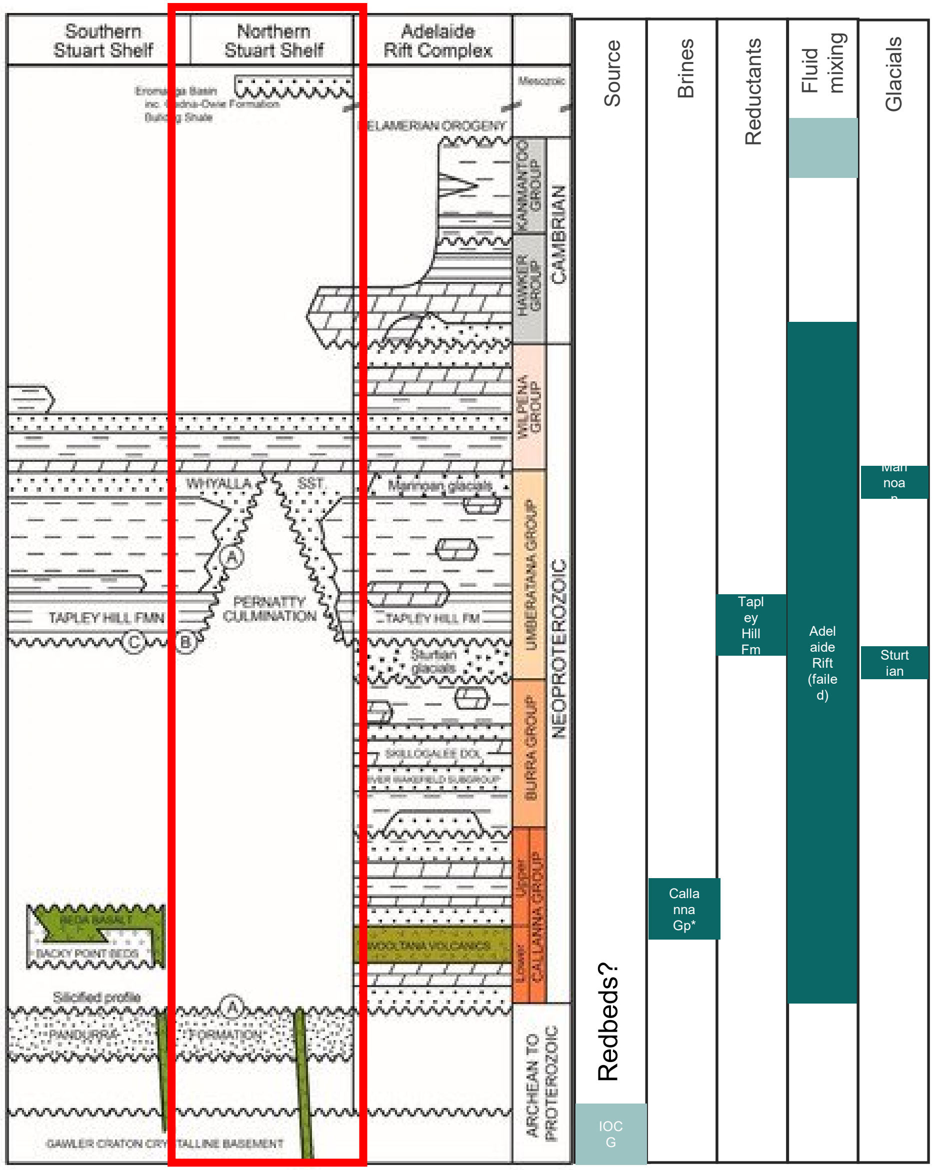


Coda Minerals presentation to RUI Sydney Recourses Roundup, 2021



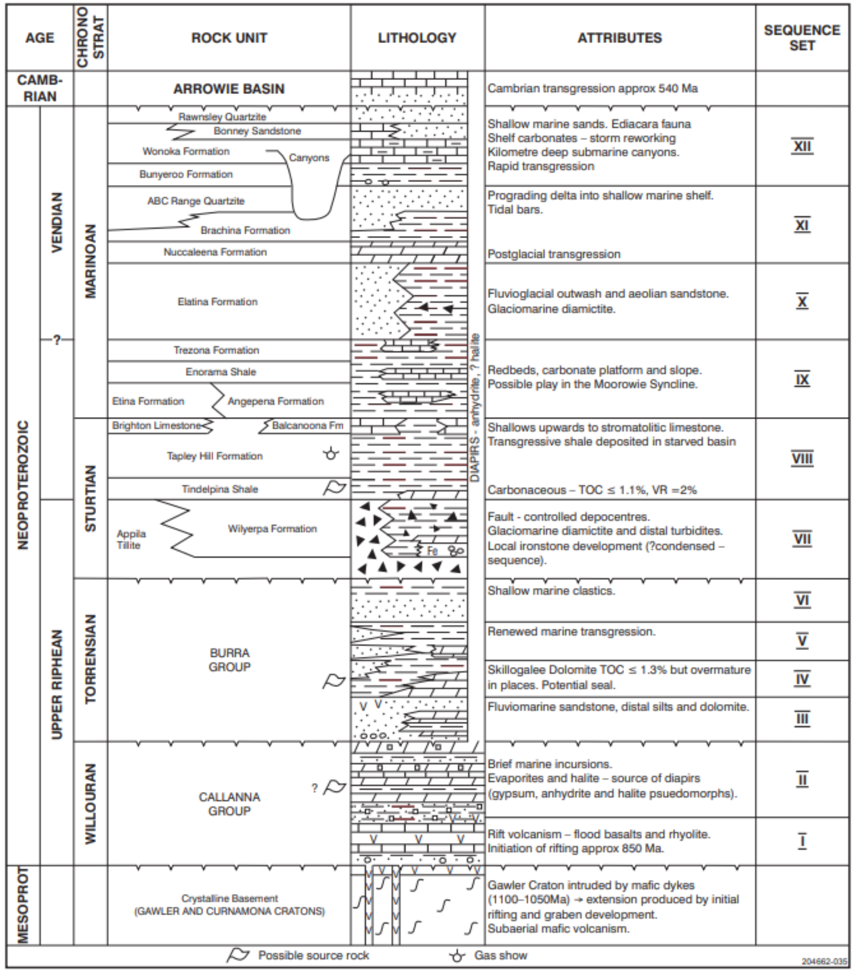
https://energymining.sa.gov.au/minerals/geoscience/gssa_projects/sedcu

Mineral system screening results



Reid, 2019. https://doi.org/10.3390/min9060371

- Mineral system events chart shows critical elements of the mineral system occurring in the right order.
- Basin contains typical components for sediment-hosted Cu (but no inversion)
- Decreases uncertainty
- Follow up with play-scale evaluations
- Sequence stratigraphy and palaeogeography are key to understanding the distribution of mineral system elements

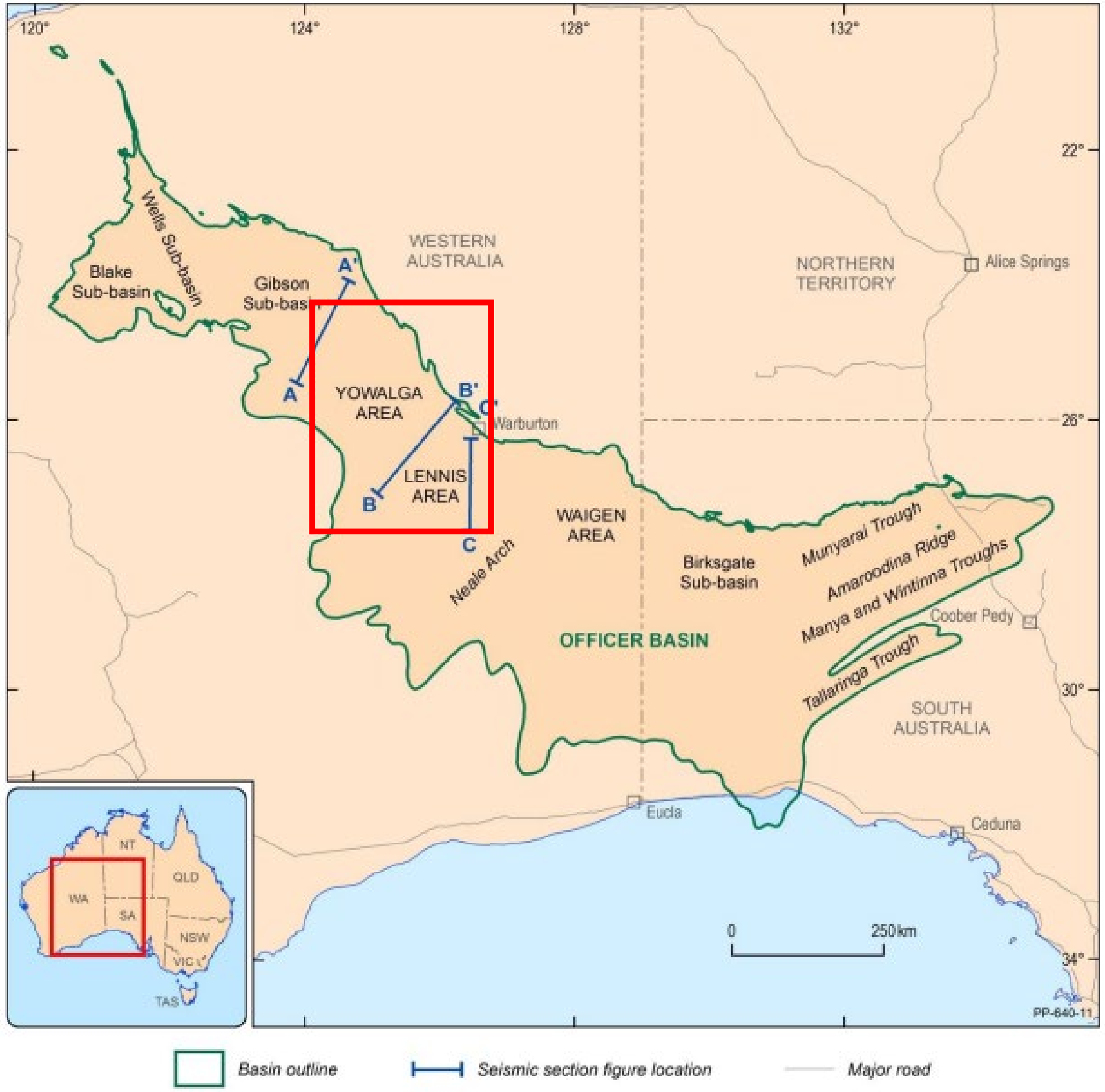


https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/plans/sarig1/image/DDD/204662-035

Case Study 2: Officer Basin

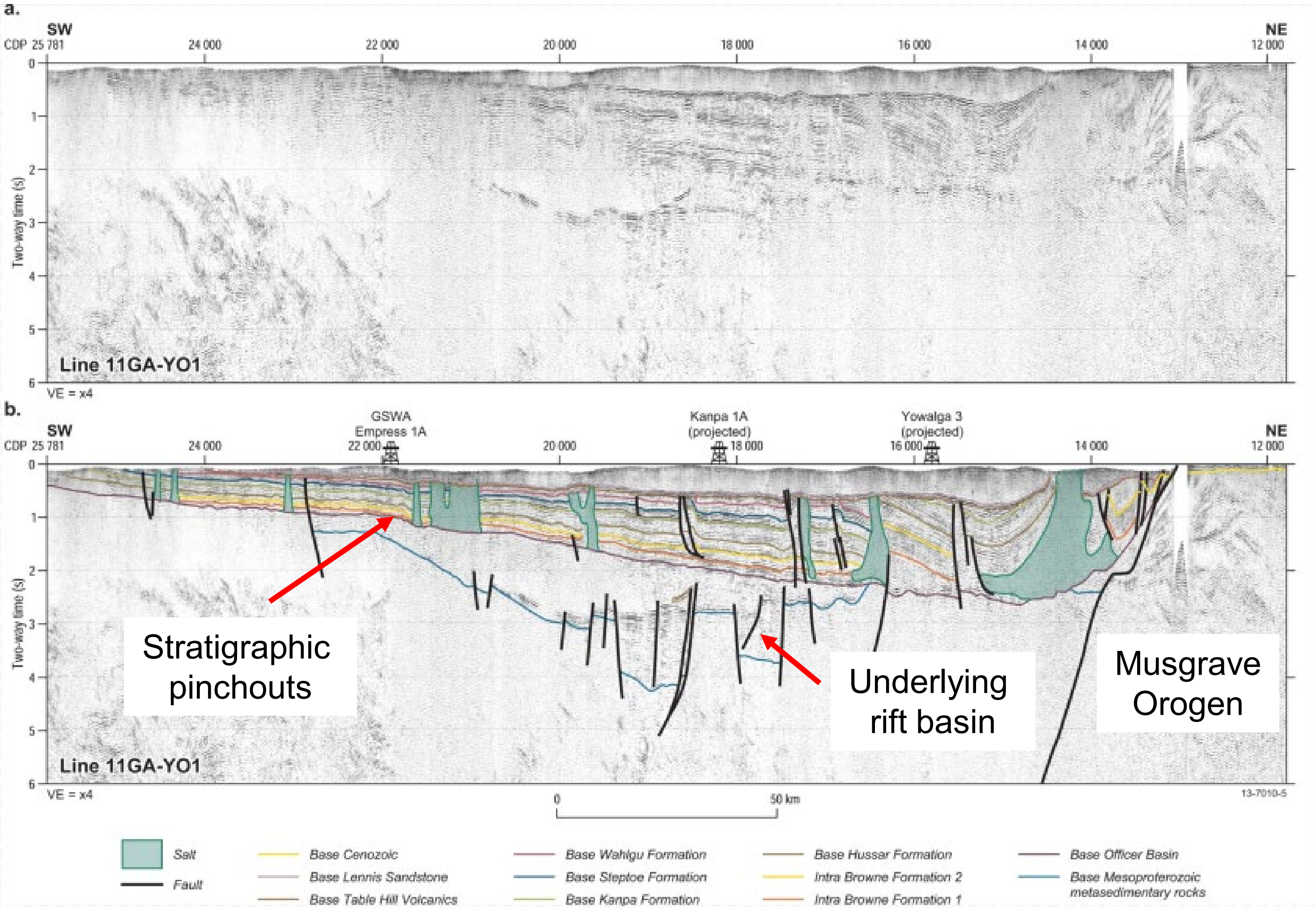
No sediment-hosted copper discoveries – yet!

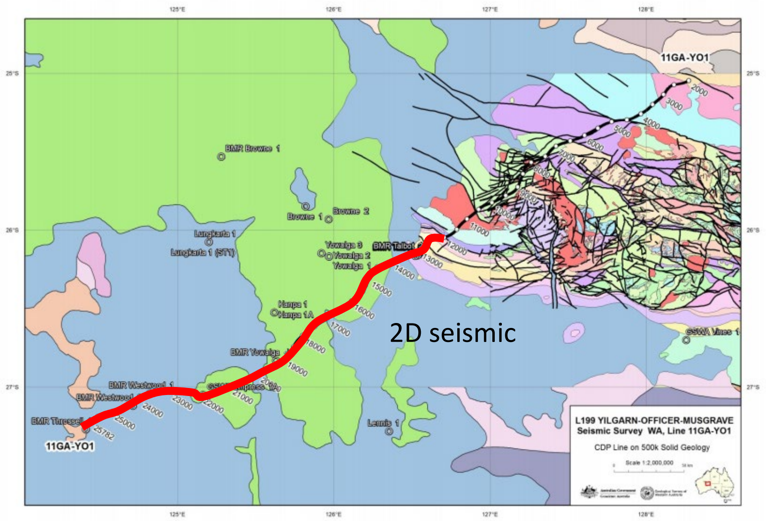
- Neoproterozoic-Paleozoic Officer Basin
- Sag basin (or foreland basin?) part of Centralian superbasin and inverted during late Neoproterozoic Petermann Orogeny (560-545 Ma) and Delamerian Orogeny (510-490 Ma)
- Very large, overlies several different basement terranes and a state boundary (stratigraphy)
- Relatively underexplored (petroleum)
- No significant petroleum accumulations but hydrocarbon shows in wells
- At least four petroleum systems, 2 Neoproterozoic, 2 Cambrian
- Lots of data available for a desktop study



Basin screening: basin architecture

- Regional deep seismic line shows basin architecture, major structures, salt diapirs, and underlying basin

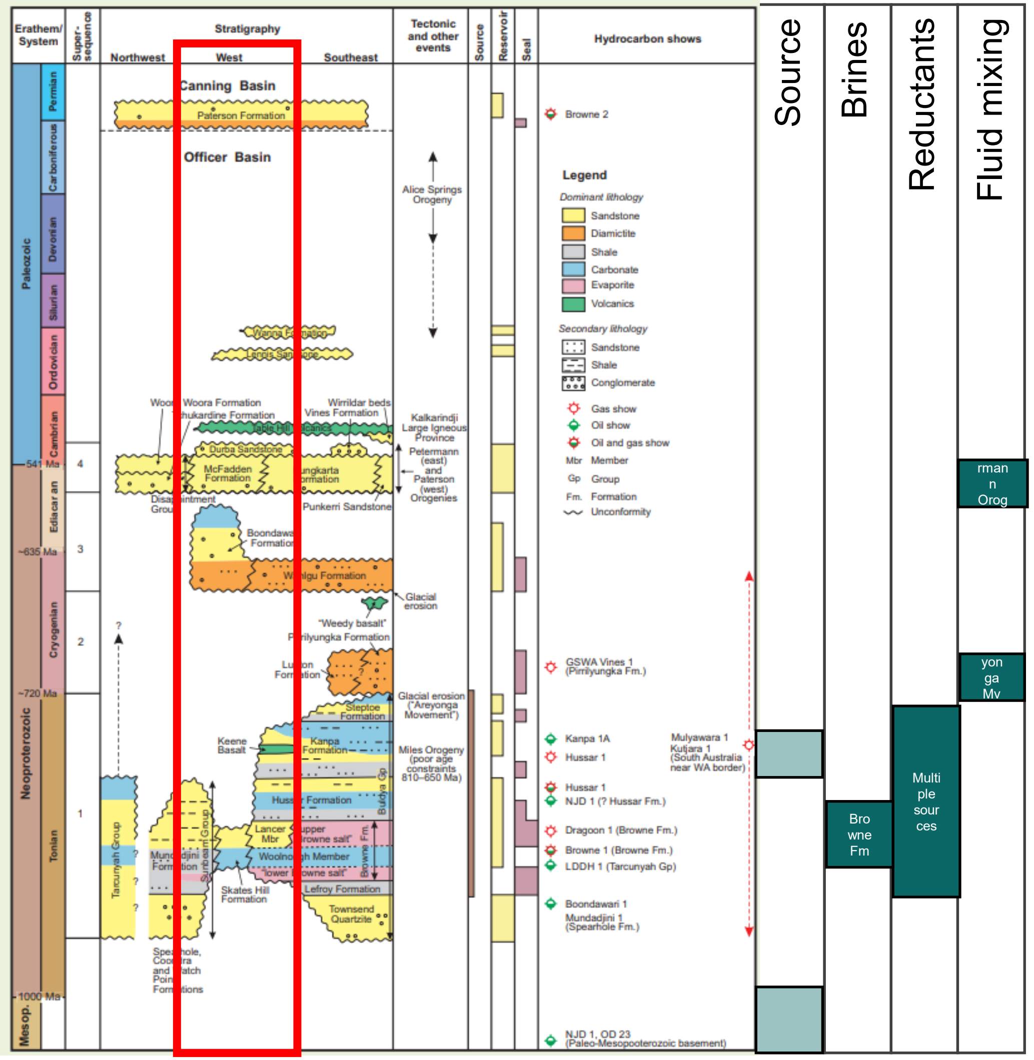




https://d28rz98at9flks.cloudfront.net/76664/Rec2013_028.pdf

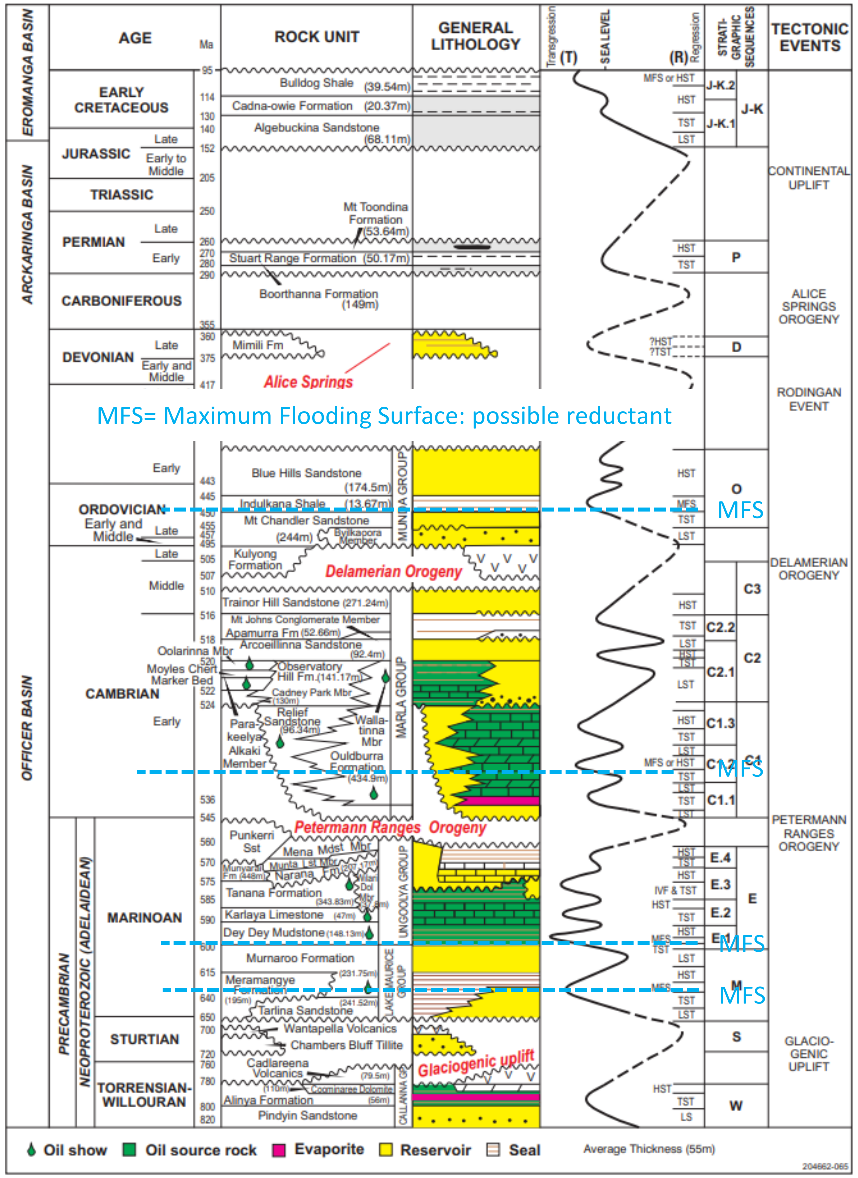
Mineral system components (time)

BASIN SCOPE CONSULTING



Risk: unproven Cu source rock

- Gairdner dolerite (~850 Ma, SE Officer Basin) correlates with Cu-rich intrusions in Yeneena Basin (Nifty deposit)
- Keene Basalt correlates with the Mundine Well Dyke Swarm (755+/- 3 Ma) (Grey et al., GSWA Rpt93, Zi et al., (2019). It has been hydrothermally altered by interaction with seawater and locally contains disseminated sulfides (Pirajno et al., 2006).



https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/plans/sarig1/image/DDD/204662-065

Mineral system components (space)

- Reduce uncertainty using petroleum system studies
- Seismic mapping of key horizons
- Extent of Keene Basalt (possible Cu source) unclear

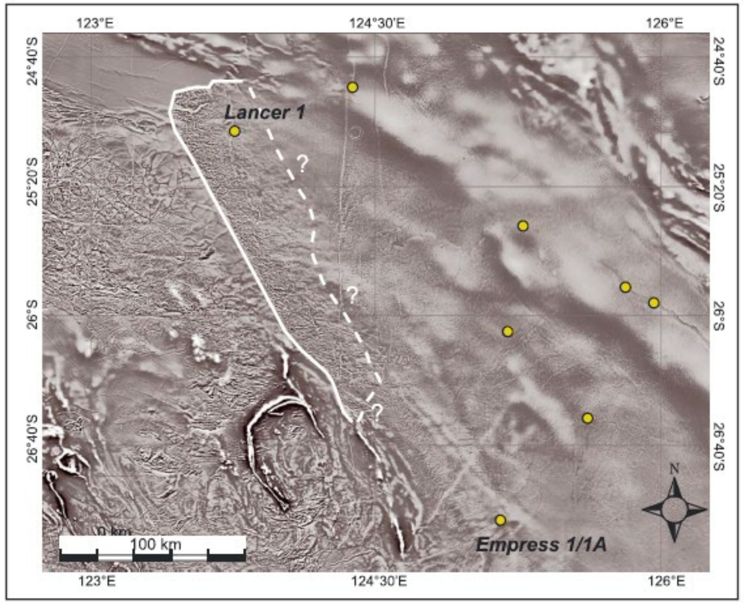


Figure 4. Inferred dimension of the Keene Basalt based on aeromagnetic data extracted from the GeoVIEW online database of Geological Survey of Western Australia (June 2017). The western margin (solid lines) of the basalt is sharp and linear, suggesting fault control, whereas the eastern, southern, and northern margins (dashed lines) appear to be more irregular and vague.

From Zi et al., 2019

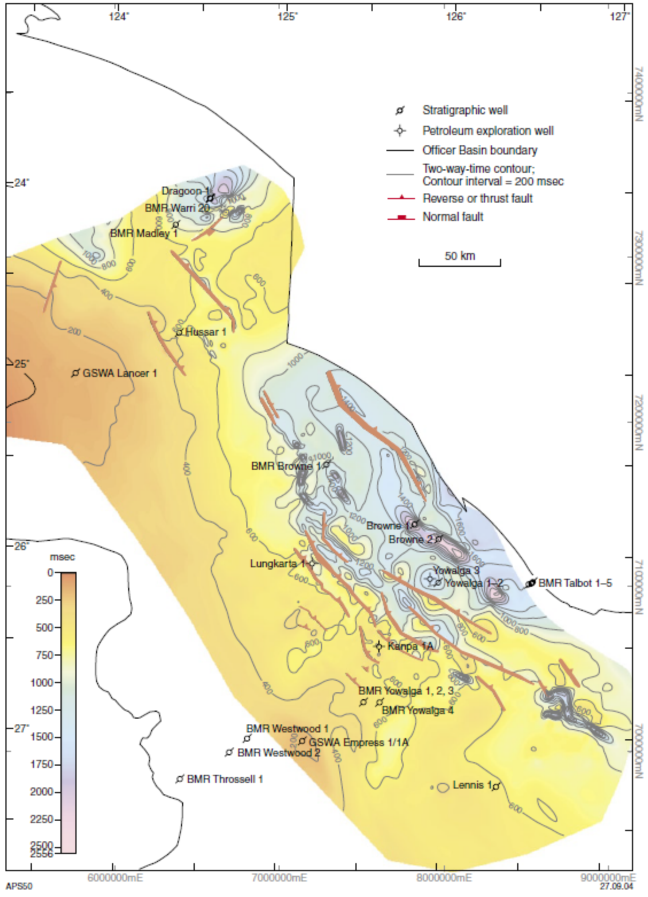


Figure 7. TWT thickness map of the Browne Formation

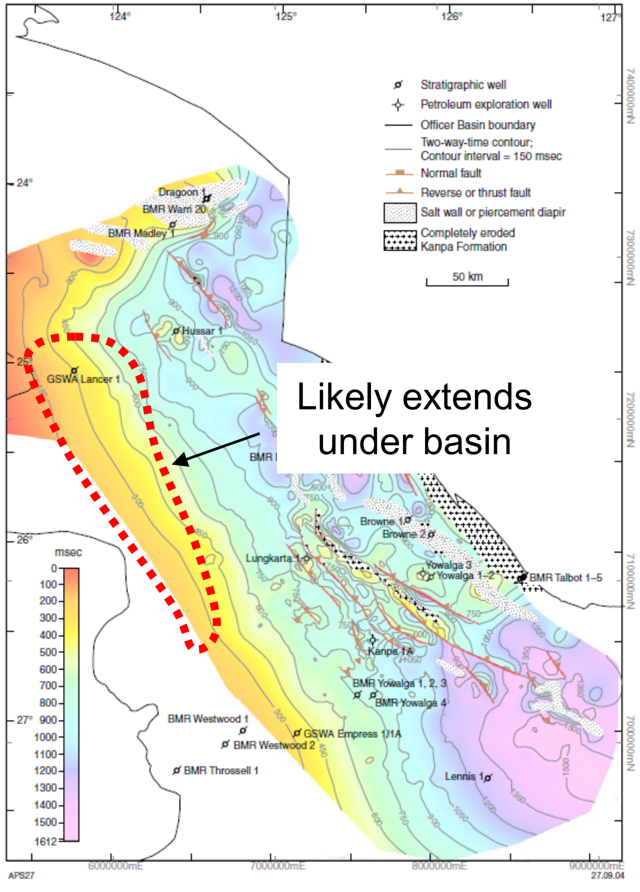


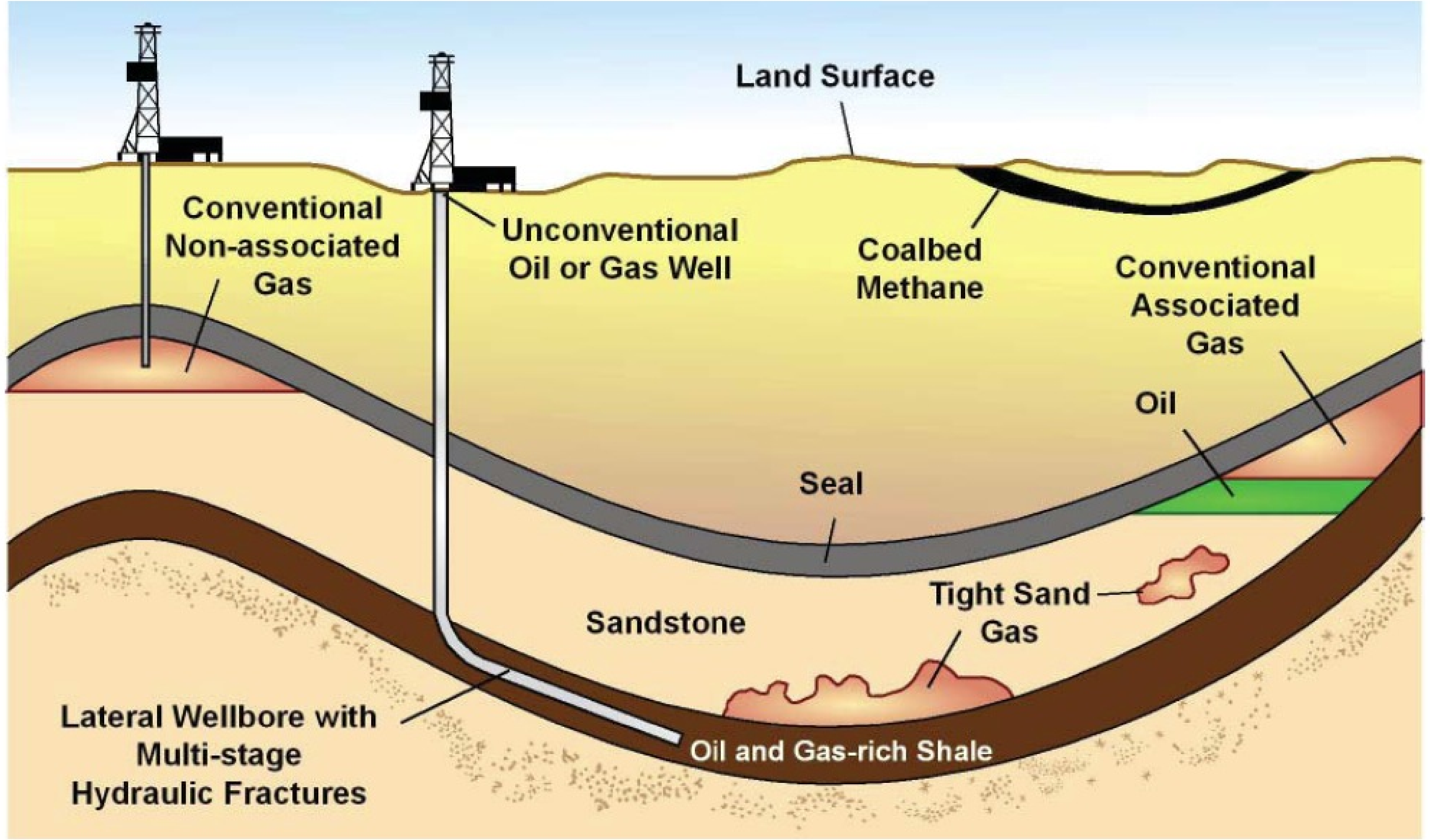
Figure 11. TWT structure map of the top Kanpa Formation horizon

Simeonova and Iasky, 1998, GSWA Report 98

Some thoughts….Unconventional petroleum systems

- Our comparisons presented here are conventional petroleum systems
- Unconventional: shale gas, shale oil, tight gas, coalbed methane
- Hydrocarbons remain in source layer – no migration or trapping.
- Reservoir (source rock) must be fracked to extract hydrocarbons – technology change
- Changes our understanding of petroleum system elements – they aren't all essential after all….
- *What can this tell us about mineral system elements?*

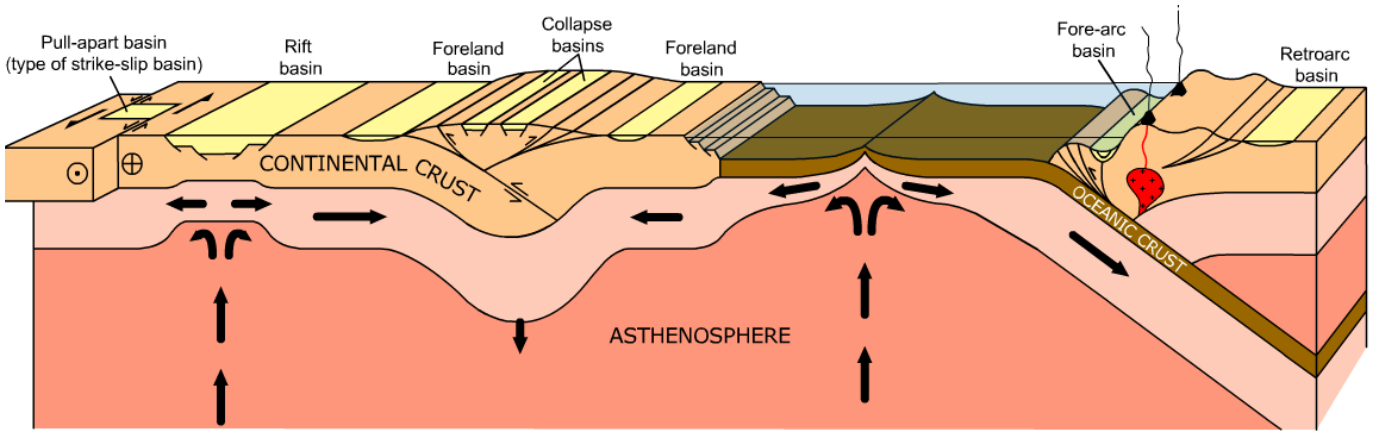
The Geology of Conventional and Unconventional Oil and Gas



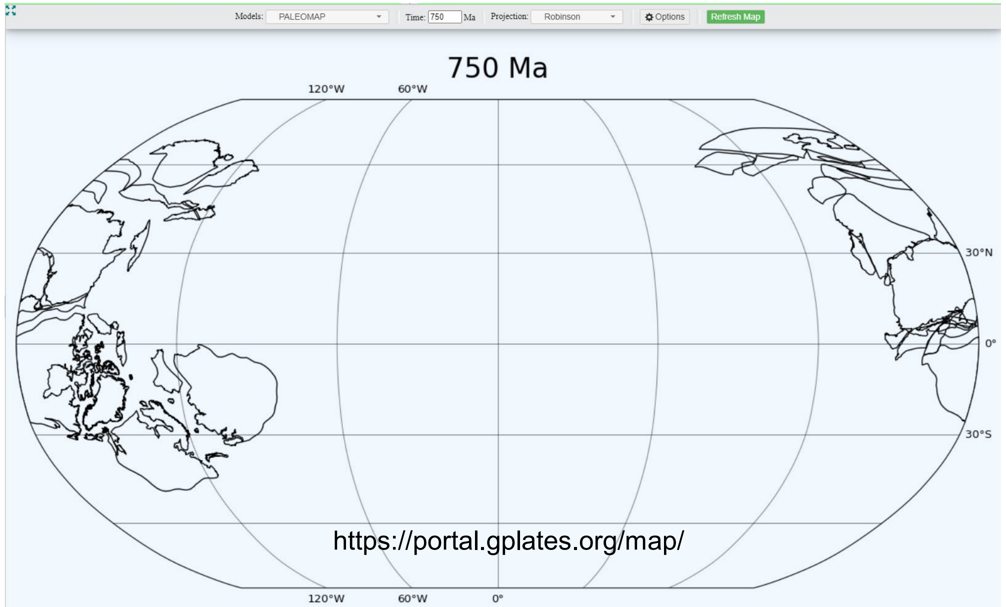
Source: EIA

Basin types: not just failed rifts or intracratonic basins

- Other types of basins can have restricted fluid flow
- Basins are <u>time-dependent</u>. Different basin types are often stacked on top of each other, or evolve into different basin types through tectonics.
- Size and basin fill are important, plus fluid pathways linked to deep crustal structures.



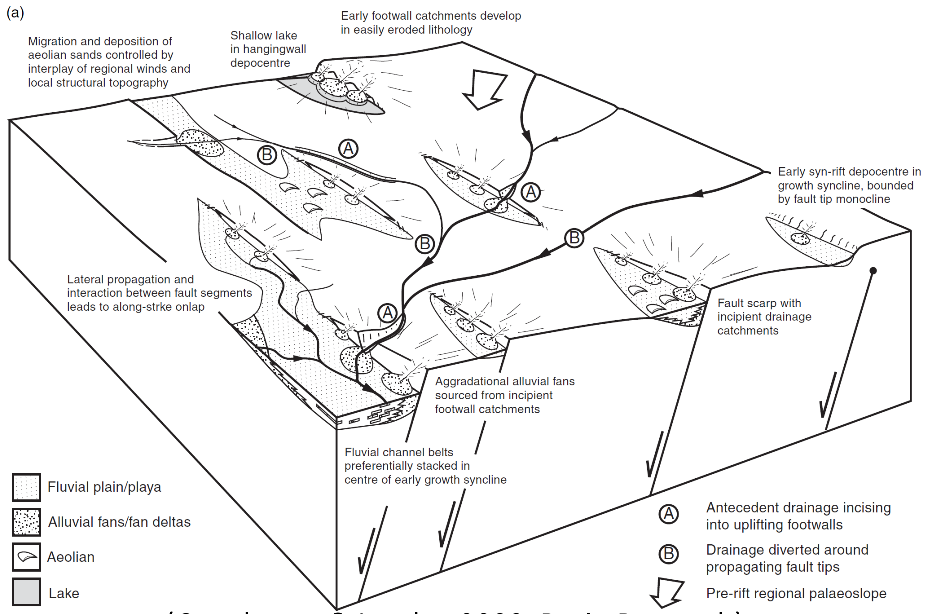
From http://folk.uio.no/hanakrem/svalex/Misc/Sedimentary_basins.swf



- Tools for predicting basin palaeoenvironment: Gplates
- Badlands: Basin and Landscape Dynamics simulates basin fill and incorporates geodynamic and climatic forces

Red beds: are they necessary?

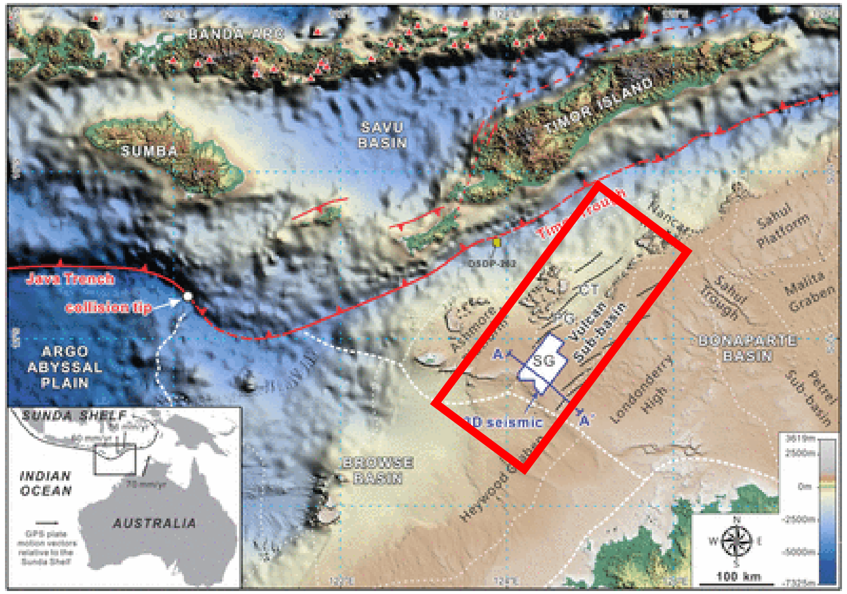
- Key component of the Hitzman model
- Common in failed rifts and intracratonic basins
- Not the only source of Cu: volcanics/basement rocks
- Correlation vs causation: are red beds necessary?
- Porosity and permeability for fluid transport
- Redox gradient between source and trap is key

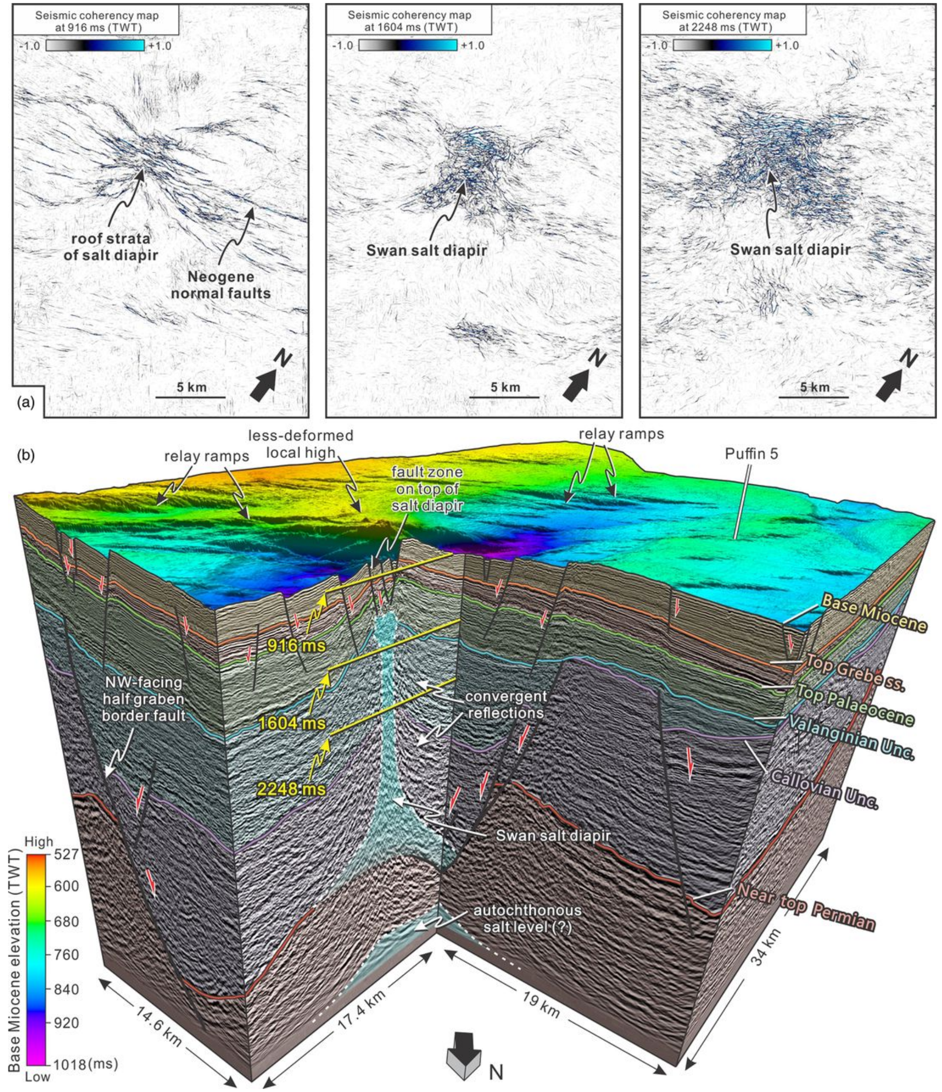


(Gawthorpe & Leeder, 2000, Basin Research)

Evaporites: Do you need to see them?

- Example from the Vulcan Sub-basin, NW Australia
- Approximately 1000 km^2
- Extensive 2D and 3D seismic datasets
- ***Only 2 salt diapirs***
- Unknown source
- Salt is very mobile: Often not visible in subsurface
- Paleoenvironment is the key

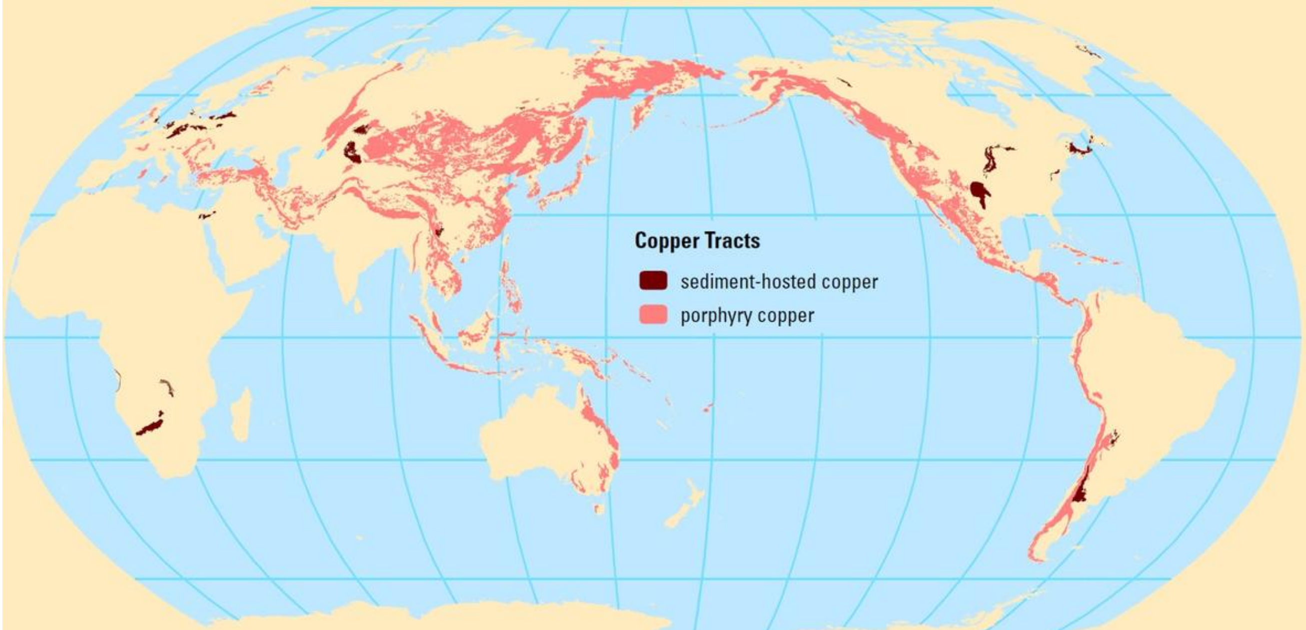




Wu et al., 2016 https://doi.org/10.1144/jgs2016-008

Conclusions

- Sediment-hosted copper systems share many critical components with petroleum systems
- A petroleum systems approach to sediment-hosted copper exploration can help to redefine the components of the mineral system
- Improved understanding of basin evolution including structures, stratigraphy and fluid pathways, especially with the use of traditional petroleum datasets like seismic
- Can this approach highlight new areas for exploration?



https://www.usgs.gov/media/images/global-copper-map-0

Next steps:

- Ensure the critical components of sed-hosted Cu mineral system are fully understood.
- Standardise the application to Cu mineral systems globally.
- Quantify each sed-hosted Cu mineral system evaluation into a business and forecasting tool.

Thank You!

jane@basinscope.com.au

Jane Cunneen, B.Sc., Ph.D.
Basin Scope Consulting Pty Ltd. www.basinscope.com.au
School of Earth and Planetary Sciences, Curtin University
Ph: 0439 931 811

route2reserves@gmail.com

Graham Banks, B.Sc., Ph.D.
Route To Reserves (https://www.route2reserves.com/)
Southern Geoscience Consultants (www.sgc.com.au)
Ph: +1 778 302 9726

BASIN SCOPE CONSULTING

CODA MINERALS

Ro 2 Res Route To Reserves

Curtin University

SOUTHERN GEOSCIENCE CONSULTANTS