

GDE Mapping Leading to Play Analysis in the onshore Otway Basin

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GDE Mapping Leading to Play Analysis in the onshore Otway Basin

1. Project aim & location of study area
2. Gross Depositional Environments (GDE) mapping
3. Play-based exploration overview
4. Stratigraphy of study area and plays reviewed
5. Lower Sawpit Shale (McEachern) play analysis
6. Pretty Hill Sandstone play analysis
7. Data availability
8. Acreage release nomination

Why the inshore Otway Basin?

- DEM has demonstrated undiscovered potential
- Discoveries can be connected
- Strategic location - connectional to the national gas pipeline. SE Australia gas market (nee 2027)
- Strategic gas storage potential



Otway Basin: Project Aim

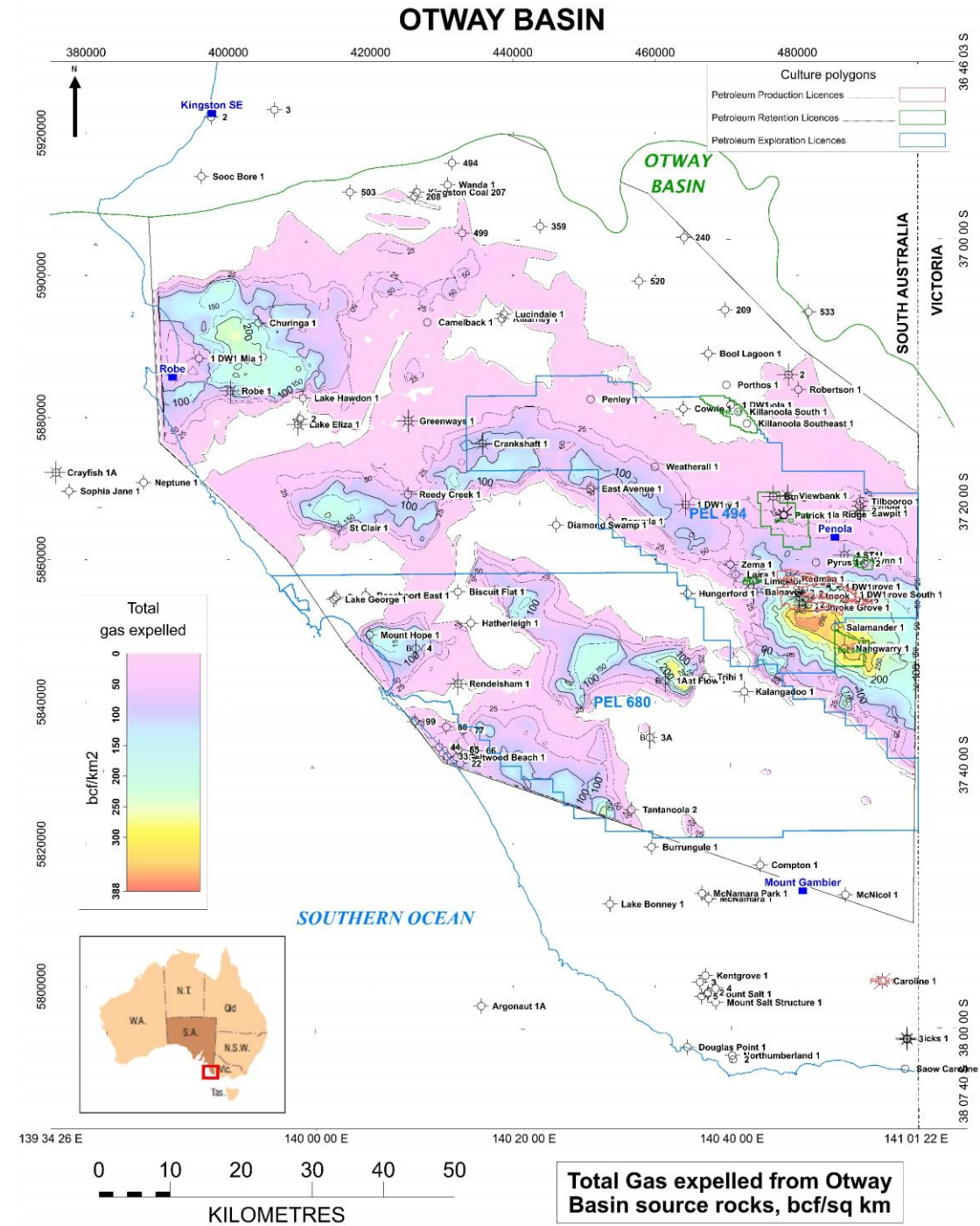
Aim:

- Generate new datasets
- Generate new exploration concepts
- Stimulate the next phase of gas exploration in the onshore Otway Basin to supply South Australian customers

- Commenced: 2020
- Completion: Q4 2023



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Project Fast Facts



Modified from Beach Energy

Whole of Basin PSM

- Petroleum system model
- Expulsion maps per key intervals



Seismic & Wells

- Stratigraphic framework – 80 wells
- 7965km seismic interpretation



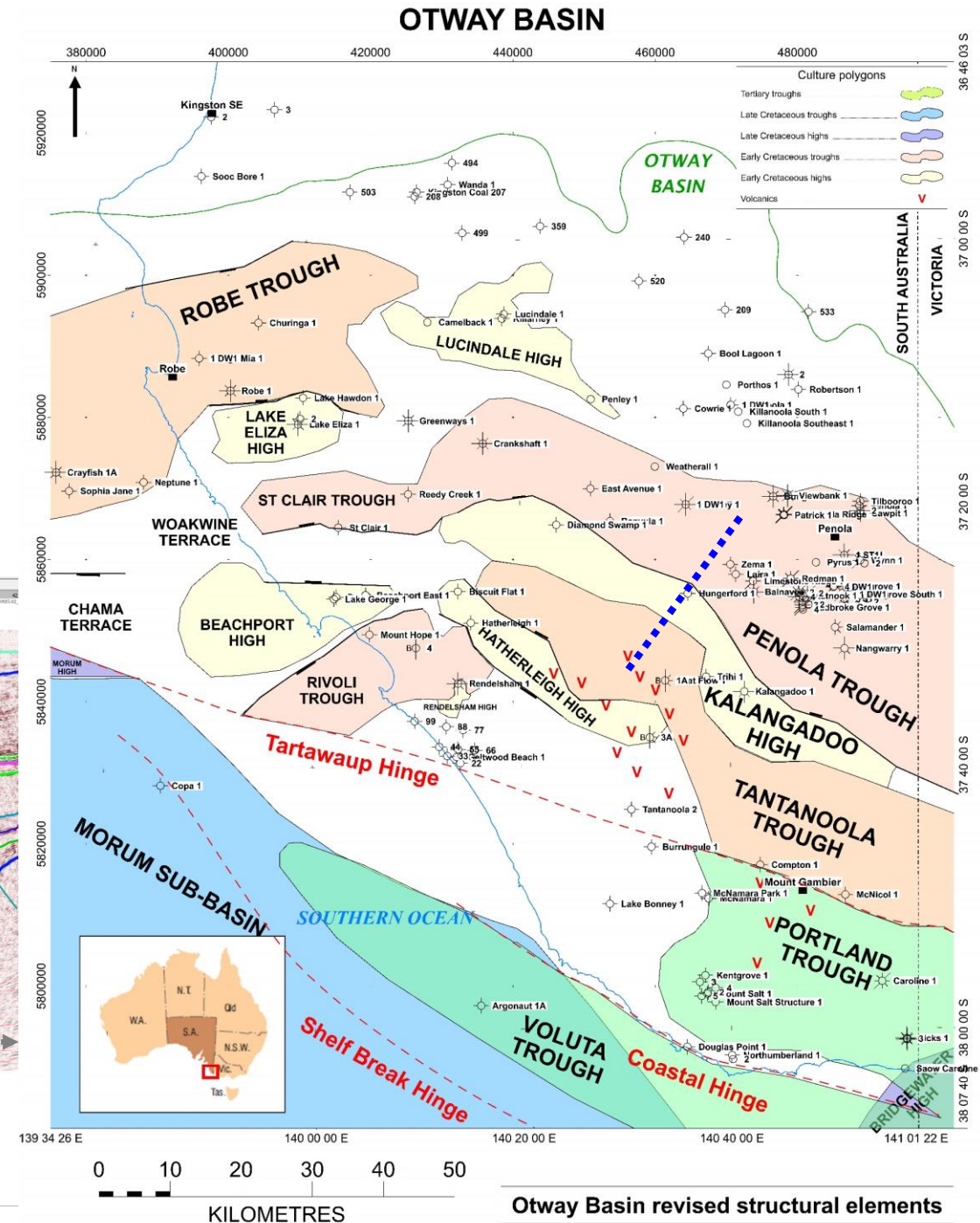
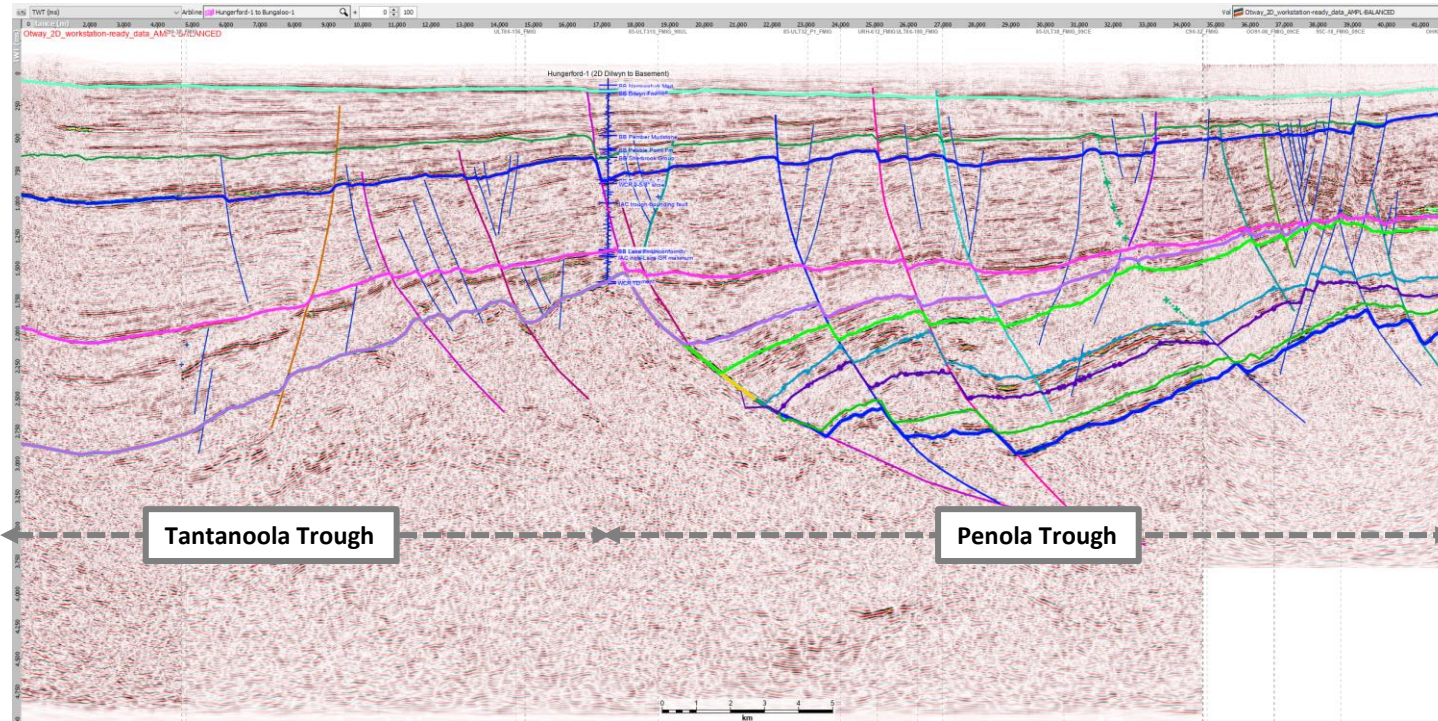
Cores & Maps

- 772m of core interpreted
- 6 geology maps constrained



Otway Basin Structure

The Otway Basin is made up of a series of (curvi-linear) buried hills and valleys (troughs) that have been filled in over time
A lot of time ~ 30million years



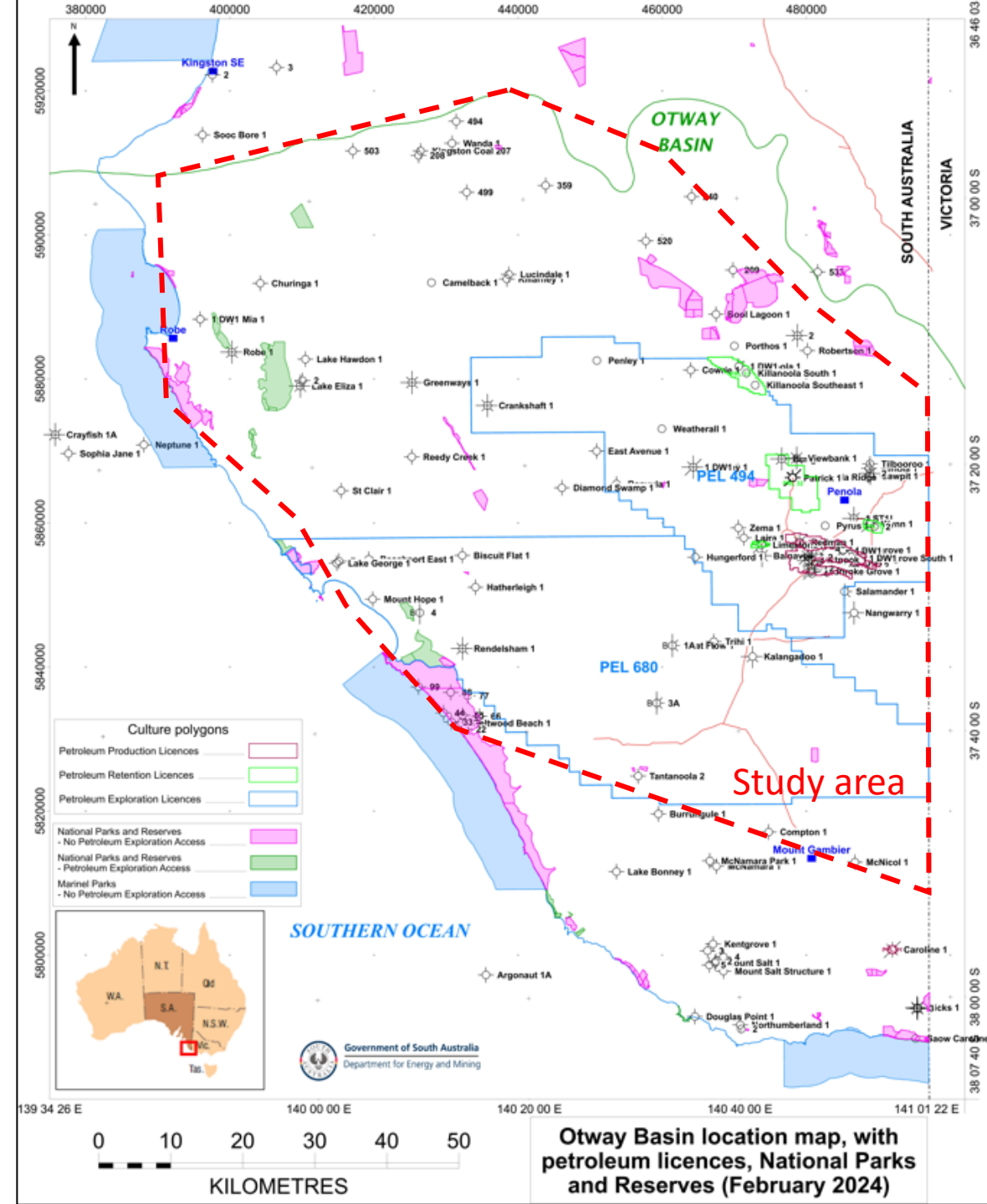
Location of Study Area

Significant production from January 1991 to Sept 2022:

- Total 444,717 barrels oil
- Total $2,444 \times 10^6 \text{ m}^3 / 86.3 \text{ Bcf}$ gas

Multiple reservoirs:

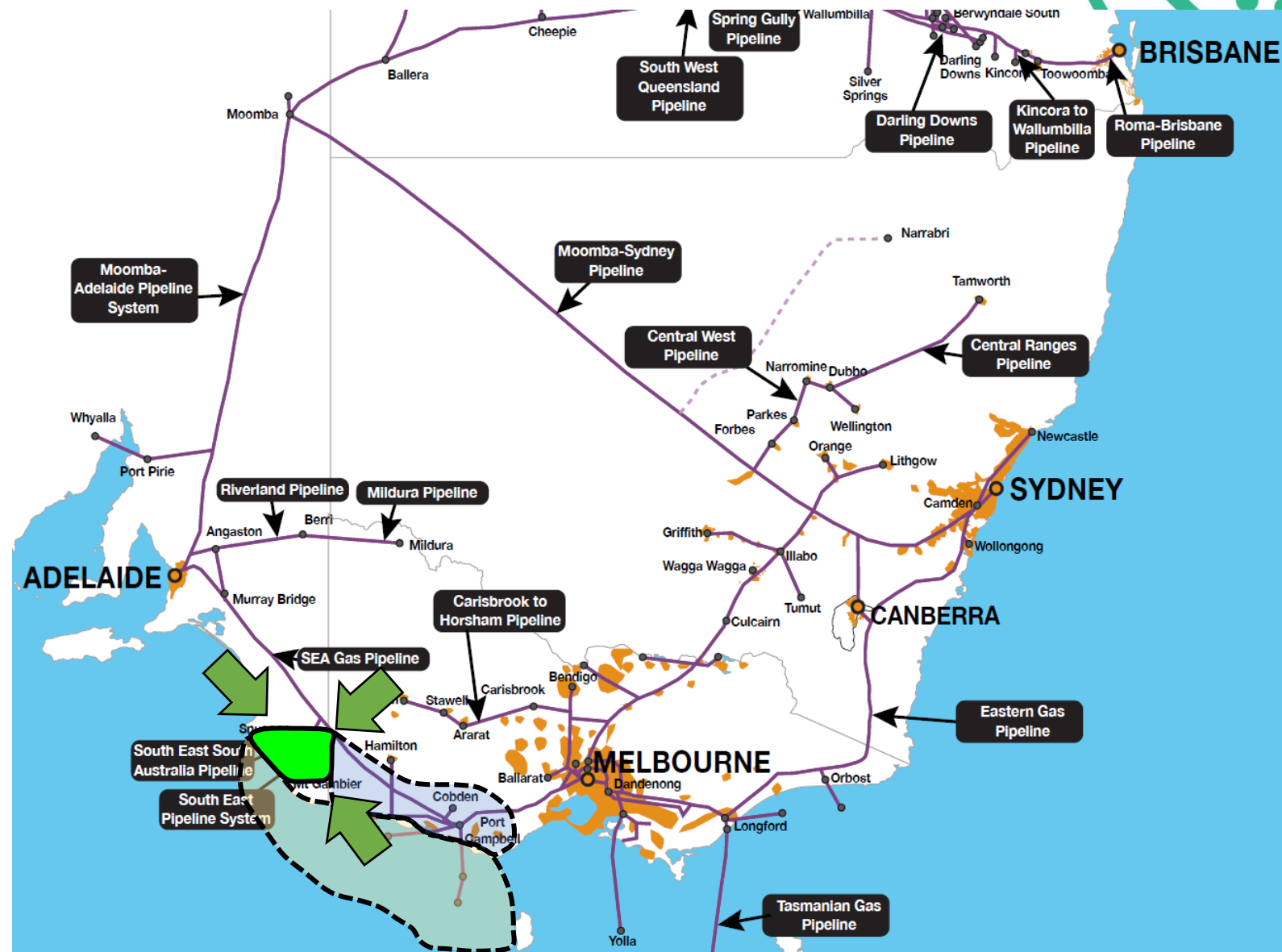
Katnook	Eumeralla Fm
Haselgrove	Pretty Hill Fm
Katnook	Pretty Hill Fm
Ladbroke Grove	Pretty Hill Fm
Limestone Ridge	Pretty Hill Fm
Redman	Pretty Hill Fm
Haselgrove	Sawpit Sandstone Member
Hollick	Sawpit Shale Member
Jacaranda Ridge	Sawpit Shale Member
Patrick	Sawpit Shale Member



Onshore SA Otway Basin Context

The onshore Otway Basin strategic location in the SE Australian gas market (in bright green)

- Geological work done
- Victoria | Onshore
 - GA | Offshore
 - SADEM.....



[From - Australian Energy Market Commission (AEMC) | 2023]

Play-Based Exploration Overview 1

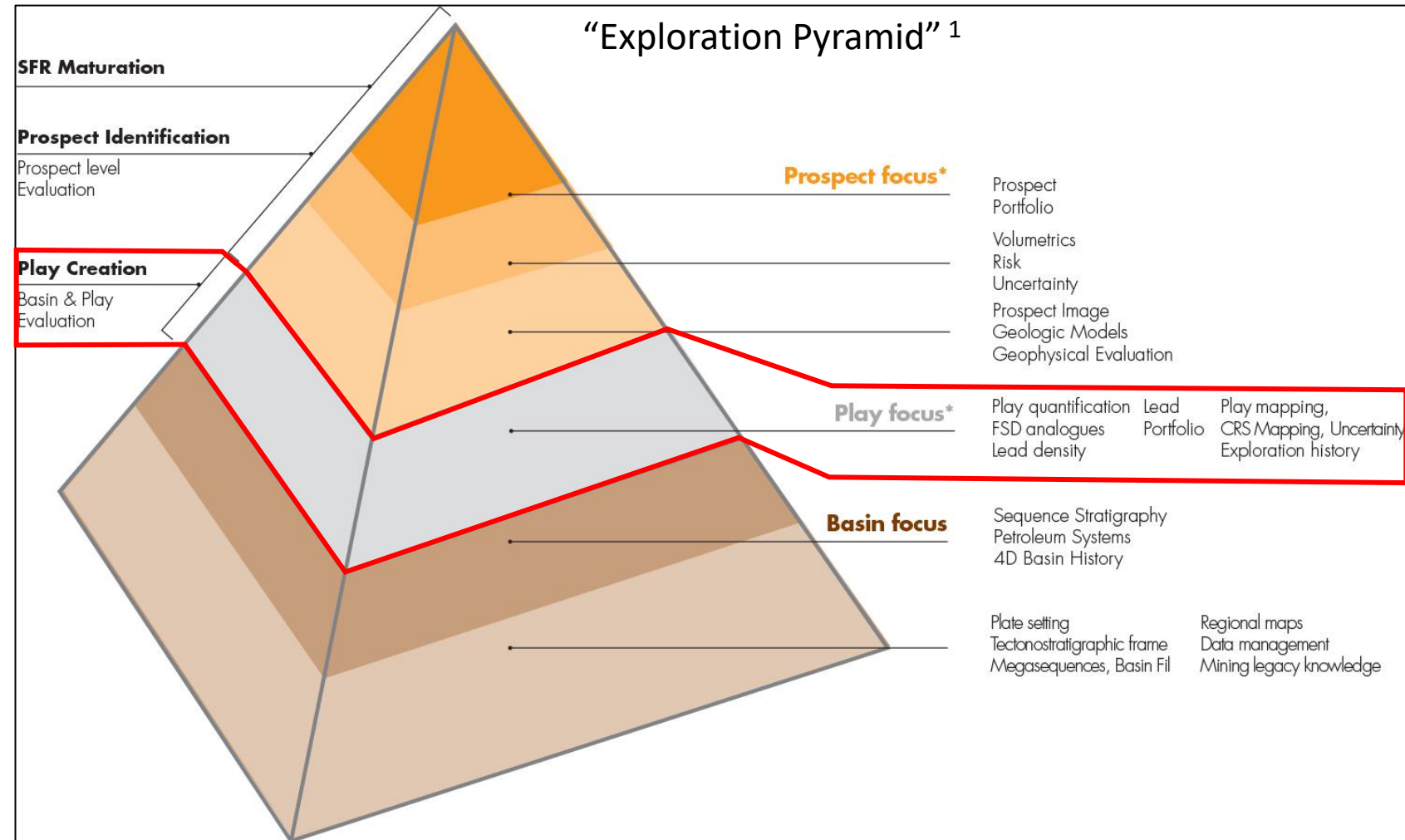


Play-Based Exploration

- Understanding of petroleum system in basin leads to identification, mapping and quantification of plays within basin
- Maps:
 - Play elements
 - Summary play maps
 - Common risk segments
 - Identification of sweet spots

Analysis of plays using this process is not static

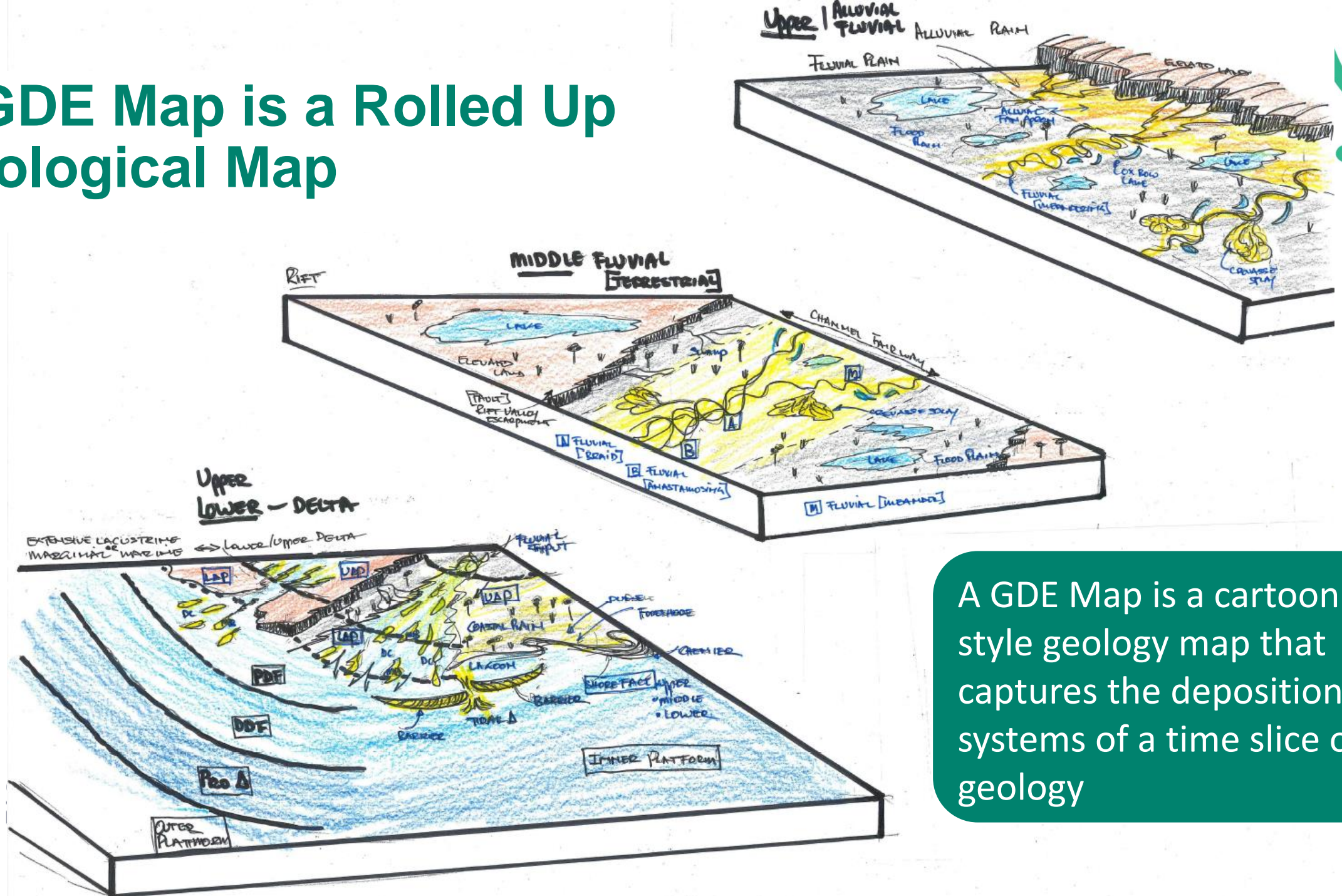
- Iterative feedback required following new information



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¹ Royal Dutch Shell, 2014: [Play Based Exploration, A Guide for AAPG's Imperial Barrel Award Participation](#)

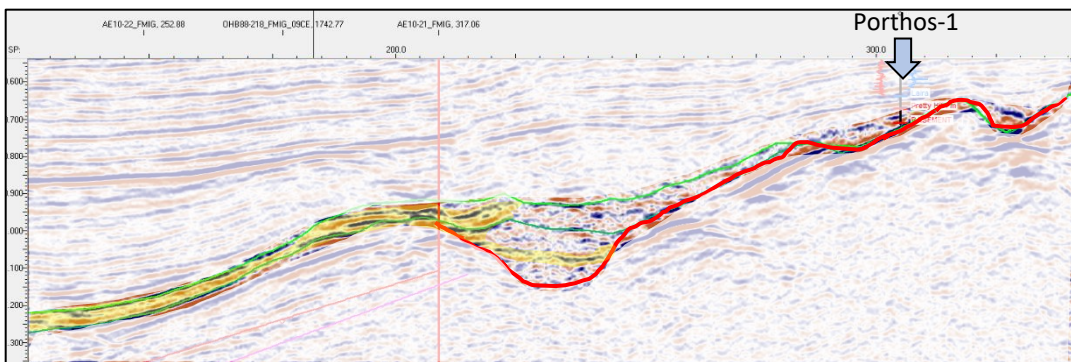
A GDE Map is a Rolled Up Geological Map



A GDE Map is a cartoon style geology map that captures the depositional systems of a time slice of geology

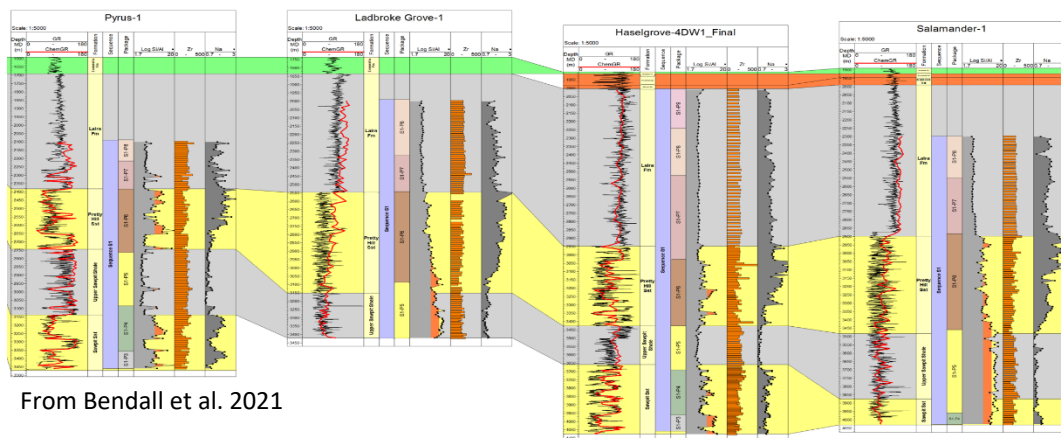
GDE Mapping Methods

Seismic – infill: horizons, faults and seismic facies mapping



From Tiainen et al. 2024

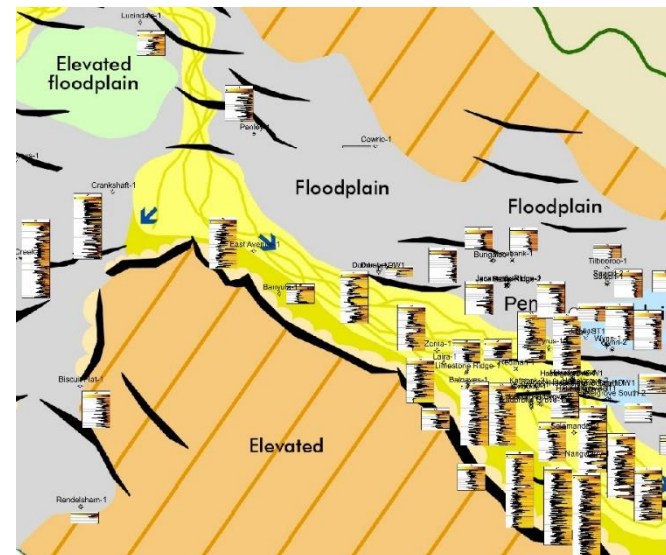
Wells – framework: provided the fundamental correlation



From Bendall et al. 2021

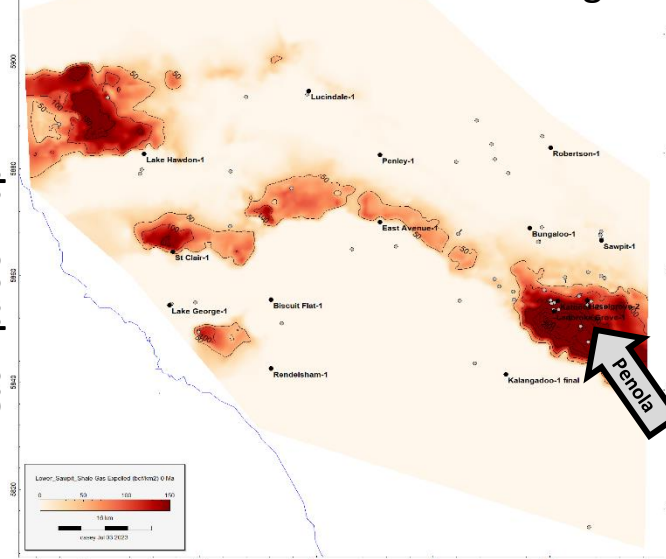
Core – ground truthing: depositional environment

GDE Mapping – All Levels



From Cubitt et al. 2024

PSM - Source Rock Modelling



From Edwards et al. 2024

Pretty Hill Sst – GDE map

Lower Sawpit Shale/Mc Eachern
- Gas Expulsion map

New Otway Opportunities

- Petroleum
- Gas storage
- Geothermal
- Hydrogen?

PESA – Onshore Otway GDE Mapping

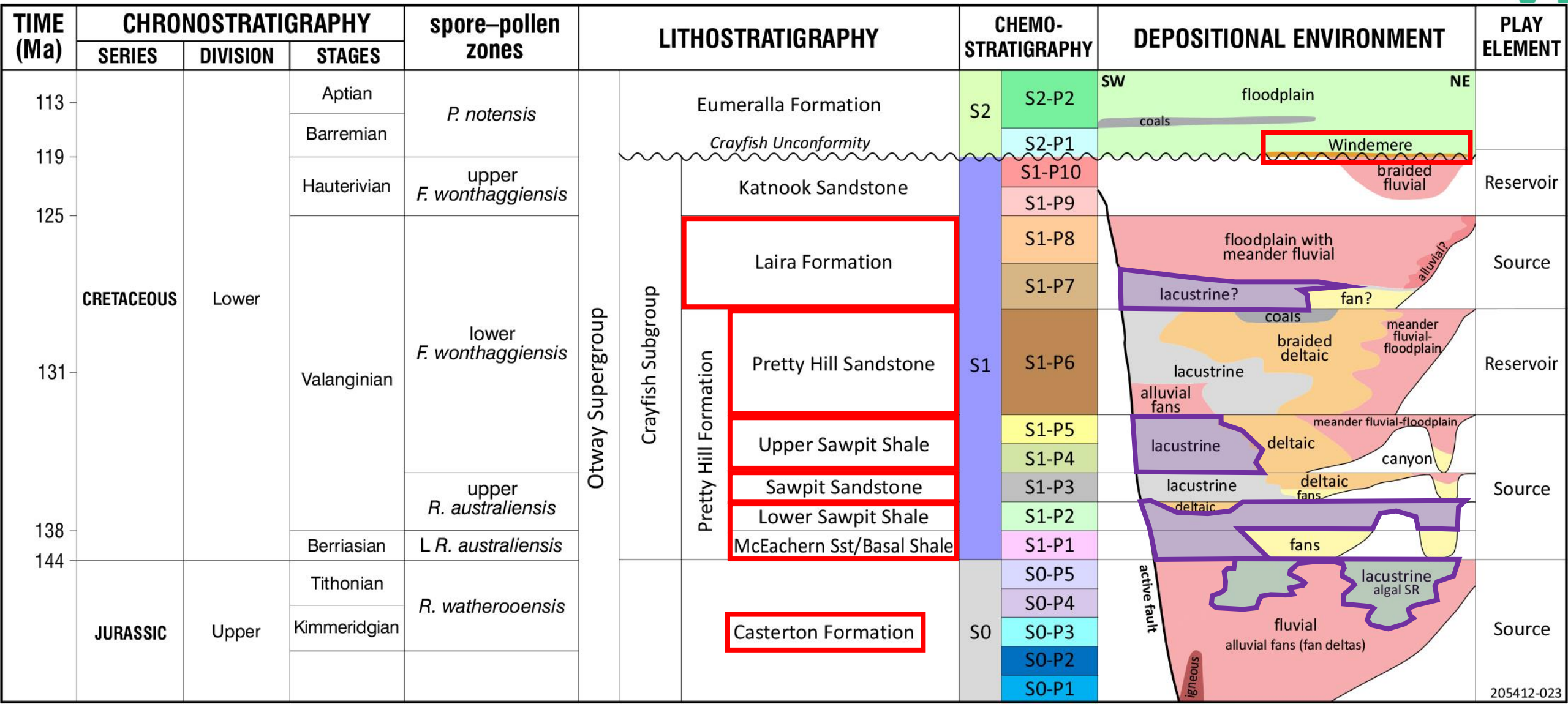
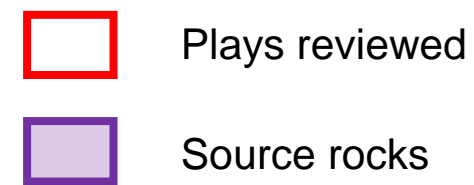


Photos from PESA core workshop 23/11/2023

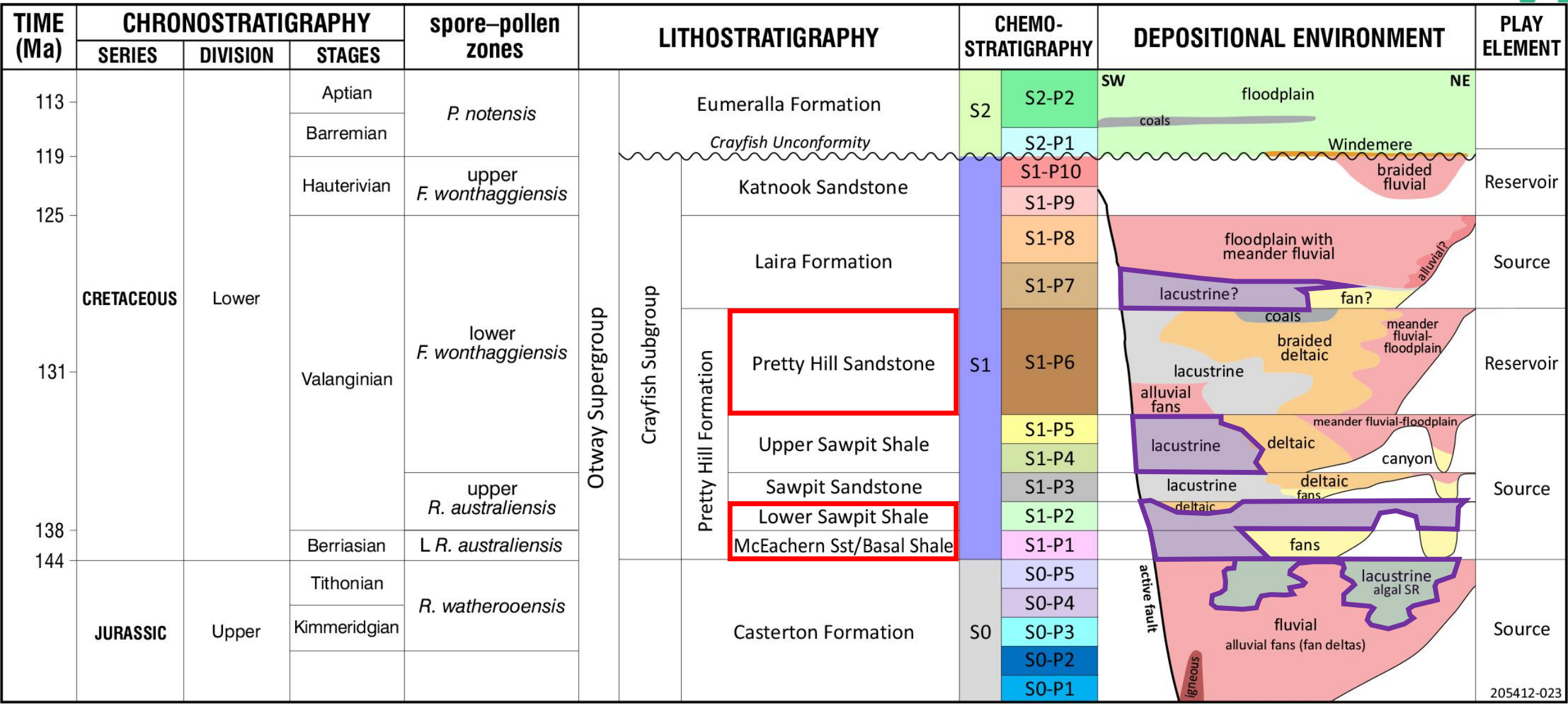
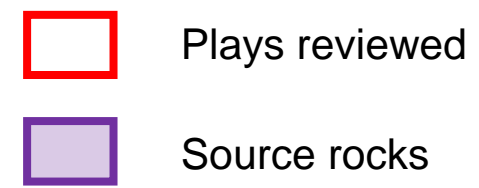


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Stratigraphy and Plays Reviewed



Stratigraphy and Plays Reviewed

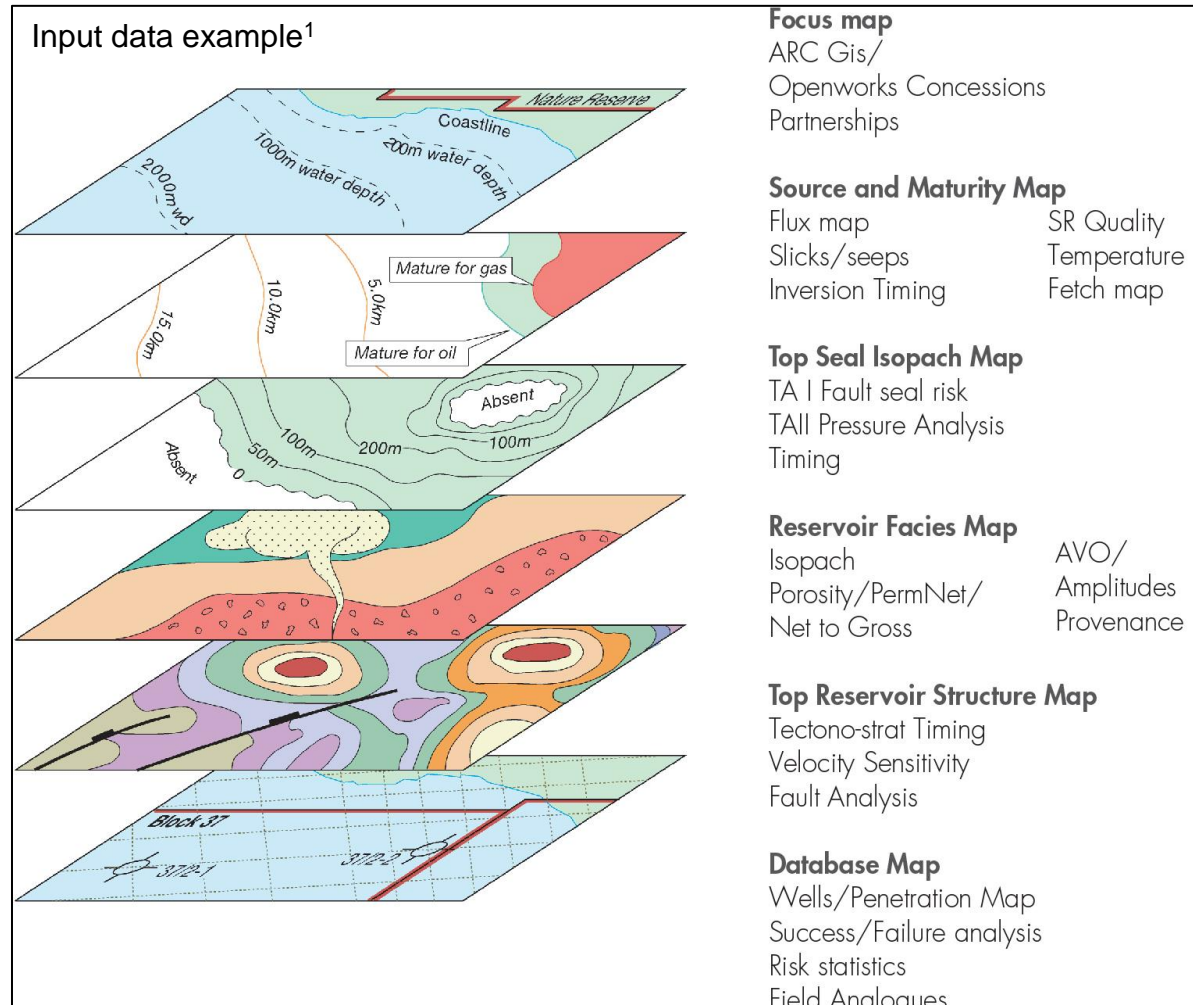


Play-Based Exploration Overview 2



Geological boundaries required for all elements of Petroleum System:

- Extent and type of Reservoir interval
- Hydrocarbon Charge:
 - Extent of likely Source Rock
 - Maturity of Source Rock
 - Limits of potential migration from Source Rock
- Entrapment:
 - Extent of Sealing interval
 - Structural elements

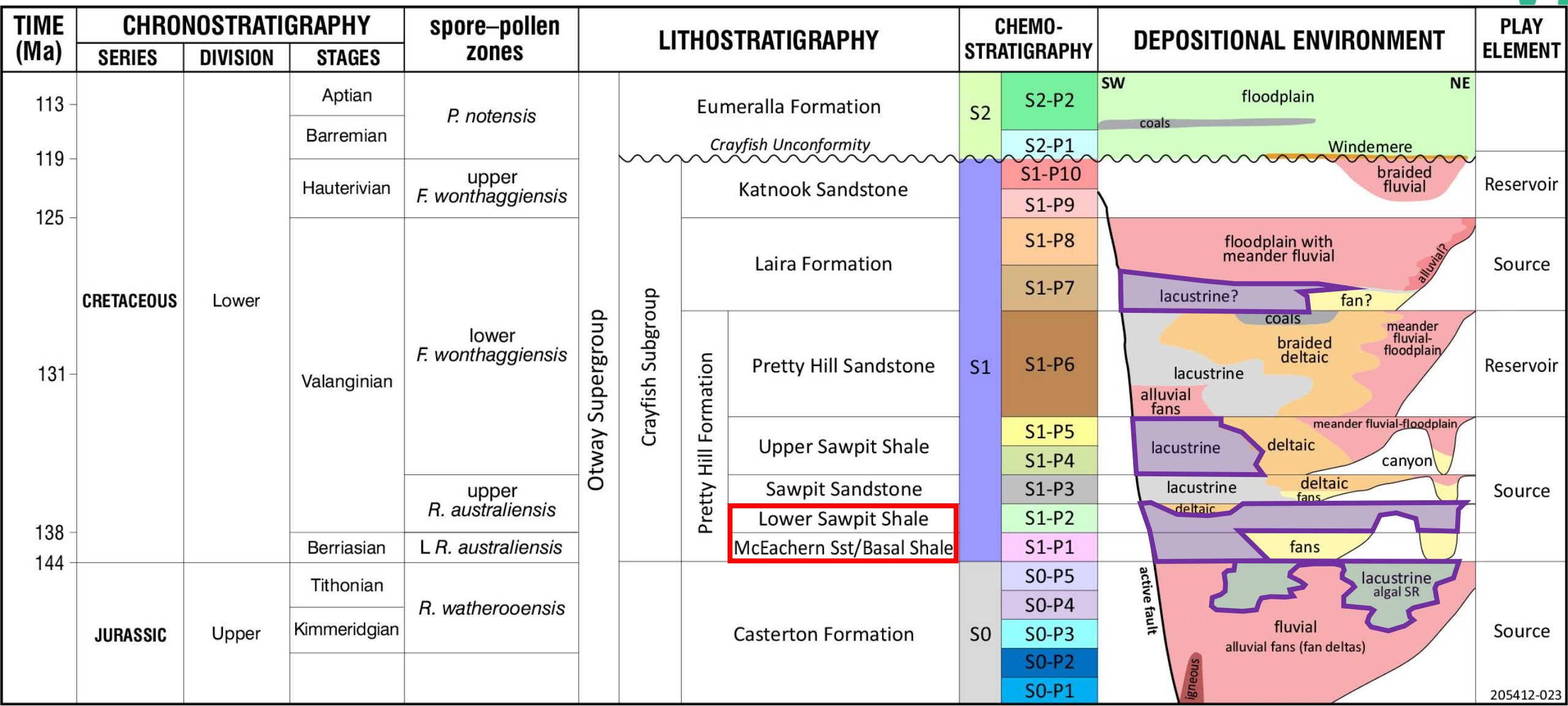


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¹ Royal Dutch Shell, 2014: [Play Based Exploration, A Guide for AAPG's Imperial Barrel Award Participation](#)

Stratigraphy and Plays Reviewed

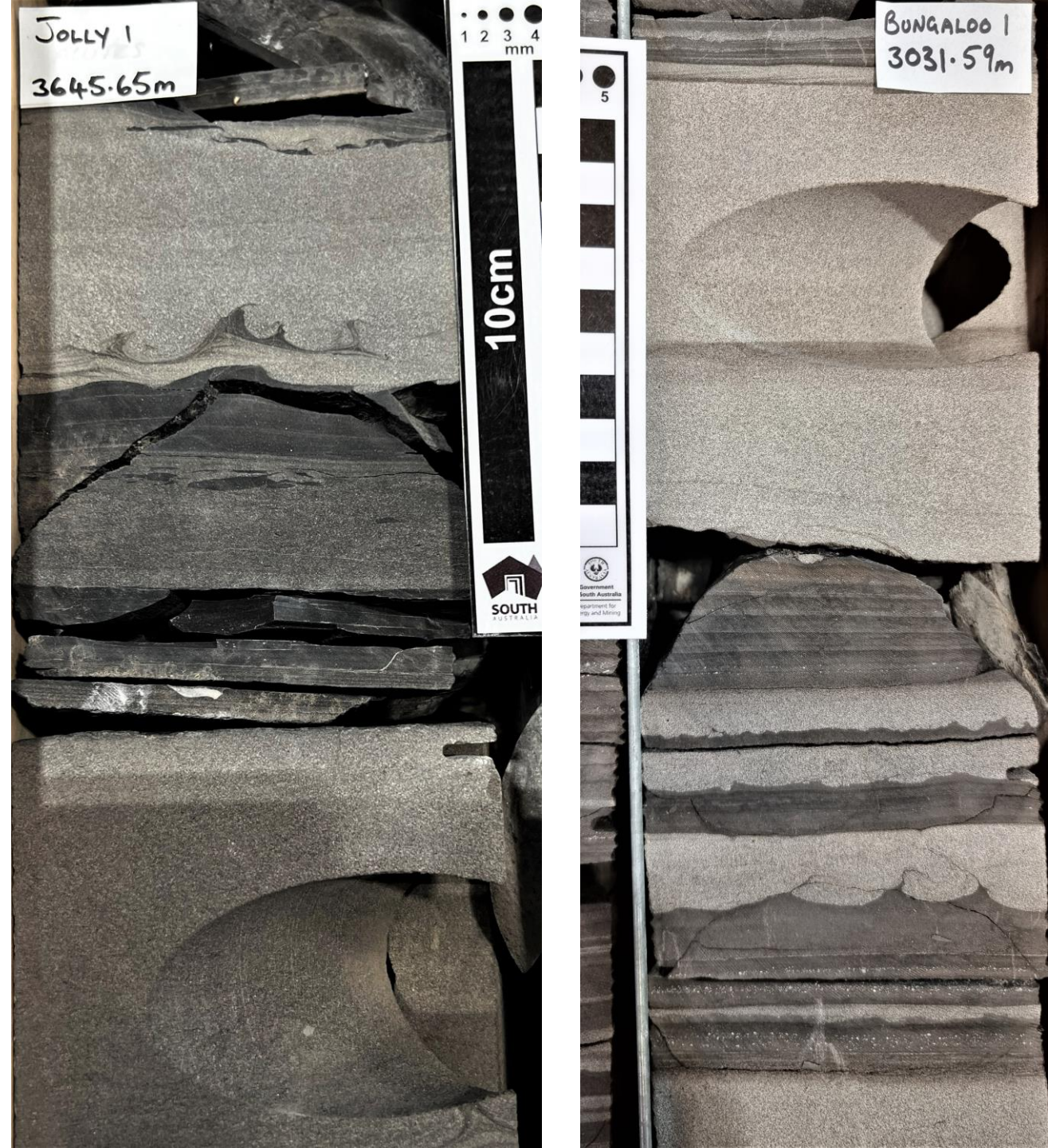
- Plays reviewed
- Source rocks



The McEachern Sst: Key Features

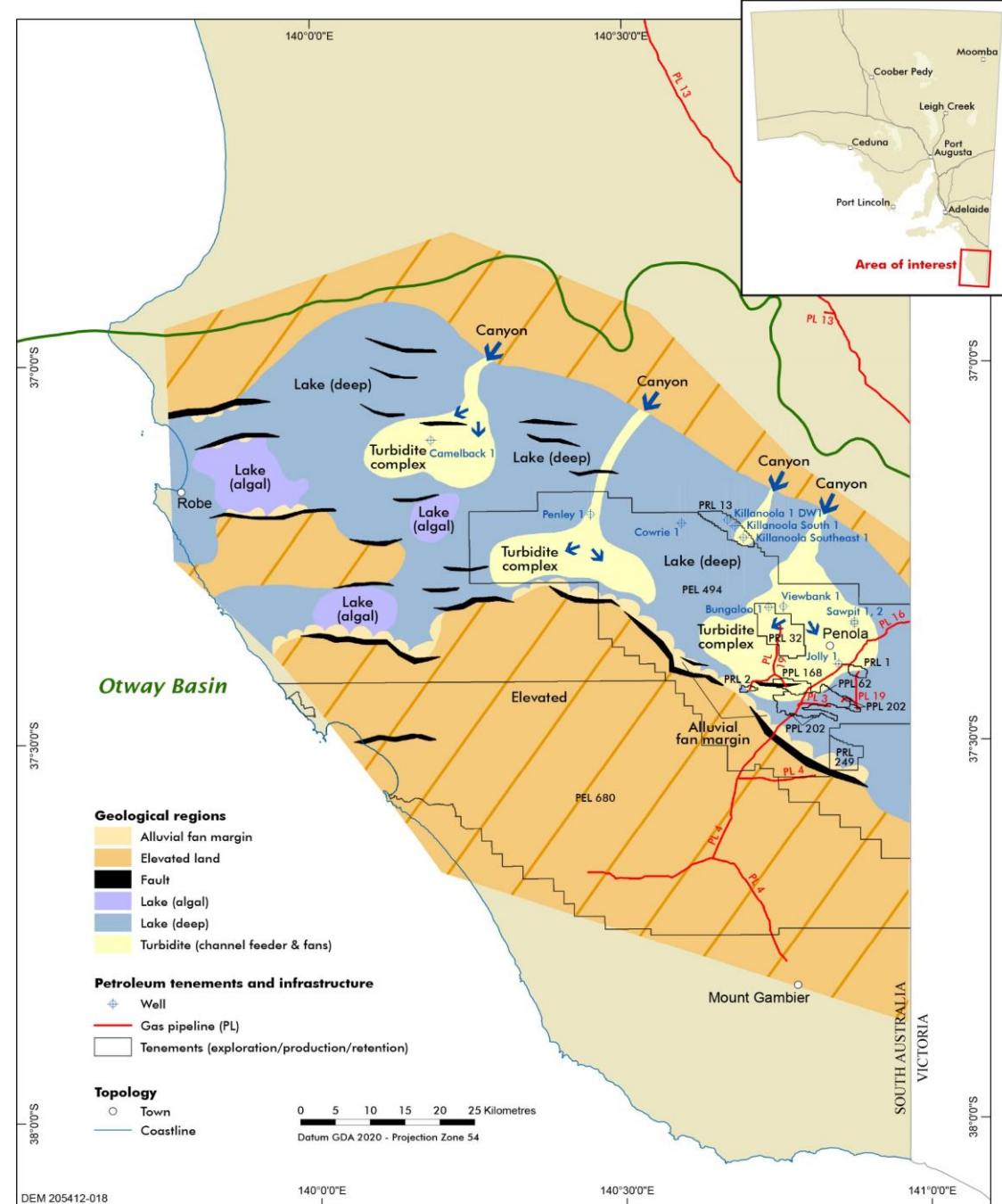
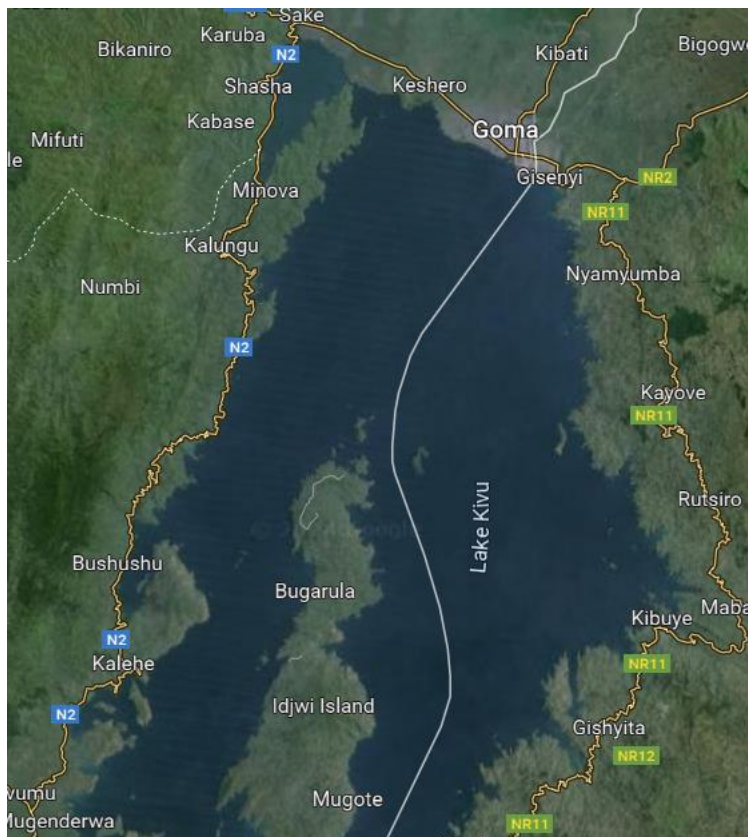
There is compelling sedimentological evidence from multiple wells that support this interpretation, including:

- Typical crevasse splay features (deceleration, coarsening upward, abandonments) are absent
- Deep water context not flood plain (ie varves)
- Consistent Bouma sequences across all 3 wells
- Abrupt sandstone/deep anoxic mudstone shut offs
- Very good sandstone sorting, commonly massive
- Common loading and sub-aqueous slumping



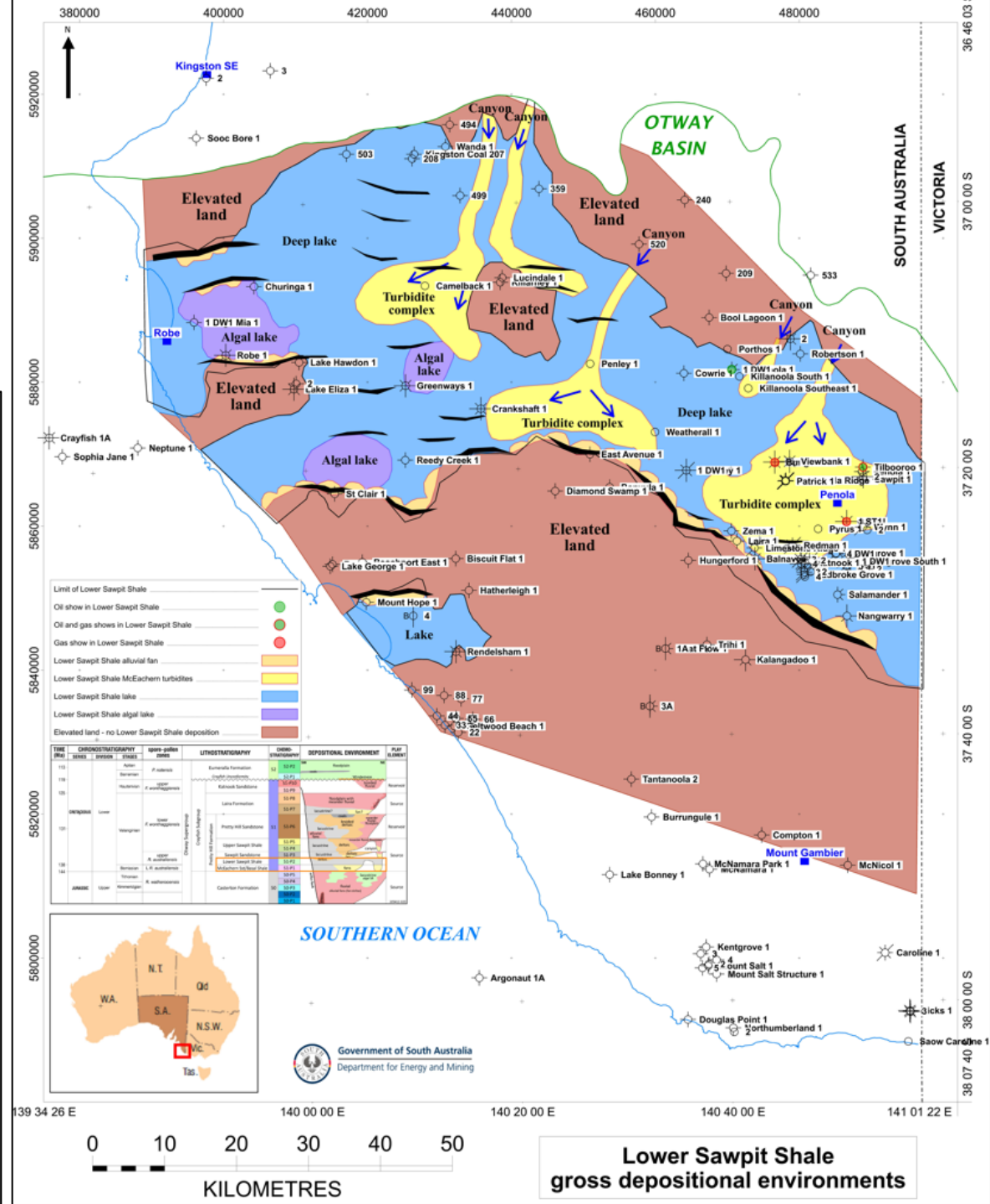
McEachern Sst GDE

- Deep lacustrine turbidite intervals were interpreted in three regions of the Lower Sawpit/McEachern Sst interval (core and seismic facies)



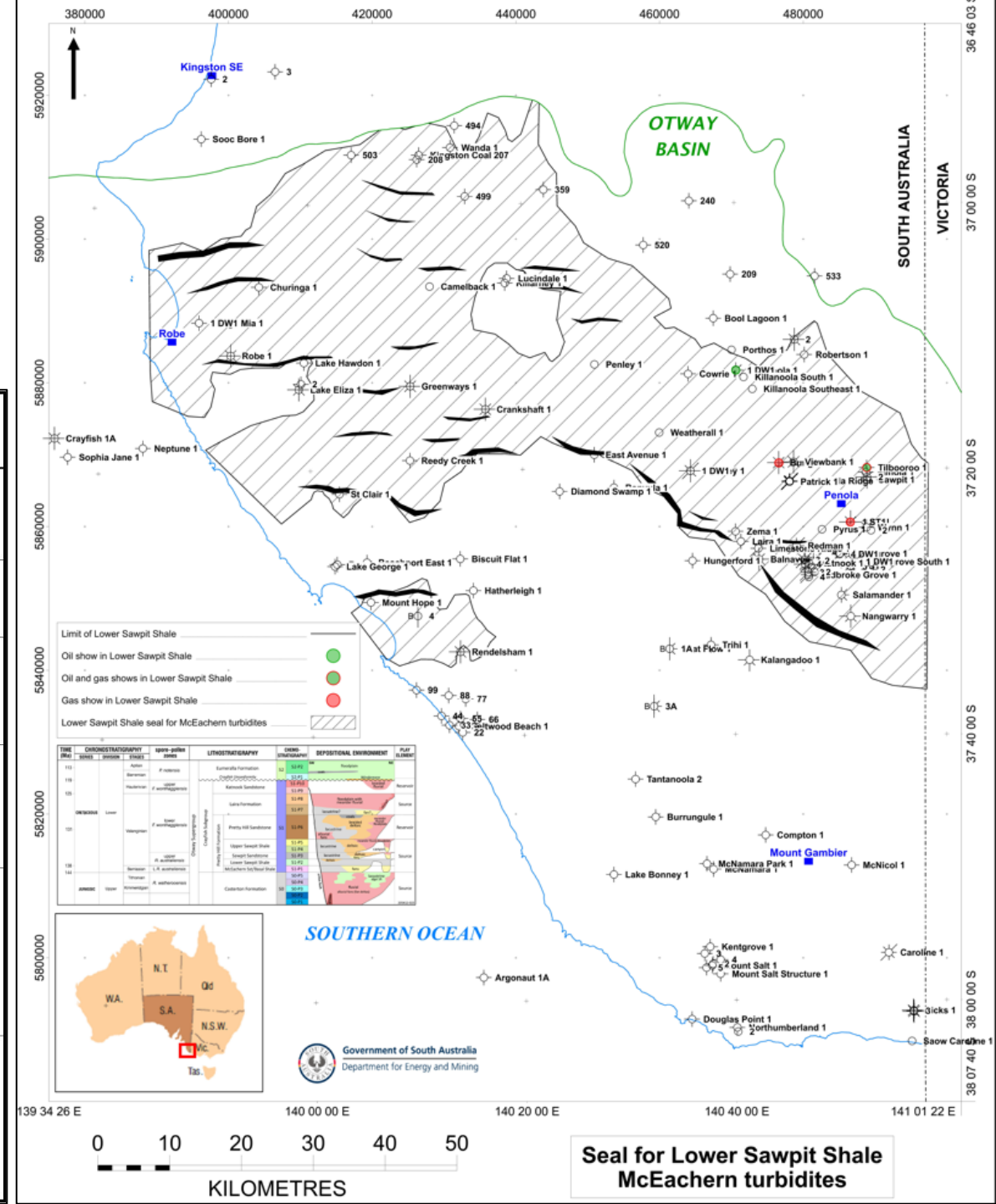
McEachern Sst Play Elements: Reservoir

LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY	DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT	
Otway Supergroup	Crayfish Subgroup	S2	S2-P2	SW floodplain NE	Reservoir	
				coals		Windemere
		Pretty Hill Formation	S1	S2-P1	braided fluvial	Reservoir
				S1-P10	floodplain with meander fluvial	
				S1-P9	alluvial?	
				S1-P8	lacustrine?	
				S1-P7	fan?	
				S1-P6	coals meander fluvial-floodplain	
				S1-P5	braided deltaic	
				S1-P4	lacustrine alluvial fans	
				S1-P3	meander fluvial-floodplain	
				S1-P2	lacustrine deltaic canyon	
Casterton Formation	S0	S1-P1	deltaic fans	Source		
		S0-P5	lacustrine algal SR			
		S0-P4	fluvial			
		S0-P3	alluvial fans (fan deltas)			
		S0-P2	igneous			
S0-P1						



McEachern Sst Play Elements: Seal

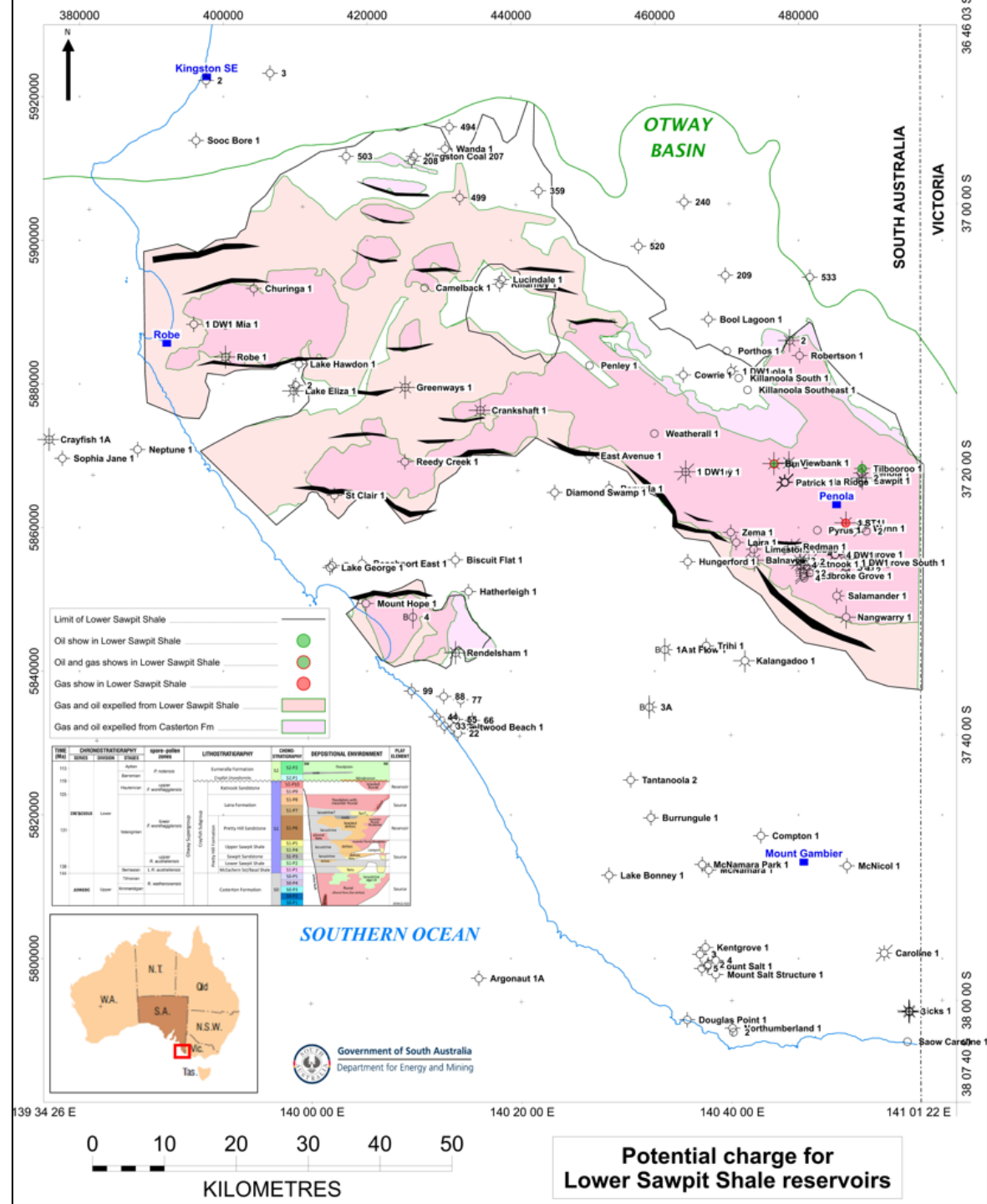
LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY	DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT
Otway Supergroup	Crayfish Subgroup	S2	SW	floodplain	NE
				coals	
	Eumeralla Formation	S2-P2	Reservoir		
	<i>Crayfish Unconformity</i>	S2-P1	Windemere	braided fluvial	
	Pretty Hill Formation	S1	S1-P10	Reservoir	
			S1-P9	Source	
			S1-P8	floodplain with meander fluvial	
			S1-P7	lacustrine? fan?	
			S1-P6	coals meander fluvial-floodplain	
	Crayfish Subgroup	S1	S1-P5	braided deltaic	
			S1-P4	lacustrine alluvial fans	
			S1-P3	meander fluvial-floodplain	
			S1-P2	lacustrine deltaic	
S1-P1			lacustrine deltaic fans		
Crayfish Subgroup	S0	S0-P5	active fault		
		S0-P4	lacustrine algal SR		
		S0-P3	fluvial		
		S0-P2	alluvial fans (fan deltas)		
		S0-P1	igneous		
Casterton Formation	S0	Source			



McEachern Sst Play Elements: Source

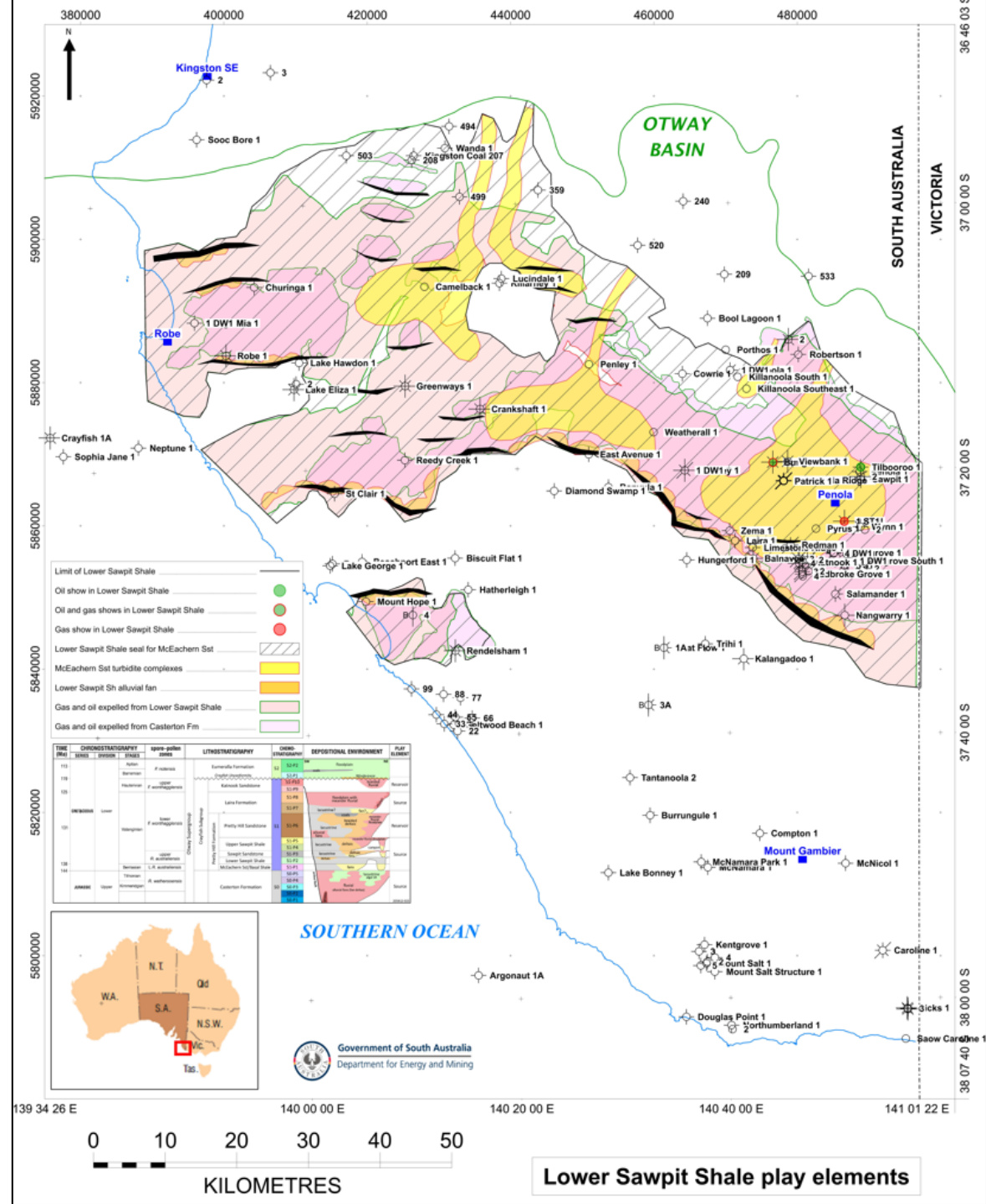
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Otway Supergroup	Crayfish Subgroup	S2	SW	floodplain	NE
				coals	
		Eumeralla Formation	S2-P2	Reservoir	
		<i>Crayfish Unconformity</i>	S2-P1	Windemere	
		Katnook Sandstone	S1-P10	braided fluvial	Reservoir
			S1-P9		
		Laira Formation	S1-P8	floodplain with meander fluvial	Source
			S1-P7	lacustrine? fan?	
			coals	meander fluvial-floodplain	
		Pretty Hill Formation	S1	S1-P6	lacustrine braided deltaic
	alluvial fans				
	S1-P5		meander fluvial-floodplain	Source	
	S1-P4		lacustrine deltaic		
	S1-P3		lacustrine deltaic fans		
S1-P2	deltaic fans				
Casterton Formation	S0	S0-P5	active fault	Source	
		S0-P4	lacustrine algal SR		
		S0-P3	fluvial		
		S0-P2	alluvial fans (fan deltas)		
		S0-P1	igneous		

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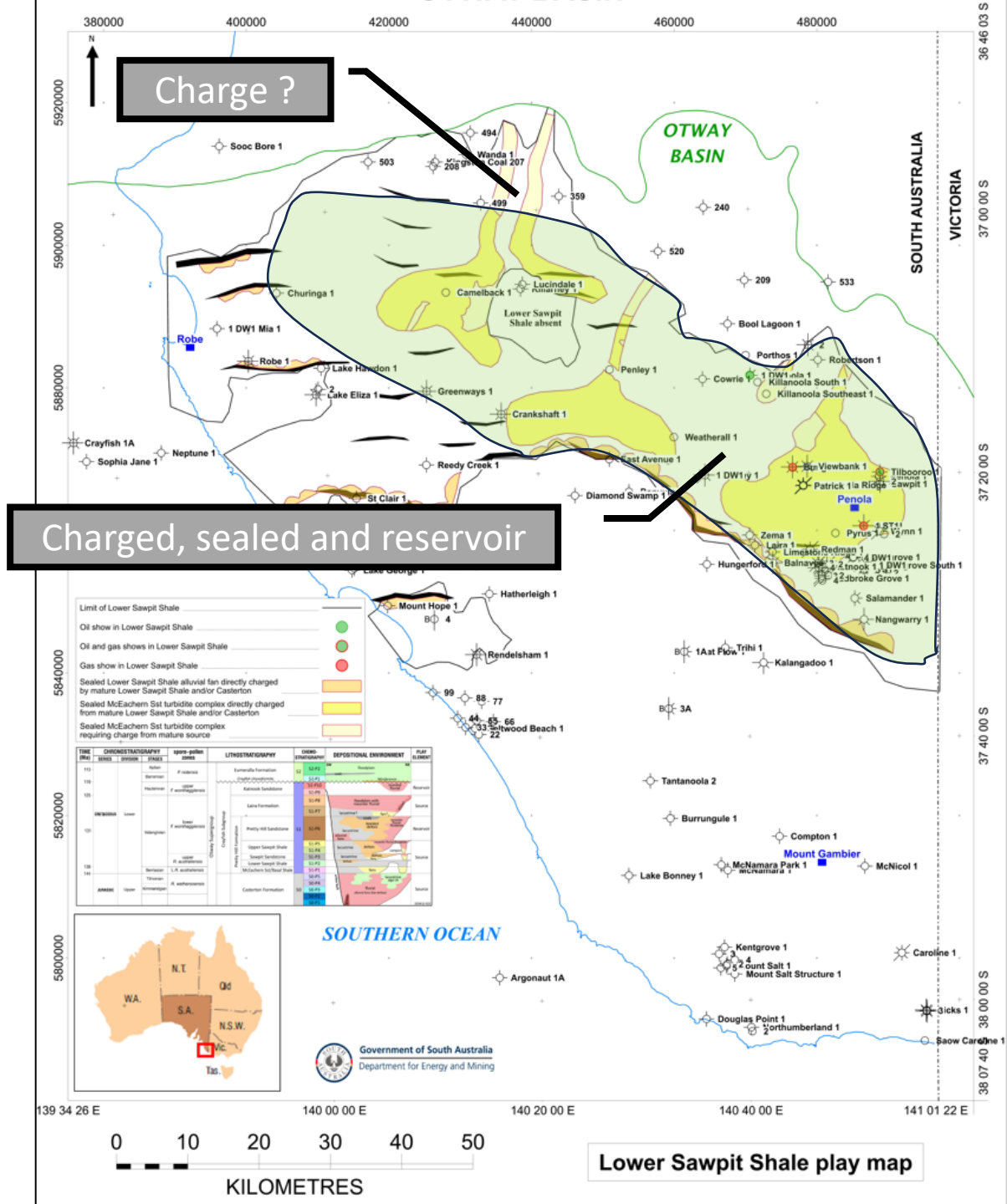
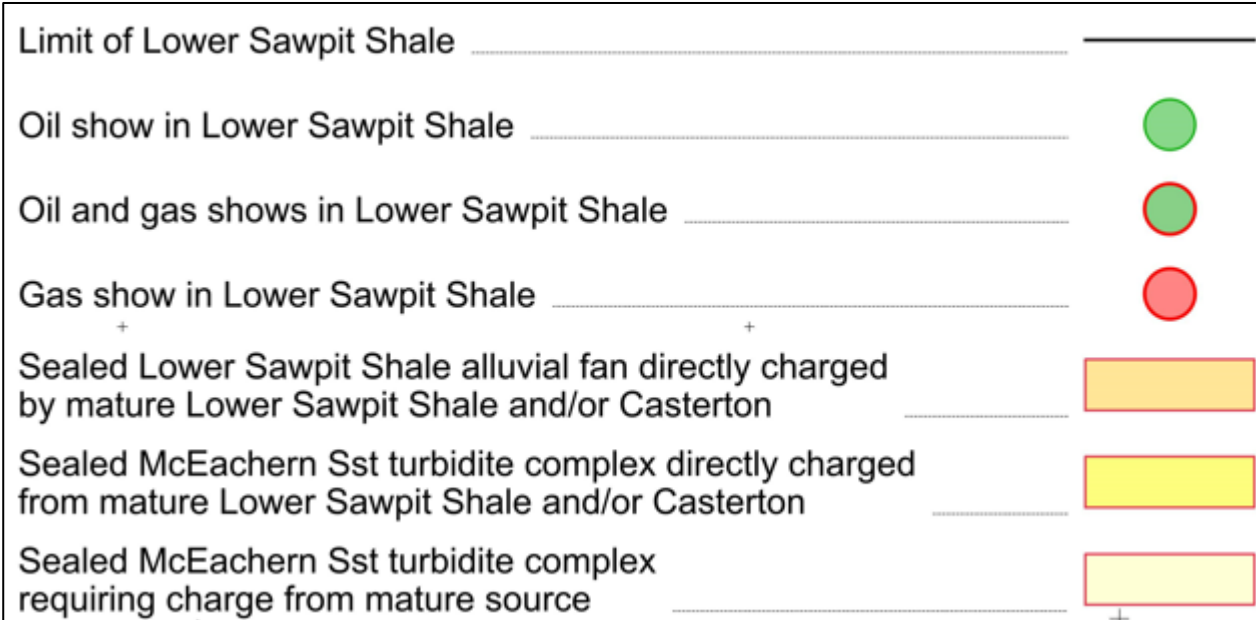


McEachern Sst Play Elements

LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY	DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT
Otway Supergroup	Crayfish Subgroup	S2	S2-P2	SW floodplain NE	Reservoir
			S2-P1	Windemere	
	Pretty Hill Formation	S1	S1-P10	braided fluvial	Reservoir
			S1-P9		
			S1-P8	floodplain with meander fluvial	
			S1-P7	lacustrine? fan? alluvial?	
			S1-P6	coals braided deltaic meander fluvial-floodplain	
			S1-P5	lacustrine alluvial fans meander fluvial-floodplain	
			S1-P4	lacustrine deltaic canyon	
			S1-P3	lacustrine deltaic fans	
			S1-P2	active fault fans	
			S0-P5	lacustrine algal SR	
	Casterton Formation	S0	S0-P4		Source
			S0-P3	fluvial	
S0-P2			alluvial fans (fan deltas)		
S0-P1					

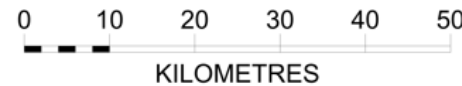


McEachern Sst Play Map





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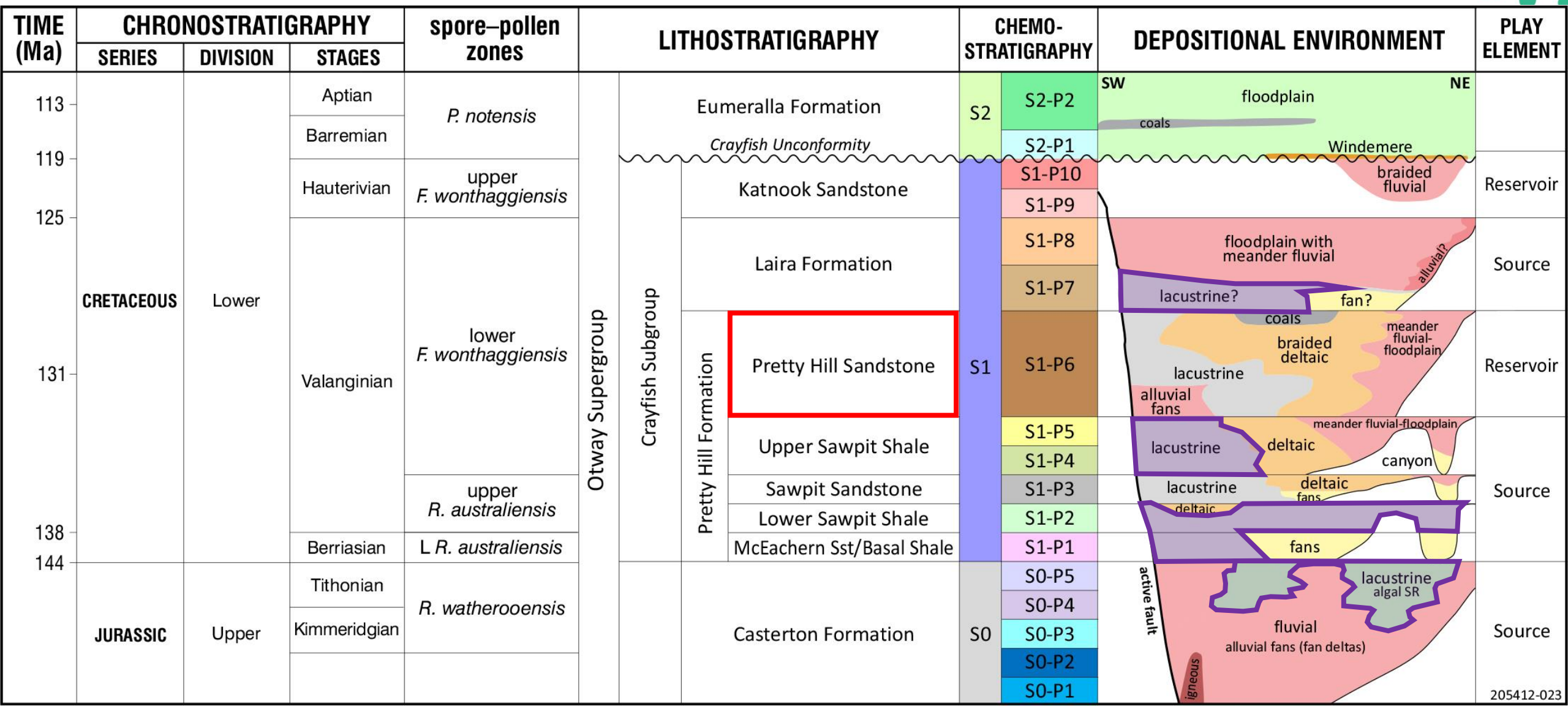
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Lower Sawpit Shale play map

Stratigraphy and Plays Reviewed

 Plays reviewed
 Source rocks



Pretty Hill Sst.

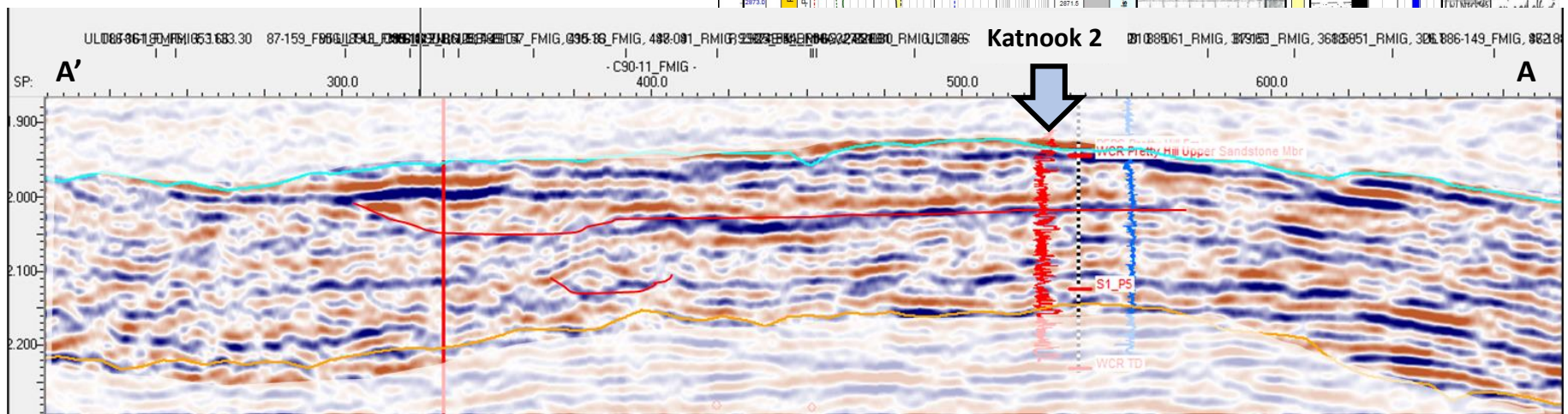
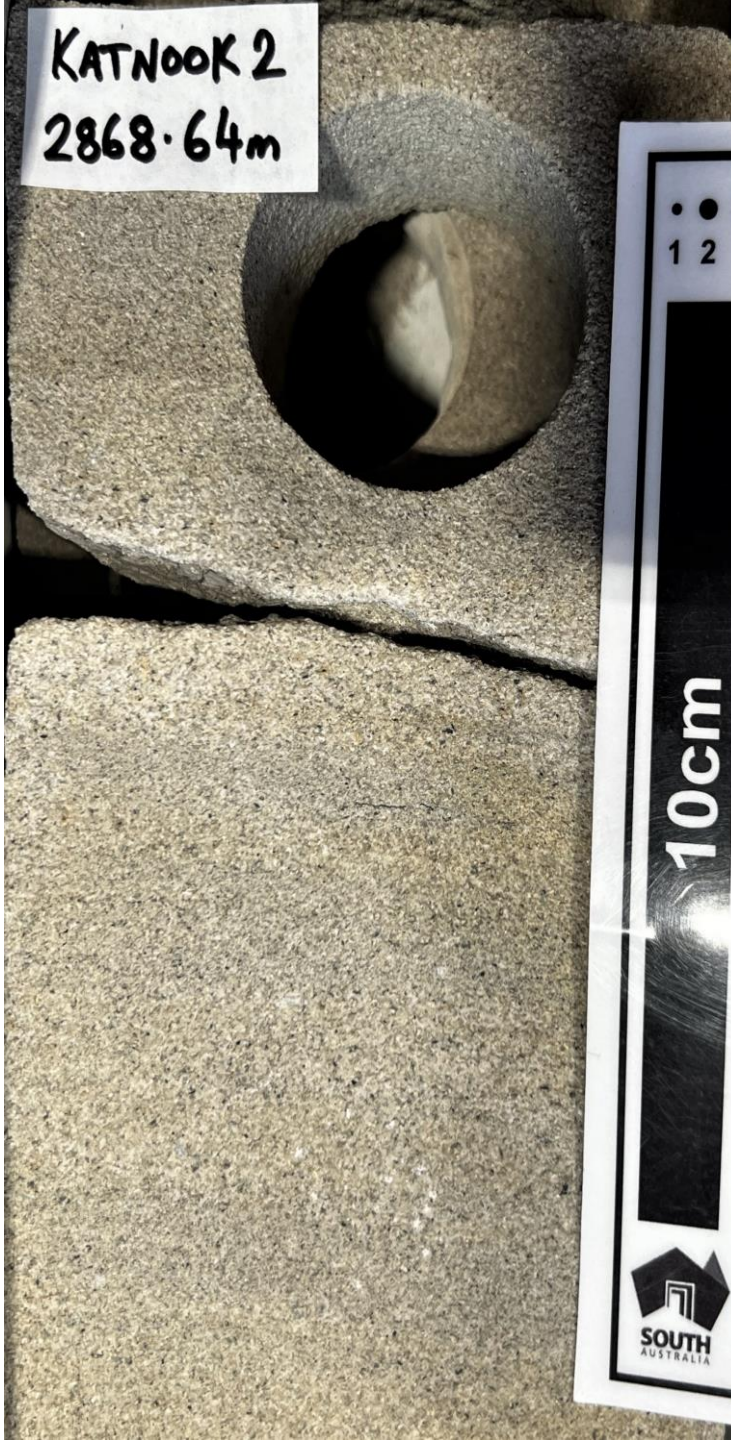
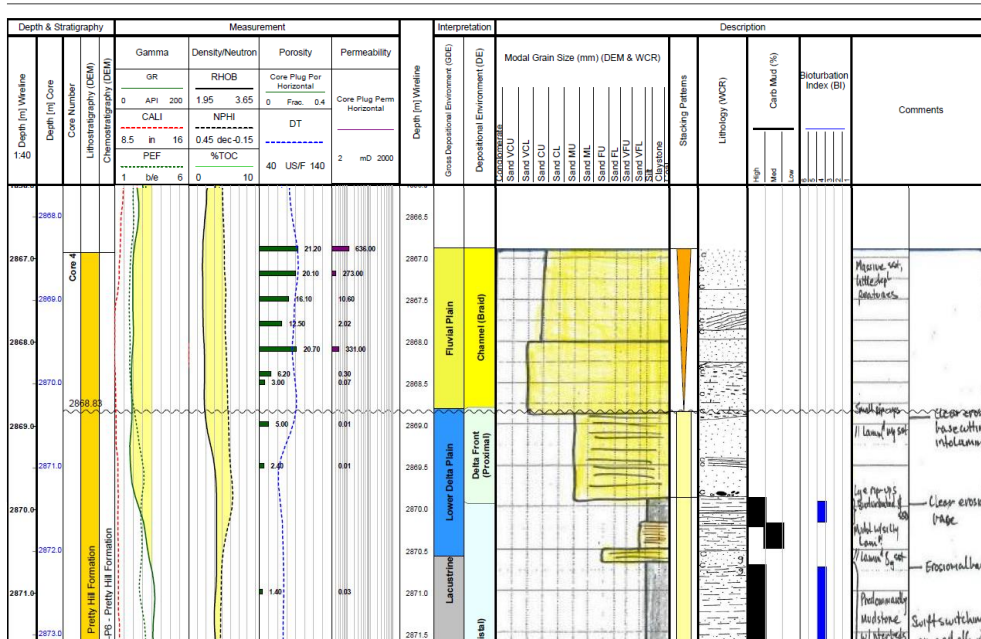
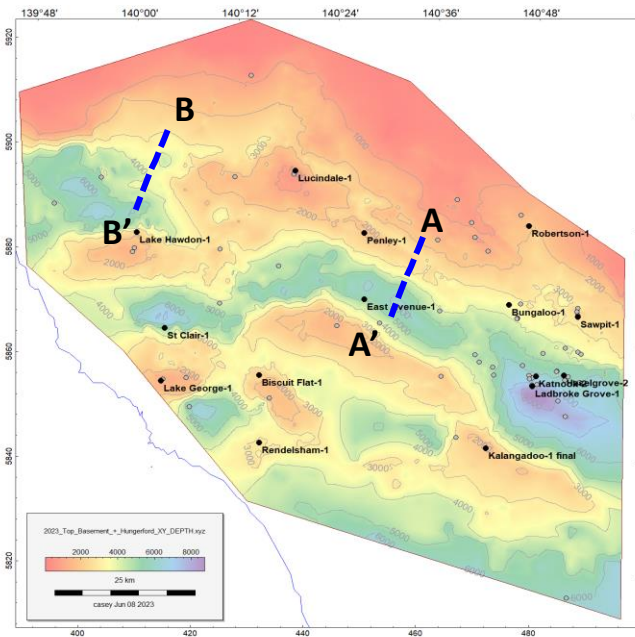
Core Description Katnook 2

Department for Energy and Mining: South Australia

Country (State): Australia (South Australia) Spud Date: 01/12/1988
 Basin: Otway (Onshore SA) KB/RT: 67.97m
 Permit (2022): PEL 32 TD: 3.478.073m
 Well Operator: Ultramar Depth Shift: C3/-0.6m & C4/-1.5m

Author: Ultramar & P. Strong (DEM-July 2023) Scale: 1:40
 Compiled By: C. Cubitt [DE-GDE] (SADEM - July 2023)

- | | |
|---------------------------------------|---------------------------------|
| Gross Depositional Environment | Depositional Environment |
| Fluvial Plain | Channel (Stream) |
| Flood Plain | Channel (Braid) |
| Lacustrine | Prodelta |
| Lower Delta Plain | Prodelta (Lacustrine) |
| | Delta Front (Prodelta) |
| | Delta Front (Braid) |
| | Lacustrine (Braid) |



Pretty Hill Sst.

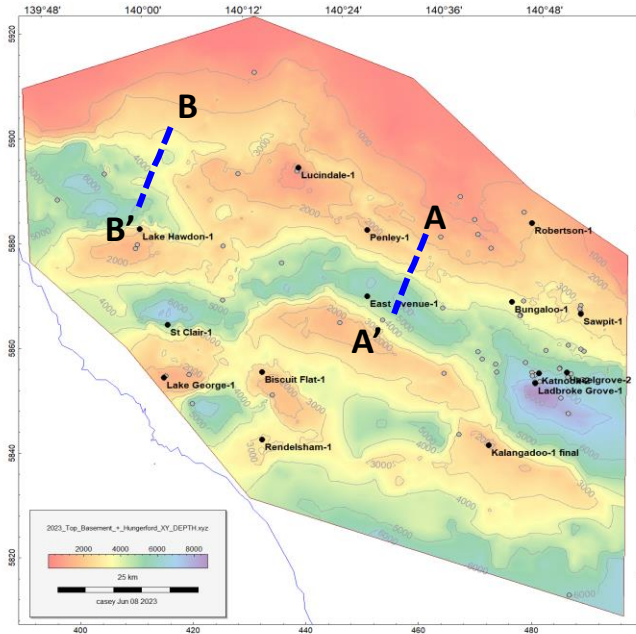
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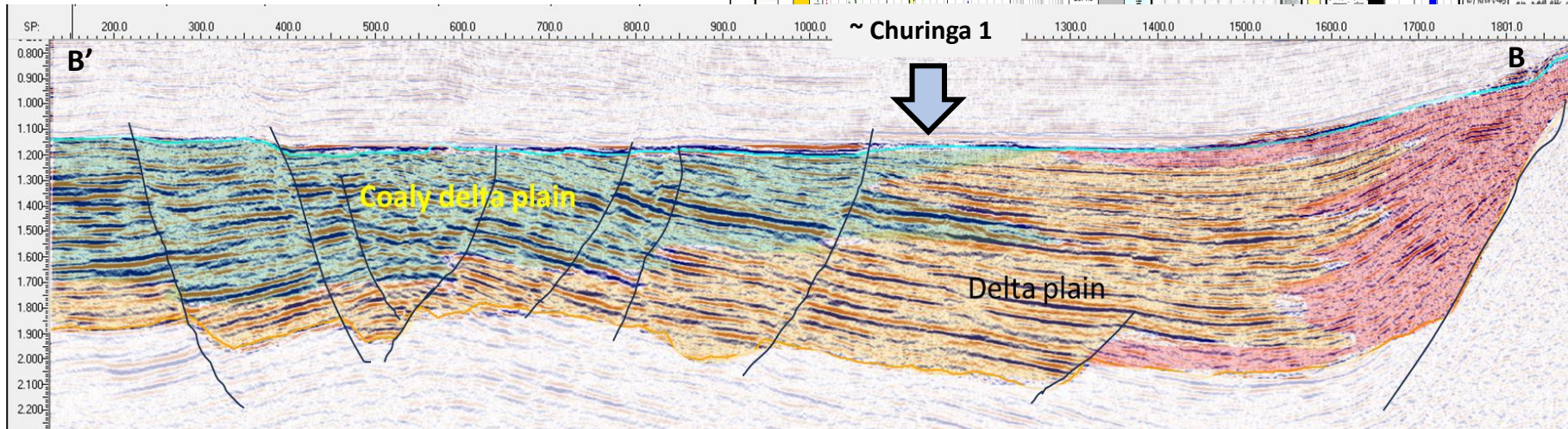
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Author: Ultramar & P. Strong (DEM-July 2023) Scale: 1:40
 Compiled By: C. Cubitt [DE-GDE] (SADEM - July 2023)

- Gross Depositional Environment
 - Fluvial Plain
 - Flood Plain
 - Lacustrine
 - Lower Delta Plain
- Depositional Environment
 - Channel (Meander)
 - Channel (Braid)
 - Floodplain
 - Floodplain (Lacustrine)
 - Delta Front (Proximal)
 - Delta Front (Distal)
 - Lacustrine (Distal)

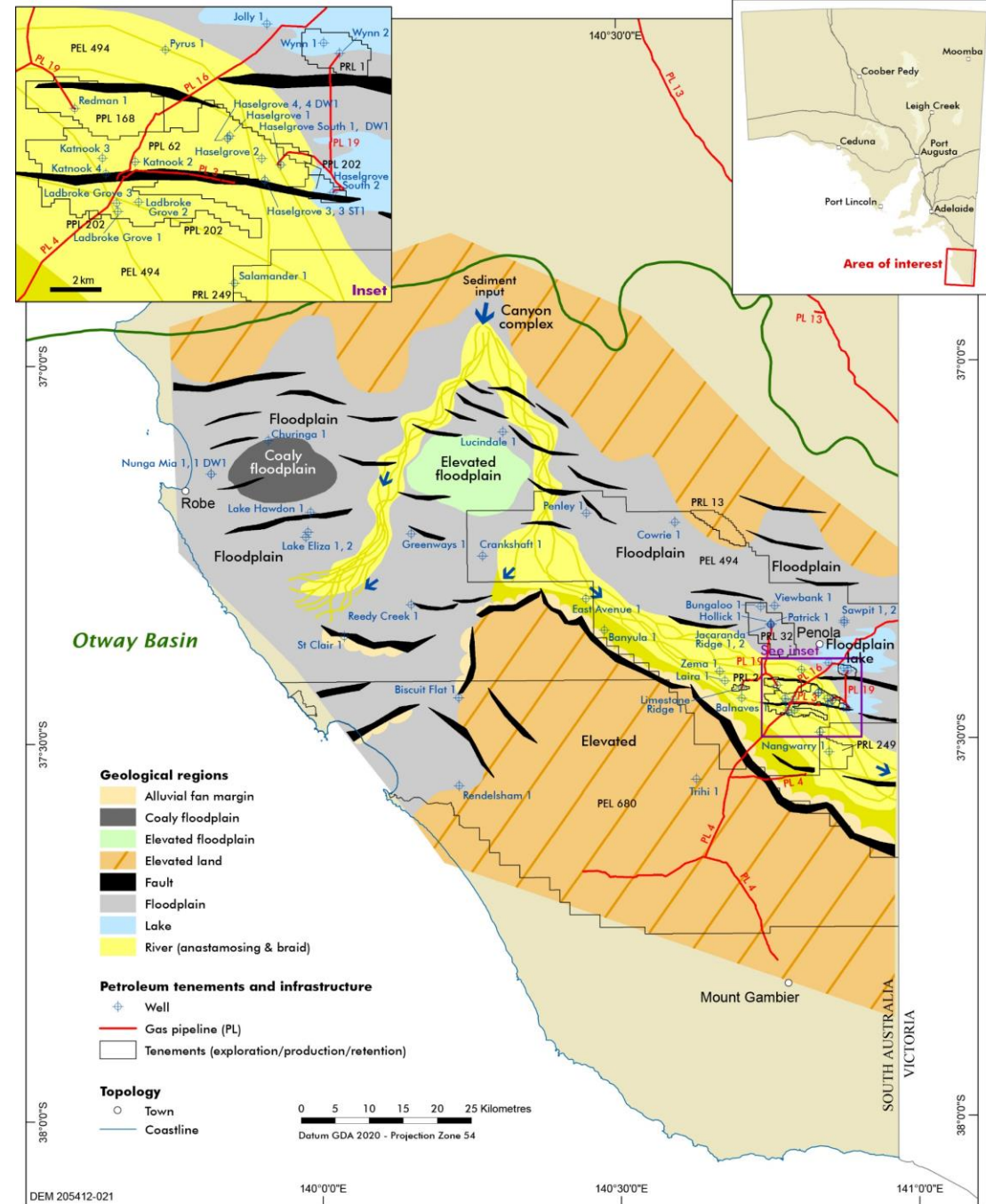
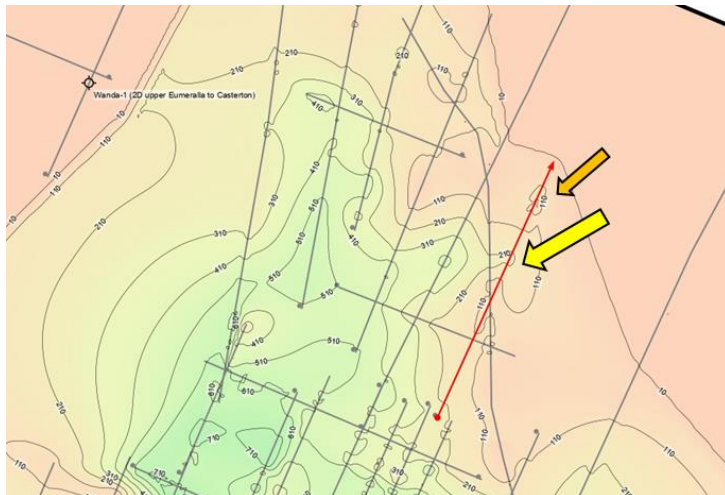


Depth & Stratigraphy		Measurement				Interpretation		Description					
Depth (m) Wellhead	Depth (m) Core	Core Number	Gamma	Density/Neutron	Porosity	Permeability	Depth (m) Wellhead	Depositional Environment (DE)	Modal Grain Size (mm) (DEM & WCR)	Lithology (WCR)	Clay Mud (%)	Bioturbation Index (BI)	Comments
			GR	RHOB	Core Plug Por Horizontal	Core Plug Perm Horizontal							
1.40			0	API 200	1.95	3.65	0	Frac. 0.4					
			CALI	NPHI	0.45 dec-0.15	DT							
			PEF	%TOC		40 US/F 140							
			1	b/c	6	0	10						
2888.0							2886.5						
2887.0							2887.0	Fluvial Plain					Messine soil lettered boundaries
2886.0							2885.5	Channel (Braid)					
2885.0							2885.0						
2884.0							2883.5						
2883.0							2883.0						
2882.0							2881.5	Delta Front Proximal					Subtle erosion late delta channel
2881.0							2880.5	Lower Delta Plain					Clear erosion face
2880.0							2879.5						Proximal
2879.0							2878.5	Lacustrine					Proximal
2878.0							2877.5						Medicine
2877.0							2876.5						Medicine
2876.0							2875.5						Medicine
2875.0							2874.5						Medicine
2874.0							2873.5						Medicine



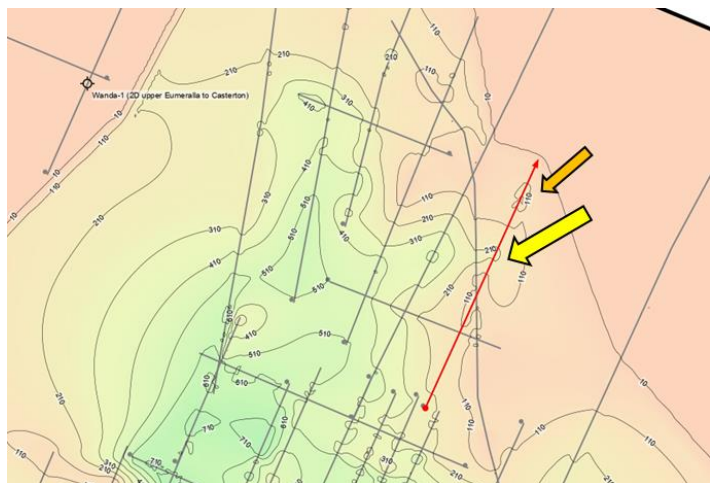
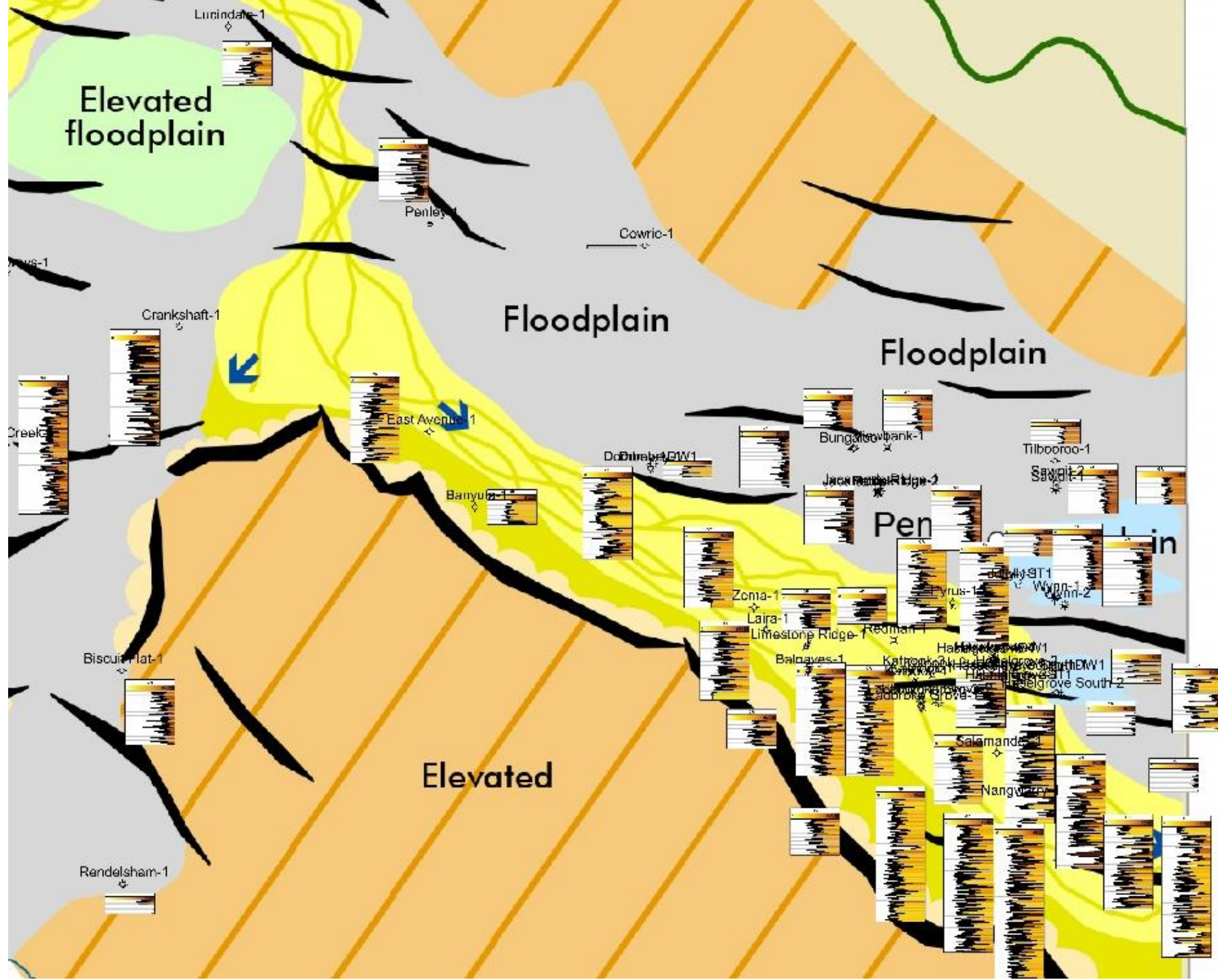
Pretty Hill Sst. Distribution

- Pretty Hill Sst. sediments enter the basin via canyons near Wanda 1 and disperse to the west (Robe Trough) and east (Penola Trough)



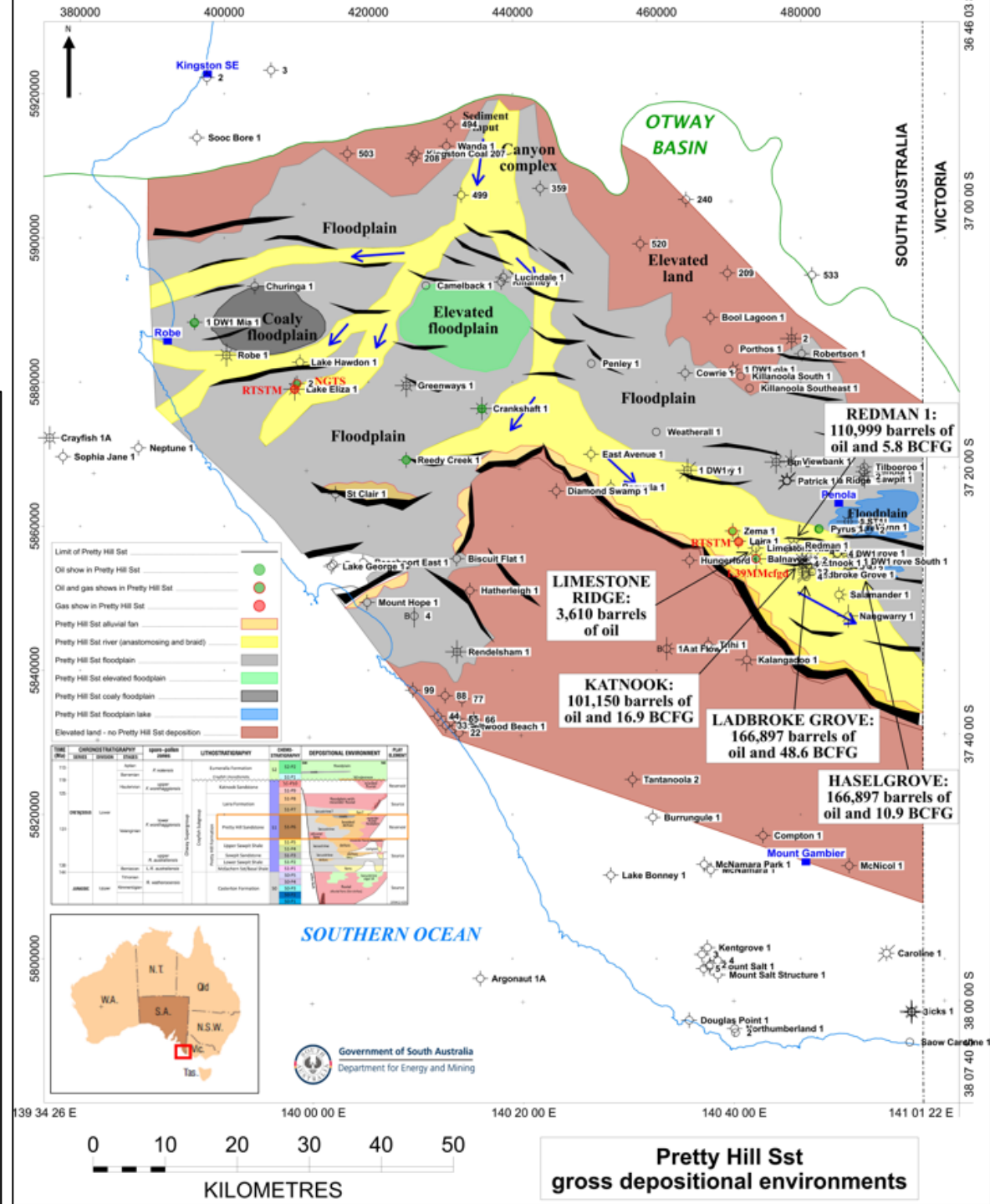
Pretty Hill Sst. Distribution

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Pretty Hill Sst Play Elements: Reservoir

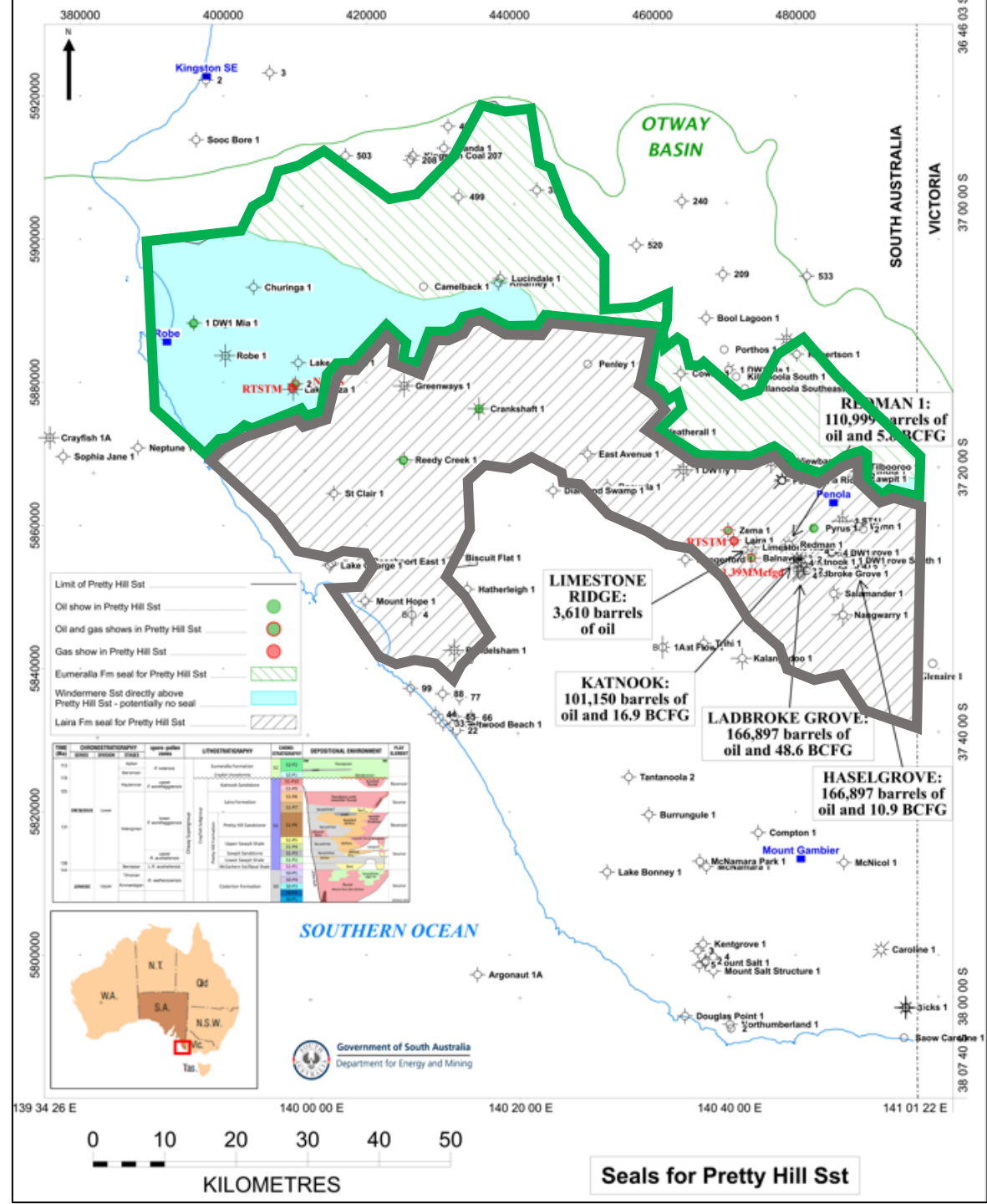
LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY		DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT	
Otway Supergroup	Crayfish Subgroup	Eumeralla Formation	S2	S2-P2	SW floodplain NE	Reservoir	
		<i>Crayfish Unconformity</i>		S2-P1	Windemere		
		Katnook Sandstone	S1	S1-P10	braided fluvial	Source	
		Laira Formation		S1-P9	floodplain with meander fluvial		
				S1-P8	lacustrine? fan?		
				S1-P7	alluvial?		
		Pretty Hill Formation	Pretty Hill Sandstone	S1	S1-P6	braided deltaic meander fluvial-floodplain	Reservoir
				S1-P5	lacustrine	meander fluvial-floodplain	Source
				S1-P4	lacustrine	deltaic canyon	
				S1-P3	lacustrine	deltaic fans	
S1-P2	lacustrine			deltaic fans			
McEachern Sst/Basal Shale	S1-P1			fans	active fault		
Casterton Formation	S0	S0-P5	lacustrine algal SR	Source			
		S0-P4	fluvial				
		S0-P3	alluvial fans (fan deltas)				
		S0-P2	igneous				
		S0-P1	igneous				



Pretty Hill Sst Play Element: Seal

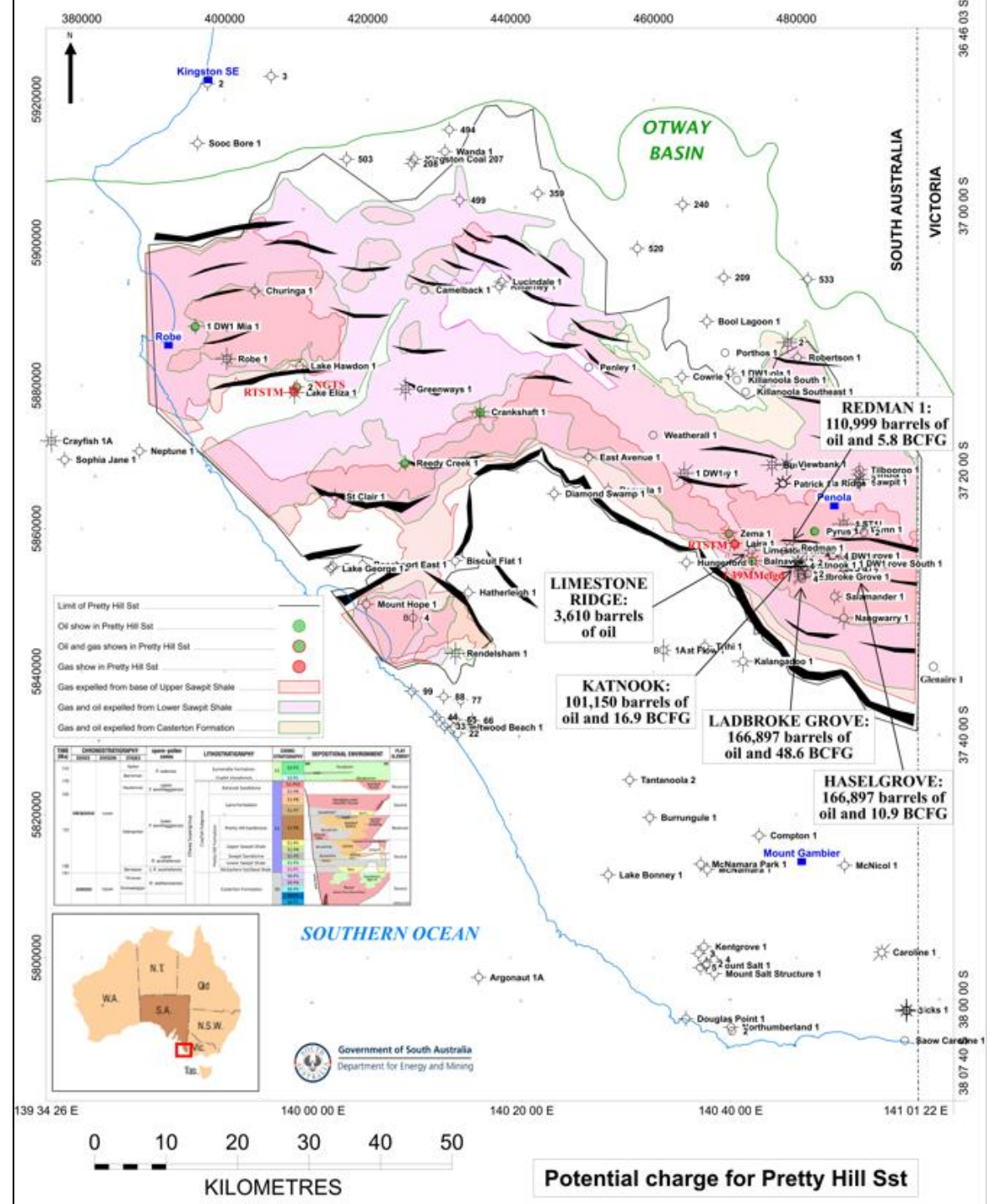
		LITHOSTRATIGRAPHY	CHEMO-STRATIGRAPHY	DEPOSITIONAL ENVIRONMENT	PLAY ELEMENT	
Otway Supergroup	Crayfish Subgroup	Eumeralla Formation	S2	S2-P2 SW floodplain NE	Reservoir	
		<i>Crayfish Unconformity</i>		S2-P1		Windemere
		Katnook Sandstone	S1-P10	braided fluvial	Source	
		Laira Formation	S1-P9	floodplain with meander fluvial		
		Pretty Hill Formation	Pretty Hill Sandstone	S1-P8	lacustrine? fan?	Reservoir
				S1-P7	alluvial?	
			Upper Sawpit Shale	S1-P6	braided deltaic meander fluvial-floodplain	Source
			Sawpit Sandstone	S1-P5	lacustrine deltaic	
			Lower Sawpit Shale	S1-P4	meander fluvial-floodplain canyon	
			McEachern Sst/Basal Shale	S1-P3	lacustrine deltaic fans	
Casterton Formation	S0	active fault	S0-P5	lacustrine algal SR	Source	
			S0-P4	fluvial		
		S0-P3	alluvial fans (fan deltas)			
		S0-P2				
		S0-P1	igneous			

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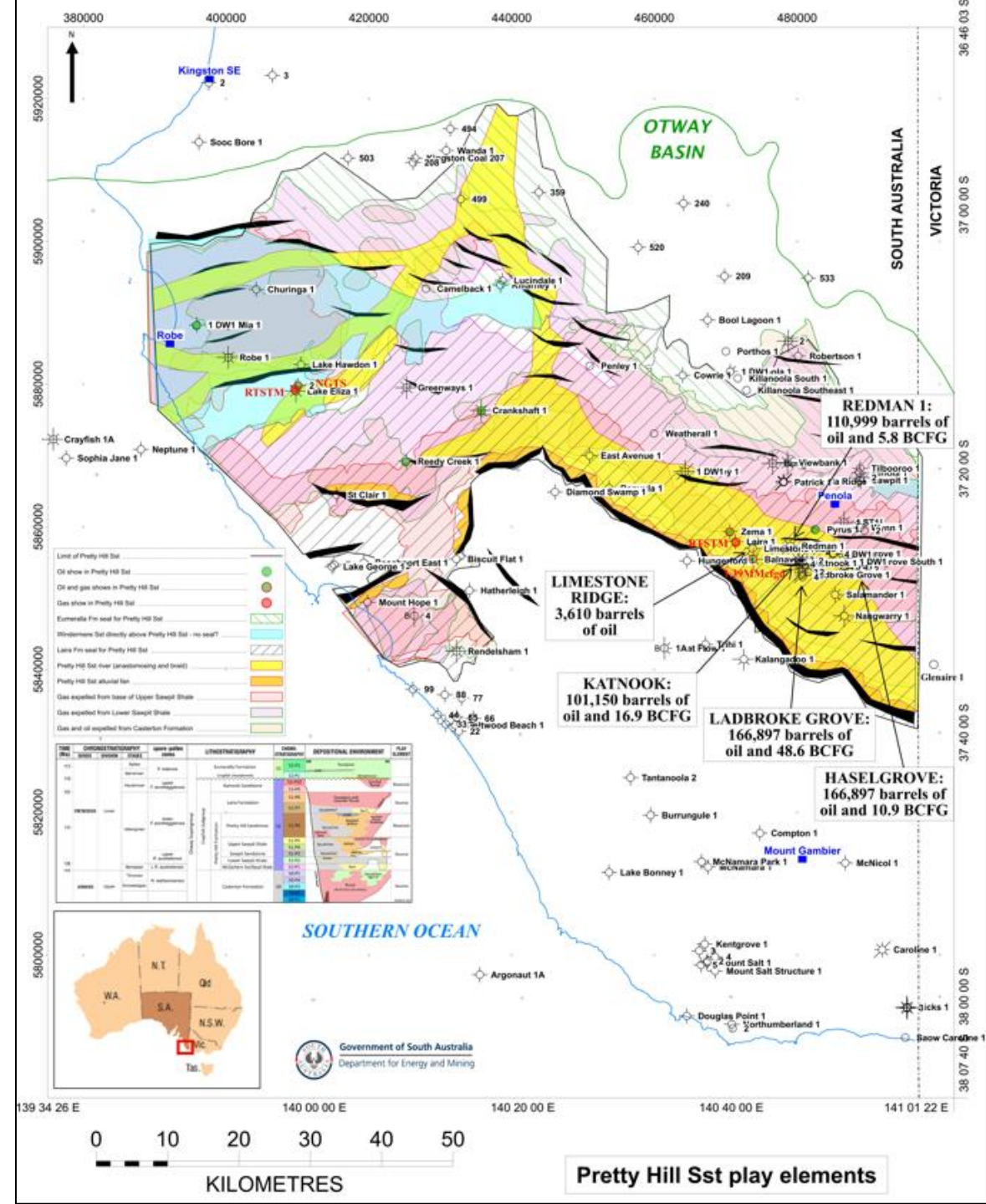
Pretty Hill Sst Play Element: Source

LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY	DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT
Otway Supergroup	Crayfish Subgroup	S2	S2-P2	SW floodplain NE	Reservoir
			S2-P1	coals Windemere	
		S1	S1-P10	braided fluvial	
			S1-P9		
			S1-P8	floodplain with meander fluvial	
			S1-P7	lacustrine? fan? alluvial?	
			S1-P6	coals meander fluvial-floodplain lacustrine braided deltaic	
			S1-P5	alluvial fans meander fluvial-floodplain	
			S1-P4	lacustrine deltaic canyon	
			S1-P3	lacustrine deltaic fans	
	Casterton Formation	S0	active fault igneous lacustrine algal SR fluvial alluvial fans (fan deltas)	Source	



Pretty Hill Sst Play Elements

LITHOSTRATIGRAPHY		CHEMO-STRATIGRAPHY		DEPOSITIONAL ENVIRONMENT		PLAY ELEMENT	
Otway Supergroup	Crayfish Subgroup	Eumeralla Formation	S2	S2-P2	SW floodplain	NE	
		<i>Crayfish Unconformity</i>		S2-P1	coals		Windemere
		Katnook Sandstone	S1	S1-P10	braided fluvial	Reservoir	
		Laira Formation		S1-P9	floodplain with meander fluvial	Source	
				S1-P8	lacustrine?		fan?
		Pretty Hill Formation	Pretty Hill Sandstone	S1	S1-P6	lacustrine, braided deltaic, meander fluvial-floodplain, alluvial fans	Reservoir
				S1-P5	meander fluvial-floodplain	Source	
				S1-P4	lacustrine, deltaic, canyon		
				S1-P3	lacustrine, deltaic fans		
				S1-P2	deltaic, fans		
				S1-P1	active fault, lacustrine algal SR, fluvial, alluvial fans (fan deltas)	Source	
		Casterton Formation	S0	S0-P5	active fault	igneous	Source
				S0-P4			
				S0-P3			
S0-P2							
S0-P1							



Pretty Hill Sst Play Map

Limit of Pretty Hill Sandstone

Oil show in Pretty Hill Sst

Oil and gas shows in Pretty Hill Sst

Gas show in Pretty Hill Sst

Sealed Pretty Hill Sst alluvial fan above mature Upper Sawpit Shale

Sealed Pretty Hill Sst alluvial fan requiring charge

Sealed Pretty Hill Sst river (anastomosing and braid) above mature Upper Sawpit Shale

Sealed Pretty Hill Sst river possibly charged by mature Upper Sawpit Shale - migration required

Pretty Hill Sst river above mature Upper Sawpit Shale, but below Windermere Sst - potentially no seal

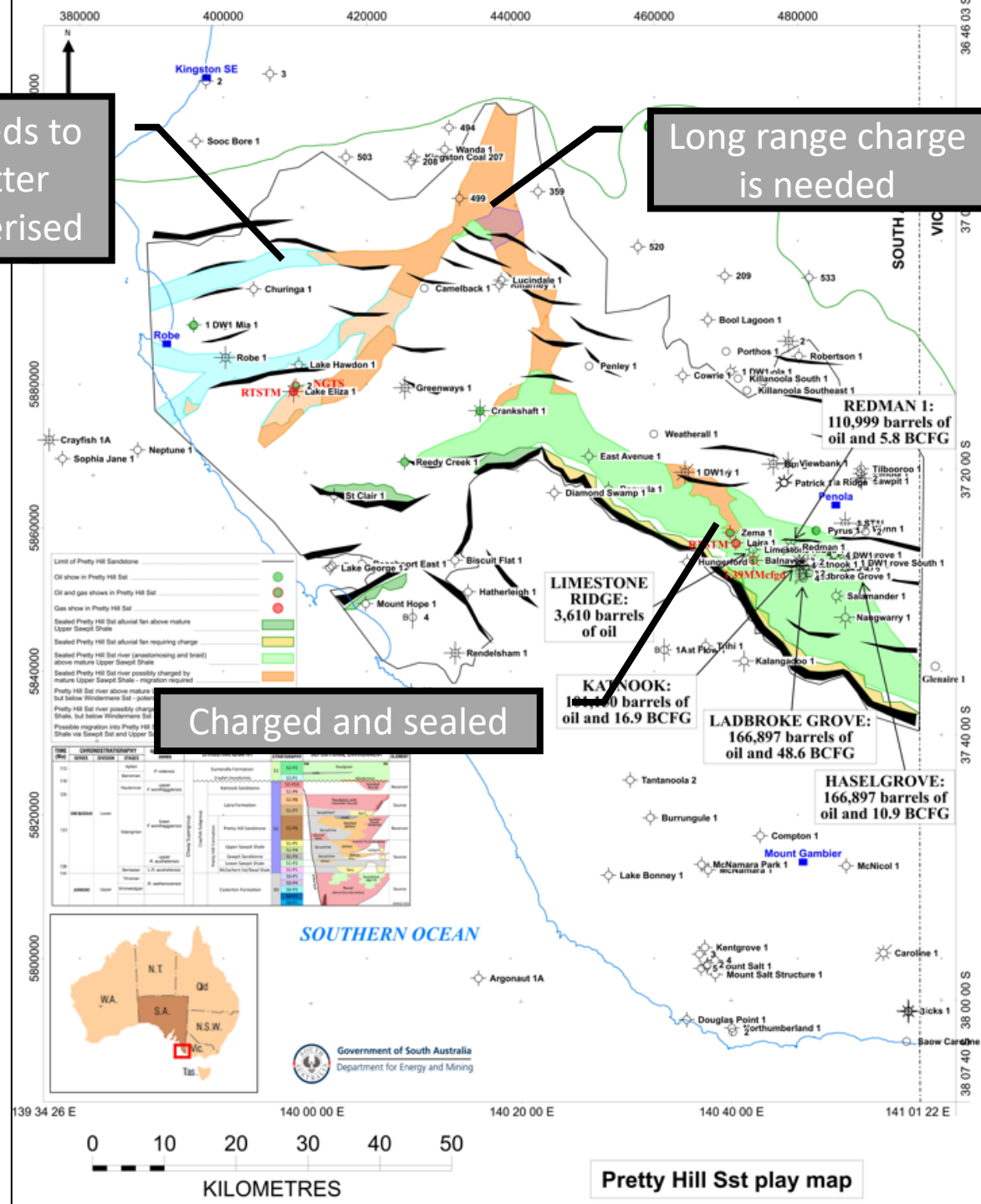
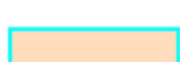
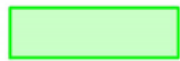
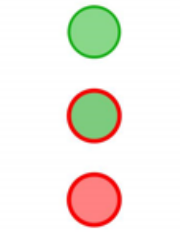
Pretty Hill Sst river possibly charged by mature Upper Sawpit Shale, but below Windermere Sst - potentially no seal

Possible migration into Pretty Hill Sst from Lower Sawpit Shale via Sawpit Sst and Upper Sawpit Shale rivers

Seal needs to be better characterised

Long range charge is needed

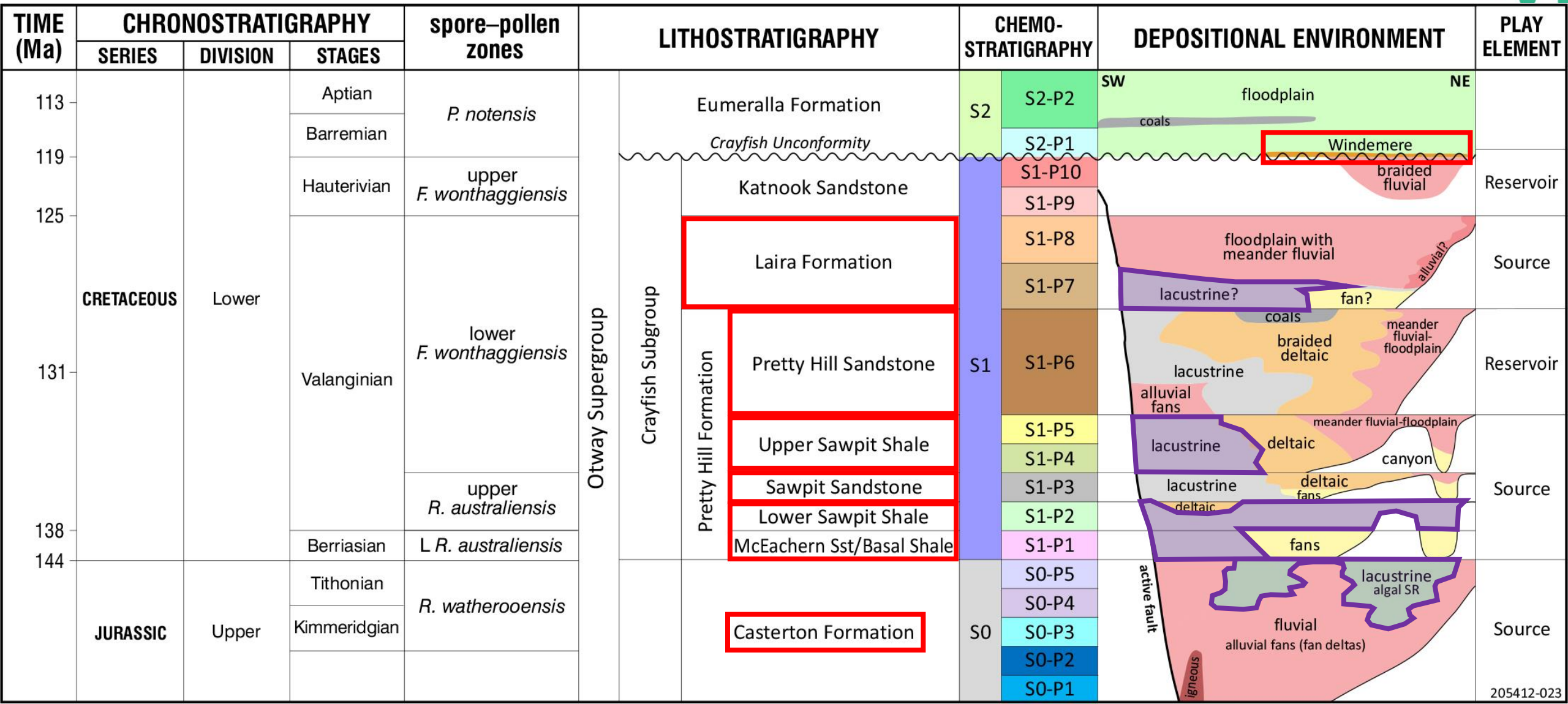
Charged and sealed



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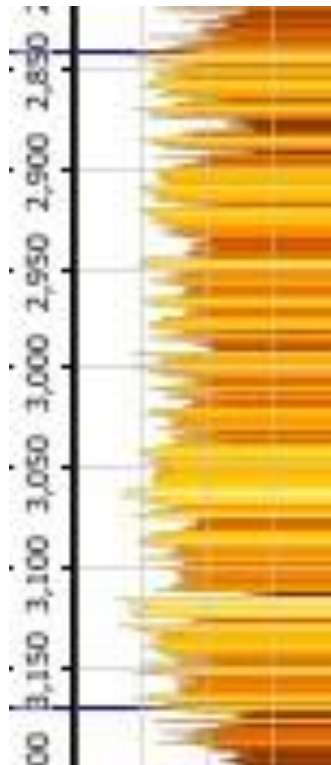
Stratigraphy and Plays Reviewed

- Plays reviewed
- Source rocks



We Know It Is More Complicated - Regional Maps

Jolly 1 ST1 – Sawpit SSt



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From SA Pet Geol 1stEd 1995

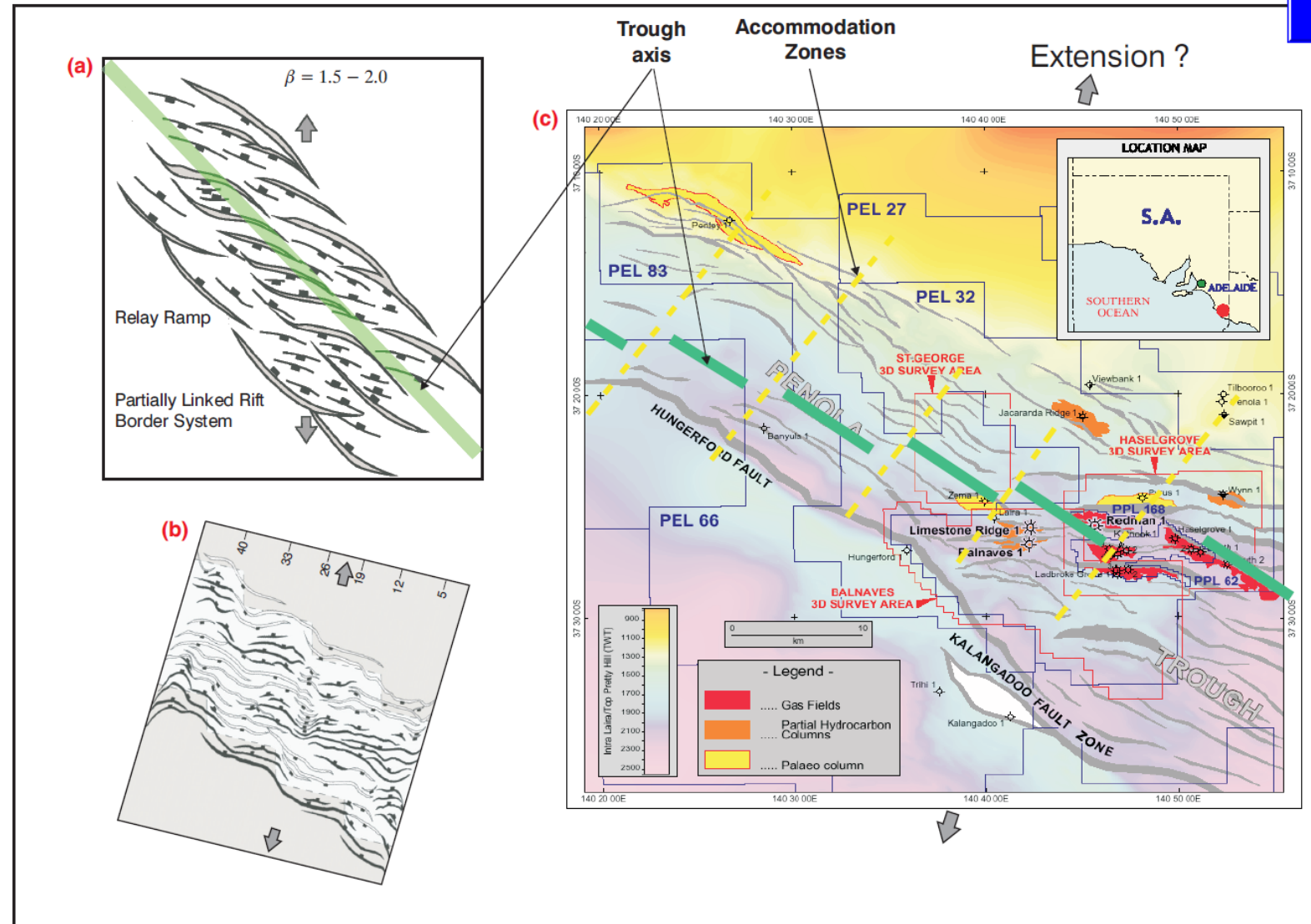
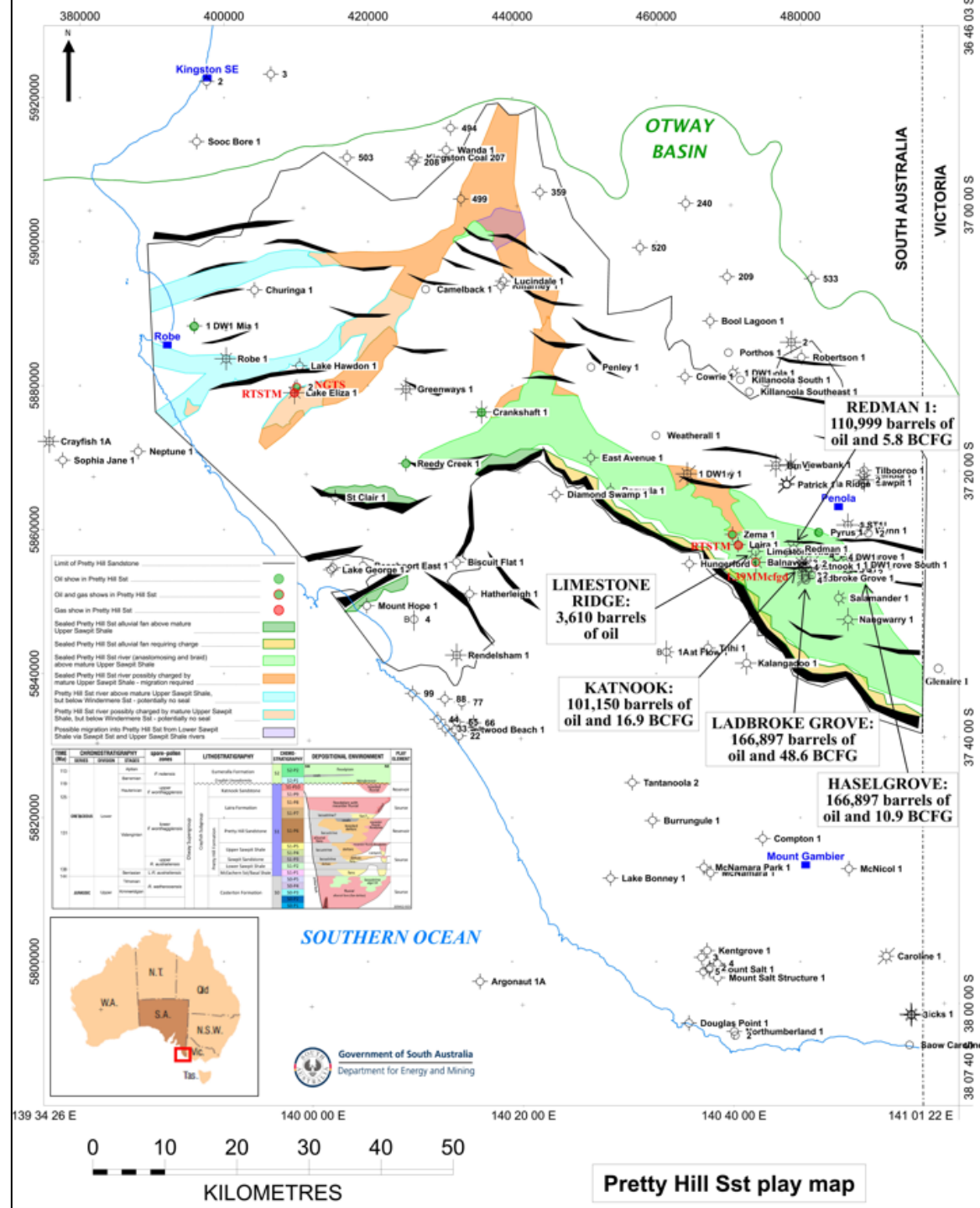


Figure 5.19 Sandbox modelling of extension oblique to trough axes: (a) simple trough axis (b) zigzag offset of trough axis; (c) Penola Trough for comparison. (After McClay, 2001; and Boulton and Donley, 2001.)

In Summary

- Using DEM's onshore Otway GDE maps play fairway maps were constructed for all intervals
- These maps highlight regions where play fairways and the juxtaposing between source reservoir and regional seals
- It is hoped that this mapping and the greater PSM project helps renew interest in this basin and underpins a new phase of hydrocarbon and geologic gas storage exploration



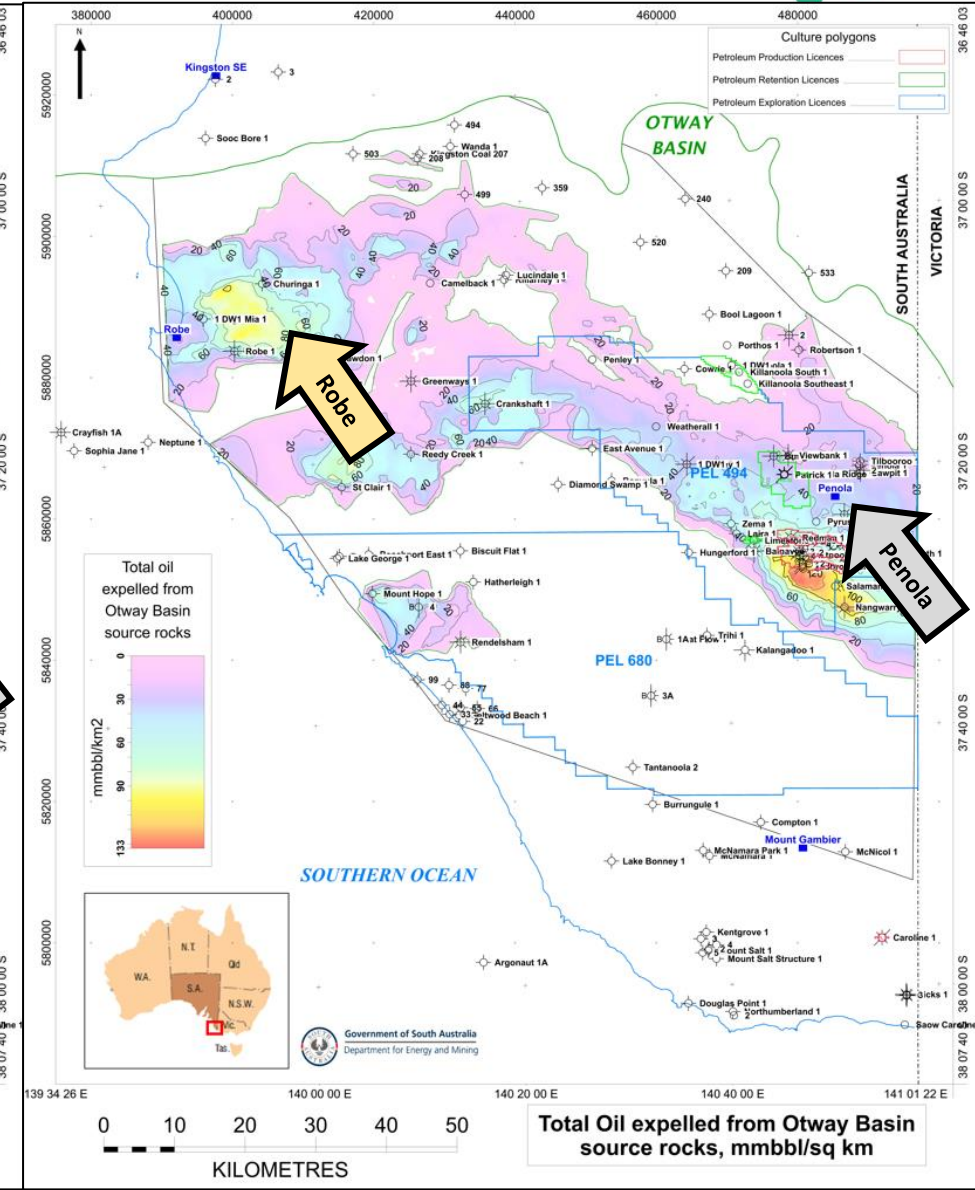
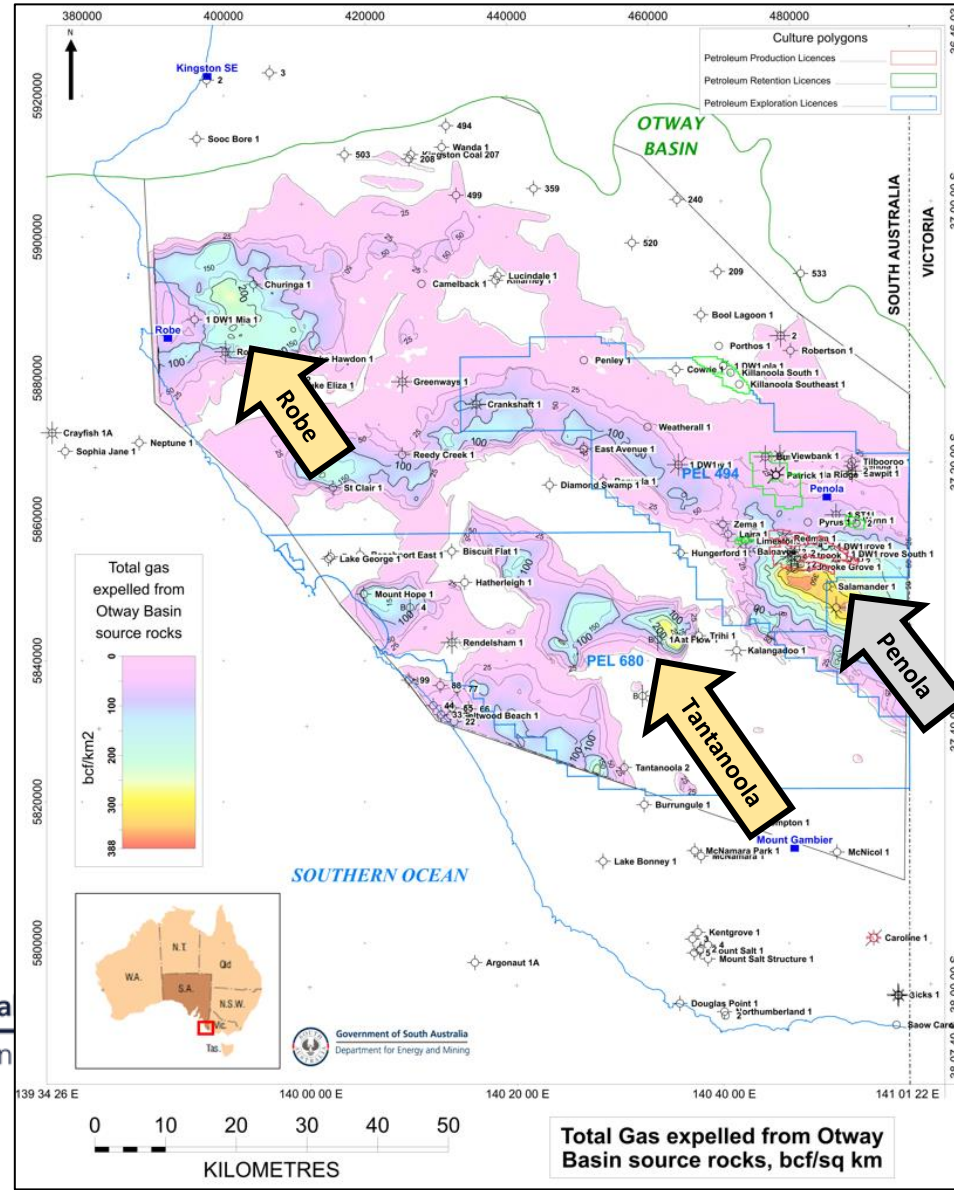
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Modelled Gas & Oil Expelled from Source Rocks



Modelled hydrocarbons expelled from source rocks:

- Gas from Laira Formation
- Gas from Upper Sawpit Shale
- Gas and oil from Lower Sawpit Shale
- Gas and oil from Casterton Formation



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Acreage Release Nominations

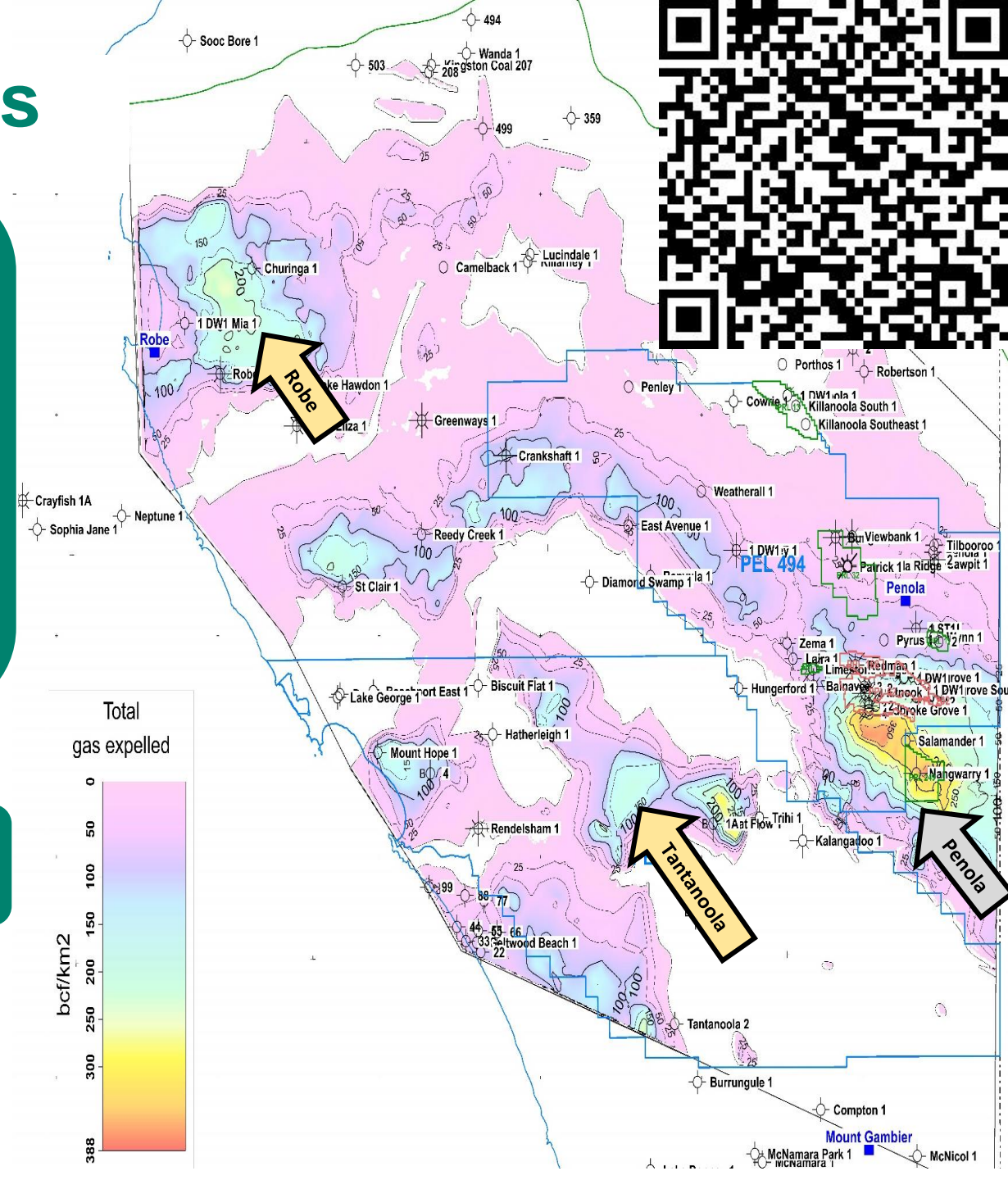
Nominations sought now for a future acreage release for:

- Petroleum Exploration Licences
- Regulated Substances Exploration Licences
- Gas Storage Exploration Licences
- Geothermal Exploration Licences

Contact DEM to nominate



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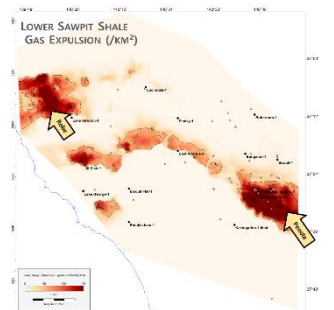
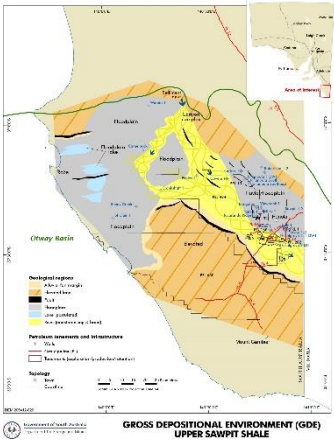
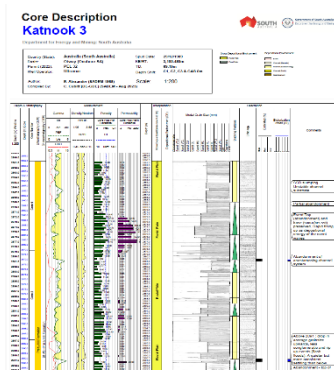


Free, New Data Products: Onshore Otway Basin



DEM has released its latest technical analysis of the onshore Otway Basin and highlighting regions of prospectivity.

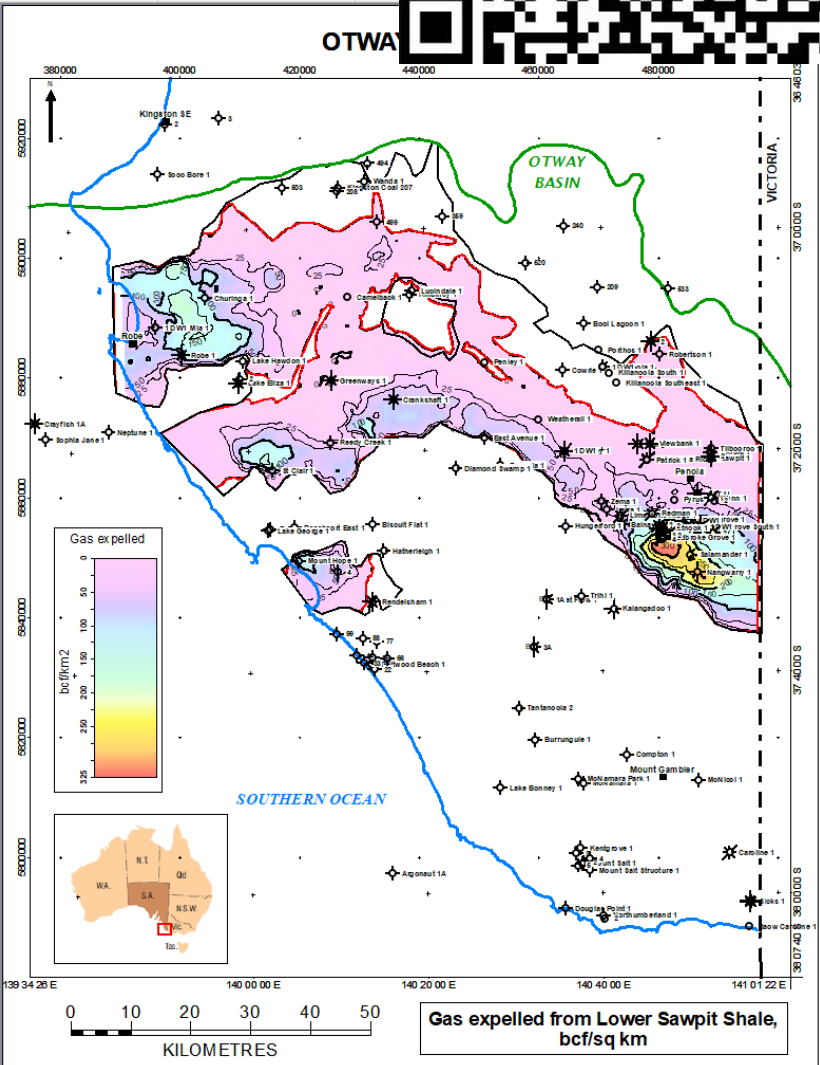
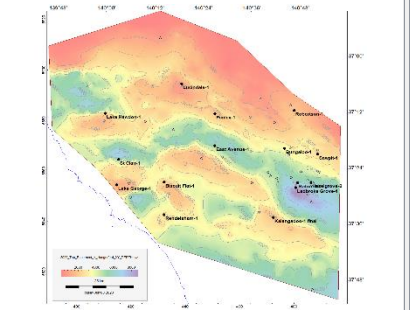
- Petroleum systems modelling (PSM) – Trinity files, movies and summaries
- Regional seismic interpretation – Horizons, faults, grids
- Chemostrat-based well tops – all wells
- Integrated core logs – from 23 wells
- Detailed and missing core imagery
- GDE maps – of all key intervals covered
- Play mapping – of all key intervals
- Arcmap and Petrosys projects



Example Petrosys project (~66 maps)

Display List

- > [] ABC Text: "SOUTH AUSTRALIA"
- > [] Map Base
- > [] Map Template
 - > [] North Arrow
 - > [] Standard kilometres - compact
 - > [] Petroleum licences
 - > [] Parks & Reserves
 - > [] Lower Sawpit Shale depth
 - > [] Lower Sawpit Shale temperature
 - > [] Lower Sawpit Shale isopach
 - > [] Lower Sawpit Shale source rock isopach
 - > [] Lower Sawpit Shale Vitrinite Ro
 - > [] Lower Sawpit Shale transformation ratio
 - > [] Gas expelled from Lower Sawpit Shale
 - > [] ABC Text: "Gas expelled from Lo..."
 - > [] Colour bar for grid of gas expelled from Lower Sawpit Shale
 - > [] Base Map (Otway)
 - > [] Aus map with Otway location
 - > [] State borders
 - > [] Wells
 - > [] GIS: Shape File SE_towns.shp
 - > [] Coastline
 - > [] Basins
 - > [] ABC Text: "SOUTHERN OCEAN"
 - > [] Lower Sawpit Shale extent
 - > [] Lower Sawpit Shale gas expelled edge
 - > [] Lwr Sawpit Sh gas expelled absent Lucindale
 - > [] Colorfill grid of gas expelled from Lower Sawpit Shale
 - > [] Oil expelled from Lower Sawpit Shale



Onshore Otway Basin Play Analysis Data Available

All plays reviewed in this study are documented on the DEM Energy Resources website under individual Basins:

<https://www.energymining.sa.gov.au/industry/energy-resources/geology-and-prospectivity/mesozoic-basins/otway-basin>

The screenshot shows the website interface for the Otway Basin. The top navigation bar includes the Government of South Australia logo, the 'ENERGY & MINING' title, and a search bar. Below this is a secondary navigation menu with links for 'About', 'Consumers', 'Industry', 'Public consultations', 'Investors', 'News', and 'Quick links'. The main content area features a breadcrumb trail: 'Industry > Energy resources > Prospectivity > Mesozoic Basins > Otway Basin'. The page title is 'Otway Basin'. On the left, there is a vertical sidebar menu with categories: 'Energy resources', 'Investment', 'Licensing and land access', 'Regulation', 'Prospectivity', 'Mesozoic Basins', 'Eromanga Basin', 'Otway Basin' (highlighted), 'Simpson Basin', 'Renmark Trough', and 'Polda Basin'. The main content area is titled 'On this page' and lists links for 'Summary', 'New Petroleum Systems Model 2023', 'Figures', and 'Prospectivity'. Below this, there is a paragraph describing the Otway Basin as a Jurassic - Late Cretaceous basin, followed by a map of the basin. A 'Summary' table is also present.

Summary	
Age	Jurassic - Late Cretaceous
Onshore area in South Australia	9650 km ² (3730 sq. miles)



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AEP 2024 Publications

Upcoming papers at AEP 2024:

- **GDE ~ Wed: May 22nd [10:45-12:15]**
- **McEachern Turbidites ~ Wed: May 22nd [10:45-12:15]**
- **PSM ~ Wed: May 22nd [12:45-13:45]**

Published last week



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The APPEA Journal

Revisiting the rocks discovers turbidites and a new exploration play in the Penola Trough, Otway Basin, South Australia

Journal:	APPEA Journal
Manuscript ID:	Draft
Manuscript Type:	Paper Proposal
Date Submitted by the Author:	n/a
Complete List of Authors:	Tiainen, Sharon; South Australia Department for Energy and Mining Kirk, Rob; South Australia Department for Energy and Mining Cubitt, Chris; South Australia Department for Energy and Mining Rady, Tim; Geomorph Energy Pty Ltd
Keywords:	As part of an integrated geological, geochemical, and geophysical study, conventionally cored intervals from the lower-most stratigraphic section of the onshore South Australian part of the Penola Trough, Otway Basin have been reviewed and reinterpreted. The three cored wells; Bungalo-1 (cores 3 and 4), Jolly-15T1 (cores 1, 2, 3 and 4) and Sawpit-2 (cores 1, 2 and 3), were described using a 'quick-look' approach to determine gross lithological and sedimentological information. Seven lithology types were observed: claystone with horizontal



The APPEA Journal

Gross depositional environment (GDE) mapping of rift fill intervals in the onshore South Australian Otway Basin: an example of data integration

Journal:	APPEA Journal
Manuscript ID:	Draft
Manuscript Type:	Paper Proposal
Date Submitted by the Author:	n/a
Complete List of Authors:	Cubitt, Chris; Department of Energy and Mining, Geoscience and Exploration Branch Energy Resources Division - DEM Kirk, Rob; Rob Kirk Consultants Rady, Tim; geomorph Tiainen, Sharon; Department for Energy and Mining, Senior Geologist - Exploration Assessment Mineral Exploration Mineral Resources
Keywords:	Gross depositional environment (GDE) maps were made for six key intervals in the onshore portion of the Jurassic to mid-Cretaceous Otway Basin in South Australia. The Department for Energy and Mining (DEM) has undertaken this comprehensive review (including a petroleum systems model - PSM) so as to stimulate conventional oil and gas exploration but also to inform Carbon Capture and Storage and subsurface hydrogen storage plays.
Abstract:	The GDE maps are the culmination of geological understanding in each interval with results from whole of-basin (chrono-stratigraphic) well correlation, seismic horizon/fault mapping, seismic facies interpretation and core interpretation integrated. Also, where available, interval-specific bore hole image (BHI) derived paleo-current directions were added, along with petrographic information. The mapping reveals varied GDEs including deep lacustrine affected by, in a lacustrine turbidite system, extensive fluvial/lacustrine, fluvial/flood plain and ribbon-like alluvial fan aprons. Well penetrations were used to control seismic horizon picking with syn-depositional faulting a key driver in understanding both the style and axes of deposition. The resulting isopachs and interval-active (growth) faults functioned as the backdrop for well signature maps. Independent core interpretation was then used as primary depositional evidence, giving spatial context and locally informing seismic facies. Subsequently seismic facies interpretations were made away from well control allowing for complete GDE map coverage for all six intervals. These powerful integrated datasets together with the PSM are focussed at firstly stimulating renewed operator interest in this basin and then

Petroleum Systems Analysis of the Onshore Otway Basin, South Australia

Casey Edwards¹, Tim Rady²Chris Cubitt², Rob Kirk³Sharon Tiainen²,

¹ Source Geoscience Pty Ltd, ² Department of Energy & Mining, Government of SA, ³ Geomorph Energy, ⁴ S. Rob Kirk Consulting. The authors would like to acknowledge the contribution and invaluable assistance of Tony Hill (Euro Exploration Services Pty Ltd) and Andrew Murray (Murray Partners PPSA Pty Ltd). Editor and Ian Campbell started

ABSTRACT

An evaluation of the South Australian portion of the onshore Otway Basin was commissioned by the South Australian Government Department of Energy and Minerals (DEM), with the aim of incorporating new seismic interpretation and detailed seismic stratigraphy along with a recent chemostratigraphy study (Bendall et al., 2021), into an updated Petroleum Systems Model. The Area of Interest (AOI) for the study included 74 wells, 16 wells commercial gas fields and non-commercial oil occurrences. The Otway Basin is rift to passive continental margin, situated in northern and southern parts by the NW trending Turturup Hinge. In the South Australian portion of the Otway Basin, the Penola Trough is the most significant hydrocarbon province to date. Sedimentation commenced in the Jurassic with the deposition of the lacustrine Catterton Formation and Unmanned Basal Unit. This was followed by rapid to rapid-lacustrine deposition of the Otway Group throughout the Early Cretaceous, with a major contribution from the onshore Eumarella Formation. The Late Cretaceous Sherbrook Group is developed predominantly in the offshore portion of the Otway Basin, and along with Palaeocene to Miocene marine sedimentation and recent volcanism (SM), was not considered in detail for this study. Seismic interpretation of the existing 2D data set provided depth covered surfaces for all major sequence boundaries and erosional surfaces and made important revisions to the existing structural understanding of the onshore Otway Basin, including the continuation of the Penola Trough into the previously unexplored Cline Trough, and a significant thickening of the Hazlerian Laine Formation in the South Australian extension of the predominantly Victorian Turturup Group. A review of the stratigraphic relationship of the Otway Group with the onshore Eumarella Formation. The Late Cretaceous Sherbrook Group is present in the Jurassic aged Catterton Formation, (Chromatitid Group zone 30-35) and the Early Cretaceous aged Lower Sawpit Shale, (31-41/51-52). Poorer quality gas prone source rocks are likely to be present in the Valanginian Upper Sawpit Shale (31-41/51-52) and Hazlerian Laine Formation (31-41/51-52). A possible lacustrine flake at the Mid-Late Cretaceous level (approximately 31-47/51-52) was also included after being identified on seismic and correlated with cores, logs and geochemistry data. 2D well and trap based modeling undertaken using the Cadwra software suite suggests the majority of liquid hydrocarbons were generated and expelled from the Lower Sawpit Shale between 125 and 100 Ma, with the greatest volume sourced from the Penola and Robe Troughs. Gas and condensate expulsion also took place from the Upper Sawpit Shale and Lower Sawpit Shale in the Penola and Robe Troughs, with expulsion completed by around 100Ma. Significant amounts of gas (and possibly condensate) are modelled to have been generated and expelled from the Hazlerian Laine Formation, between around 100Ma and the present day.

1. PROJECT AREA OF INTEREST AND AVAILABLE DATABASE

The Area of Interest (AOI) for the project is located in South Australia, adjacent to the border with Victoria, in the onshore, western part of the Otway Basin (Figure 1 and 2). 74 wells were located in and around the AOI, with its producing fields (including the Caroline City field).

A geochemistry database of 36 wells was compiled from open file reports, with historical RockEval, VR, gas composition, whole rock mineralogy and isotopic data available. Temperature data was compiled from open file reports and corrected using Homor or Time Since Circulation methods.

Well stratigraphy was provided by DEM, which included correlation with a chemostratigraphy study undertaken in 2020⁴.

Depth covered surfaces for the surface topography, near top Dwyren Formation, top Sherbrook Group, top Eumarella Formation, Cynflin Unconformity, top Priddy Hill Formation, top Upper Sawpit Shale, top Sawpit Sandstone, top Lower Sawpit Shale, top Catterton Formation and Basement were provided by DEM. These were provided already incorporating only underlying formations in order to give a consistent grid extent for the map based modeling.

2. GEOCHEMISTRY REVIEW AND INTERPRETATION

The available RockEval (RE) database (Figure 4) was screened for suitable values, with multiple wells being affected by contamination. The effects of Omelette contamination (indicated by RE1) were evident in several wells (e.g. Mount Salter) and the data from these wells was treated with caution.

Initial RE screening (that did not take a reduction in source rock quality due to maturation into consideration) indicates:

- good quality, liquid prone coals in the Early Cretaceous Eumarella Formation (30-36), but are unlikely to be mature for generation and expulsion in the AOI;
- isolated instance of good quality, liquid and gas prone carbonaceous clastics and shales from the Hazlerian Laine Formation (31-41/51-52);
- good quality, liquid prone, only shales from the Catterton Formation (30-35 to 35) and Unmanned Basal Unit (30-35 to 35) in Sawpit-2;

Gas composition and isotopic data indicate the majority of gas recovered from the AOI is light and relatively dry, with the exception being lacustrine ridge, which shows the addition of dry methane to a wetter gas fraction.

CSIA data, whole liquid GCMS data (Figure 4 and 5) and previous interpretations from the authors⁴ indicate liquids recovered from Nungla Mine, Katoona, Badman-3, Sawpit-2, Hazlerian and Hazlerian South were derived from a mixed terrigenous and fresh water origin source, with varying degrees of lacustrine influence and variable levels of aromatics.

CSIA data from lacustrine ridge also indicates separate sources for oil and gas, suggesting a complex charge history in the Penola Trough which includes a late dry gas charge.

Work undertaken by Hill et al. (2022)⁵ suggests the fluid recovered from the 'Basement' at Sawpit-2, which is geochemically distinct from other analysed fluids, was derived from a volcanics/weathered basement dominated lacustrine source with significant organic content and aromatics, representing the initial, cold oil-rich response described directly on

3. SOURCE ROCK MODELS

Sequence stratigraphy and geochemistry indicate potential good quality, lacustrine source rocks are present in the Jurassic aged Catterton Formation, (30-35) and the Early Cretaceous aged Lower Sawpit Shale, (31-41/51-52) (Figure 7a). These were modelled as a C-Organic Type III and Paper and Corn (1992)⁶ scheme, with generation and expulsion of predominantly liquid hydrocarbons as a maturity equivalent to around 0.7-0.72% VR (or 115-118°C).

Poorer quality, gas prone source rocks were modelled in the Valanginian Upper Sawpit Shale (31-41/51-52), (Figure 7b) and Hazlerian Laine Formation (31-41/51-52), with generation of predominantly gas taking place from a CII-Organic type at a maturity equivalent of around 1.0% VR (or 140°C). A possible lacustrine flake at the Mid-Late Cretaceous level (approximately 31-47/51-52) was also included after being identified on seismic and correlated with cores, logs and geochemistry data; this was modelled as per the Lower Sawpit Shale.

Figure 1: Overview map of the Otway Basin showing the Area of Interest (AOI) in red. Figure 2: Structural map showing the Penola Trough and other features. Figure 3: Stratigraphic column showing the Otway Group and other formations. Figure 4: RockEval scatter plot showing source rock quality. Figure 5: GCMS chromatograms showing gas composition. Figure 6: Seismic interpretation showing structural features. Figure 7: Source rock models showing generation and expulsion of hydrocarbons. Figure 8: 5D modelling showing depth grids and general stratigraphy. Figure 9: Maturity modelling showing the Catterton Formation, Lower and Upper Sawpit Shale and the Lower Laine Formation. Figure 10: 6MfP based maturity and expulsion modelling showing depth grids and general stratigraphy.

Figure 10 models were built at well locations (Figure 2) and extended to basement using depth grids and general stratigraphy with corrected temperature, vitrinite reflectance and pressure data used for calibration (see Figure 6). The bottom boundary condition was constrained to a fixed temperature at the base lithosphere, and a general lithosphere model incorporating the primary rift event in the Late Jurassic-Early Cretaceous, and additional rifting in the Late Cretaceous resulting from the Antarctic-Australia separation. A shallow lithosphere was reduced to the present day to represent recent volcanism.

A map based model was built using depth grids provided by DEM, incorporating the 10 models, source rock models discussed in part 4, and an understanding of the regional tectonic evolution, paleogeography and thermal history of the Basin. Maturity modelling suggests the Catterton Formation, Lower and Upper Sawpit Shale and the Lower Laine Formation are mature for generation and expulsion of hydrocarbons (Figure 8a, 8b, 8c).

Expulsion modelling indicates the majority of liquid hydrocarbons were generated and expelled from the Lower Sawpit Shale between 125 and 100Ma, with the greatest volume (up to 100mmbbl/torr) sourced from the Penola and Robe Troughs. Gas and condensate expulsion also took place from the Upper and Lower Sawpit Shale in the Penola and Robe Troughs, with expulsion completed by around 100Ma (Figure 9c, 9d, 9e).

Up to 200mmbbl/torr of gas is modelled to have been generated and expelled from the Laine Formation in the Penola and Robe Troughs, with expulsion completed by around 100Ma and present day (Figure 9g).

A pseudo-time-late depth surface was created to test the maturity of the Mid-Late Cretaceous source rock model, with the sequence above to mid-maturity for liquid generation and expulsion in the Turturup Trough.

Hydrocarbon migration modelling was outside the scope of the study, and the significance of migration loss should be taken into consideration when assessing expelled volumes. Regardless, the results suggest prospectivity remains in the SA onshore Otway Basin, with the new Turturup Trough interpretation representing some intriguing underexplored potential.

2. STRUCTURAL SETTING, STRATIGRAPHY AND TECTONIC EVOLUTION^{4*}

The Otway Basin is rift to passive continental margin straddling the border of South Australia and Victoria, which has a complex present day structural regime encompassing localized grabens with variable basement, in the onshore South Australian portion of the basin, these in addition across the north-west-south-east trending Turturup Hinge (Figure 1), with the area to the north dominated by the myr-PN, Early Cretaceous Otway Supergroup, and the area to the south containing predominantly post-PN, Late Cretaceous Sherbrook Group sequences (Figure 3). To date, the Penola Trough is the most significant hydrocarbon province in the SA Onshore Otway, containing all producing hydrocarbon fields, namely the Katoona, Ladbroke Grove, Hazlerian, Hazlerian South and Hazlerian commercial gas fields, along with non-commercial oil at Katoona and Jankania Ridge.

Initial input of rapid rifting in the basement was the result of the myr-PN Catterton Formation on Basement (eroded during Permian glaciation). The sequence is composed of carbonaceous mudstone deposited under lacustrine conditions, including a basal (unconformal) unit of weathered basement, shale and volcanic material with potentially excellent source rock potential.

The Basement to Basement Cynflin Group was initially deposited as clastics in rift-related half grabens under fluvial and lacustrine conditions, with low viscosity channels and floodplain development strongly controlled by local tectonics and basin accommodation space, resulting in maximum sediment thickness concentrated to creek flats.

The Hazlerian Laine Formation shows zones of high silt/clay content in the upper half of the sequence, suggesting changes from fluvial to shallow lacustrine (and resulting lake meandering).

A sag phase in the Aptian resulted in deposition of the Early Cretaceous Eumarella Formation flood basin sediments, with coal swamps present at the base. The sequence shows an angular unconformity with the Cynflin Group and also the overlying Sherbrook Group (see 6.5 myr duration).

Late Cretaceous Sherbrook Group deposition was driven by renewed subsidence associated with onset of Australian-Antarctic plate separation and consist of post rift sequences.

Fluvio-lacustrine and peatland sediments (indicated) deposited on a subsiding continental margin, with the Turturup Hinge Zone interpreted as the tectonic boundary.

Marine mud and carbonate deposition took place from the Eocene, with Tertiary and recent volcanism introducing magmatic CO₂ into the basin.

3. 5D MODELLING

Figure 10 models were built at well locations (Figure 2) and extended to basement using depth grids and general stratigraphy with corrected temperature, vitrinite reflectance and pressure data used for calibration (see Figure 6). The bottom boundary condition was constrained to a fixed temperature at the base lithosphere, and a general lithosphere model incorporating the primary rift event in the Late Jurassic-Early Cretaceous, and additional rifting in the Late Cretaceous resulting from the Antarctic-Australia separation. A shallow lithosphere was reduced to the present day to represent recent volcanism.

A map based model was built using depth grids provided by DEM, incorporating the 10 models, source rock models discussed in part 4, and an understanding of the regional tectonic evolution, paleogeography and thermal history of the Basin. Maturity modelling suggests the Catterton Formation, Lower and Upper Sawpit Shale and the Lower Laine Formation are mature for generation and expulsion of hydrocarbons (Figure 8a, 8b, 8c).

Expulsion modelling indicates the majority of liquid hydrocarbons were generated and expelled from the Lower Sawpit Shale between 125 and 100Ma, with the greatest volume (up to 100mmbbl/torr) sourced from the Penola and Robe Troughs. Gas and condensate expulsion also took place from the Upper and Lower Sawpit Shale in the Penola and Robe Troughs, with expulsion completed by around 100Ma (Figure 9c, 9d, 9e).

Up to 200mmbbl/torr of gas is modelled to have been generated and expelled from the Laine Formation in the Penola and Robe Troughs, with expulsion completed by around 100Ma and present day (Figure 9g).

A pseudo-time-late depth surface was created to test the maturity of the Mid-Late Cretaceous source rock model, with the sequence above to mid-maturity for liquid generation and expulsion in the Turturup Trough.

Hydrocarbon migration modelling was outside the scope of the study, and the significance of migration loss should be taken into consideration when assessing expelled volumes. Regardless, the results suggest prospectivity remains in the SA onshore Otway Basin, with the new Turturup Trough interpretation representing some intriguing underexplored potential.

4. 6MfP BASED MATURITY AND EXPULSION MODELLING

Figure 10 models were built at well locations (Figure 2) and extended to basement using depth grids and general stratigraphy with corrected temperature, vitrinite reflectance and pressure data used for calibration (see Figure 6). The bottom boundary condition was constrained to a fixed temperature at the base lithosphere, and a general lithosphere model incorporating the primary rift event in the Late Jurassic-Early Cretaceous, and additional rifting in the Late Cretaceous resulting from the Antarctic-Australia separation. A shallow lithosphere was reduced to the present day to represent recent volcanism.

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Expulsion modelling indicates the majority of liquid hydrocarbons were generated and expelled from the Lower Sawpit Shale between 125 and 100Ma, with the greatest volume (up to 100mmbbl/torr) sourced from the Penola and Robe Troughs. Gas and condensate expulsion also took place from the Upper and Lower Sawpit Shale in the Penola and Robe Troughs, with expulsion completed by around 100Ma (Figure 9c, 9d, 9e).

Up to 200mmbbl/torr of gas is modelled to have been generated and expelled from the Laine Formation in the Penola and Robe Troughs, with expulsion completed by around 100Ma and present day (Figure 9g).

Acreage Release Nominations

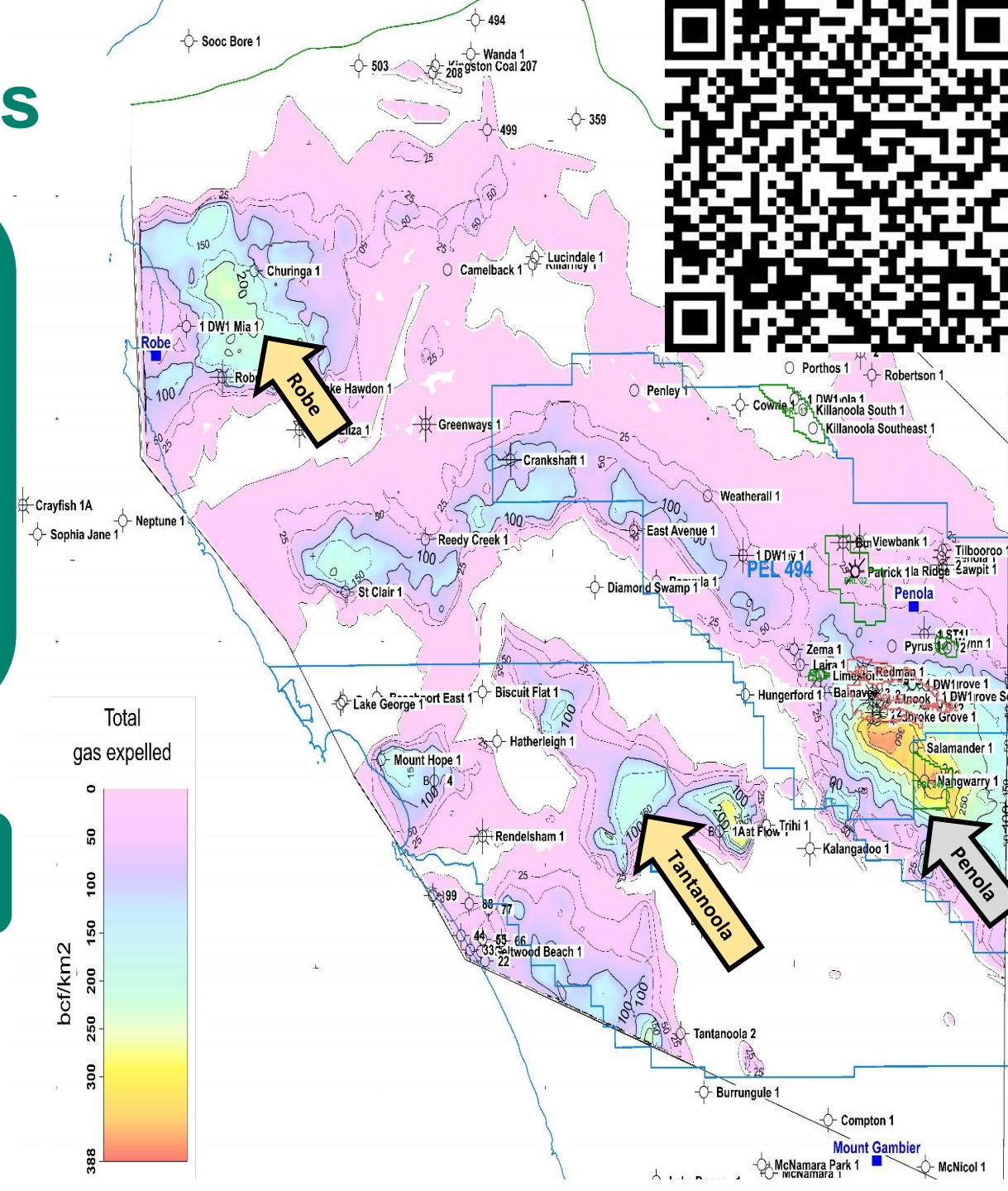
Nominations sought now for a future acreage release for:

- Petroleum Exploration Licences
- Regulated Substances Exploration Licences
- Gas Storage Exploration Licences
- Geothermal Exploration Licences

Contact DEM to nominate



Government of South Australia
Department for Energy and Mining



Thanks!

Seismic Team

- Iain Campbell
- Tim Rady
- Rob Kirk

Wells Team

- Betina Bendall

Core Team

- Chris Cubitt
- Paul Strong
- Sharon Tiainen
- Dave Groom & Dale Groom (and the entire Tonsley core team)

PSM Team

- Casey Edwards & Tony Hill

GDE Mapping Team

- Chris Cubitt
- Tim Rady
- Rob Kirk
- Sharon Tiainen

Play Mapping

- Paul Strong

GIS Team

- Steven Curnow

- Jess Bonsell

Photography/DB Team

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- Steven Curnow
- Carmine Grasso

Data Delivery Team

- Jess Bonsell
- Steve Fabjancic



Contacts

Chris Cubitt and Paul Strong

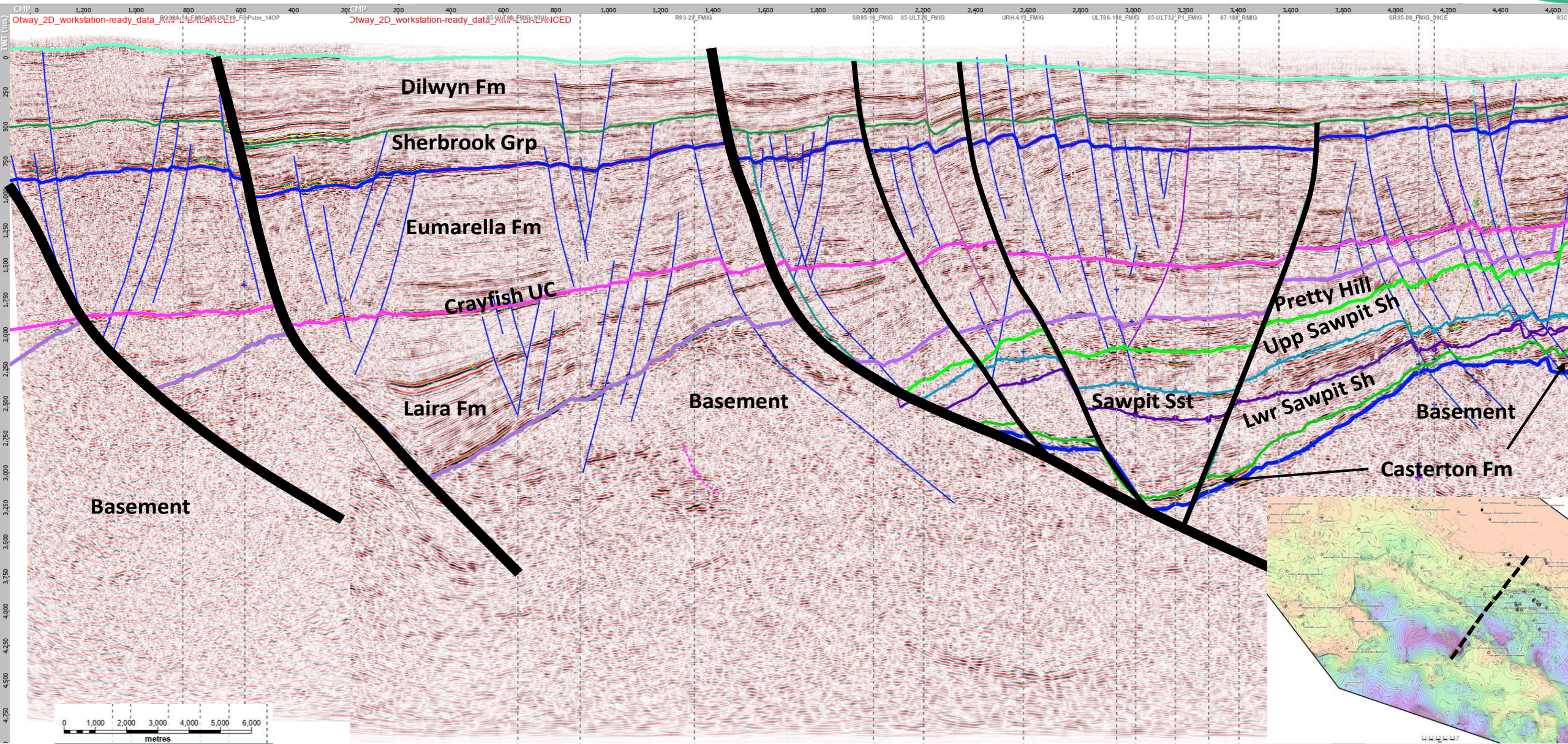
**Basin Prospectivity Team, GSSA
Department for Energy and Mining**

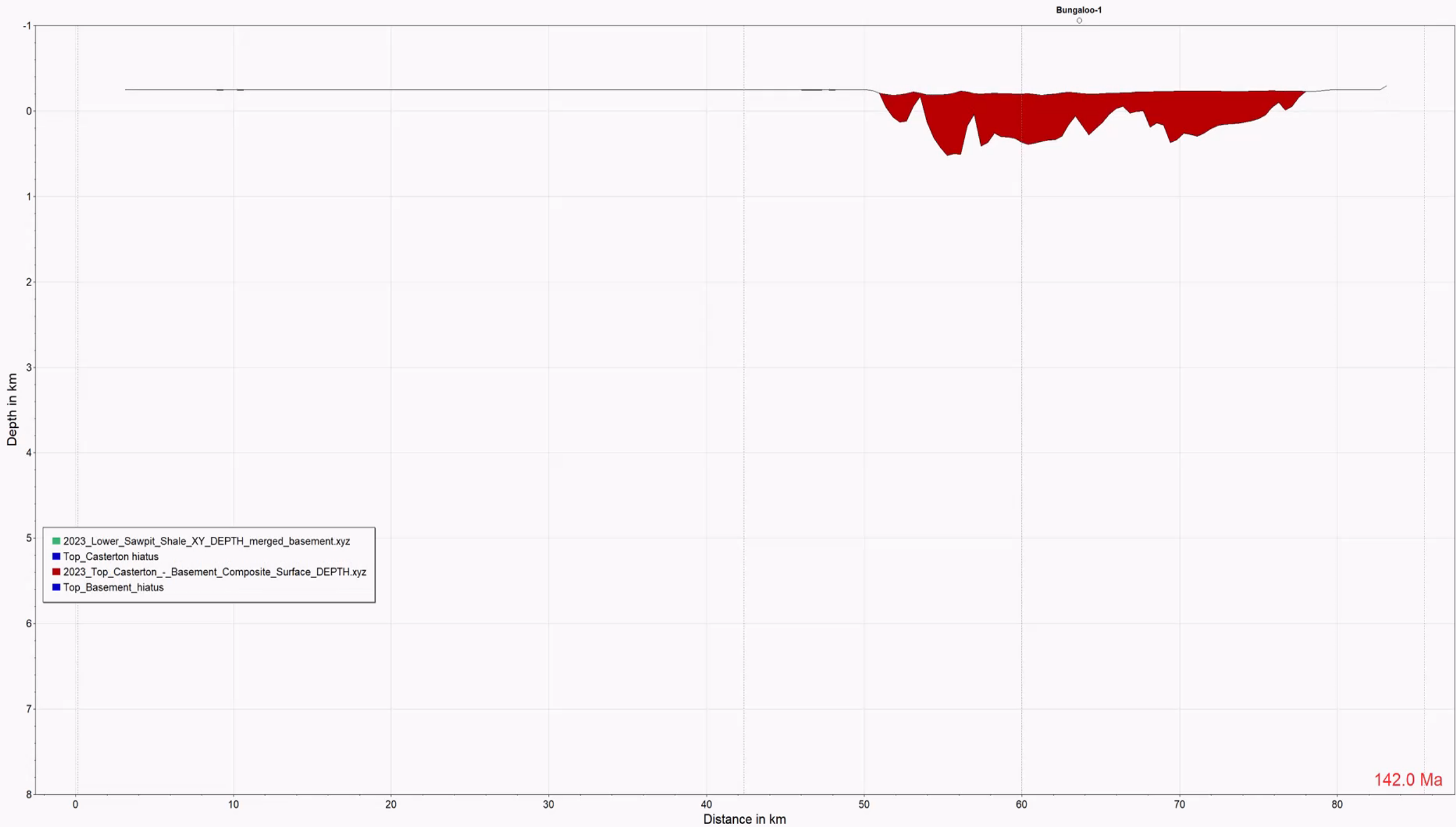
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The Onshore Otway's Troughs: Penola and Tantanoola





Bungalow-1

Depth in km

Distance in km

- 2023_Lower_Sawpit_Shale_XY_DEPTH_merged_basement.xyz
- Top_Casterton hiatus
- 2023_Top_Casterton_-_Basement_Composite_Surface_DEPTH.xyz
- Top_Basement hiatus

142.0 Ma

Core: Reservoir and Source Rocks

~770m of core from 23 wells across the basin in all intervals

Conventional reservoir rocks are deposited in fluvial channel fairways

- Good quality source rocks are deposited in deep rift lakes (algal)
- Moderate quality source rocks were deposited on flood plains associated with fluvial channel fairways

