Landscape and basin evolution modelling elucidates sediment supply and accommodation relationships in the Cretaceous Crayfish Sub-group of the Otway Basin

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SUMMARY

In the Otway Basin, the early Cretaceous Crayfish Sub-group infills syn-rift half grabens and has produced petroleum and commercial volumes of CO_2. Naturally occurring Hydrogen has also been recorded in historic exploration wells. Previous work focusing on the depositional environment and tectonostratigraphic evolution within the depocenters indicates that variations in accommodation and sediment supply strongly influences the stratigraphic architecture of the Crayfish Sub-group. To evaluate this influence, we use a landscape and basin evolution numerical model (Badlands). First, we generate a series of simulations with varied tectonic, climate and erodibility parameters using a design of experiments method. From these, we select scenarios with a correspondence between the modelled and observed stratigraphy of the Crayfish Sub-group at specified well locations. We then propose that the observed stratigraphy of the Otway Basin Crayfish Sub-group can be explained by sediment supply variations caused by the evolution of the surrounding landscape across four phases which are: Phase 1: Limited sediment supply as the drainage systems start to develop in response to the rift formation. Phase 2: Sediment supply peaks as high erosion in the steep rift escarpment proximal to the depocenters increases sediment volumes delivered to the depocenters. Phase 3: Relatively high sediment supply continues thanks to an efficient connection between upstream region and the depocenter. Phase 4: Differential sediment supply controlled by a distal and a proximal source. Sediment from the distal escarpment is supplied at a constant rate and buffered within the landscape, while proximal, high sediment supply pulses are generated when the proximal rift escarpments steepen.
By extending and quantifying existing conceptual models that link stratigraphy to sediment supply and accommodation, this work demonstrates how source-to-sink models enhance our understanding of the complex stratigraphy taking place within rift systems.

Key words: Landscape evolution, source-to-sink model, sediment supply, stratigraphy.

INTRODUCTION

The earliest stages of the Otway Basin are represented by the Late Jurassic to Early Cretaceous Casterton formation and Crayfish Subgroup. These fluvio-lacustrine sediments were deposited in half grabens (Duddy, 2003; Perincek & Cockshell, 1995) as part of the southern rift system formed by the breakup of the Gondwana supercontinent (Willcox & Stagg, 1990).

Here we use Badlands, a source-to-sink landscape evolution model (Salles et al., 2018; Salles & Hardiman, 2016), to simulate erosion, transport and deposition within the earliest stages of the formation of the Otway Basin. The Crayfish subgroup, fluvio-lacustrine sequences contain a working petroleum system, with gas discoveries and production part of the Sawpit formation (Camac & Boult, 2008; Eid et al., 2021). Calibration is performed using a design of experiments method that tights up model predictions to observed stratigraphy from well datasets.

BADLANDS MODEL DESIGN CONSTRUCTION AND SELECTION

Crayfish Subgroup stratigraphy

The Crayfish Subgroup, from oldest to youngest, consists of the Sawpit Formation, Pretty Hill Formation and the Laira Formation as well as the Katnook and Windemere Sandstone Members within and overlying the Laira Formation and the McEachern Member of the Sawpit Formation (Eid et al., 2021). The lithology over this sequence varies between claystones, siltstones and sandstones. The Casterton Formation is an organic rich claystone with occasional basaltic flows (Eid et al., 2021; Mitchell et al., 1997). The Sawpit Formation consists of siltstones and sandstones, often with a thick sandstone layer. The Pretty Hill formation consists of siltstone, with significant sandstone interbeds and the Laira Formation is predominantly a siltstone with thin sands.

Initial Topography

While the initial topography during the early stages of the rifting process is unknown, some initial assumptions can be made from the available dataset. The Palaeozoic basement rocks were accreted to eastern Australia in a series of orogens oriented approximately North-South. The pre-existing topography was assumed to be influenced by these Palaeozoic rocks and an initial undulating surface, biased towards elongated North-South features, was generated by randomly assigning a range of point values to a grid which was then heavily smoothed (using a gaussian method with a trend in this direction).

Tectonic forcing

Existing horizons, maps and studies of the Otway Basin (Finlayson et al., 1994; Romine et al., 2020) were merged to generate a basement to top Crayfish Subgroup isopach map. Contours of the isopach were hand drawn and a new, amalgamated surface was generated from those contours. As a result, the tectonic signal represents a smoothed, lower complexity surface designed to reduce the potential for anomalous results.

Compaction

Compaction is a continuous process taking place during deposition (Athy, 1930). Badlands accounts for it using Athy's porosity loss equation. A sonic porosity was calculated for 3 wells with significant Crayfish Subgroup intersections by varying both the coefficient and exponent values used by Athy's equation until the obtention of a satisfactory match between predicted and observed depth-dependent porosity decrease.

Landscape factors

Badlands uses a detachment-limited equation to model landscape erosion (Eq. 1). Here, $\dot{\epsilon}$ is the erosion rate, κ_d is a dimensionless coefficient describing erodibility of the channel floor, P is precipitation, A is the area of the upstream catchment, S is the local slope, m is an exponent modifying the effect of the upstream catchment water supply from precipitation, n is an exponent modifying the effect of slope. The ratio of m to n has been determined to be approximately 0.5 (Salles et al., 2018) however this ratio has some dependency on the resolution the model.

$$\dot{\epsilon} = \kappa_d P^l (PA)^m S^n \qquad \text{(Eq. 1)}$$

A and S are determined by the properties of the landscape at each step. By varying precipitation, the erosion coefficient (κ_d) and the m and n exponents, a series of simulations are run and predicted evolution and stratigraphy compared to observations. Here we used a Design of Experiments python utility (DoEgen https://github.com/sebhaan/DoEgen), combined with a Badlands specific implementation of DoEgen (Badlands DoE toolset) to build, calibrate and evaluate our set of experiments.
This approach enables an efficient evaluation of the parameter space of the model variables. Configurations for 210 Badlands models were generated and run using the Badlands DoE toolset utility. The variables for the final experiment design are shown in Table 1.

Parameter name	*Parameter type*	*Level numbers*	*Minimum*	*Maximum*	*Categorical data*
Precipitation (m/year)	Continuous	3	1.5	2.5	
κ_d	Continuous	5	2.72E-06	6.36E-06	
n	Continuous	3	0.9	1.1	
m/n ratio	Continuous	4	0.275	0.425	
Fillmax(m)	Continuous	3	175	225	
Tectonic scenario	Categorical	2			scenario1.xml, scenartio2.xml

Table 1: Parameters design used in DoE multi-experiment configurations.

Selection of a calibrated model

The methods used to calculate surface changes in landscape modelling do not produce explicit information about lithology, additionally, any information about depositional environment can only be inferred by the relative position of surfaces and parameters included in the model such as sea level or other water level proxies. While the available well data primarily measures the physical properties and geometries of the rocks. Badlands uses the Planchon & Darboux depression filling method (Planchon & Darboux, 2002) to account for depressions when propagating surfaces changes across a terrestrial landscape, this is shown in Figure 3. A maximum filling depth limit is set for depressions in a landscape. Within those depressions surface changes that reach the edge are diffused from their entry point. Outside of these depressions, the fluvial detachment and diffusion equations are used to modify the surface. The extent and depth of these depressions across the landscape are part of Badlands outputs. As it is affected by proximal and distal changes to the surface, this “lake depth” attribute can be used as to evaluate relative accommodation variations for the experiments. The change in this attribute will combine the results of fill by sediment supply and subsidence from the forced tectonics applied.

Four wells from the Penola Trough were compared to the 210 experiments to determine which experiments most closely matched the observed data. This was done by extracting the lake level attribute from the final volumetric model at each of the 4 well locations as shown by the red line in Figure 1. The gamma ray log, in this case, represents a good first order approximation of lithology and is strongly affected by variation in sediment supply and accommodation (Martinius et al., 2014; Catuneau, 2006) . Similarly, lake level from the Badlands experiments is affected by sediment supply and accommodation variations. If the measured and experimental attributes show some concordance this should indicate how well calibrated an experiment is. The similarity of the gamma log and lake level attribute were ranked automatically using a discrete frechet distance method (Danziger, 2022) then plotted against each other for visual confirmation and to determine the best matching experiment, Figure 2.

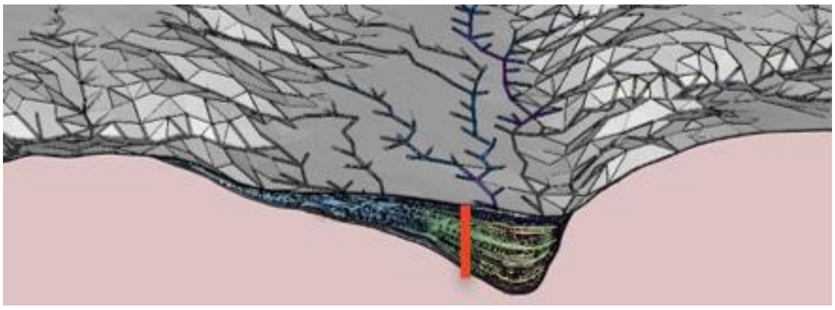

Figure 1: Example section through volumetric Badlands model with well data extraction shown in red.

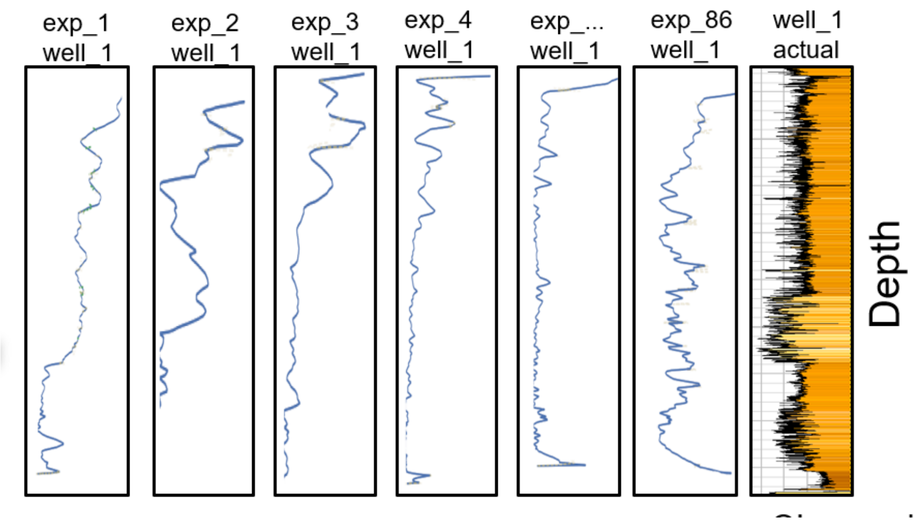

Figure 2: Comparison between lake level extracted from multiple experiments against gamma log at well location.

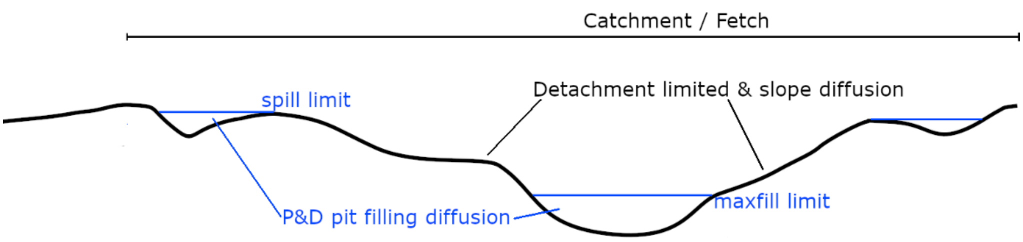

Figure 3: Schematic describing operation of detachment limited and pit-filling equations in Badlands.

RESULTS

A single model was chosen based on the calculated and observed similarity of the model stratigraphy to evaluate in detail. Experiment 86 showed the most similarities with observed well logs, depositional environment and stratigraphy. We used the model produced from this experiment to analyse the evolution of the early rift landscape and resulting stratigraphy.

Phase 1:
Rifting is initiated by imposing tectonic subsidence after 5 Myr of simulation. Pre-existing drainage systems begin to be cannibalised; yet connection of the upstream catchments to the depocenter is reliant on the pathways established by those pre-existing drainage systems. This is demonstrated at 8 Myr in Figure 5, where a large system is not yet connected to the depocenter. Erosion on the slope formed by the forced subsidence is relatively low while the catchment develops, and the slope is poorly connected to the upstream catchment. While we note an initially low sediment supply regime, it increases during this phase as the different upstream catchments become better connected to the rift depocenters.

Phase2:
At the end of phase 1, all pre-existing catchments that intersected the new depocenters have been cannibalised (Figure 6, 15 Myr). Between 9 and 14.5 Myr, the excess accommodation is filled (green shading in Figure 6). Steep slopes coinciding with well-connected catchments result in a high sediment supply, however this is offset by the excess available accommodation.

Phase 3:
Excess accommodation from the earliest phase has been filled prior to 14.5 Myr. Between 14.5 and 18 Myr into the experiment, the steepest slopes along the erosional escarpment are relatively close to the rift depocenters. High erosion and an efficient connection to the depocenter indicates that during this stage, sediment supply was relatively high.

Phase 4:
As the erosional escarpment migrates towards the catchments drainage divides, slopes decrease as well as the erosive power of the different streams connecting the upstream regions to the different depocenters. As a result, sediment supply decreases. In addition, the sediment supply is buffered within the landscape. Towards the end of this stage a more distributed escarpment begins to develop close to the depocenter. The low slopes, some of which are distal to the depocenter, coupled with a low water discharge, result in a relatively low but constant sediment supply. The buffers within the landscape are shown in purple shading in Figure 6 and in the pale blue deposits at 21.5 Myr in Figure 5.

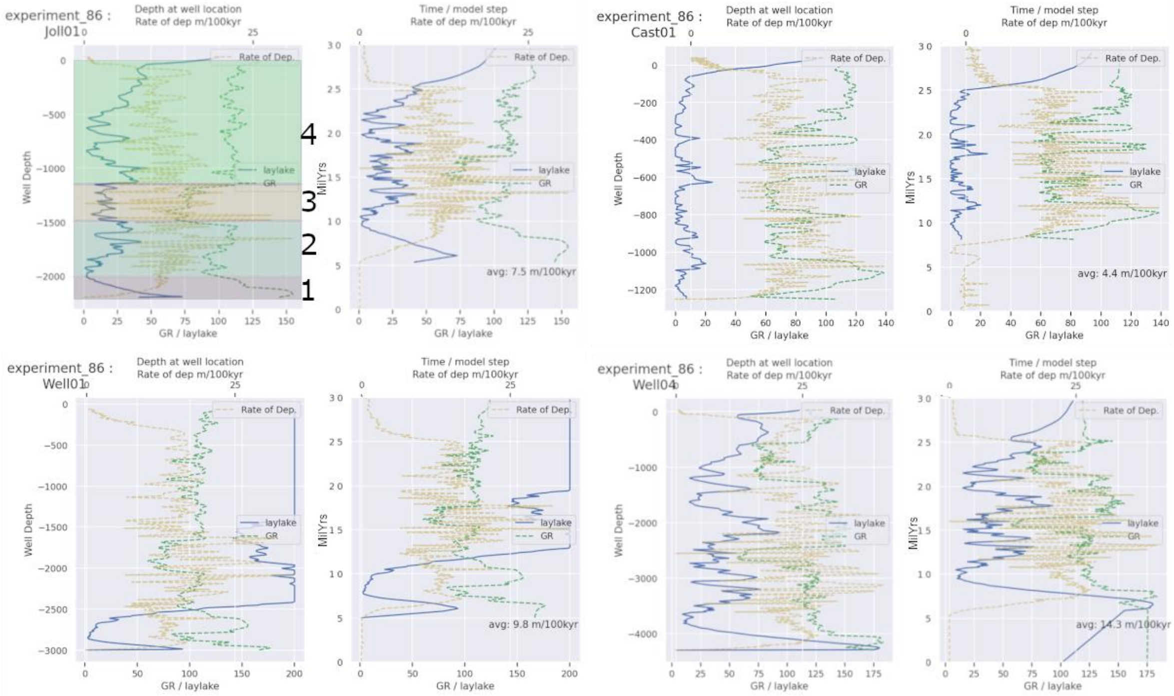

Figure 4: Lake level and gamma ray log plots at each of the 4 wells from the selected experiment. the Joll01 well shows the model phases based on the variations in lake level, sediment supply and landscape evolution.

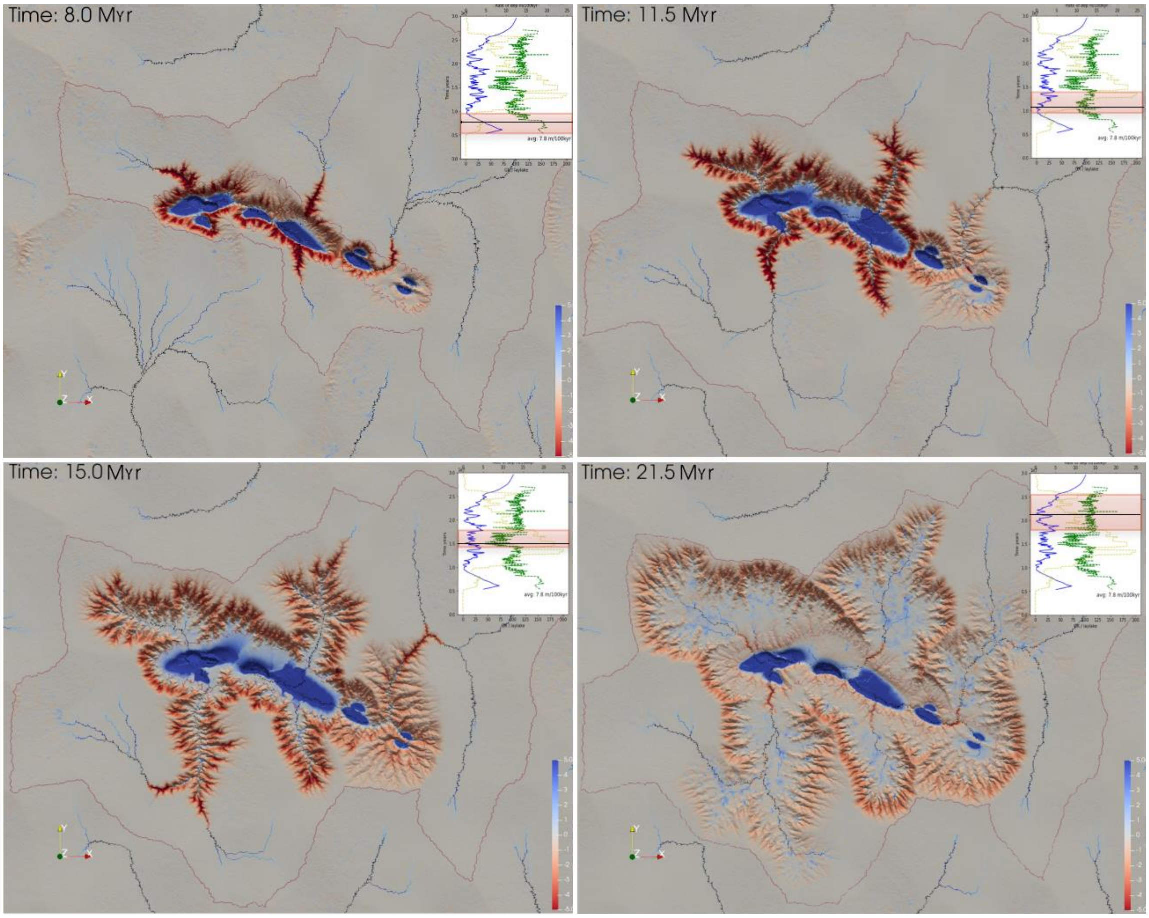

Figure 5: Topographic surface examples during each phase. Erosion (red) and deposition (blue) over a 100,000 year time step. Insets are lake level and gamma log plotted against time of deposition with the corresponding time highlighted in red.

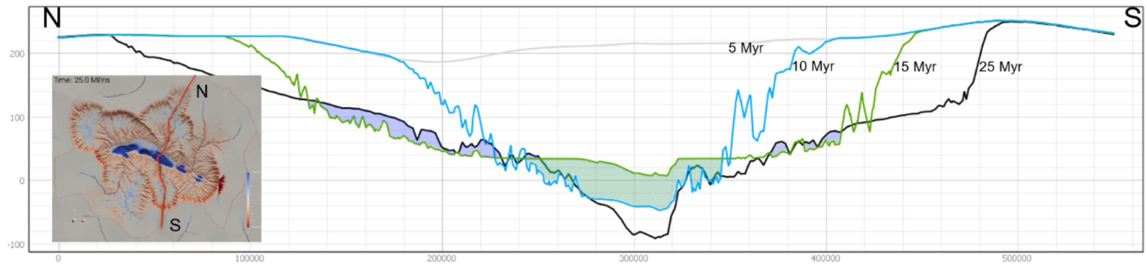

Figure 6: Section through topography at 5, 10, 15 and 25 million years of model run time. The green shading shows accommodation generated in phase 1 and filled in phase 2. Purple shade shows landscape storage (buffering) of sediment in stage 4.

CONCLUSIONS

The landscape phases correlate well to the fluvio-lacustrine stratigraphy of the Crayfish Subgroup as proposed by Eid et al. (2021). Conceptual models such as those by Leeder & Gawthorpe (1987) recognise that sediment supply and accommodation variation both play a large part in the depositional environment and resulting lithology, here landscape models provide a quantitative method to test those concepts. While only a single model was evaluated in detail here, 210 models, generated as part of the Design of Experiments workflow can be examined for additional insights into the evolution of the stratigraphy and landscape dynamics.

Sediment supply variations in the Otway Basin during the early rifting phases are strongly linked to the erosion and transport in the region proximal to the rift depocenter. While subsidence due to tectonics drives this process, sediment aggradation rates are more closely linked to the evolution of the surrounding landscape.

Linking sequence stratigraphic accommodation and sediment supply relationships to a source-to-sink sediment supply model provides insights into the permeability and porosity architecture that may host resources in basins.

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