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Gippsland Basin 3D forward modelling in Badlands

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SUMMARY

The Gippsland basin geological history is modelled using the Badlands software constrained by a realistic 3D structural and stratigraphic model built in Petrel. The aim is to assess and calibrate the theoretical tectonic and sedimentary models using empirical data for a rift basin. The theoretical models are used to assess and measure the relative effect of significant variables for sedimentary basins, including climate, extension, subsidence, uplift, erosion and sedimentation.

The modelling results indicate several insights for the Gippsland Basin. The initial paleo-topography at ~145 Ma was an extensive highland area. The Early Cretaceous paleo-environment was intracratonic, with sediment transport from east to west, and at some stage included an inland sea. The Mid Cretaceous uplift caused emergence of the entire basin, substantial regional erosion and changed the basin architecture. Subsidence associated with Tasman Sea rifting formed the Central Deep and flipped the fluvial paleo-drainage system towards the east. Latrobe Group sediments filled the basin being progressively transgressed by rising sea level to flood most areas by the Oligocene. The models simulate the progradation of the carbonate shelf sediments, sub-marine channels and anticlines over the basin since then.

Key words: Gippsland Basin, Badlands, 3D basin modelling, palaeotopography, basin evolution.

INTRODUCTION

The Gippsland Basin is located in South-Eastern Australia (Figure 1) and contains an Early Cretaceous to Recent section that records a good example of a young rift basin developed on a divergent margin (Figure 2). Two rifting events occur, the first along an east-west axis in the Early Cretaceous associated with Australia-Antarctica breakup, the second along a NNE-SSW axis associated with the Late Cretaceous Tasman Sea breakup. The basin is a prolific petroleum and coal basin with extensive geological datasets including 3D and 2D seismic, many onshore and offshore wells with logs, analytical and biostratigraphic data, gravity and aeromagnetic data.

A full suite of 3D theoretical forward scenario models of the onshore and offshore Gippsland Basin are being used to recreate the basin history from the Early Cretaceous to Recent using the Basin and Landscape Dynamics software (Badlands, 2019). The models are calibrated to a corresponding full 3D realistic structural, stratigraphic and property model of the basin built in Petrel (Schlumberger software) that is used to constrain the sedimentary, stratigraphic, burial and thermal histories.

The Badlands forward modelling allows rapid recreation of various sedimentary and structural scenarios of the paleo-environments that occur with subsidence and extension over the geological history of the Gippsland basin. Hence, it allows testing and improvement of existing theoretical tectonic and sedimentary models, especially for rift basins, by calibration to actual seismic, well and outcrop data. The results are being used to better understand many aspects of the geology in the Gippsland Basin and improve prediction of the occurrence and distribution of sediments, petroleum, coal and water resources.

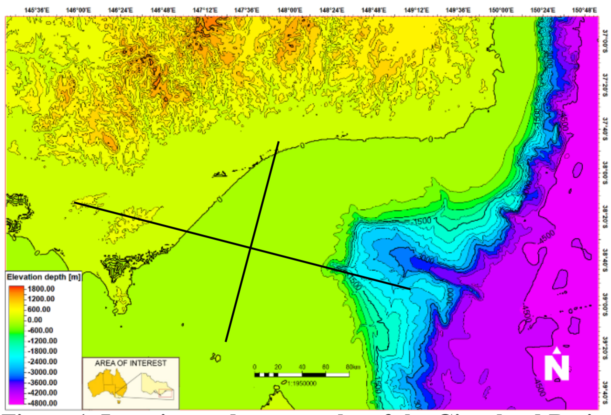

Figure 1. Location and topography of the Gippsland Basin (derived from Geoscience Australia onshore topography and offshore bathymetry digital data gridded at 1 km).

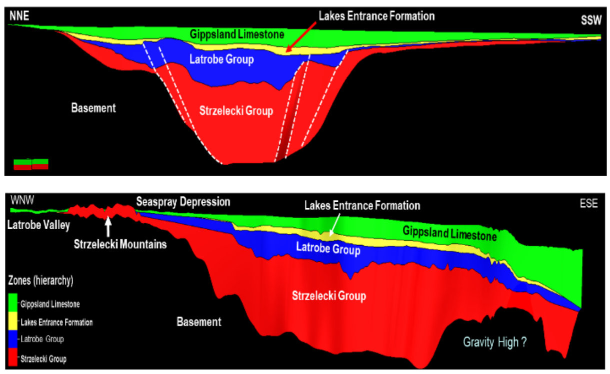

Figure 2. Simplified structural sections through the 3D realistic model of the Gippsland Basin showing high level stratigraphic zones (location of sections shown in Figure 1).

METHOD

The forward modelling in Badlands requires a large number of inputs. The Docker container and Python scripts are used to direct inputs and construct selected scenario mixes, based on an

Experimental Design. This minimises the number of necessary scenarios from many thousands possible with the large number of variables, while ensuring that the full multi-dimensional space is statistically populated, and that all of the main effects and interactions are tested (Collinson et al., 2008). The main variables and some of the criteria are given in Table 1.

The input maps are generated from the 3D realistic Petrel model. This model is based on seismic interpretation of all the open file 3D and 2D seismic surveys and correlation of over 250 offshore wells and more than 1000 onshore wells or bores. The interpreted seismic surfaces and well data are used to create thickness maps between the main horizons (e.g. topography, mid Miocene, top Latrobe Group, base Tertiary, top Strzelecki Group, top Basement). Additional maps are being added as the modelling progresses to better constrain the palaeotopography.

The thickness maps are input as burial displacement maps to simulate subsidence history. These burial thickness maps can be decompacted in Petrel before input using the lithological components but then they have to be compacted in Badlands. This adds another uncertainty in the modelling that analysis indicates is just a scaling factor and not highly significant.

The Badlands model results are visualized in ParaView, or imported back into Petrel, to compare with the original realistic model surfaces. The model simulation runs covering 145Ma to 0Ma are difficult to show in a paper especially since the large number of scenarios and ranges for each variable result in many outcomes at each time step. Only a few examples for the Reference Case scenario are shown here as 2D maps, noting that this scenario is not necessarily a mid-case.

Model Variable	Input Data
Age	Time Steps in Ma
Sea Level	Sea Level Curve (Haq)
Topography	Initial Map
Subsidence/ Uplift/Extension	Displacement Maps/Lateral Grid
Rainfall	Topographic Control or Constant
Sediment Flux	River Diffusion Co-efficient
	Aerial Diffusion Co-efficient
	Marine Diffusion Co-efficient
Sediment Erosion and Deposition	Slope Critical Point
	Max Basin Fill
	Erodibility Map
	Steps to Distribute Marine Deposits
	% Marine Deposition on Current Node
	% Onshore Deposition on Current Node
Submarine Canyons	Sediment Density
	Deep Basin Critical Depth
Carbonate Deposition	Pelagic Growth

Table 1. Main variables and inputs used in Badlands.

RESULTS

Initial Topography

One of the main challenges in simulating subsidence, extension and sedimentation is to match the subsidence with the sediment budget to obtain a correct balance. This is particularly difficult when there are so many variables controlling the sedimentation such as climate, rainfall, initial topography, stream grade, erodibility, facies, sea level and subsidence. Typical values for many of these variables are known from landscape studies. These default values can be used as a starting reference case but here they have been adapted for the Gippsland Basin using a range (low to high).

The initial topography, however, cannot be estimated from the current topography but has to be found by running a range of cases to match the required sediment budget in the Early Cretaceous. The modelling indicates that highland areas to the north, east and south of the basin are necessary to source the Early Cretaceous sediments (Figure 3). This is consistent with Edwards and Baker (1943), who indicated that coarser sediments flanked both the northern and southern margins of the east-west trough in the Wonthaggi coalfield, with mudstones and coals occurring along the east-west axis.

The volcanolithic nature of the Strzelecki Group (and Otway Group equivalents) indicates derivation from the Palaeozoic basement rocks in the adjacent highlands, and from contemporaneous Jurassic to Early Cretaceous volcanics, that occur to the south in Tasmania and the north in western Victoria. Veevers (1982) also suggested derivation from the andesitic arc to the east which requires a palaeoslope from east to west that switched after the mid Cretaceous (Smith, 1982). The modelling indicates that these highland areas needed to be mountainous and or that sediments were probably being transported a long distance from outside the Gippsland Basin.

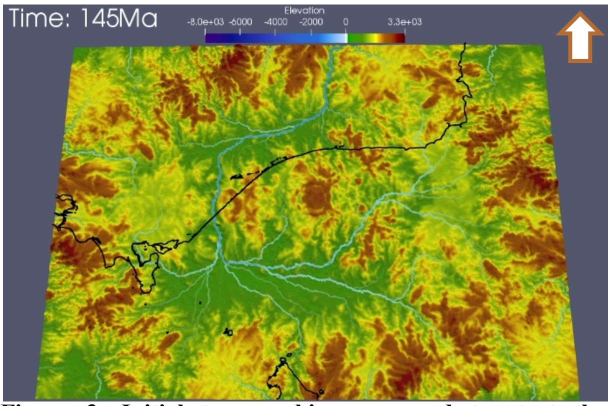

Figure 3. Initial topographic map used to start the simulations of the Gippsland Basin, showing the entire region is mountainous. Black line shows present coastline and red arrow points North.

Starting the simulations using a topographic map with mountains in the north and west only, similar to the present day topography, quickly produces deep open marine palaeoenvironments in offshore Gippsland, which does not fit the onshore or offshore well data (Figure 4). Gippsland is not expected to become open marine earlier than 90Ma with the start of the Tasman Sea rifting (Willcox et al., 1992; Norvick, 2005).

In contrast, model runs with mountains to the north, south and east provide enough sediment input to balance the sediment budget in Gippsland during the first syn-rift event. East-west orientated rift basins are produced by about 125Ma, with associated inland drainage and shallow lakes of varying sizes, from small to large, dependent on the scenario run (Figure 5).

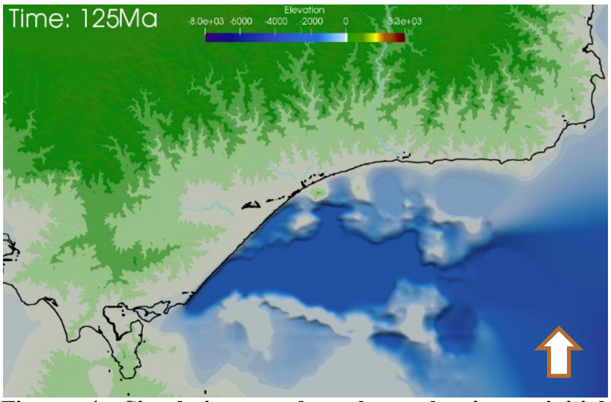

Figure 4. Simulation results where the input initial topographic map only has mountains to the north and east. Black line shows present coastline.

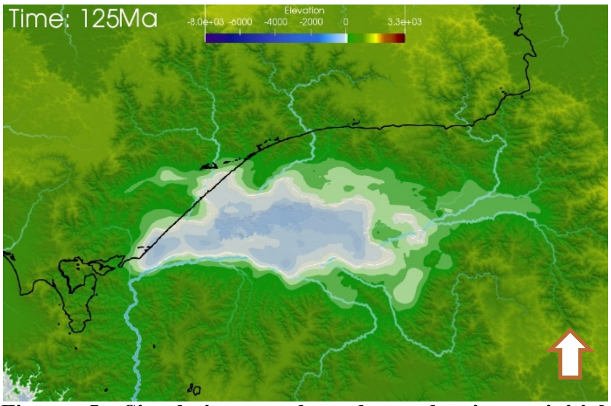

Figure 5. Simulation results where the input initial topographic map has highlands all around the Strzelecki basin (Figure 3). Black line shows present coastline.

Strzelecki Group Rift Phase

The approximately east-west rifting between Australia and Antarctica, which began in the latest Jurassic to Early Cretaceous, resulted in deposition of the Stzelecki Group in the Gippsland Basin and the Otway Group in the adjacent Otway and Bass basins (Smith, 1982; Duddy and Green, 1992; Willcox et al., 1992, 2001; Norvick, 2005). The Strzelecki Group spans the *D. speciosus* to *T. pannosus* spore-pollen zone (Berriasian to Albian) although the oldest samples are thought to be Hauterivian (A. Partridge, pers. comm.). The Strzelecki Group is entirely non-marine making it difficult to differentiate in contrast to the Otway Group. It comprises fining up megasequences of lower conglomeratic fan units (Tyers Conglomerate), overlain by sandy arkose and litharenite sections (Rintouls Creek Sandstone) that pass into braided muddy channels and overbank mudstones with thin discontinuous coals in the Wonthaggi Formation (Constantine, 2001; Holdgate, 2003).

The model simulations of this first north-south extensional synrift phase were started from 145 Ma. The topographic gradients produce mostly erosion of the upland areas, with only minor sedimentation preserved until ca. 137 Ma, when the rivers stabilise and small lakes develop in the basin. The floodplain and associated lakes gradually expand to produce an east-west trending basin including an inland sea by ca. 108~98 Ma (Figure 6). The lack of correlateable stratigraphic control makes it difficult to constrain the precise extent of the fluvial environments and the inland sea for each time step in the current simulations. Nevertheless, the overall transport direction from east to west is consistent with known palaeocurrent data from the Wonthaggi and Eumeralla formations (Constantine, 2001). The development of an inland sea is also consistent with paleontological evidence including the fish beds, pleiosaur fossils, dental and postcranial remains, found from Early Cretaceous inland freshwater lakes within the Wonthaggi and Eumeralla formations, in both the Gippsland and Otway basins (Kear, 2006). Adult Pleiosaurians vary in length from 1.5 metres to about 15 metres (Tarlo, 1959) confirming these were at times large and reasonably deep inland seas.

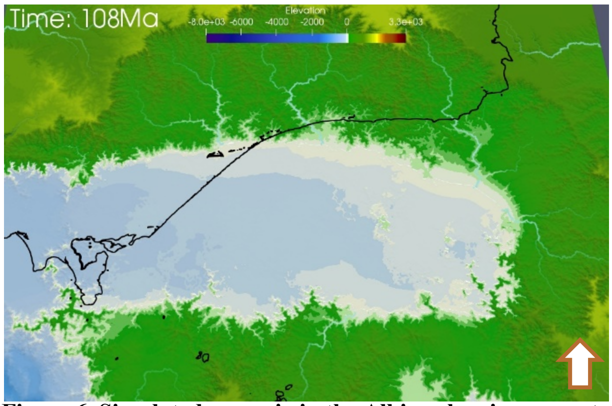

Figure 6. Simulated scenario in the Albian showing an east-west inland basin with a fluvial system surrounding an inland sea. Black line shows present coastline.

Mid Cretaceous Uplift

A regional uplift occurred in the Gippsland and eastern Otway area from 100-90Ma (Duddy and Green, 1992) associated with basaltic intrusives (Older Volcanics). This major tectonic event in SE Australia is associated with cessation of rifting in the Otway Basin, prior to initiation of sea floor spreading between Australia and Antarctica, with transfer of rifting into the Gippsland Basin associated with Tasman Sea formation.

An uplift map for the 100-90 Ma period was input to Badlands and produces rapid re-emergence of the basin in the simulations from ca. 97 to 91 Ma. The simulations are consistent overall with the stratigraphic record in Gippsland which records a significant unconformity between the Strzelecki and Latrobe groups, with missing section of 1-2km and more in some areas (Holdgate et al., 2015). The inland sea gradually vanishes with widespread erosion and development of fluvial systems as the dominant sedimentary facies. The main palaeodrainage direction flips to head south-east towards the offshore Gippsland area (Figure 7).

The basin has re-emerged entirely except perhaps for parts of the Central Deep where low-lying fluvial and lacustrine environments are possible. The low lying parts of the basin retain the NE-SW orientation of the uplifted Strzelecki Mountains indicating inversion of the original faults. Notably, the continual uplift is able to remove large thicknesses of Strzelecki Group sediments, without needing to attain great height and the rift valley remains considerably below the original palaeotopography.

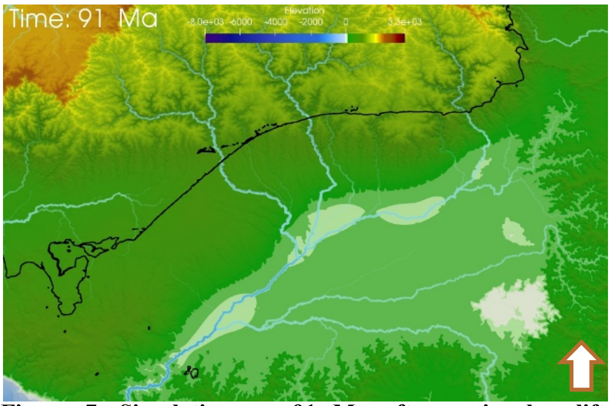

Figure 7. Simulation ca. 91 Ma after regional uplift beginning at 100 Ma, showing re-emergence of the basin. Black line shows present coastline.

Tasman Sea Rift Phase

The second rifting event associated with the Tasman Sea opening produced a short synrift phase characterised by extensional faulting, that was confined mostly to the offshore Gippsland basin, which essentially became a failed arm of the Tasman Sea rift (Smith, 1982). The Badlands simulations initiate this spreading event from ca. 90 Ma (Figure 8), which is slightly earlier than assumptions based on gravity data (Gaina et al., 1998). The fluvial drainage system has changed in direction clearly by now going from west to east. Detailed examination of the simulations show that erosion continues to remove most sedimentation throughout onshore Gippsland, including in the Latrobe Valley, and over the north and south platform offshore areas, which matches the stratigraphic record. Emperor Group sediments began to accumulate in the Central Deep including fluvio-deltaic sediments and probably organic rich shallow lacustrine sediments (Kipper Shale). These possibly passed into restricted shallow marine sediments further east.

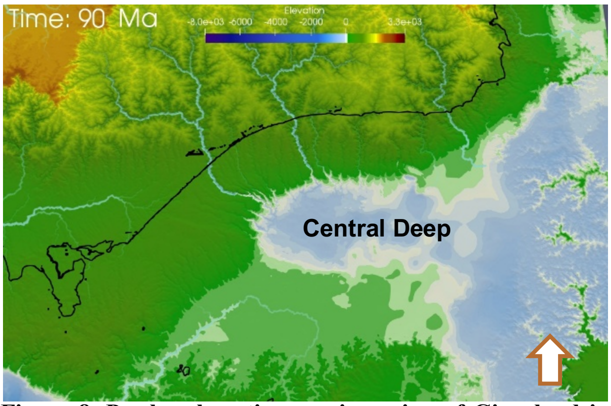

Figure 8. Pre-breakup time, main region of Gippsland is onshore, inland lake appears again, sedimentary transport direction tilted to west-east trend. Black line shows present coastline.

The Golden Beach Formation is recorded in the offshore Central Deep area from Santonian to Campanian. The simulations around 85~82 Ma show deposition of fluvio-deltaic sediments in the Central Deep passing into shallow marine sediments (Anenome Formation) with transgression towards the west, consistent with localised ocean floor spreading initiating in the south Tasman Sea.

Tasman Sea Post Rift Phase

Oceanic spreading had moved north in the Tasman Sea to Gippsland by 80Ma (Campanian) producing minor unconformities in the Central Deep and basalts (Kipper Volcanics). The extensional growth faulting diminishes along with subsidence rates in this phase. The Badlands simulations from 81~70 Ma show significant regression with deposition of fluvial and deltaic sediments west of thin marine sediments, succeeded between 70~50 Ma by aggradation with gradual transgression (Halibut Sub-Group).

After about 50 Ma, the simulations show more frequent transgressive-regressive cycles resulting from slower subsidence and the rapid rise and fall of sea level. The fluvio-deltaic and marine sediments are pushed back by the marine transgressive sediments during the Eocene to Oligocene, in a series of retrogradational steps across the offshore basin, with the development of the first submarine canyons (Cobia Sub-Group). However, in the current simulations the main transgressions westward into the Seaspray Depression are too early. This means the Badlands model needs finer calibration to model the rapid shoreline changes that occurred during this phase. This period also saw the first inversion of the faults by compression causing uplift which is not yet captured by the simulations due to lack of resolution.

Oligocene to Recent

The Gippsland Basin was flooded at ca.32 Ma moving the shoreline into the Seaspray Depression by 20 Ma. The paleo-topography of the near Top Latrobe simulation indicates a marine environment offshore not too dissimilar from the present day (Figure 9). The submarine canyon module in Badlands has produced a sub-marine canyon system, including detailed cut and backfill with rising sea level, though currently their location is not precise. Also, the paleo-water depths become too deep further offshore in the reference simulation. The Oligocene saw further compression and submarine anticline development which is shown by the simulations.

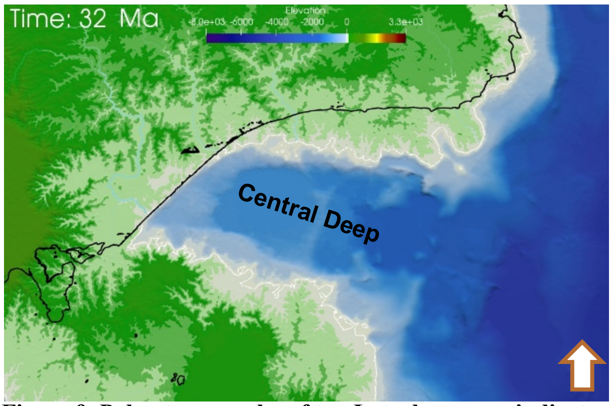

Figure 9. Paleo-topography of top Latrobe group, indicates submarine channels and anticlines. Black line shows present coastline.

The Gippsland offshore area started a phase of cold water carbonate deposition from the Oligocene onwards in addition to the clastic input. Recently the Badlands carbonate module was used to add a carbonate rain to the clastic dispersion from the land. This added complication has improved the fit of the Gippsland Limestone sedimentation to the realistic model to produce a reasonably close match of the present day coastline after 145 Ma of simulation (Figure 10).

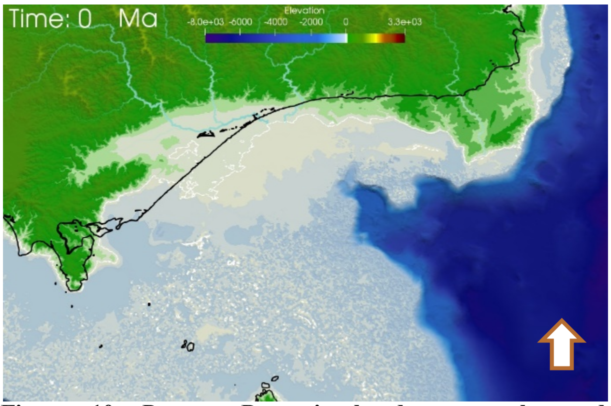

Figure 10. Present Day simulated topography and bathymetry after 145 Ma of simulation. White line is simulated zero contour. Black line is present coastline.

CONCLUSIONS

The Badlands landscape simulation program is proving useful for investigating the geological history of the Gippsland Basin. The theoretical simulations are much better when constrained by actual data from a realistic 3D model of the basin.

The simulations indicate that the paleotopography at the start of the Early Cretaceous (~145 Ma) requires a highland area over most of south-east Australia including to the east. The rift subsidence required to accommodate the Strezelecki Group resulted in development of a valley system, in which fluvial sediment was eroded from the adjacent highlands, and moved along the valley system from east to west. Continued erosion eventually reduced the highlands to produce an east-west rift valley with the development of an inland sea or seas.

The simulations show how the erosion accompanying the mid Cretaceous regional uplift gradually removed large amounts of sediment from the stratigraphic record across most of the basin. This was achieved without requiring restoration of the original topography to highland elevations.

The transfer of rift subsidence from the Otway/Strzelecki rifts to the Central Deep in the Gippsland Basin caused profound changes to the region. The drainage system flipped to head south-east to east. A second synrift sequence developed of non-marine coarse clastics, organic rich lacustrine shales, and possibly restricted marine shales. The post-rift sequences accumulated slower from 80Ma with deposition of fluvio-deltaic coal measures west of transgressive marine sediments that flooded the offshore basin by the Oligocene.

A thick shelf has developed since for which the Badlands carbonate module simulates the clastic and cold climate carbonate sediments and the channel module simulates the sub-marine canyon cut and fill systems. The development of the offshore anticlines is simulated using a series of isopachs.

The Badlands theoretical simulations are starting to match the realistic model and published paleogeographic maps (e.g. Norvick, 2005). They allow simulaton of a range of scenarios quickly to test various hypotheses. This includes testing factors such as subsidence, extension, uplift, sedimentation, sea level, erodibility, paleo-topography and paleo-environments. The accuracy and precision of the simulations is improved significantly by realistic calibration.

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REFERENCES

Badlands, 2019. A parallel TIN-based landscape evolution modelling software. Earthbyte Group, Sydney University. https://www.earthbyte.org/category/resources/software-workflows/badlands/

Collinson R., Gupta R., Smith G.C. and Van Elk J.F., 2008. Scenario Analysis Tool for Probabilistic Analysis of Reserves. SPE Asia Pacific Oil and Gas Conference and Exhibition; 2008 Society of Petroleum Engineers, SPE 116378.

Constantine, A. E. (2001). Sedimentology, stratigraphy and paleo-environment of the Late Jurassic–Early Cretaceous Strzelecki Group (Unpublished PhD thesis). School of Geosciences, Monash University, Victoria.

Duddy, I.R. and Green, P.F., 1992. Tectonic development of the Gippsland Basin and environs: identification of key episodes using apatite fission track analysis (AFTA).

Gaina, C., Müller, R.D., Roest, W.R. and Symonds, P., 1998. The opening of the Tasman Sea: a gravity anomaly animation. Earth interactions, 2(4), 1-23.

Holdgate, G. R., Wallace, M. W., & Forbes, S., 2015, Pre-Cenozoic geology of the Latrobe Valley Area—onshore Gippsland Basin, SE Australia: Australian Journal of Earth Sciences, 62(6), 695-716.

Jones, J.G. and Veevers, J.J., 1982. A Cainozoic history of Australia's southeast highlands. Journal of the Geological Society of Australia, 29(1-2), 1-12.

Kear, B.P., 2006. Plesiosaur remains from Cretaceous high-latitude non-marine deposits in southeastern Australia. Journal of Vertebrate Paleontology, 26(1), 196-199.

Norvick, M.S., 2005. Plate tectonic reconstructions of Australia’s southern margins. Geoscience Australia Record 07.

Smith, G. S., 1982. A review of the Tertiary–Cretaceous tectonic history of the Gippsland Basin and its control on coal measure sedimentation. Australian Coal Geology 4, 1–38.

Tarlo, L.B.H., 1959, Stretosaurus gen nov., a giant pliosaur from the Kimmeridge Clay: Palaeontology, 2 (2), 39–55.

Willcox, J.B., Colwell, J.B. and Constantine, A.E., 1992. New ideas on Gippsland Basin regional tectonics. Proc. Joint PESA/AIMM Gippsland Basin Symposium, 93-110.

Willcox, J.B., Sayers, J., Stagg, H.M.J. and Van De Beuque, S., 2001. Geological framework of the Lord Howe Rise and adjacent ocean basins. EABS, PESA, 211–225.