The greater McArthur Basin 3D modelling project: Updates, developments and steps towards the future

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3D models are designed to provide a structural and stratigraphic framework for an area of fundamental or economic interest. Models can synthesise available data and interpret geological architecture at depth. The Northern Territory Geological Survey (NTGS) initiated the 3D modelling project of the greater McArthur Basin in late 2013 (Bruna *et al* 2014, 2015). Products developed through this project are available in Digital Information Package 012 (Bruna and Dhu 2015); DIP 012 is updated and released publically on an annual basis. The model released in 2015 has been updated with new structural data from the poorly constrained Tijunna Group of the Birrindudu Basin. This phase of the modelling project aims to answer the following questions:

i. Is there a structural transition between shelf and basin in the Birrindudu Basin?
ii. Is the style of deformation in the Birrindudu Basin similar to the one observed in the McArthur Basin?

The structural data were modelled using the MOVE software, a program that allows multiple scenarios to be developed from a single set of data.

In late 2015, a high resolution model (HR model) was built for an area centred in the Beetaloo Sub-basin. Four surfaces were created in this 3D model, then transformed as a volume to be populated by reservoir properties acquired from a concurrent basin study (Revie 2016). Total Organic Carbon (TOC) and brittle mineral content extracted from x-ray diffraction (XRD) analyses were imported into the model as primary data. A complementary hyperspectral dataset from the HyLogger™ instrument was also integrated into the model as secondary data, expressed as vertical proportion curves (VPC). VPC give access to the relative proportion of all of the considered facies in each cell of the grid. The purpose of this integrated approach was to answer the following questions:

i. How to represent the variability of selected properties in a constrained 3D environment?
ii. How can geostatistic methods be used to identify the location of sweet-spots?
iii. What are the limitations and capabilities of such an approach in the greater McArthur Basin?

This work provided a detailed and accurate model designed for property testing. It was released by the NTGS during 2015 as DIP 012 (Bruna and Dhu 2015).

The most recent phase of the modelling project during 2015 investigated the geometry of selected Glyde package horizons. Several key units of this package are currently targeted by petroleum and mining explorers for their potential to host unconventional resources and lead-zinc deposits. The workflow followed this year was comparable to that followed earlier in 2015 for the Wilton package model (Bruna *et al* 2015; Bruna and Dhu 2015). The work addresses the following questions:

i. What is the geometry of the Glyde package at depth in the greater McArthur Basin?
ii. What is the geometry of the Glyde package before the deposition of younger packages?

Geophysical interpretation by Betts *et al* (2014) sequenced the movement of faults within the greater McArthur Basin during tectonic phases of the Meso- and Palaeoproterozoic period. A restoration of the fault movement to initial phase (null movement) will be targeted in further work.

Geological setting

The greater McArthur Basin is a huge Palaeo- to Mesoproterozoic series of stacked basins located in the northern half of the Northern Territory of Australia. It covers an area of 50 000 km². The basins have a cumulated thickness varying between 8 and 15 km of siliciclastic and carbonate rocks with subordinate occurrences of volcanic rocks. Five packages are defined in this basin separated by regional unconformities (Ahmad *et al* 2013). Two of them, the Mesoproterozoic Wilton package and the Palaeoproterozoic Glyde package represent the best potential to host unconventional hydrocarbon resources or economic mineralisation (Ahmad *et al* 2013, Munson 2014).

Economic targets in the greater McArthur Basin

The Wilton package is the shallowest package in the greater McArthur Basin. It contains mainly clastic sedimentary rocks separated by minor unconformities. Two horizons, the Velkerri Formation and the Kyalla Formation, are known to have greater potential to host unconventional hydrocarbon resources than other formations within the Wilton package (Munson 2014). This potential is also highlighted by the geochemical data collection conducted for the Wilton package by Revie and Edgoose (2015). This extensive dataset provided an opportunity to investigate the distribution of geochemical parameters (TOC and brittle/clay mineral content) in the HR model.

The Glyde package is bounded by the younger Favenc package and the older Redbank package. The Glyde package is up to 5 km thick, consisting of dolomite and sandstone formations (Ahmad *et al* 2013). The package outcrops in the Batten and Walker fault zones. Equivalent groups can be found in the Birrindudu Basin (Wattie Group and Limbunya Group), Urapunga Fault Zone (Vizard Group), the Tomkinson Province (Namerinni Group)

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and the north-eastern part of the McArthur Basin (Jalma Formation). The upper part of the Umbolooga Group in the Glyde package presents particularly good potential for both conventional and unconventional hydrocarbon resources (Munson 2014). The Barney Creek Formation contains the HYC Pyritic Shale Member that hosts McArthur River base metals mine. The occurrences of known mineral deposits are currently restricted to a small part of the Batten Fault Zone where they are associated with syn-sedimentary fault processes. However these mineral occurrences seem ubiquitous in the Glyde package and further work needs to be dedicated to investigate these syn-sedimentary fault structures in the Batten and Walker fault zones.

Tectonic setting

Initial deformation of the Glyde package occurred during the syn-Glyde NE-SW extensive phase (Betts *et al* 2014). This phase induced large northwest-trending normal faults and northeast-trending strike-slip faults. These faults are particularly observable in the Batten and Walker fault zones and in the south of the Birrindudu Basin.

This first extensive phase was followed by a secondary phase of extension during the deposition of the Favenc package. The stress state appears to be the same as the one recorded during the syn-Glyde extensive phase on the southern part of the greater McArthur Basin (Birrindudu area). The stress state rotates locally towards east-northeast on the northern part of the greater McArthur Basin, in the MOUNT MARUMBA[3] map area (Sweet *et al* 1999) and in the Walker Fault Zone.

The last deformation phase is the 1580–1500 Ma syn-Isan orogeny inversion phase. This inversion mainly affects the Batten and Walker fault zones, reactivating faults inherited from the syn-Glyde event. The stress regime is globally oriented east-northeast.

Material and methods

SKUA-GOCAD™ software was used to update existing models of the Wilton package, and to build the 3D regional model of the Glyde package. The following work was conducted:

- The 3D regional model of the Wilton package was updated in the Birrindudu Basin on the DELAMERE 1:250 000 map series (Beier *et al* 2002). A balanced cross-section was prioritised in this area of poor structural constraint in order to establish the link between outcrop and the nearby Pangaea Resources Pty Ltd exploration seismic survey (Hoffman 2015). The cross-section was constrained with field data collected during the 2015 field season. Thickness variations were extracted from Beier *et al* (2002) and Ahmad *et al* (2013).
- The Wilton package 3D regional model was used as a starting point for building the HR model of the Wilton package. The HR model was built over a smaller area than the regional model in order to allow the use of finer resolution mesh to better constrain the geometry. The results of the structural model are available in the updated DIP 012. The structural model was then transformed to a discontinuous volume model. The number of cells used to create the volume between two surfaces was varied depending on its importance and available data. For instance, in the volume containing the Velkerri Formation, the cell height was set at 25 m. A grid was created to analyse TOC and relative amount of brittle versus clay mineral content using geostatistical simulations. Sequential gaussian simulation (SGS) and sequential indicator simulation (SIS) stochastic algorithms (Gringarten and Deutch 2001; Felleti *et al* 2004) were used to represent the variability of the measured properties within selected layers of the 3D model.
- A revised stratigraphic partitioning was created for the Favenc and Glyde packages in order to define units that are thick enough to be resolved within the implicit modelling process. As per the partitioning applied to the Wilton package in Bruna *et al* 2015, the partitioning of the Glyde package was based on sequence boundaries and major unconformities. Model inputs are a classical combination of:

  i. surface data collected from fieldwork and existing geological maps in the area of interest
  ii. a down-sampled SRTM extract bounded by the model limits
  iii. a series of interpreted seismic horizons in the Birrindudu Basin (Pangaea Resources Pty Ltd) and in the Batten Fault Zone (Rawlings *et al* 2004)
  iv. interpretation of fault geometry at depth from both primary data and secondary *a priori* data using the GeolToolBox gOcad Research plug-in (Le Carlier de Veslud *et al* 2009)
  v. synthesis of well markers for the Glyde and Favenc packages compiled from mineral and petroleum company reports and from waterbore reports.

Results

Update of the Wilton package model

The newly constructed cross-section is based on field data only and was designed to better constrain the western extension of the greater McArthur Basin 3D model. This cross-section highlights the low amount of deformation recorded by the Wilton package equivalents in this region (**Figure 1**):

i. the Tijunna Group composed of the Wondoan Hill Formation and the Stubb Formation has an average bedding variation of 7.5° across the entire area
ii. rare observed faults do not display significant offsets unlike those observed in the McArthur Basin *sensu stricto*
iii. no major or pronounced folding processes were observed in this zone.

[3] Names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters, respectively, eg MOUNT MARUMBA, WILTON RIVER.

Nevertheless, fracture measurements collected at four stations identified some consistency in fracture orientation between the McArthur Basin *sensu stricto* (Bruna *et al* 2015) and the Birrindudu Basin in the 130° direction. Due to the minimal deformation recorded in this zone, further efforts should be concentrated on determining systematic fracturing characterisation. This work will lead to characterisation of diffuse fracturing that is crucial for unconventional hydrocarbon reservoir assessments.

MOVE software was used to construct the cross-sections. The software incorporated apparent dip calculations, bedding projections on cross-section trace, determination of best cross-section orientation from bedding measurement statistics, and fault displacement evaluation. This complete integration allows the construction of a valid balanced cross-section (**Figure 1**). Unfortunately, thickness variation could not be handled by the MOVE software. This should have an impact on fault throw estimations. Nevertheless, the low amount of deformation recorded in the area implies that this limitation has minimal consequence on the global geometry of the targeted zone.

Once constructed, the section was digitised in SKUA-GOCAD™ and used to update the existing regional model (DIP 012). The correlation between surface data and subsurface interpretation displays a smoothly deepening profile towards the east. This situation contrasts with the McArthur Basin *sensu stricto* / Beetaloo Sub-basin where the depocenter location is controlled by the major Mallapunyah Fault (Bruna *et al* 2015). This leads to the question: Are the Birrindudu and McArthur basins structurally disconnected?

The Wilton package high resolution model: an integrated perspective

The model of the Wilton package in the greater McArthur Basin has a cell resolution of 550 m × 160 m (horizontal × vertical) covering an area of 12 000 km². The model contains four horizons including the base of the Moroak-Velkerri group. It has approximately 45 fault surfaces that have major displacements. The model also contains 64 wells that are used to constrain the geometry at depth. The base of the Moroak-Velkerri group (Bruna *et al* 2015) is considered the base of the gridded zone of interest. This group of formations contains two economic targets within the Wilton package – the Velkerri Formation and the Kyalla Formation. The gridding cell size used for this group is 25 m vertical and about 2 km horizontal.

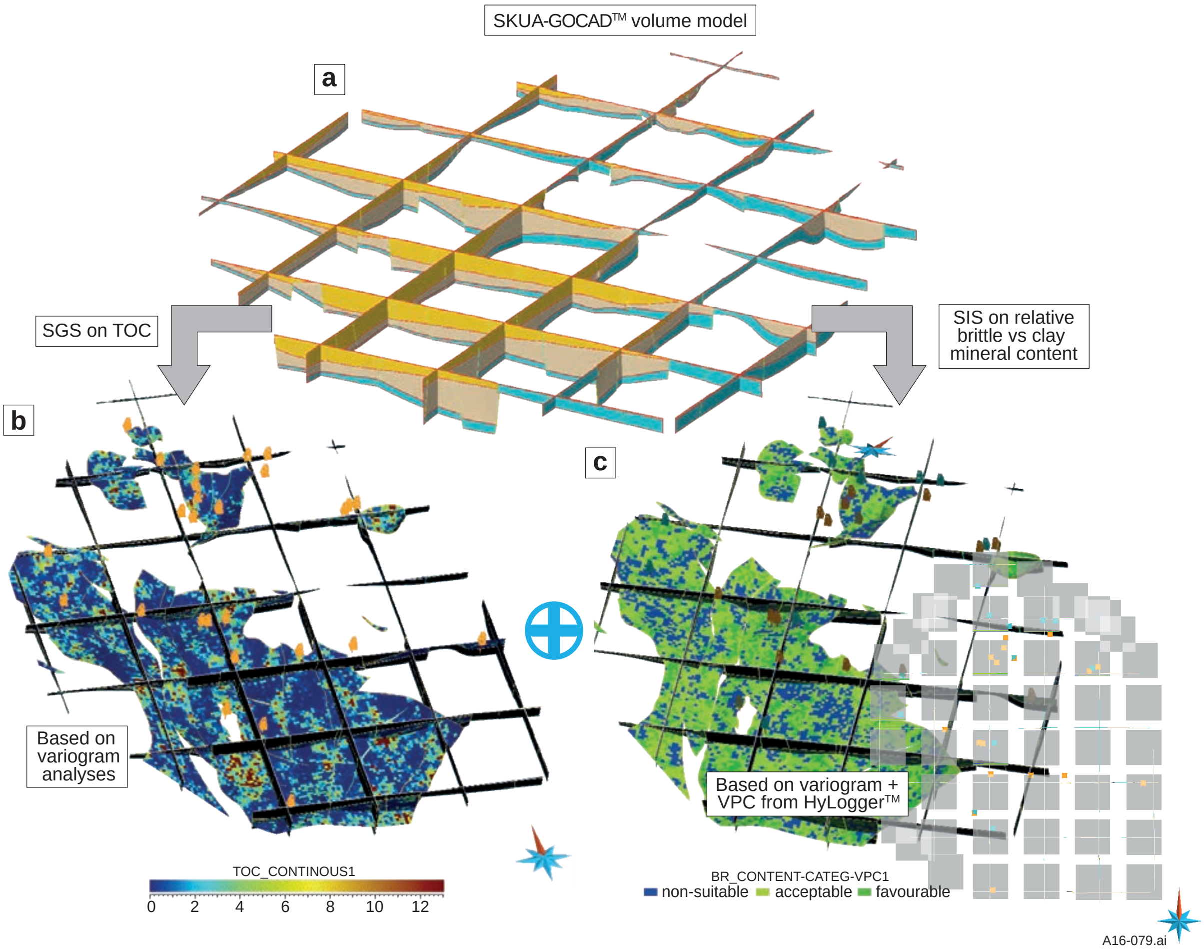

Figure 1. Developments on the HR model. (**a**) the HR volume model gridded discontinuously (cell dimension is finer in the yellow part than in the beige and blue parts). The yellow interval contains the target of the present study: the Velkerri Formation. (**b**) SGS simulation #1 for TOC values. This simulation shows the patchy organisation of high TOC values. (**c**) SIS simulation #1 for brittle mineral content facies. Three facies were defined during this process: non-suitable (brittle mineral content is between 0–35% or above 90%), acceptable (brittle mineral content is between 65 and 90%), favourable (brittle mineral content is between 35 and 65%). The grey squares indicate the regional VPC calculated from the HyLogger™ tool and integrated as secondary data.

The potential of black shale to host economic unconventional resources can be described using the series of parameters outlined by Zou (2013). Two of these parameters are: i) high TOC content and ii) high brittle mineral versus clay mineral content. An extensive collection of geochemical data including TOC and brittle mineral content are available in the majority of the wells present in the model (Revie 2015). These data were stochastically simulated using a SGS algorithm. The aim of this analysis was to represent the 3D repartition of high and low TOC values in the 3D model. This geostatistical analysis indicated that high TOC values are vertically organised as cyclic bodies. The small number of wells available in the model is not optimal to investigate the lateral extension of these high TOC value bodies (**Figure 2**).

The amount of available data on brittle mineral content from XRD analyses is scarce, but mineral data derived from the HyLogger (Mason and Huntington 2012) augmented the XRD data. Spectra from the thermal infrared (TIR) wavelengths (6000–14500 nm) are matched to an inbuilt mineral library to produce a mineral mix. The mineral mix is categorised into brittle (quartz, carbonates, and feldspars) and clay (white micas, kaolins, smectites) minerals. These results were combined with XRD data to obtain vertical proportion

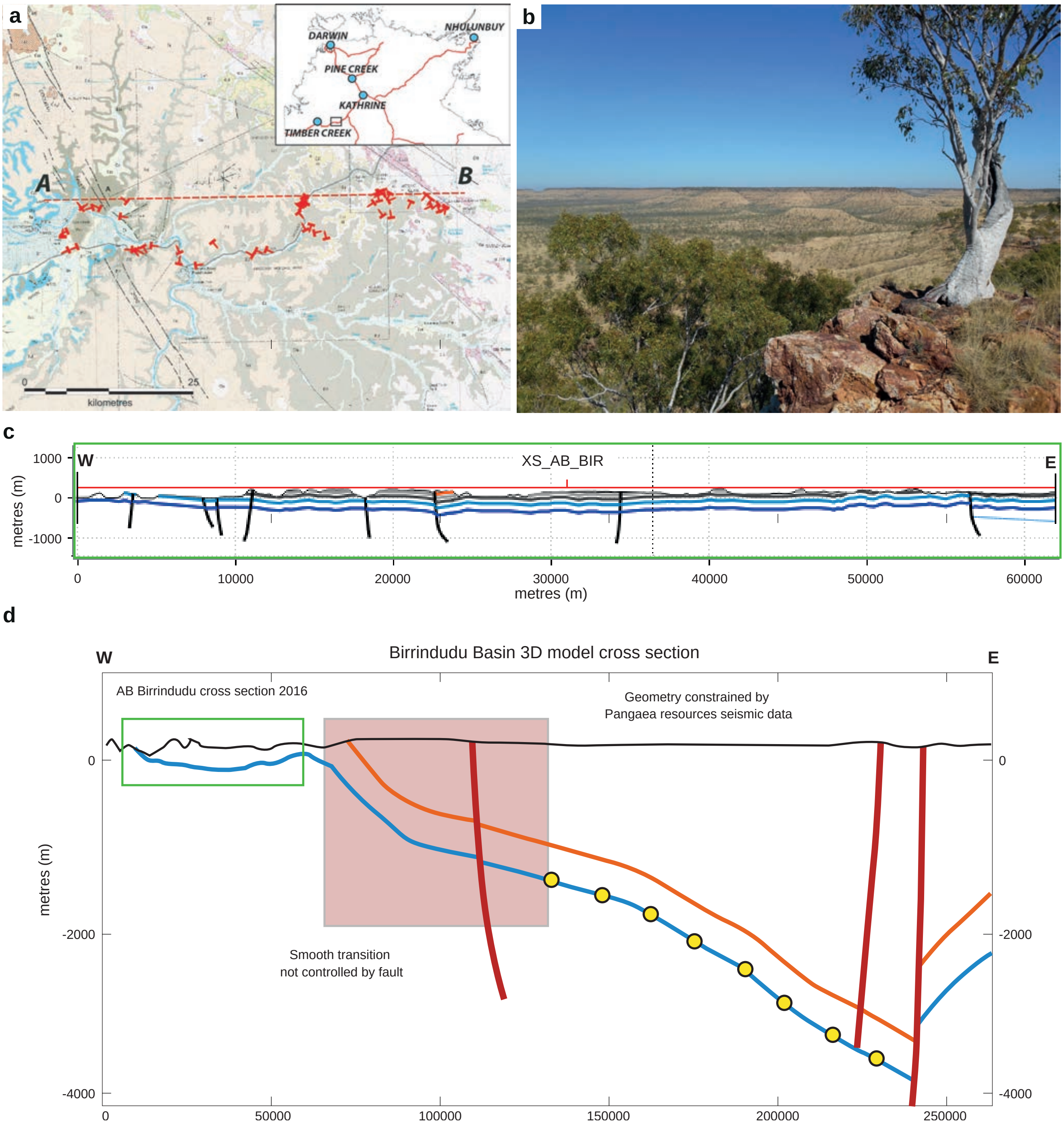

Figure 2. Update of the regional 3D model. (**a**) location and data distribution of the Birrindudu Basin AB cross-section. (**b**) aspect of the landscape where the Tijunna Group and Bullita Group outcrop (Coolibah Station area). (**c**) version α of the AB cross-section. (**d**) close up of a cross-section from the updated regional model with the location of available data marked (vertically exaggerated). This cross-section emphasises the very smooth shelf to basin transition which appears very different from the one observed between the McArthur Basin *sensu stricto* and the Beetaloo Sub-basin.

curves in some wells. The brittle versus clay mineral content was simulated with a SIS algorithm. Non-suitable, suitable and favourable facies were defined for these properties and simulated using 3 different variograms. While results were improved by using the vertical proportion curves, the final results reflect the lack of data in contrast to the high variability of the property (**Figure 2**).

The next step will be to combine the two approaches (TOC and brittle versus clay mineral content simulations) in a single algorithm to calculate whether parameters are suitable in each cell of the model to define sweet-spots (**Figure 2**). Another possible approach is to concentrate efforts on the Batten Fault Zone, an area of greater well coverage and therefore more detailed data available on critical parameters.

The Glyde package regional 3D model

This model contains six key horizons that honour available surface and subsurface data. Because this model is the continuation of the Wilton package, the same cell resolution of 1200 m × 400 m was used. The Favenc package has a limited potential for hosting economic resources (Munson 2014). This package was defined in the 3D model as a layer between the base Roper Group provided in Bruna and Dhu (2015), and the top Glyde package or top Amos Formation.

The Glyde package regional model is constrained by surface geology in the Batten and Walker fault zones, Tomkinson Province and in the eastern part of the Birrindudu Basin, and by seismic data in the Birrindudu Basin and wells sampling in the greater McArthur basin. The Beetaloo Sub-basin suffers a lack of data for the Glyde and Favenc packages. Further seismic interpretation and assessment of industry drilling focussed on the Glyde package should provide more data to better constrain the area. This model delivers the first structural framework of the Glyde package at the scale of the greater McArthur Basin.

As with the previous model (Bruna and Dhu 2015), thickness maps of each of the generated surfaces were produced that display of the geometry of key units at depth. These data are available as tessellated surfaces readable in many of the available geomodelling software tools.

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