Chapter 18: Statewide 3D Mapping Project at the Geological Survey of New South Wales

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Introduction

The Geological Survey of New South Wales (GSNSW) is creating a statewide 3D geological model as part of its flagship New Frontiers Initiative. The model is being developed in conjunction with the NSW Seamless Geology geodatabase (Colquhoun et al., 2018) which combines all New South Wales (NSW) geological information and presents the geology at the present-day topography, as well as at major geological time interfaces. The statewide 3D model is consistent with structures and lithologies from the Seamless Geology geodatabase, and incorporates data and interpretations from drillholes, seismic sections, and magnetic, gravity and airborne electromagnetic images and models.

The statewide 3D model delineates major basins, orogens, deep-crustal faults and fault networks. These features are represented as interlocking sets of 3D surfaces and volumes located within a common reference frame. Hydrocarbon, coal, mineral, geothermal and groundwater resource models and other detailed small-scale models will be embedded into the statewide 3D model framework.

Organizational Structure and Business Model

The New Frontiers Initiative (NFI) commenced in its current form in 2012 and is funded directly by area-based rental fees placed on all NSW mineral and petroleum exploration and production titles. Detailed NFI project deliverables are set on an annual basis under the guidance of a rolling five-year plan, with the first version of the statewide 3D model due in July 2021. The organizational structure of 3D modelling capability at the Geological Survey of NSW is illustrated in Figure 1. Construction of the regional- and basin-scale components of the statewide 3D model is the responsibility of the Geoscience Acquisition and Synthesis (GAS) unit, while mineral, hydrocarbon and geothermal resources models will be produced by the Strategic Resource Assessment and Advice (SRAA) unit. The 3D modelling project team works closely with the Seamless Geology project team that is also part of GAS. The models also draw heavily on drillhole data, which is collated and delivered by the Geoscience Information (GI) unit. GI are also responsible for the collation and delivery of all GSNSW datasets and products, including 3D models.

Overview of 3D Modelling Activities

The major focus of 3D modelling activity within GSNSW is the NFI program to create a statewide 3D model, comprising a series of interlocking province-scale models coupled with a statewide 3D fault network. Models at this scale will incorporate digital terrain, basin and basement interfaces, major tectonic subdivisions, crustal-scale structures, major stratigraphic horizons and geological age boundaries. Small-scale models of coal, gas, petroleum, water, geothermal and mineral resources will be embedded in the surfaces and volumes of the statewide 3D model framework.

The statewide 3D model has applications for land use management, mineral and energy exploration, scientific research, water resource management, civil engineering and waste management. GSNSW also undertakes 3D modelling on a more detailed scale for interpretation and presentation of specific resource assessment projects such as coal seams or groundwater aquifers.

Resources Allocated to 3D Modelling Activities

Roles currently committed to 3D modelling activities within the GSNSW are listed in Table 1. The deployment of the various teams within the organizational structure is shown in Figure 1. Staff in the GI unit also contribute to modelling by populating and maintaining drillhole databases that are base data for modelling projects, and through delivery of 3D models through GSNSW data systems.
The oldest rocks in NSW occur in the Curnamona Craton around Broken Hill in the state’s far west and are placed into the Willyama Supergroup, which comprises meta-sedimentary rocks and meta-volcanic rocks deposited in one or more rift basins about 1730–1650 million years ago. These Paleoproterozoic rocks were later incorporated into the Rodinian supercontinent, which was assembled around 1100 million years ago and started breaking up about 800 million years ago (Li et al., 2007). In the Rodinian supercontinent, North America lay to the east of Australia and Antarctica. It was a forerunner to Gondwanaland that existed for much of the Paleozoic (540–250 million years ago).

**The Delamerian Orogen**

The Late Proterozoic to Cambrian (1000–490 million years old) rocks of the Delamerian Orogen record the break-up of Rodinia, which occurred over a period of 200 million years. This orogenic belt mainly occupies the eastern third of South Australia where the Adelaide Rift Complex contains mixtures of sedimentary and volcanic rocks that record the rift and sag phases of crustal extension. The eastern part of the Delamerian Orogen extends into far western New South Wales (Figure 2) where rocks north of Broken Hill form part of the Adelaide Rift Complex. Stretched crust thinned to form rift basins, some containing volcanic rocks and glacial deposits, and thinned even more to give way to oceanic crust and seafloor spreading. Seafloor spreading changed to east-dipping subduction about 530 million years ago, with the formation of Cambrian island arc volcanic rocks.

**Palaeozoic Plate Interactions with the Proto-Pacific Ocean – the Lachlan Orogen**

The erosion of mountains formed by the deformation and uplift of the Delamerian Orogen shed vast amounts of mud and quartz-rich sand into ocean basins to the east, where they covered the Cambrian basalts that formed the oceanic igneous crust.

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**Overview of Regional Geological Setting**

The evolution of the orogens and basins in NSW are described in Schneibner and Basden (1998) and summarised below. The locations are shown in Figures 2 and 3.

**The Curnamona Craton**

The oldest rocks in NSW occur in the Curnamona Craton around Broken Hill in the state’s far west and are...
Figure 2. Map of New South Wales showing the extents of the Pre-Permian orogens over an image of the total magnetic intensity.

Figure 3. Map of New South Wales showing the Permo-Triassic, Mesozoic and Cenozoic basins over an image of the isostatically corrected bouguer gravity.
These sediments are now preserved as the widespread turbidites of the Lachlan Orogen. Destruction of the Cambrian subduction zone caused a new subduction zone to form hundreds of kilometres to the east. A new island-arc system, the Macquarie Arc developed above a west-dipping subduction zone. Several phases of volcanism have been documented in the arc from earliest to latest Ordovician. Quiet periods in volcanism are marked by the formation of tropical limestone reefs. Arc volcanism died out at the end of the Ordovician with the intrusion of monzonites, before plate tectonic movements in the Early Silurian caused the arc to collide with the back-arc basin turbidites. This caused the major Benambran deformation which rifted the Macquarie Arc into several belts, separated by rift-sag basins.

**Paleozoic Darling Basin**

The Late Silurian to Early Carboniferous Darling Basin is interpreted to have formed during syn-rift, short-lived thermal sag and foreland basin phases (Willcox et al., 2004). The rift fill phase was terminated by an Early Devonian inversion event that relates to the Taberraberan Orogeny. During the Middle Devonian, subsidence driven by thermal relaxation resulted in deposition of ‘layer cake’ sedimentary units, before the basin moved into a foreland basin tectonic setting. Mid Devonian to Early Carboniferous sedimentary units deposited to the west of a convergent plate boundary. Middle Carboniferous inversion coeval with the Kanimblan Orogeny resulted in inversion and erosion of the basin (Willcox et al., 2004).

**Thomson Orogen and New England Orogen**

The Thomson Orogen lies north of the Lachlan Orogen and extends north into central Queensland (Figure 2). In NSW, the orogen has an arcuate east-west orientation and is mostly covered by younger sedimentary sequences that have prevented detailed geological study. The Thomson Orogen may have a similar tectonic history to the Lachlan Orogen because it also contains Ordovician basalts and turbidites, Mid-Silurian to Mid-Devonian rock packages and interpreted Late Devonian basins (Li et al., 2007).

The evolution of the New England Orogen began with the deposition of fragmentary Cambrian to Ordovician convergent-margin volcanic and volcaniclastic rocks, as well as disrupted Cambrian ophiolites and Ordovician blueschists. A second phase was marked by plate convergence between the Australian Plate with the Proto-Pacific Plate, resulting in a mix of intra-oceanic arc and accretionary prism rocks. During a third phase, the New England Orogen was the site of a Late Devonian continental-margin arc of mafic character sitting above a west-dipping subduction zone. Multiple deformation, metamorphism, and emplacement of granites occurred in the Late Carboniferous and Permian. Convergence along this plate margin became extensional in the Early Permian leading to the formation of small rift basins and a major back-arc rift basin that formed the early stage of the Sydney and Gunnedah basins.

**Permo-Triassic Basins**

The Sydney and Gunnedah basins lie between the Lachlan and New England orogens. Starting as back-arc rifts in the earliest Permian, they developed into foreland basins. Most of their fill was generated by uplift in the New England Orogen and this alternated with lesser fill from the Lachlan Orogen. These basins gradually converted into west-verging foreland fold and thrust belts during westward migrating deformation which persisted until the Mid-Triassic (Figure 3).

**Mesozoic and Cenozoic Basins and Modern Topography**

In the north-eastern corner of New South Wales, the Triassic to Jurassic Clarence-Moreton Basin covers about 27 000 km² and contains up to 3 km of predominantly continental sediments. The basin formed by crustal extension of long-lived, north-trending dextral strike-slip faults (Korsch, 1985). Trans-tensional tectonics was followed by a period of thermal relaxation and subsidence (sag phase) in the latest Triassic to Late Jurassic (Harrington and Korsch, 1989). During the Cretaceous, an eastward shift in tectonic activity occurred. Activation of sinistral strike-slip faults was associated with continental rifting and formation of the Tasman Sea (O’Brien et al., 1994). Jurassic and Cretaceous rocks were deposited in the Great Australian Basin which covers the northern inland of New South Wales, and adjoining areas of Queensland and South Australia. The basin is sub-divided into the Eromanga and the Surat basins and date from the Early Jurassic to Late Cretaceous (Figure 3).

About 90 million years ago, the Tasman Sea between Australia and New Zealand began to open by seafloor spreading. The western edge of this rift basin was tectonically and thermally uplifted to form the Great Dividing Range and the broad shallow Cenozoic Murray Basin formed to the west of the range as a sedimentary response to this uplift (Figure 3).

**Data Sources**

Base data for 3D modelling are sourced from the NSW Seamless Geology geodatabase (Colquhoun et al. 2018), seismic sections, drillholes (petroleum, minerals, coal and water bores) structural measurements and geophysical images (gravity, magnetics and radio-element). The models are dynamic and are updated after new data are collected. The spatial distribution and resolution of data varies across the state, from very dense to very sparse.

NSW legislation requires that all drilling, geological, geophysical and
When a modelling project is completed, the constraints for the model surfaces are exported and saved as a snapshot of the data in the BACON database. BACON lists the spatial XYZ location of the constrained points for each model surface and categorizes them as either a drill hole intersection, seismic interpretation, or other constraint. The data stored in BACON provides a quick way of checking whether parts of a model are well constrained or poorly constrained and allows an experienced modeller to re-create the model surfaces without having to recompile the separate constraining datasets.

3D Modelling Approach

Robinson (2016) described the 3D modelling process developed by GSNSW. The workflow recognizes the scalar and interlocking nature of orogenic provinces and basins, as well as the structures and stratigraphy contained therein. It prioritizes large-scale features and then works down in scale to infill models with increasing detail.

All models are constructed using implicit modelling that relies on relatively sparse constraining data. The exact methods selected will depend on the type, quality and spatial distribution of the constraining data.

There are three basic end-member modelling methods:
1) Compile a series of key datasets in the areas where they occur. These data are usually the drill hole intersection tops and bottoms, seismic interpretation point-sets, geophysical models, and surface maps. Then use stratigraphic tables and the Seamless Geology to link the datasets to create surfaces that span the areas with sparse or no data.
2) Work directly from seismic and drillhole data to interpret horizons and structures. Then link these together guided by surface mapping line-work.
3) Use the surface mapping line-work from the Seamless Geology as the primary reference dataset. Constrain the dips of horizons and structures in the surface mapping with information from structural measurements, drillhole intersections, seismic interpretations and potential field modelling.

A combination of these methods may be used in a single model as required.

One of the major challenges of the NSW Statewide 3D model is to match the surface geology shown in the NSW Seamless Geology geodatabase (Colquhoun et al., 2018) with the horizons interpreted from the drillhole and seismic data. It is paramount that all geological synthesis products (maps, GIS, 3D models) released and distributed by GSNSW be consistent with each other. In areas where the NSW Seamless Geology geodatabase was compiled from limited information (i.e. poor outcrop, or coarse-scale mapping) then the modelled 3D surfaces may contribute to improving the interpretation and modifying the NSW Seamless Geology geodatabase. In other situations, the coarse scale of the NSW 3D model creates a mismatch in resolution between the 3D surface elements and the line segments in the NSW Seamless Geology geodatabase. This is addressed through the creation of smaller model surface elements near the intersection with surface mapped geology.

Geological cross-sections are used to link interpretations to seismic sections, establish structural and stratigraphic relationships and to assess the interpretations from gravity and magnetic forward models. Figure 4 shows cross-sections used to constrain the location and geometry of faults in the Eastern Lachlan Orogen.

Where available, seismic horizon picks are combined with the NSW Seamless Geology geodatabase and drillhole data to interpret cross-sections. In the absence of seismic data,
the geometry of horizons or faults is constrained using mapped relationships and magnetic and gravity data. Variations in width and gradient of geophysical anomalies across structures are particularly useful for estimating the dip of major faults. Horizons are also constrained by applying previously defined stratigraphic relationships. Where more than one relationship exists within horizons, manual post-processing of modelled surfaces and volumes is necessary to ensure the correct relationships are maintained.

An example of the layers and datasets used to construct the structural-stratigraphic models that comprise the GSNSW statewide 3D model is shown in Figure 5.

**Clients**

The GSNSW collaborates with other governmental agencies and industry partners through the delivery of 3D models and accompanying advice which support:

- the strategic release of exploration areas
- assessment for economic potential
- decisions about land use
- assessing environmental impacts
- addressing community concerns about land-use decisions.

The 3D modelling will benefit the NSW Government, the resources industry, academia and, at more detailed levels, civil and environmental engineering.

For example, the NSW Office of Water referred to a GSNSW 3D model of the southern Sydney Basin to assess the possible impact of a proposed coal mine extension on the groundwater resources within the Sydney metropolitan water supply catchment (see below). The 3D model was used to predict depth to aquifer and water flow rates for proposed monitoring wells and to estimate the recharge areas for each well.

In 2018, GSNSW used LiDAR data and Shuttle Radar Topography Mission data to construct a 3D model of the volcanic terrain of the extinct Warrumbungle volcano in central NSW for the NSW National Parks and Wildlife Service. The model was transformed into a physical diorama by a specialist 3D printing and routing company in the USA for display at the new visitors centre at the Warrumbungle National Park.

The GSNSW’s 3D modelling benefits the resources industry by improving the understanding of regional architecture and its broad-scale relationships to resource distribution through improved understanding of crustal structure, the distribution of key source units at depth and mapping large-scale fluid pathways that assist in the reduction of the exploration search space and recognition of areas.
of mineral and hydrocarbon potential not previously identified. Constraint on depth to target horizons is also a key outcome and includes depth of sedimentary cover overlying potential metalliferous resources, depth to aquifers for water resources and depth to target stratigraphy for energy resources.

**Recent Jurisdictional-Scale Case Study**

**Showcasing Application of 3D Models**

The NSW Office of Water referred to a GSNSW 3D model of the southern Sydney Basin to understand the possible impacts of potential future mining activities on aquifers and groundwater flow within the Sydney metropolitan water supply catchment. The boundary of the model area is shown in Figure 6. The model was constructed in stages, with robust scoping and planning early in the project’s lifecycle to ensure changes in design could be made before major effort was expended constructing model surfaces.

A total of 130 wells were imported and assessed. Four wells were discarded due to inconsistencies in the interpreted horizons. No seismic data was used to constrain the model, but pre-existing interpreted geological cross-sections provided constraints for the structure of the basin throughout the modelled area. The NSW Seamless Geology geodatabase provided constraints at the topographic surface. The resolution of the model was 200 m x 200 m horizontally and 50 m vertically. Modelling focused on the depth to stratigraphic formations. Faults were not modelled because of time limitations. However, fault surfaces were incorporated into a later model created for the entire Sydney Basin.

The accuracy and fitness for purpose of the model were peer-reviewed by geologists within the GSNSW. The final model provides an overview of the geology, structure and geometry of the southern Sydney Basin, as well as mapping the extent and depth of coal resources. Figure 7(a) shows a perspective view of the final model while Figure 7(b) shows a cross-section derived from the model depicting the depth to the coal measures and the relationship with the water-bearing Narrabeen Group, Hawkebury Sandstone and Wianamatta Group.

**Current Challenges**

Current challenges facing the 3D modelling projects at GSNSW include the selection of an appropriate model scale, and the integration of datasets with a wide range of scales, spatial densities and resolutions. Data quality is also highly variable and is often related to the age of the data.

With a team of 10 staff, GSNSW currently has the largest number of active 3D practitioners in the NSW Government, from a range of technical backgrounds, with access to up-to-date computer hardware and industry-standard modelling software. Despite this, there are still significant computational hardware and software constraints on the modelling resolutions that can be delivered, particularly when representing spatially dense datasets such as the NSW Seamless Geology geodatabase at statewide and regional scales. The GSNSW is cur-

**Figure 5.** Some of the datasets used for the Eromanga-Surat Basin region of the NSW 3D modelling Project and the final model surfaces (ES3DM). The view is 900 km east-west by 300 km north-south.
Figure 6. Southern Sydney Model boundary over the Seamless Geology Map of NSW. The Permo-Triassic sediments of the Sydney basin are shown in blue and aqua colours while the pink, purple and red colours denote the meta-sediments, volcanics and granites of the Lachlan Orogen. A stratigraphic column showing the main formations in the Sydney Basin is shown in Figure 7(b).
Figure 7. Perspective view of the Southern Sydney Model showing location of section A-A’ (Top). The view has a 50x vertical exaggeration. Cross section along A-A’ derived from the model showing coal seam depths under the greater Sydney Metropolitan area (Bottom).
rently investigating the issue of delivering multiple model resolutions through a single online viewing platform. There are also resolution issues when detailed, data-dense resource models are embedded within the less-detailed data-sparse regional models.

**Lessons Learned**

Potential improvements in procedures and workflows are documented upon completion of each 3D model. Improvements which have been implemented include:

- the difference in density of points between two datasets can cause undesired gridding effects when creating 3D surfaces. Reducing the number of points by distance (usually 30 m) or adjacent angle (usually 60°) from the contact produces a smoother result
- small ‘workarounds’ which ensure the best fit of the modelled surfaces to the NSW Seamless Geology geodatabase and the topography
- adjacent modelled grids and surfaces are usually added to each new modelling project to ensure a perfect fit between models
- for large-scale models, creating a basement layer using topography where orogenic provinces are outcropping will ensure that grids and surfaces for adjacent basins do not extend beyond their limits or above the current topographic surface.

**Next Steps**

The statewide framework model of basins and orogens will be finished by mid-2021. In parallel with the development of the framework, GSNSW will focus on resource-scale models that will be embedded in the statewide model. Models will also incorporate soil character and thickness, small-scale faulting, and other geological data collected prior to and during major construction projects. These models will inform decision making about the location and form of major infrastructure as well as site assessments for future civil engineering works. GSNSW is also a member of the Loop Consortium led by Monash University, which is developing next-generation open-source tools to enable 3D geological modelling guided by statistical analysis of probabilities. The Loop Consortium algorithms will increase the productivity of 3D modellers as well as quantifying the error and uncertainty of models.

GSNSW commenced a major 10-year program in 2018 to drill through post-Permain sedimentary rocks to investigate the underlying basement in five under-explored regions of central and western NSW. This drilling and the supporting data acquisition will generate new geological information that will constrain ongoing re-interpretation of model surfaces. The statewide 3D geological model of NSW will continue to provide a versatile platform for data integration and visualisation to support the development of new geological concepts, guide mineral and energy exploration in the state, and inform decisions about land use and resources.

**References**


