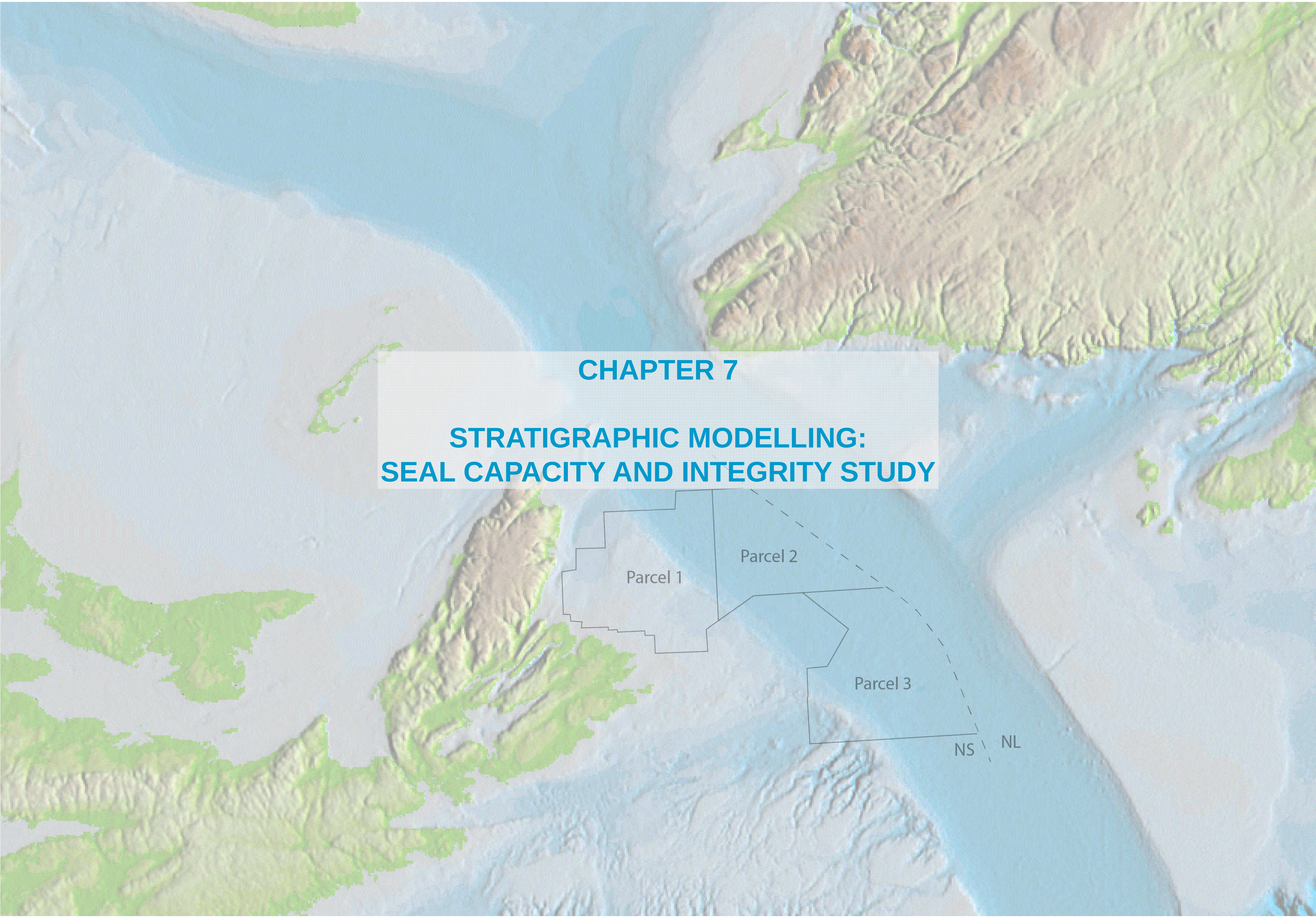
CHAPTER 7

STRATIGRAPHIC MODELLING: SEAL CAPACITY AND INTEGRITY STUDY



Objectives of the DionisosFlow® Forward Stratigraphic Modelling and Multi-Realization Modelling

1. To provide a 4D geological reconstruction of the Windsor Group (Sydney Basin) in the Lower Carboniferous at Visean ages (346 - 331Ma) using forward stratigraphic modeling approaches (Figures 1 and 2).

2. To validate and/or improve previously established GDE maps (see Chapter 6). DionisosFlow® takes into account sedimentary processes in order to simulate sediment deposition (Figures 3, 4 and 5) .

3. To evaluate the seal capacity / integrity of the Windsor Group and associated risks using the Multi-Realization approach.

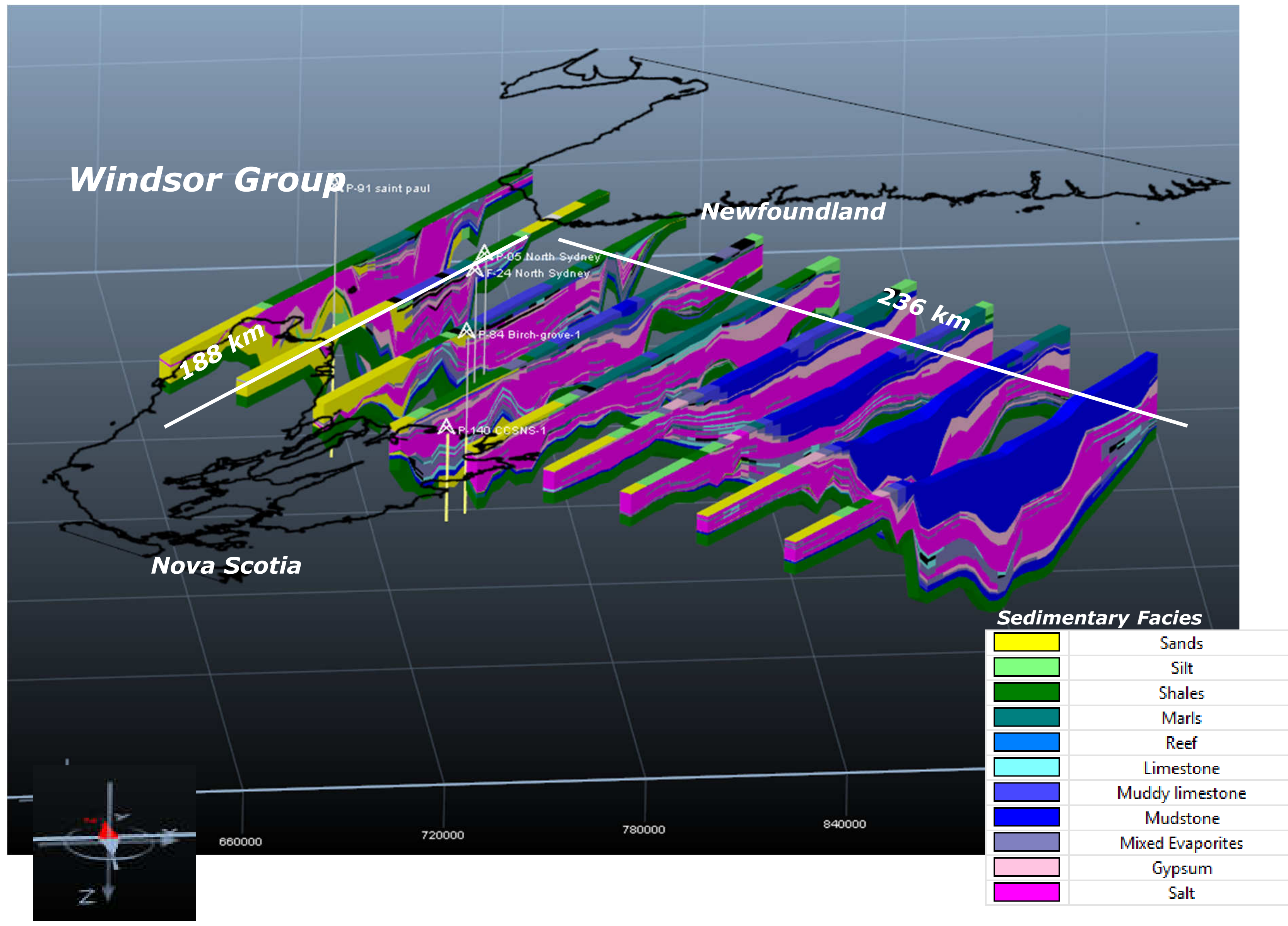


Figure 1: Simulated forward Stratigraphic Model of the Sydney Basin underlining the main vertical and lateral variations of sedimentary facies

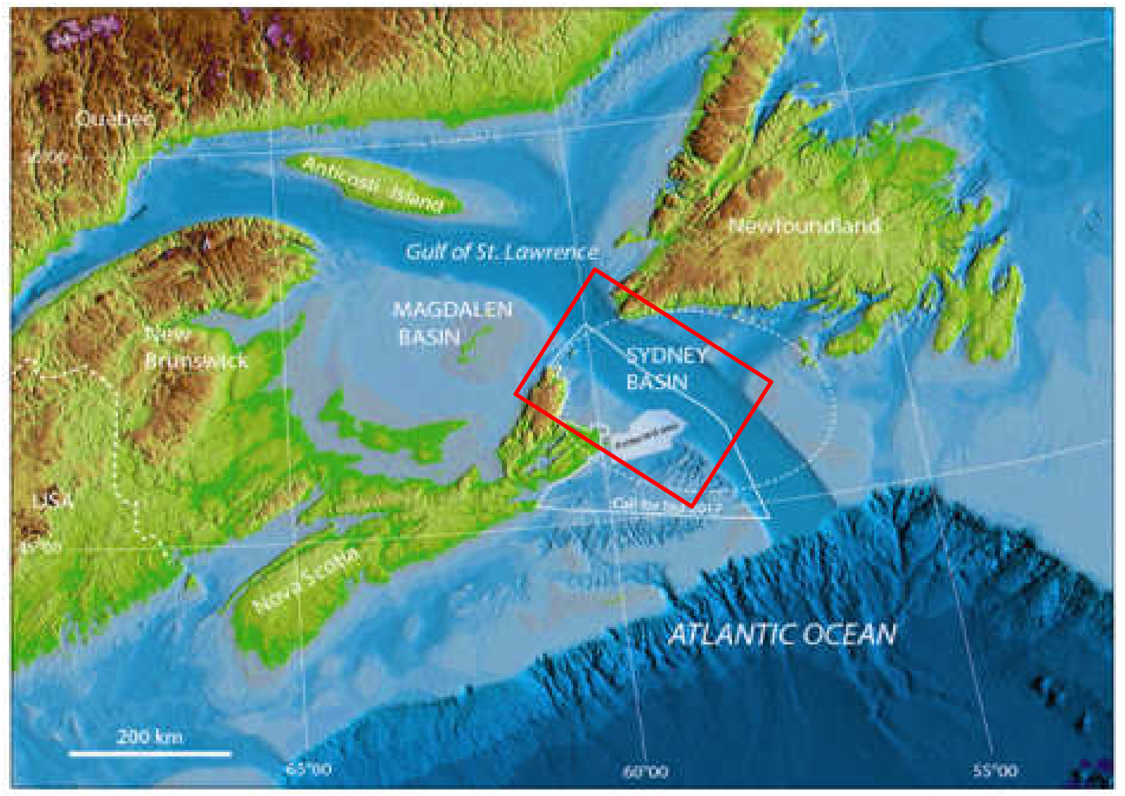
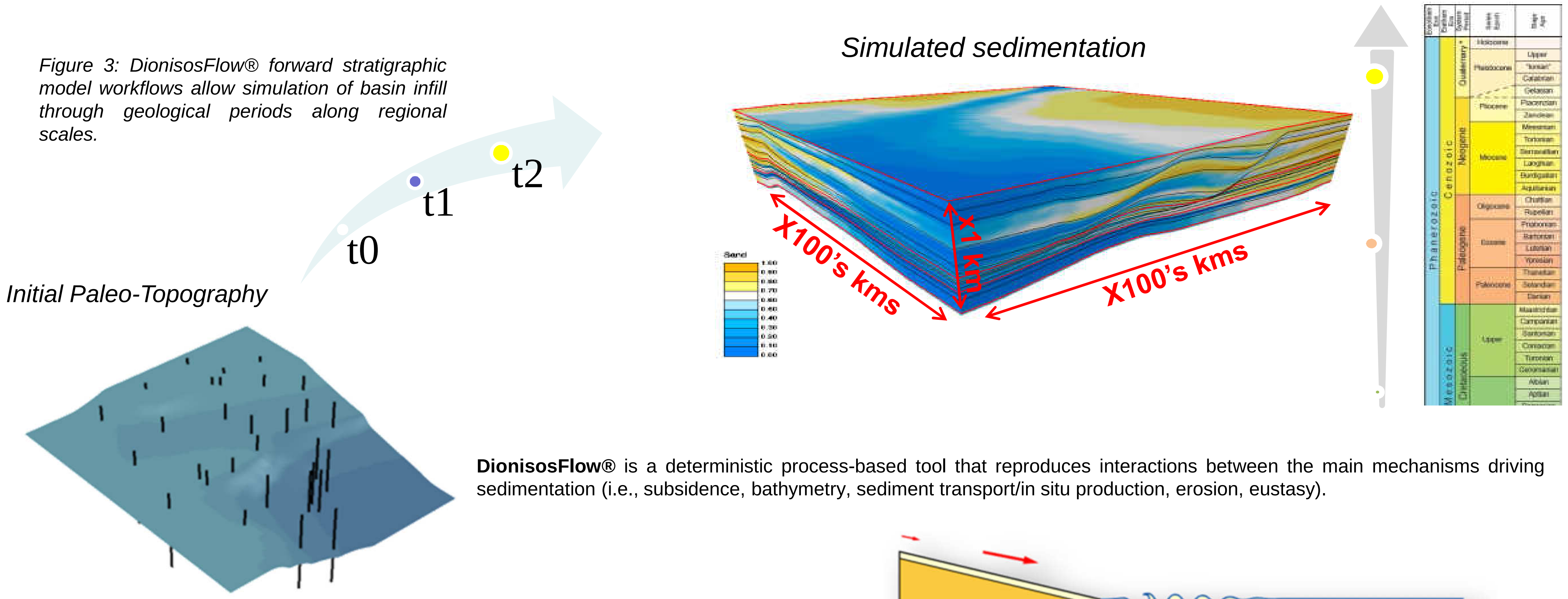


Figure 2: Location map of the Sydney Basin.

Figure 3: DionisosFlow® forward stratigraphic model workflows allow simulation of basin infill through geological periods along regional scales.



DionisosFlow® is a deterministic process-based tool that reproduces interactions between the main mechanisms driving sedimentation (i.e., subsidence, bathymetry, sediment transport/in situ production, erosion, eustasy).

Multi-disciplinary and multi-scale approaches

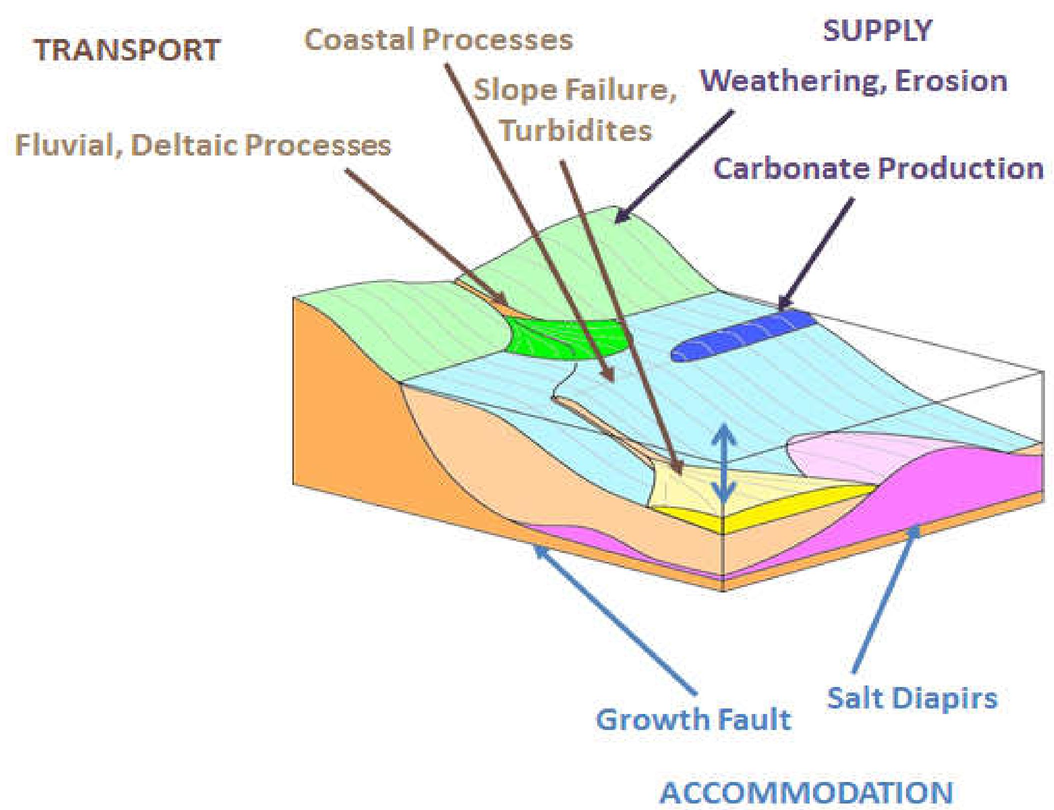


Figure 4: Diagram showing the interaction of several processes related to sedimentary erosion, transport and deposition.

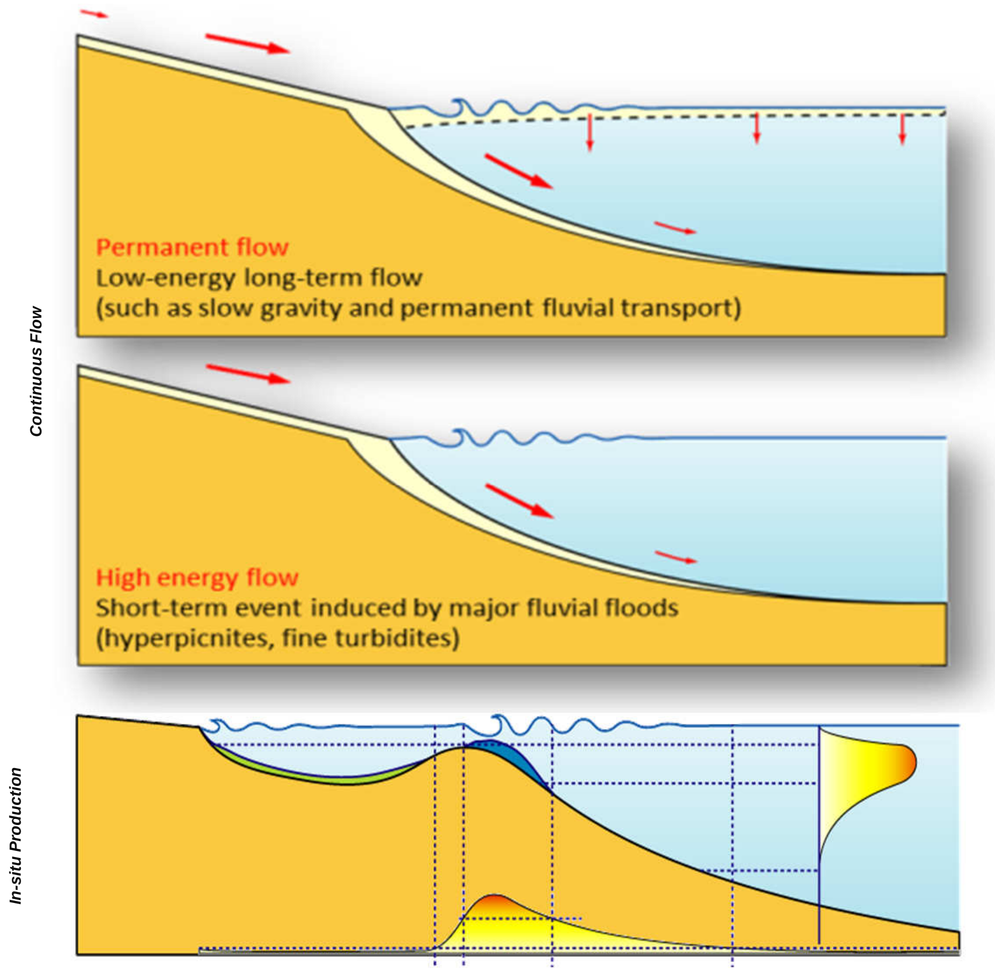


Figure 5: Different sedimentary processes modelled in DionisosFlow®.

The transport rate is proportional to basin slope and water discharge:

$$Q_S\ (km^3/My) = K * Q_W * S$$

- Q_S = sediment inflow
- Q_W = water flow
- S= depositional slope degree
- K = diffusive coefficient

In-situ production depends on production laws:

P_i (m/My) = Pref .i(t) * Pbathy.i * Pwave.i * Pecology.i

- Pi = production rate by sediment
- Pref (t) = production reference function of time
- Pbathy.i = bathymetric factor
- Pwave.i = wave influence
- Pecology.i = ecology influence

DionisosFlow® Forward Stratigraphic Modelling Workflow

Forward stratigraphic modelling using DionisosFlow® allows:

- Integration of multidisciplinary and multi-scale datasets
- Validation of geological & facies models
- Study of large-scale sedimentary processes (carbonate & siliciclastic)
- Delineation of petroleum system elements (i.e., reservoirs, seals, source rocks)
- Assessment of the impact of deformation (e.g., salt, listric faulting) on sedimentary pathways
- Improved basin models (P-T and migration simulations) through refined facies modeling

Forward simulations of sedimentary processes are conducted in 4D in a sequence stratigraphic framework where subsidence and eustasy drive accommodation (Figure 6)

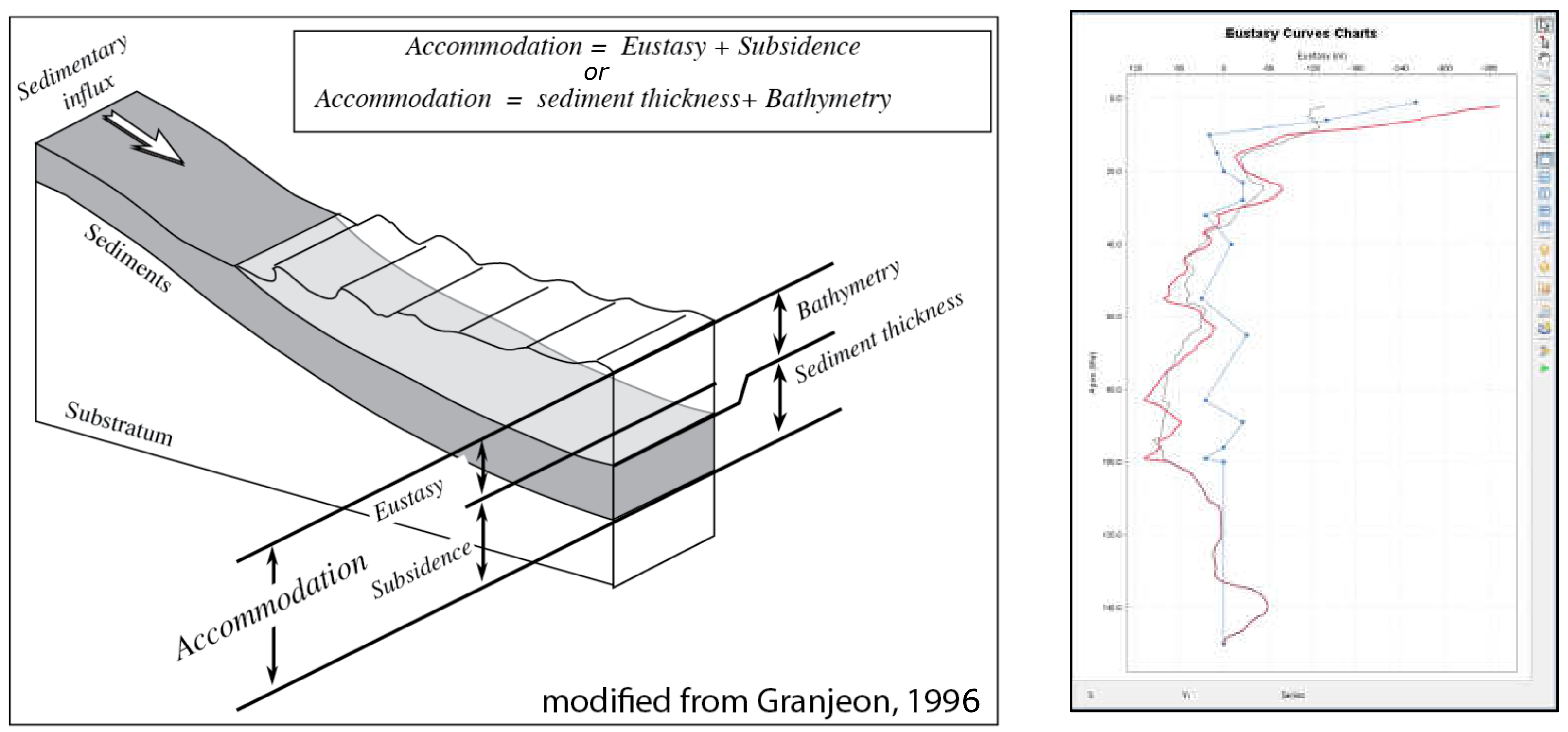


Figure 6: Calculation of accommodation in DionisosFlow® software.

Transport is simulated through diffusive equations and is dependent on slope, water discharge, sediment load, sediment, grain size and the paleo-environments.

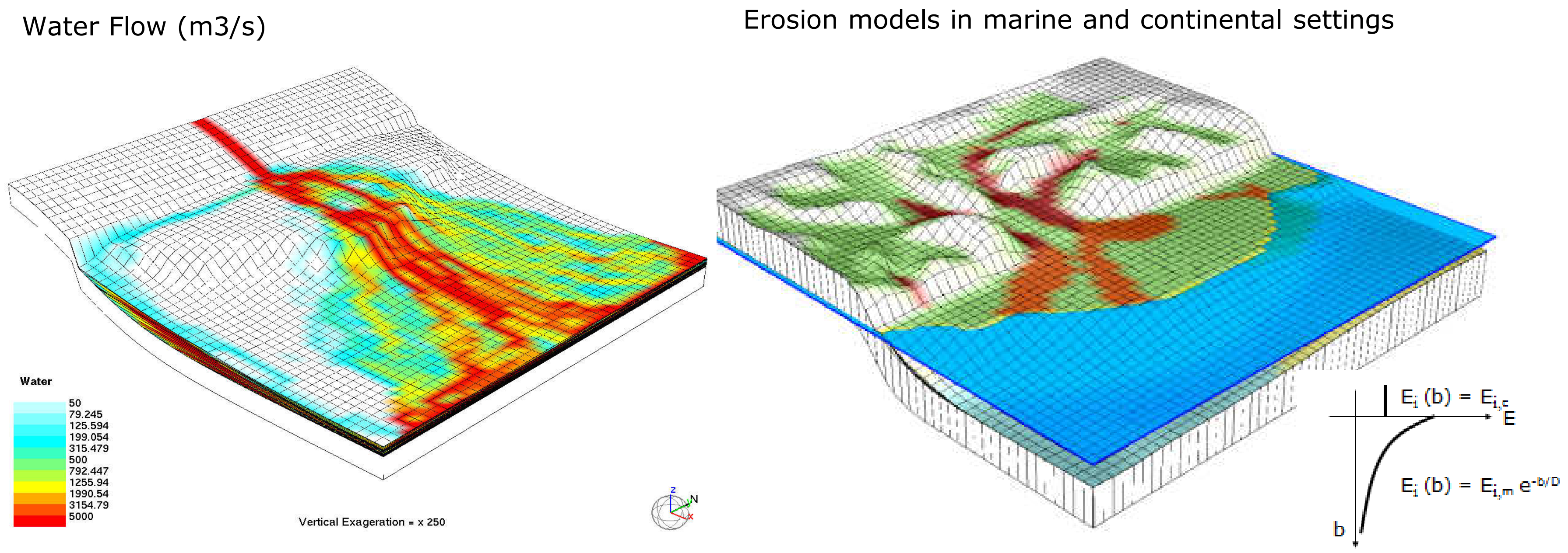
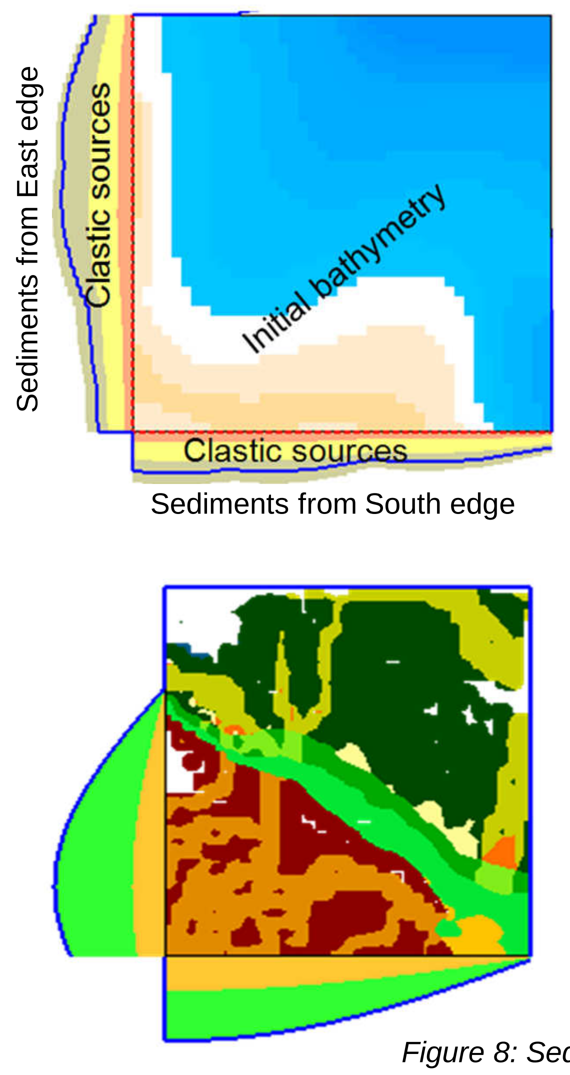


Figure 7: Examples of simulated models showing sediment transport and erosion in continental and marine environments.

Sources are defined along geological periods



- ***Source Location***
- ***Source Width***
- ***Water Discharge***
- ***Sediment Load***
- ***Sediment Proportions***
- ***Source Activation Age***

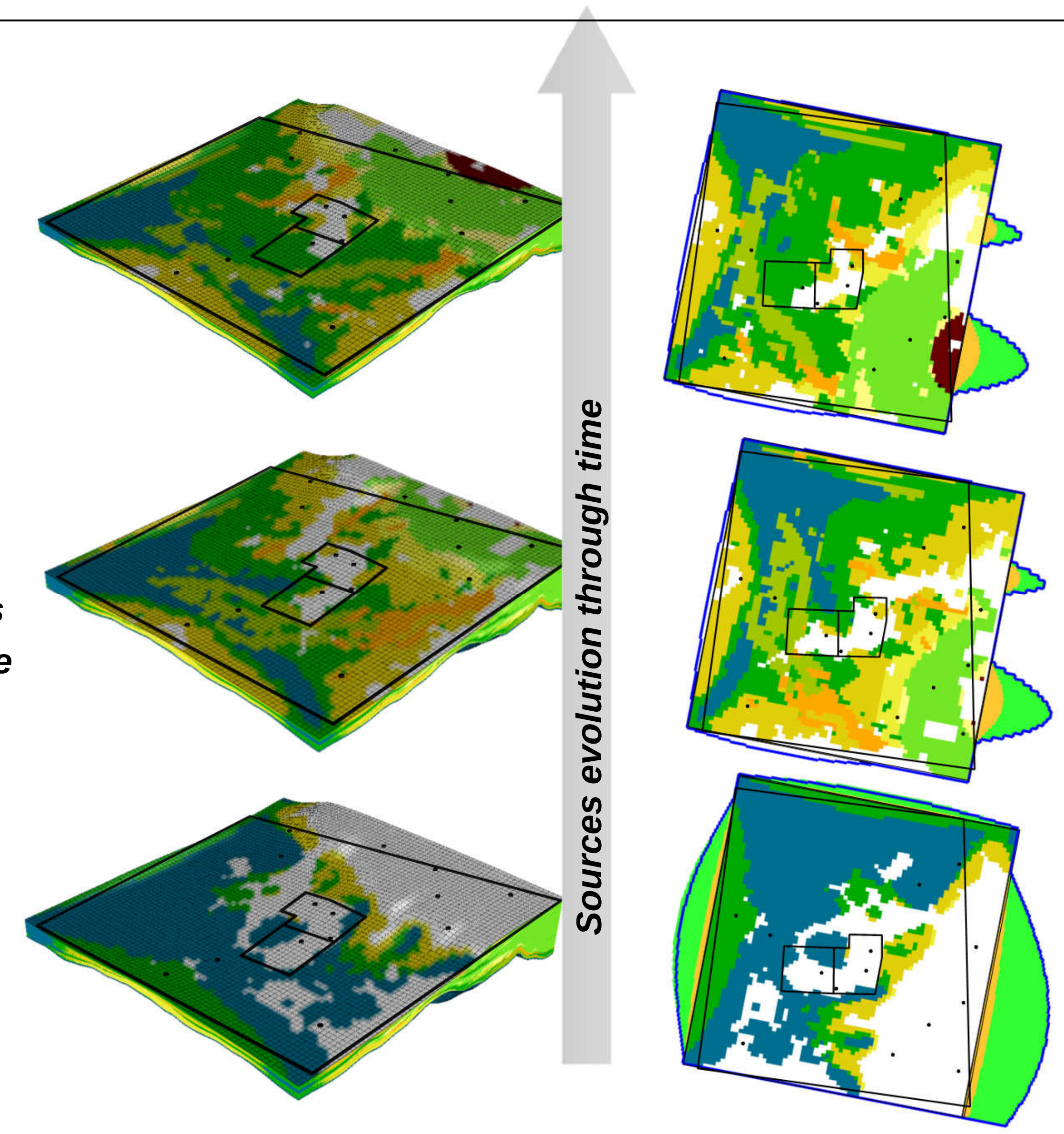


Figure 8: Sediment source location and evolution through time are accounted for in the DionisosFlow® model.

Forward stratigraphic modelling using a **DionisosFlow® loop workflow** (Figure 9) allows the testing of multiple of basin deformation and infill scenarios to generate high resolution stratigraphic models allowing a better characterization of the petroleum system elements (i.e., reservoir, seal, source rock, stratigraphic trapping).

Outputs

Depositional environment properties
- *Paleobathymetries*
- *Water flow*
- *Wave energy*
- *Slope*

Lithological information
- *Thickness maps*
- *Sediment concentrations*
- *Net To Gross maps*
- *Body connectivity*

Facies model
- *Detailed facies maps*
- *Reservoir/seal quality*

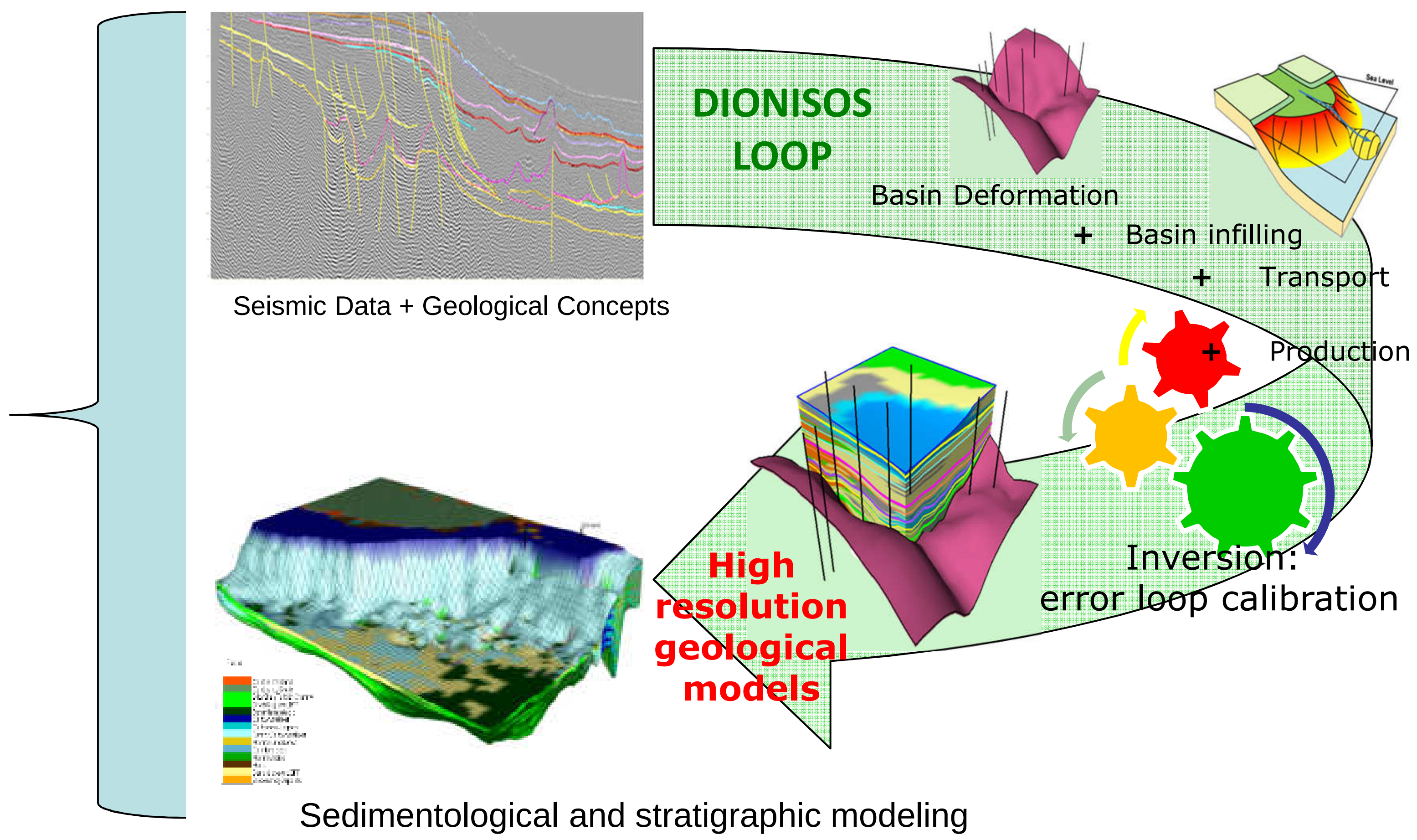


Figure 9: DionisosFlow® forward stratigraphic modelling workflow loop and consequent outputs

CougarFlow® Multi-Realization Workflow

Multi-Realization workflow using CougarFlow® allows:

- Generation of alternative scenarios according to an experimental design which explores a range of input parameters;
- Assessment of the impact of the main parameters influencing thickness and facies calibration (Figure 10).

An experimental design is a set of simulations generated by CougarFlow® in order to optimize the exploration of an uncertain space domain. From these simulations, a Response Surface Model (RSM) is produced. This nD RSM (n is the number of uncertain parameters) is carried through all simulations in order to predict all possible results.

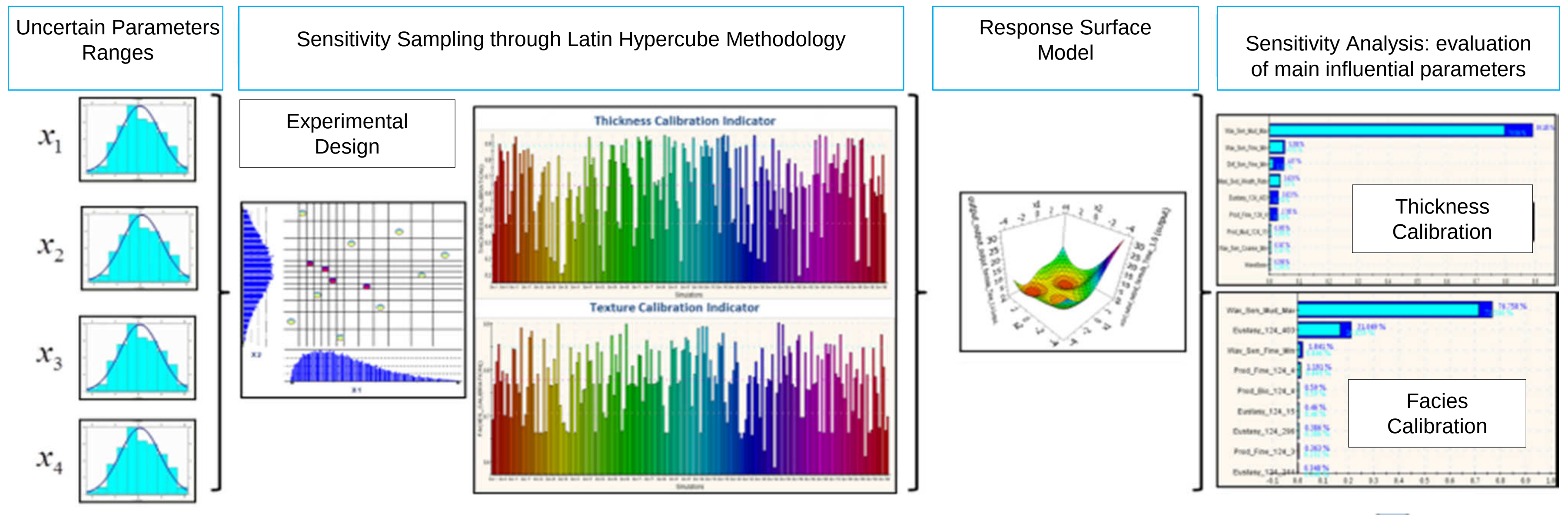


Figure 10: Multi-Realizations workflow

A Monte-Carlo sampling allows the production of Pareto plots. These plots help to determine which uncertain parameters are the most influential on model calibration.
Moreover, all simulations are evaluated using calibration indicators:

- one assessing the thickness,
- a second assessing the facies.

If each indicator value is above certain thresholds, the simulation is assumed to be calibrated. When a simulation is calibrated it is used to compute:

- the mean salt thickness map and its associated standard deviation map – seal capacity characteristic,
- salt occurrence confidence 3D block – seal integrity characteristic (Figure 11).

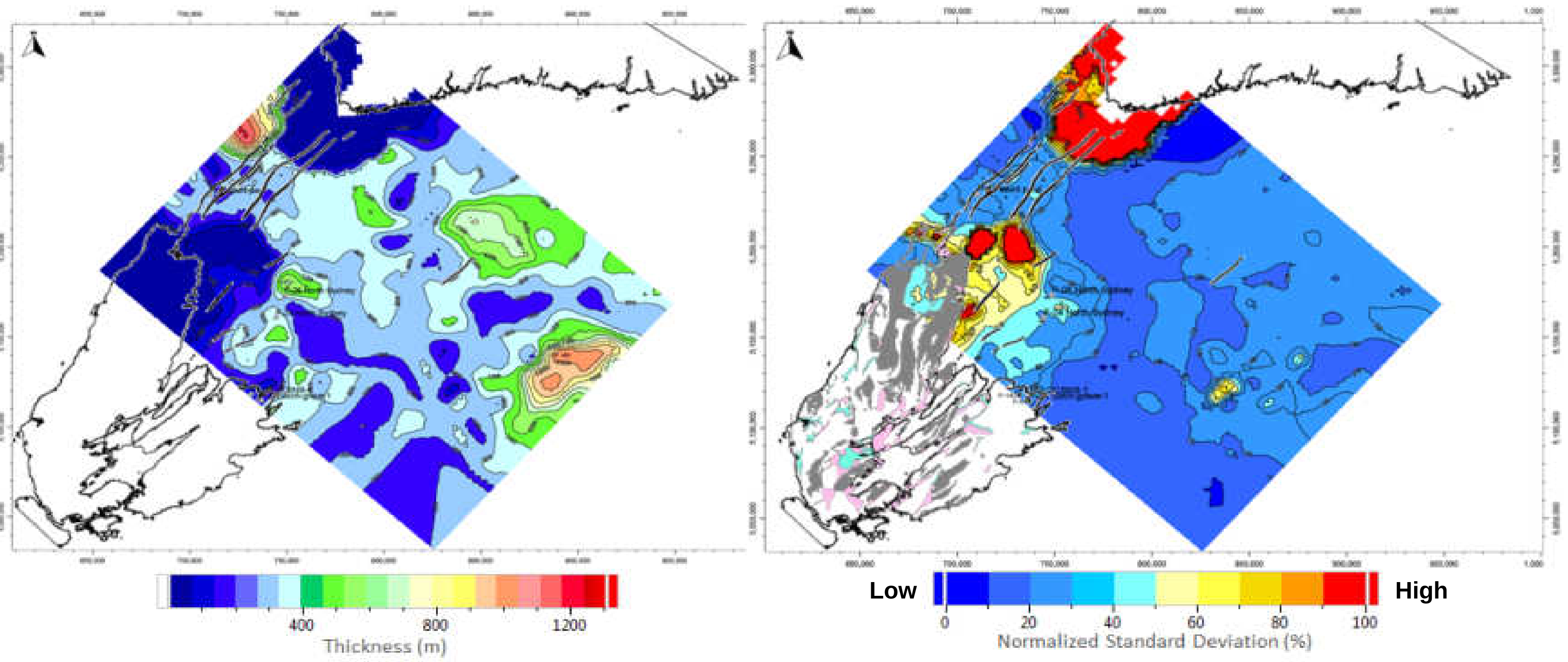


Figure 11: Mean salt thickness map on the left associated to its normalized standard deviation map (right) showing high risk areas (red)

Multi-Realization calibrations are assessed using two indicators:

- A Thickness Map Calibration indicator (comparison between the seismic thickness map and the simulated thickness in each cell) (Figure 12)
- A Facies Log Calibration indicator (comparison between the interpreted lithofacies log and the simulated facies log at well location) (Figures 13 & 14)

The Thickness Map Calibration indicator evaluates calibration through the following computation, and results are given in percentage:

$$Thickness\ Map\ Calibration(\%) = \frac{\sum_{i,j}\left(1-\frac{sim_{i,j}-obs_{i,j}}{obs_{i,j}}\right)*obs_{i,j}}{\sum_{i,j}obs_{i,j}}*100$$

Where:

- i,j are the cell indexes,
- $Sim_{i,j}$ is the simulated thickness,
- $Obs_{i,j}$ is the seismic thickness.

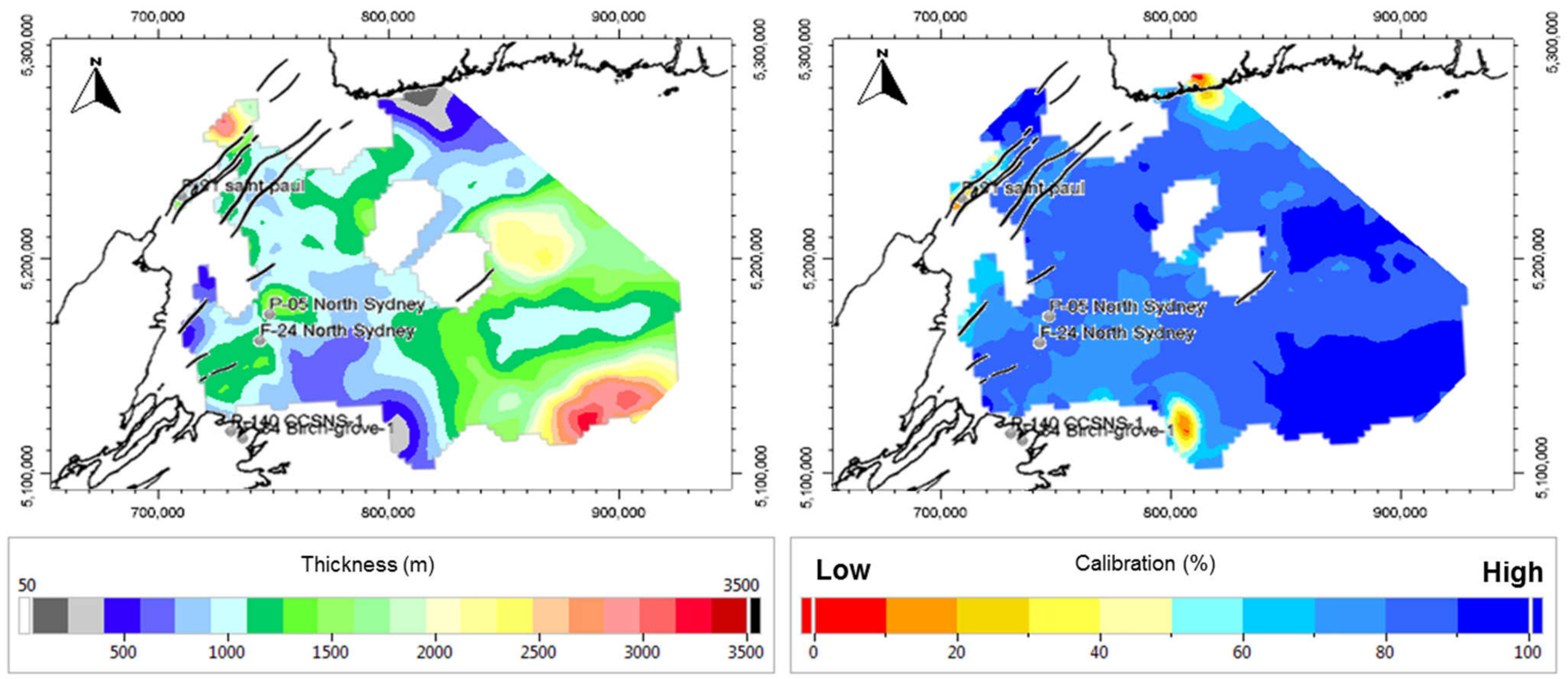


Figure 12: Seismic thickness of the Windsor Group (left) and Thickness map calibration map (right)

The Facies Log Calibration indicator evaluates calibration at a well location comparing simulated facies to interpreted facies using a matrix of difference. This matrix allows the assessment of errors between facies.

$$Facies\ Log\ Calibration\ (\%) = \frac{\sum_{sim,int}\left(1-Diff_{sim,int}/MaxDiff\right)*thick_{sim,int}}{\sum_{sim,int}thick_{sim,int}}*100$$

Where:

- $Diff_{sim,int}$ is the value assessed by the matrix between one simulated facies and one interpreted lithofacies,
- MaxDiff is the maximum of difference in the matrix,
- $Thick_{sim,int}$ is the thickness of the observation.

		Interpreted lithofacies							
		Grey sdst	Red sdst	Siltstone	Shale	Carbonate	Volcanic	Coal	Anhydrite
Simulated Facies	sands	***0***	***0***	1	2	3	3	3	*5*
	silt	1	1	***0***	1	2	*5*	*5*	*5*
	shales	2	2	1	***0***	*5*	*5*	*5*	*5*
	marls	*5*	*5*	2	1	2	*5*	*5*	*5*
	reef	*5*	*5*	*5*	*5*	***0***	*5*	*5*	*5*
	limestone	*5*	*5*	*5*	*5*	***0***	*5*	*5*	*5*
	muddy limestone	*5*	*5*	4	***0***	2	*5*	*5*	*5*
	mudstones	*5*	*5*	3	***0***	2	*5*	*5*	*5*
	mixed evaporites	1	1	1	1	1	*5*	*5*	1
	gypsum	*5*	*5*	*5*	*5*	*5*	*5*	*5*	***0***
	salt	*5*	*5*	*5*	*5*	*5*	*5*	*5*	***0***

Figure 13: Matrix of difference between the interpreted lithofacies and the simulated facies

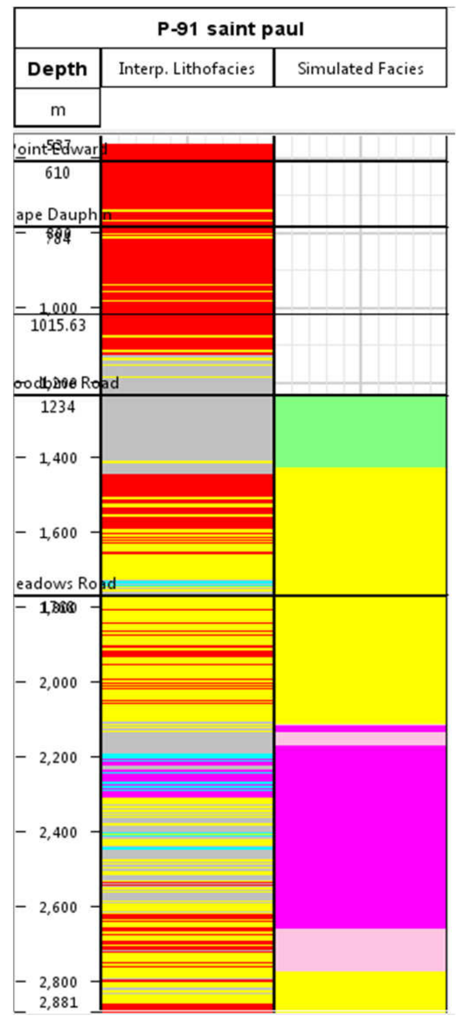


Figure 14: Comparison of log for Well P-91

DionisosFlow® Modelling Framework

Overall stratigraphic and sedimentological assessment

Windsor Group (Figure 15) corresponds to a major marine transgression during the Visean. This marine incursion during the Early Carboniferous period is associated first with carbonate deposits (Macumber Fm. – Lower Windsor) throughout the basin then by massive evaporite deposits and siliciclastic input on the basin edges. During the Upper Windsor, evaporite deposits decrease and tend to be interbedded with carbonate. The end of the Windsor sees the return of continental siliciclastic deposits across the basin.

During the Visean, basin evolution is dominated by thermal subsidence with some local transpression stresses which reactivated pre-existing faults.

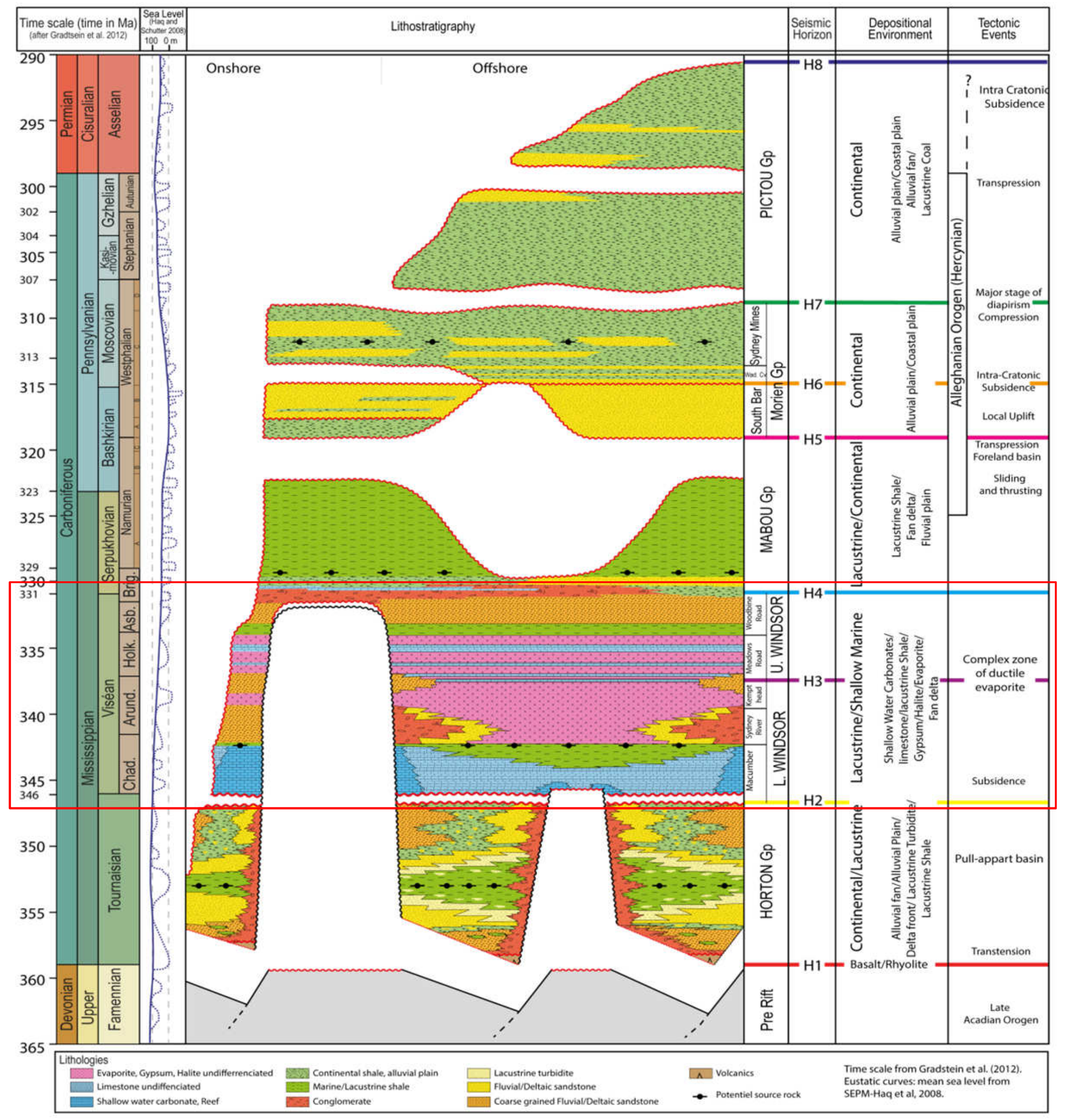


Figure 15: Tectono-stratigraphic chart of the Sydney Basin.

Modelling specifications

Modelling specifications rely on available data and seismic data density and quality. In our case, model specifications are (Figure 16):

- **Model Size**: 188 km x 236 km
- **Cell Size**: 4x4 km
- **Time Steps**: 500 kyrs
- **Period**: 346 to 331My
- **Eustatic curve**: Snedden & Liu, 2010

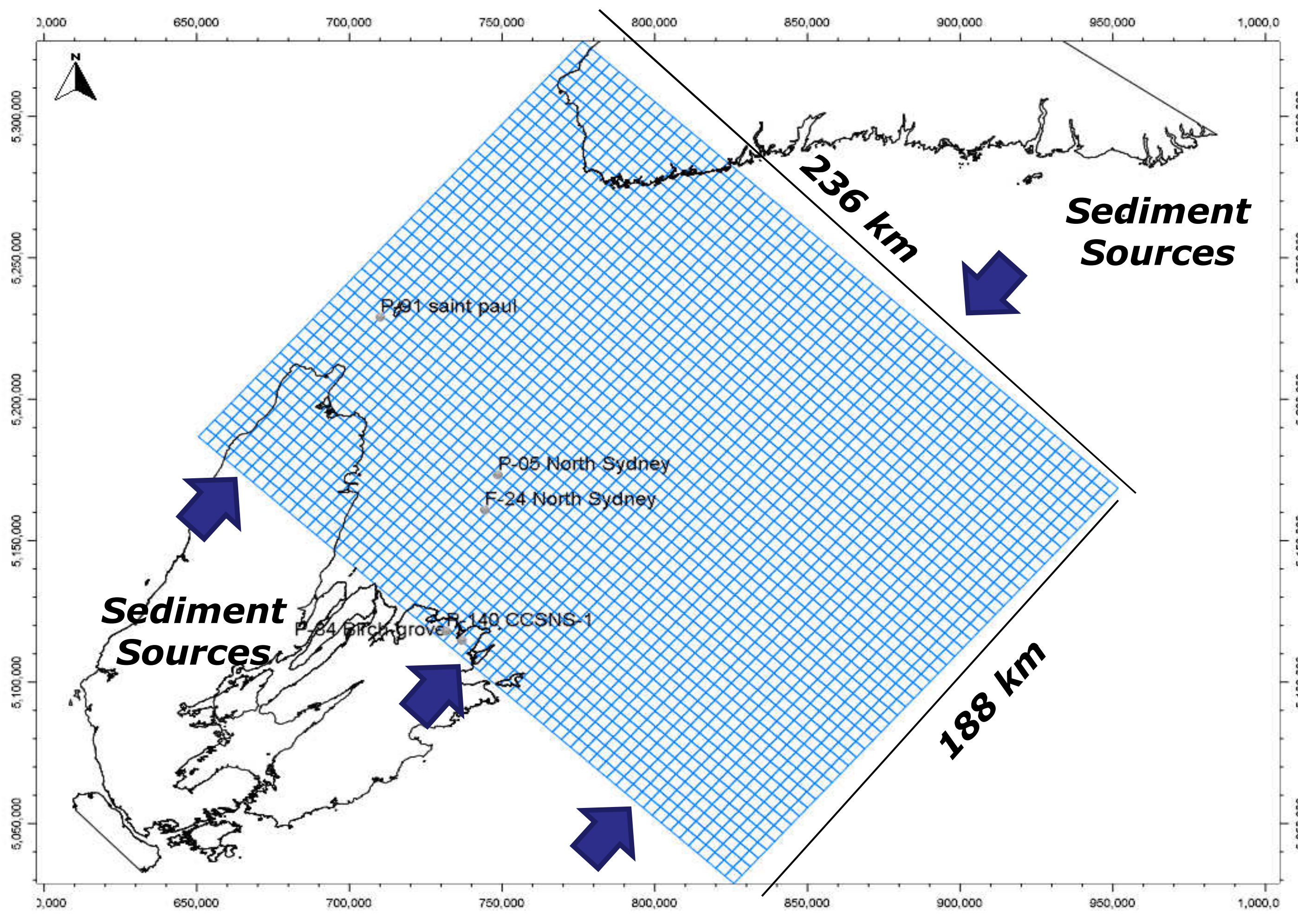


Figure 16: DionisosFlow® model framework, locations of tested sediment sources as well as available well data – only P-91 penetrated Windsor Group.

Initial paleo-bathymetry

The initial paleo-bathymetry map (Figure 17) is a key input for stratigraphic modelling because it constrains the start of the model and the subsidence history.

To compute the initial paleo-bathymetry map, we use the thickness map between Top Horton and Top Lower Windsor. From this map, 0m thickness areas are assumed to be onshore and positive thickness values are assumed to be depocenters. Initial maximum water depth at the Horton – Windsor transition is around 200m (see Chapter 3; Gilles et al., 2009). This value divided by the maximum thickness values gives the ratio to apply to the whole thickness map in order to generate the initial paleo-bathymetry map. The advantages of this method are that it avoids smoothing effects and better highlights the topographic trends.

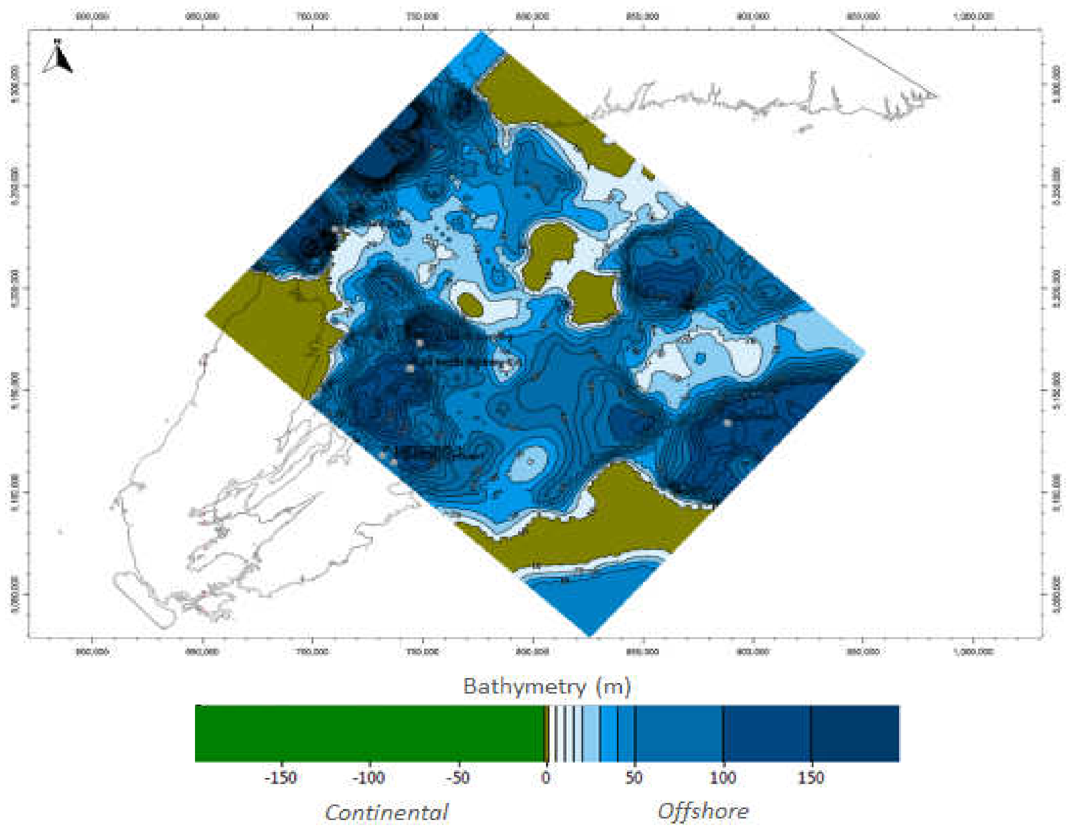


Figure 17: Initial paleo-bathymetry map at 346My – Top Horton.

Windsor environment

During the Visean period, the Sydney Basin climate is assumed to have been arid (Scotese, C., 2000). From this climate and analogs, certain environmental conditions can be deduced (Figure 18). Rainfall was about 100mm/year, evaporation ranged from 1000 to 2000mm/year. Siliciclastic sediments were mainly deposited by torrential processes. Moreover, the marine part of the basin was under meromictic conditions (stratified waters, Schenk et al., 1994) and sea water salinity was from restricted marine to saline.

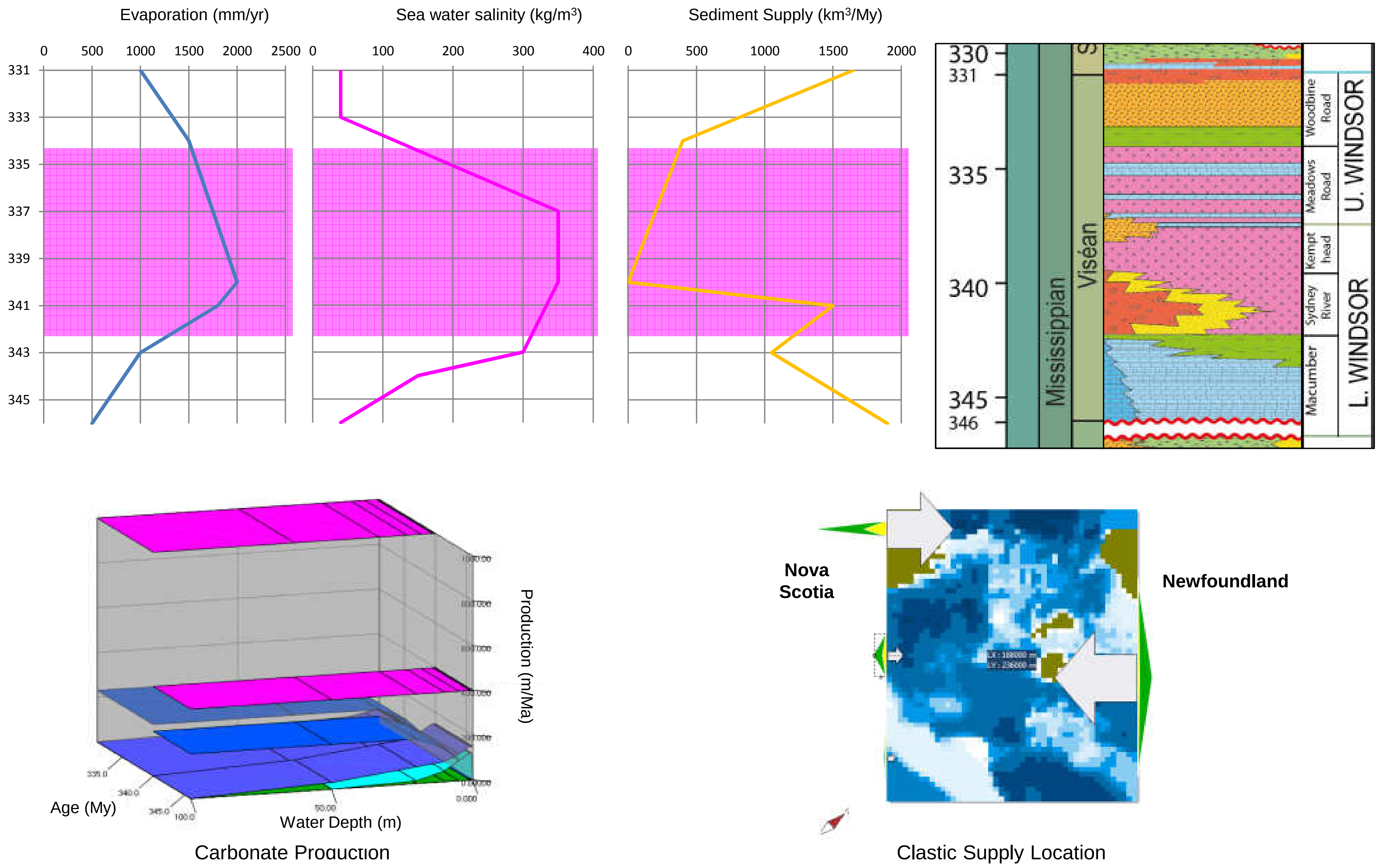


Figure 18: Input parameter ranges for DionisosFlow® modelling.

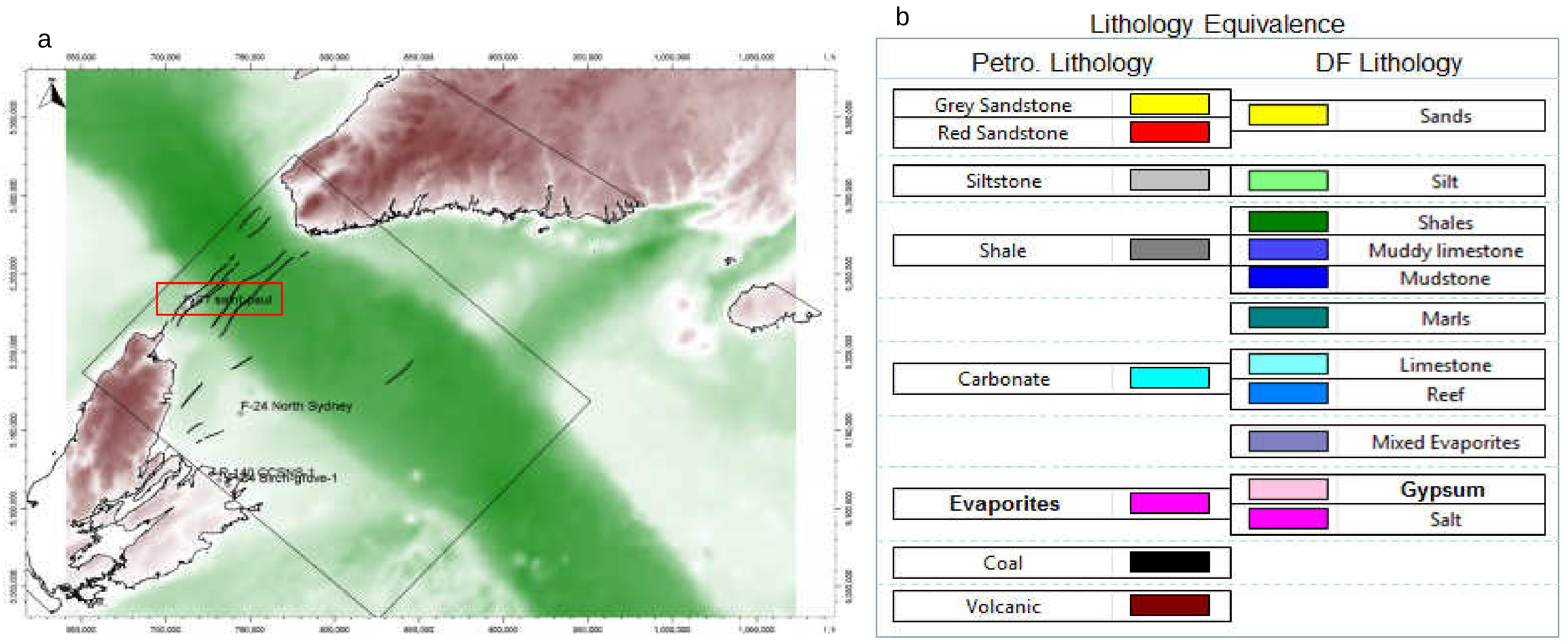
DionisosFlow® Modelling Results

Calibration control (P-91 Saint Paul well and GDE maps)

Well P-91 Saint Paul is the only well that penetrated the Windsor Group. Its calibration is essential to validate stratigraphic modelling results (Figure 19). Nonetheless, well P-91 is located within the Cabot Fault complex, which is an anomalous area with respect to the Sydney Basin. This area records a slightly different tectonic history than the rest of the Sydney Basin, since the bounding faults were active throughout the entire history of the basin (see Chapters 2, 4 and 5.3).

Other calibration control points come from the GDE maps which are based on seismic data and outcrops (see Chapters 3 and 6). Calibrating modelling results against these maps is essential to validate the results (Figures 20 & 21).

However it is to be noted that DionisosFlow® models sedimentary processes through time. In our case, it appears that stratigraphic modelling outputs are more relevant than hand drawn GDE maps due to the lack of hard data in the basin. GDE mapping relies on concepts whereas stratigraphic modelling includes sedimentary processes.



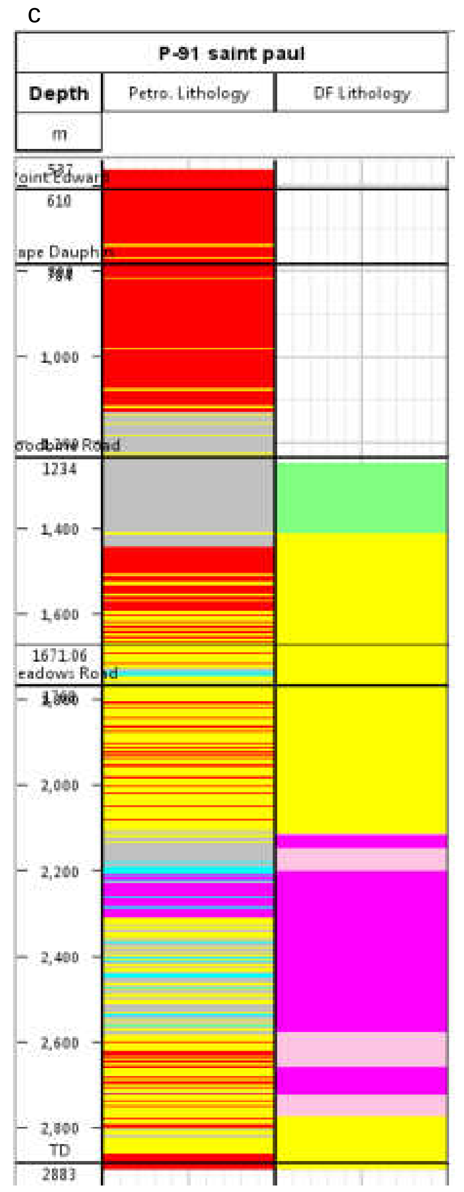


Figure 19: a) location of well P-91; b) Equivalence in lithology between the well (left) and the model (right); c) Comparison between interpreted log (left) and simulated log (right) on well P-91, lithofacies trends are respected.

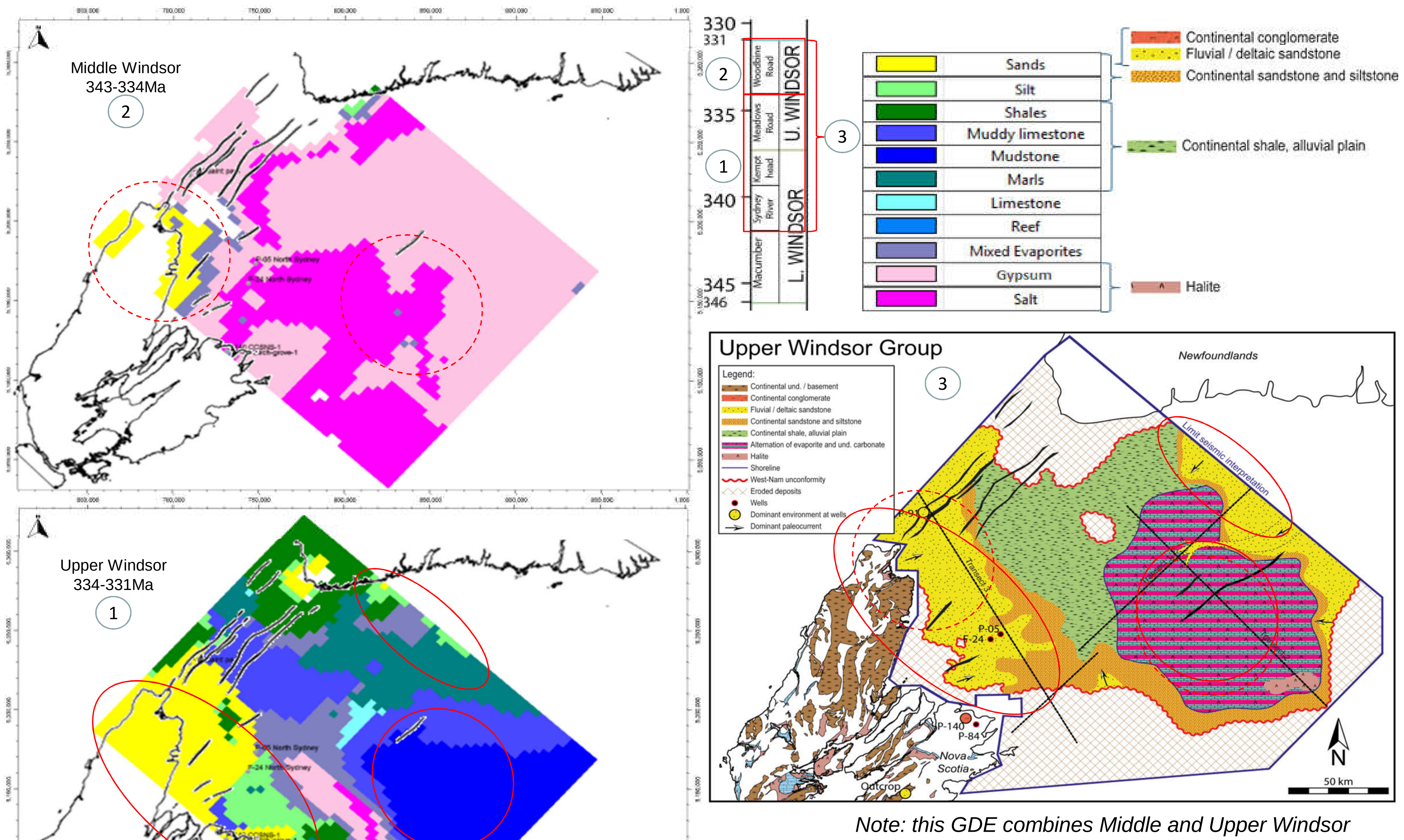


Figure 21: Comparison between DionisosFlow® facies (left) and GDE map (right) for Middle and Upper Windsor.

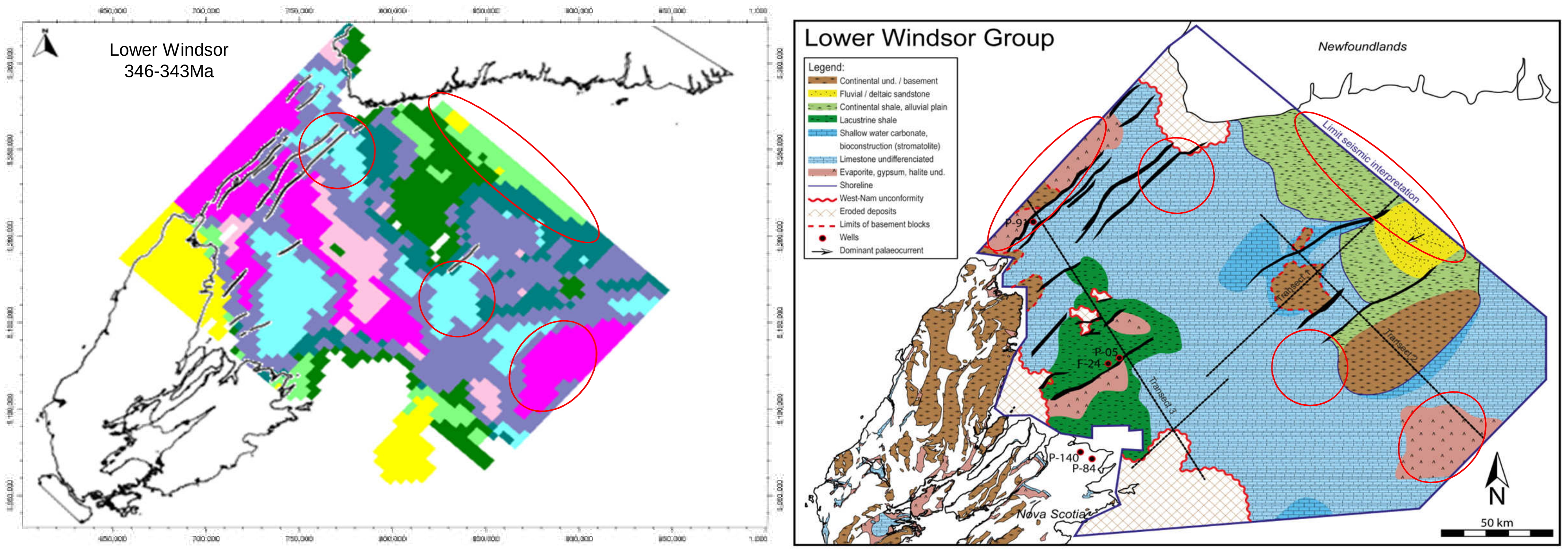
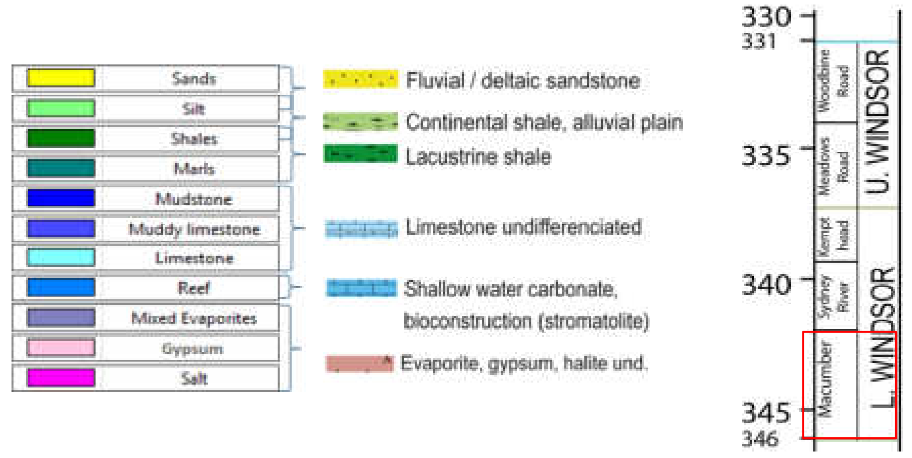


Figure 20: Comparison between DionisosFlow® facies (left) and the GDE map (right) for Lower Windsor (Macumber Fm).; Red circles show areas of similarity

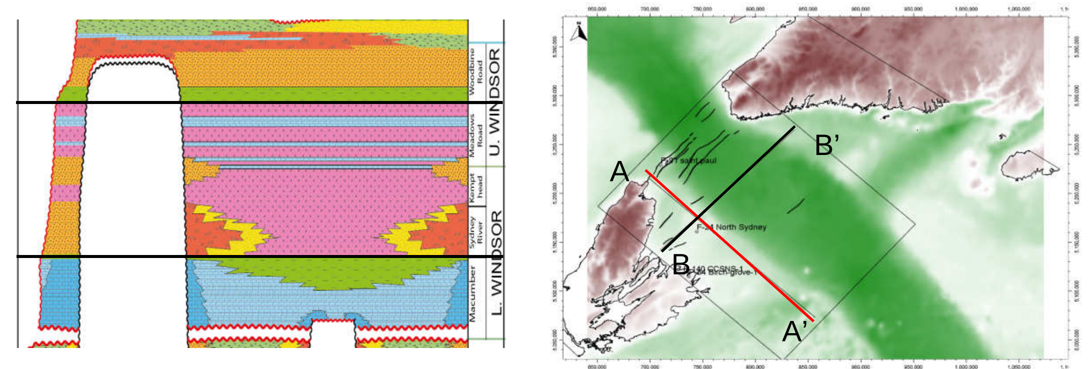


The DionisosFlow® facies map was computed for the whole Macumber interval (i.e. from 346Ma to 343Ma). Facies are defined according to sediment proportions in a time slice. Sediment proportions are recomputed from time slice to the whole interval in order to represent the main facies present in the interval.

Wheeler diagrams

Wheeler diagrams show the timing of different formations through time. The sections presented here are extracted from the DionisosFlow® model with a vertical time axis (Figure 22).

The two diagrams show that evaporite deposits cover a large period of the Visean. The SW-NE diagram shows a stratigraphic record very similar to the stratigraphic chart. The second transect shows that clastic inputs are restricted and that the basin is evaporite and carbonate-dominated.



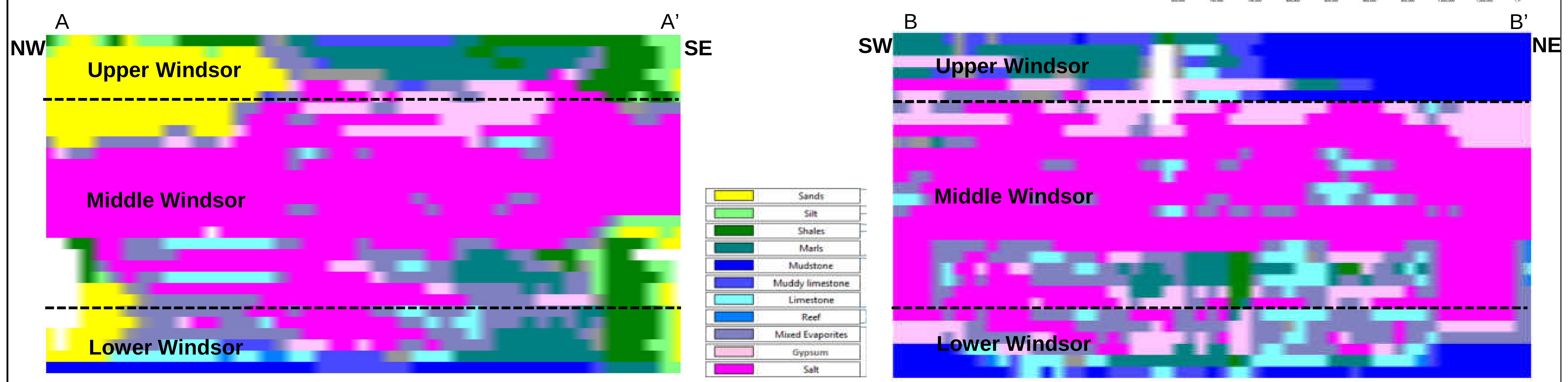


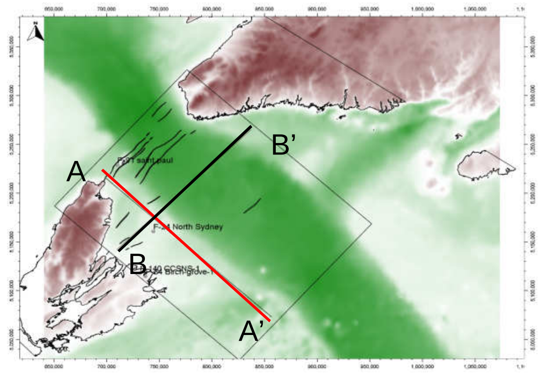
Figure 22: Wheeler diagrams extracted along strike (AA') and dip (BB') in Sydney Basin.

DionisosFlow® Modelling Results

Extracted sections along strike and dip

Sections extracted from DionisosFlow® model (Figure 23) show:

- Lower Windsor (~Macumber Formation) is dominated by carbonate deposits across the basin,
- Middle Windsor (~Sydney River, Kempth Head and Meadows Road Formations) is dominated by thick evaporite deposits (mainly salt),
- Upper Windsor (~Woodbine Road Formation) registers a transition from marine environment to continental with siliciclastic deposits present at the basin edges.



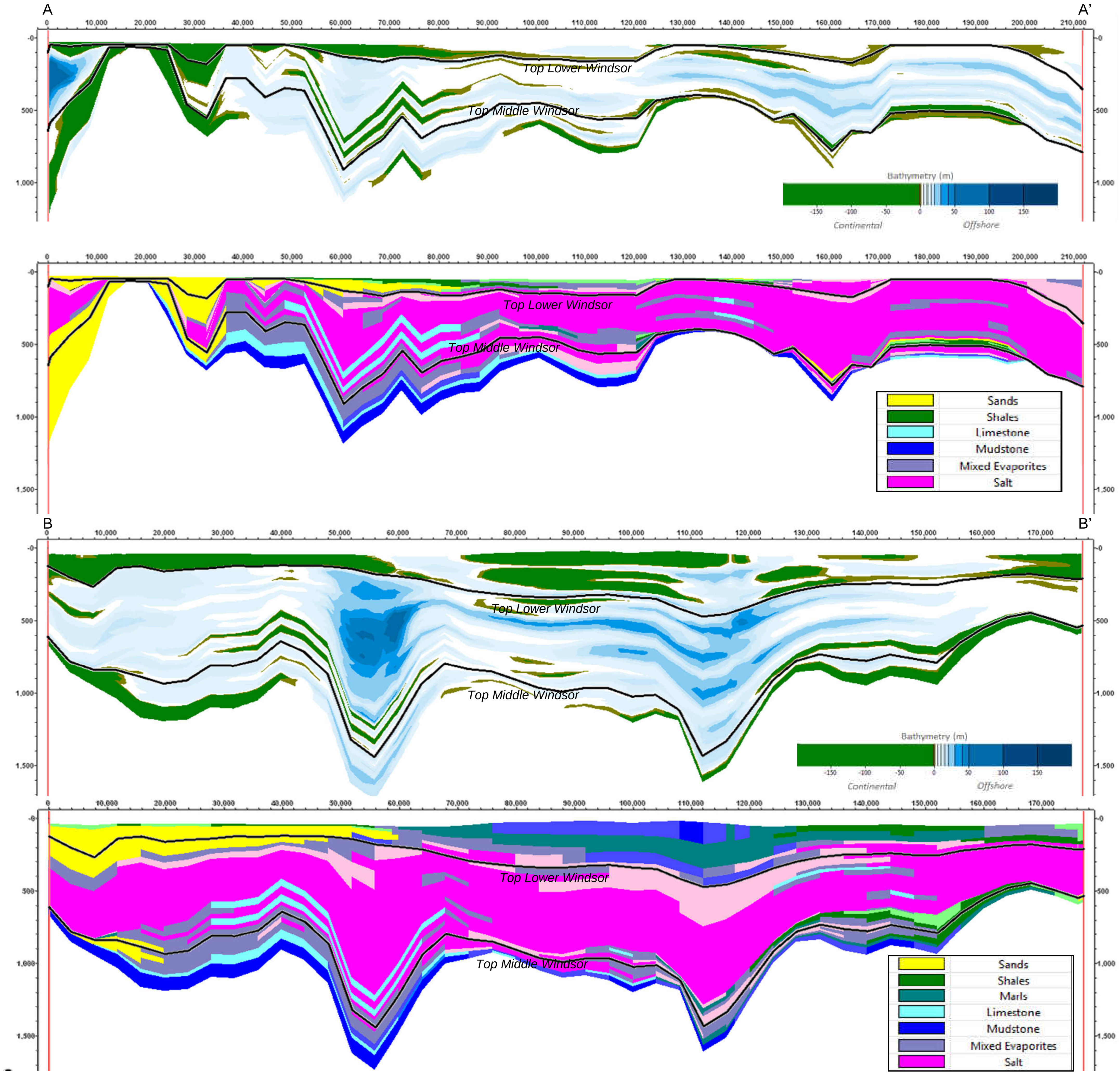


Figure 23: Paleo-bathymetry (upper) and facies (lower) sections extracted along strike (top – AA') and dip (bottom – BB') in Sydney Basin.

Salt thickness maps

In order to generate salt thickness maps, we simulate the production of evaporitic sediments using laws of production and salinity concentration in sea water. Results show that salt is deposited as thick banks. The following maps (Figure 24) show that the Middle Windsor interval appears to be very efficient in terms of seal capacity across the basin. Mean salt thickness ranges from 200 and 1100 m. The salt extent is quite continuous during the Middle Windsor. The extent of the salt and its thickness suggest a good seal. However, as DionisosFlow® cannot take into account fault activity after the Visean, seal integrity and capacity is restricted to presence, thickness and quality.

As DionisosFlow® follows a process-based approach, various combinations of parameters can lead to a good data-calibrated model, i.e. there is no single answer. Therefore an assessment of the different possible combinations is needed. Thus, seal capacity and integrity will be assessed and risk better understood through the analysis of multiple iterations ("multi-realizations").

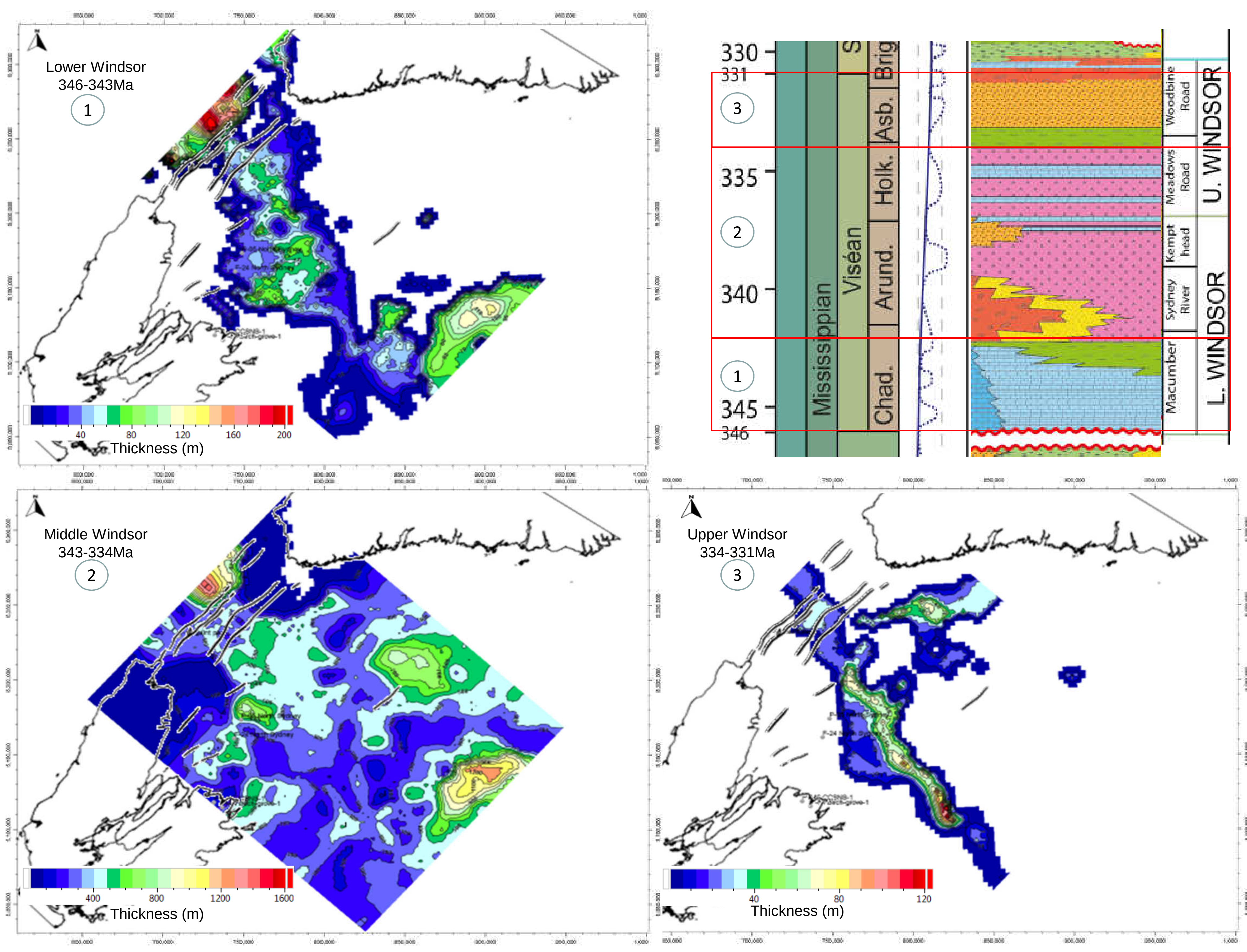


Figure 24: Salt thickness maps extracted from DionisosFlow® model, NB: Salt = Halite + Potash.

CougarFlow® Multi-Realization Parameter Uncertainty Ranges

Parameter uncertainty ranges

DionisosFlow® produces a deterministic model based on a set of input parameters. These inputs are determined by experience, literature and trial and error loops. Each of these parameters has an uncertainty range resulting in potentially non-unique solutions. It is possible that many combinations of parameters can lead to a calibrated model. As seal integrity and capacity is the objective of the study, input parameters involved in the modelling have to be tested. The following parameters are the ones that contribute to the seal modelling:

- Evaporation (mm/year) and sea water salinity (kg/m³) are embedded within the same uncertainty meta-parameter since their evolution is interconnected. Their variation is of the same order of magnitude. Ranges of uncertainty are set at +/-20% of the default values (Figure 25) because these values are averages for arid climates.

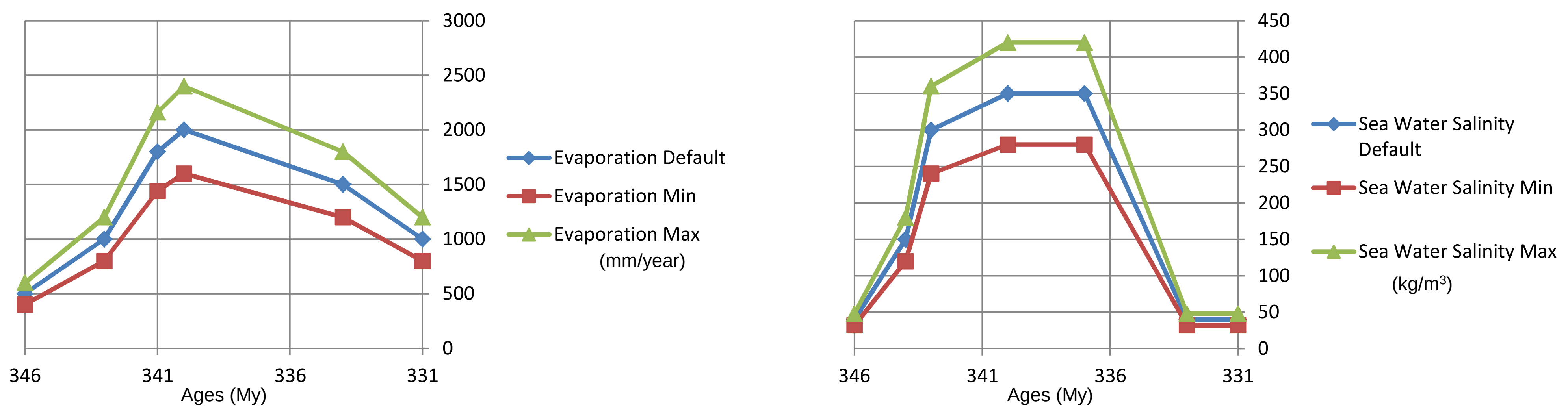


Figure 25: Evaporation uncertainty range (left) and sea water salinity uncertainty range (right).

- Reef production (m/My) parameter: Giles (2009) suggests a production of 500m/My, but results from stratigraphic modelling rather suggest values around 150m/My at its maximum. Therefore, taking into account literature values, the upper limit of carbonate production will be doubled (Figure 26).

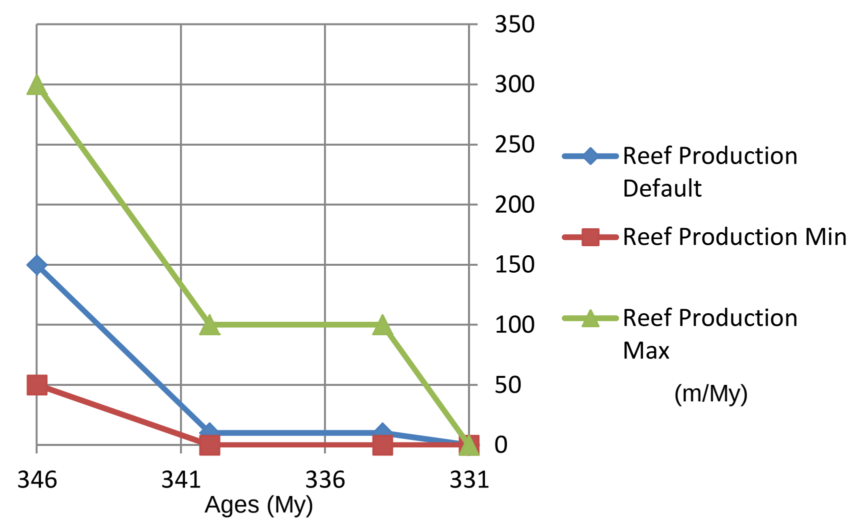


Figure 26: Reef production uncertainty range (left).

- Clastic sediment sources and properties: Siliciclastic inputs, sediment supply (km³/My) and fluvial discharge (m³/s) are embedded in a similar uncertainty meta-parameter. Ranges vary from 0 to 160% of the default values (Figure 27). The 0 value describes an extreme scenario where there is no external siliciclastics except those coming from erosional processes. The 160% scenario is based on maximum rain fall values reached in arid climates. As a reminder, the default model was calibrated with rainfall at 100mm/year. It has been assumed that siliciclastic influx was extremely low around 340My because well and field information show large transgressions where sediment will be probably trapped upstream preventing siliciclastic transfer to the basin.

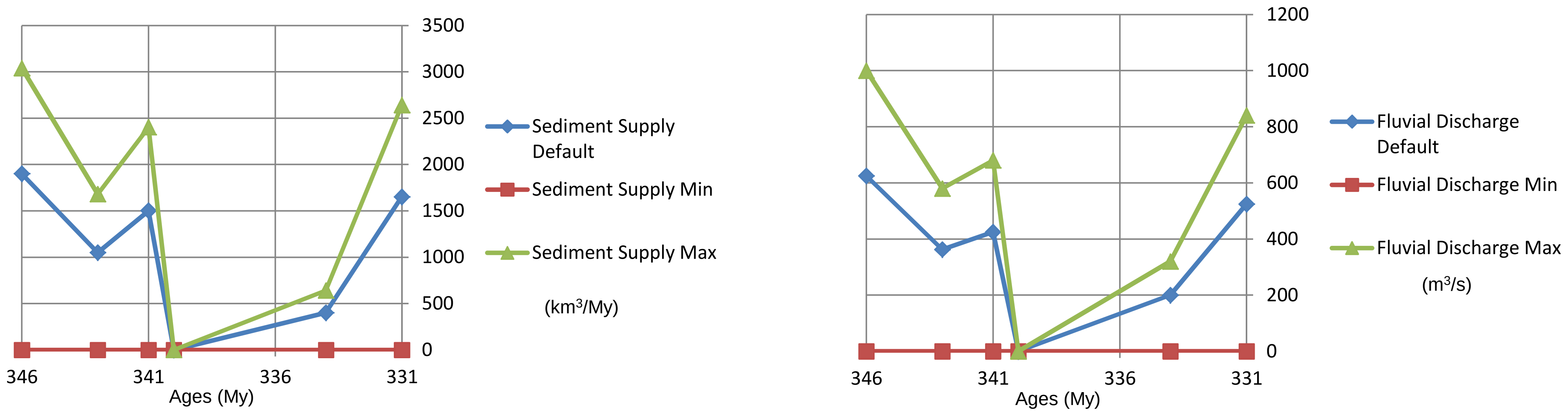


Figure 27: Sediment supply uncertainty range (left) and fluvial discharge uncertainty range (right).

- Sea level (m): the default curve comes from Snedden & Liu (2010) which is derived from the Haq curve. A range of +/-20m has been selected for the basin which corresponds to a shallow marine setting during the Visean (Figure 29).

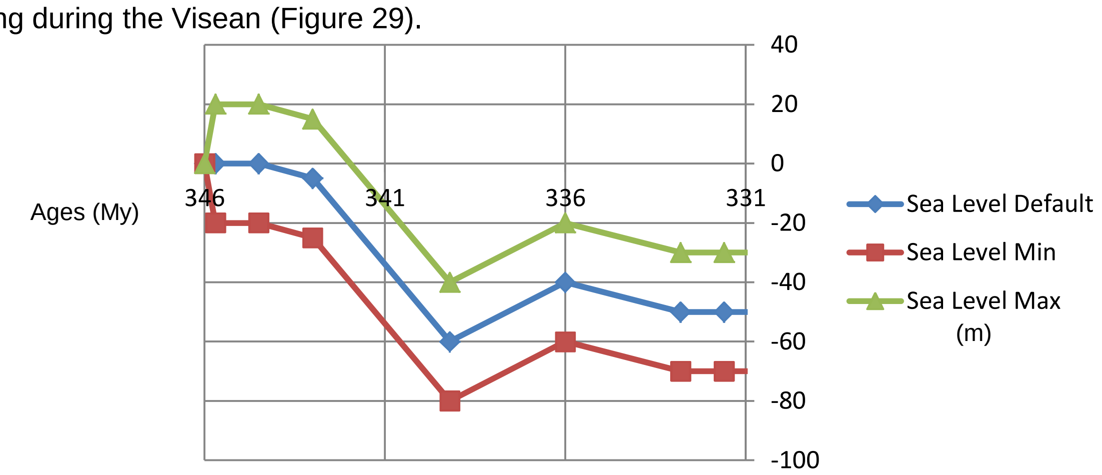


Figure 29: Sea level uncertainty range.

- Subsidence at 340Ma (m) – intra Middle Windsor: Differential subsidence from one side to the other side of Cabot Fault was defined as uncertainty parameter. Amplitude of vertical movement was modified in these scenarios. The F-24 well area also varies, as seismic data highlight that it is a depocenter for Lower Windsor and early Middle Windsor (Figure 30).

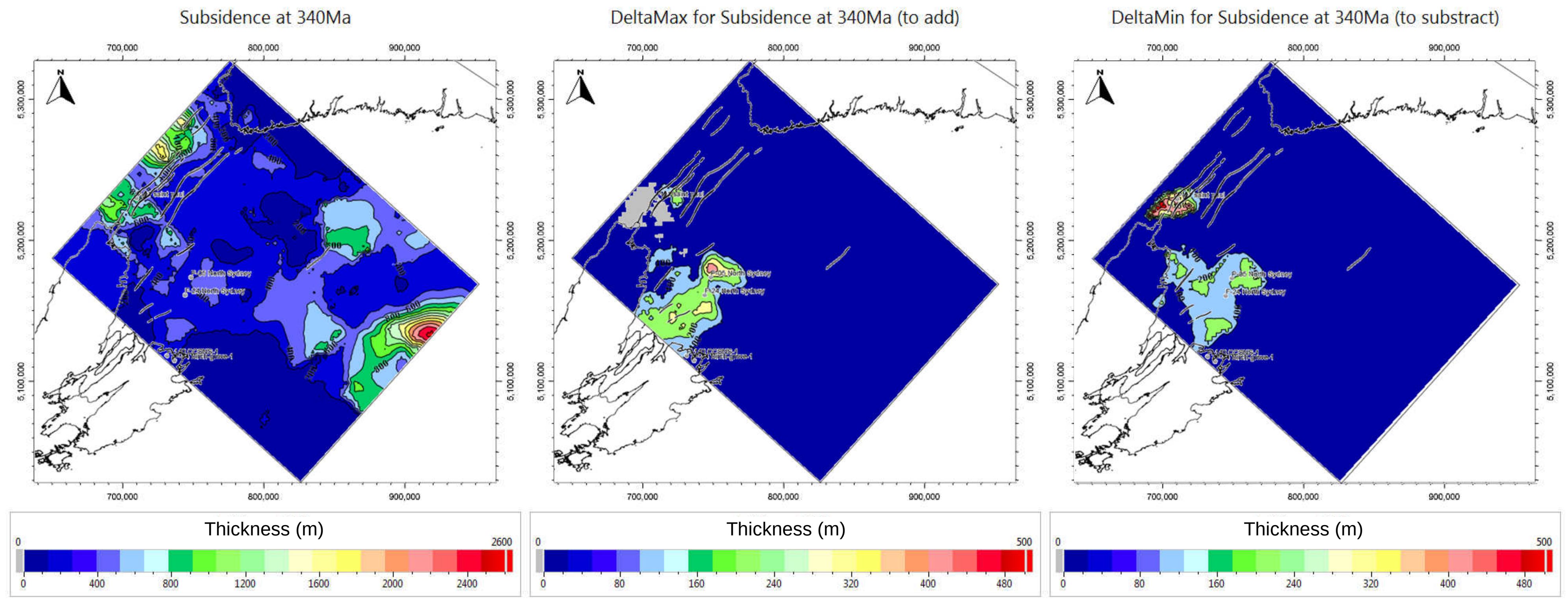


Figure 30: Default subsidence map of intra Middle Windsor with associated deltas to add/substract in order to produce an uncertainty range.

- Subsidence at 334Ma (m) – Top Middle Windsor: From the seismic interpretation (Chapter 5.3) we observed a shift in depocenter during the Middle to Upper Windsor. The northern depocenter is in place earlier than the southern one (Figure 31). As the timing of depocenter migration is not well constrained, we attribute a range of uncertainty to this as well.

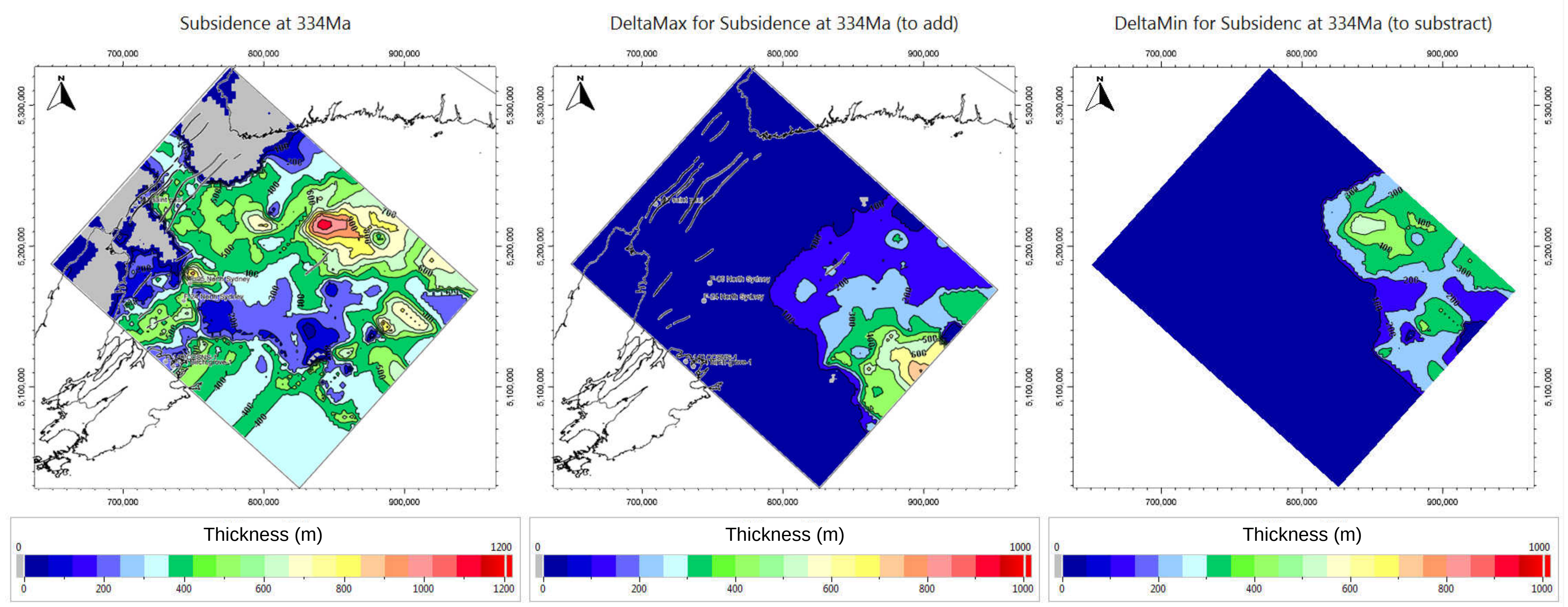


Figure 31: Default subsidence map of top Middle Windsor with associated deltas to add/substract in order to produce an uncertainty range.

CougarFlow® Multi-Realization Results

Multi-Realization calibration results

103 simulations were run and 93 finished successfully. Others failed to converge on a solution. Of the 93 successful runs 83 are selected because they produced reasonable calibration values.

All simulation results were assessed through calibration indicators (facies and thickness) (Figure 32). Thresholds for both indicators were defined following literature (Koeck et al., 2015; Barrois et al., 2016). If both calibration values are above these thresholds, the simulations are considered to be calibrated. The map thickness calibration threshold was set at 80% and well facies calibration threshold was set at 70%.

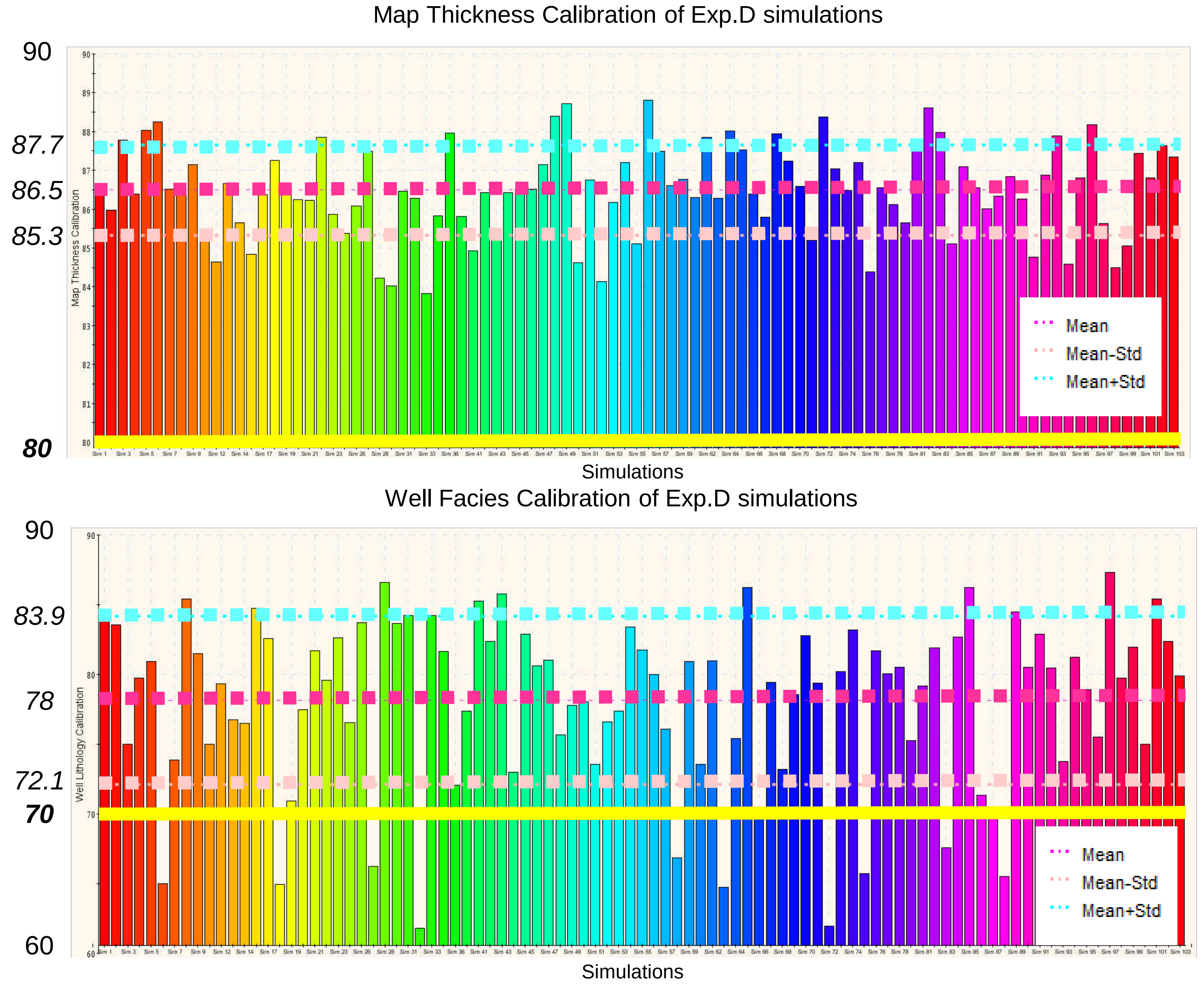


Figure 32: Map thickness calibration values (top) and well facies calibration values (bottom); on Y-axis, bold value with yellow line indicates the threshold, italic values with dashed lines indicate from top to bottom, Mean + Standard deviation, Mean, Mean – Standard deviation.

Multi-Realization main influential parameters

Using the sensitivity analysis, the influence of each parameter's uncertainty can be evaluated on both calibration indicators. Figure 33 illustrates that for facies calibration, three parameters primarily control the results: sea level, subsidence at 334Ma (top Middle Windsor) and siliciclastic inputs. For facies calibration, two parameters are most influential: siliciclastic input and subsidence at 340Ma (intra Middle Windsor).

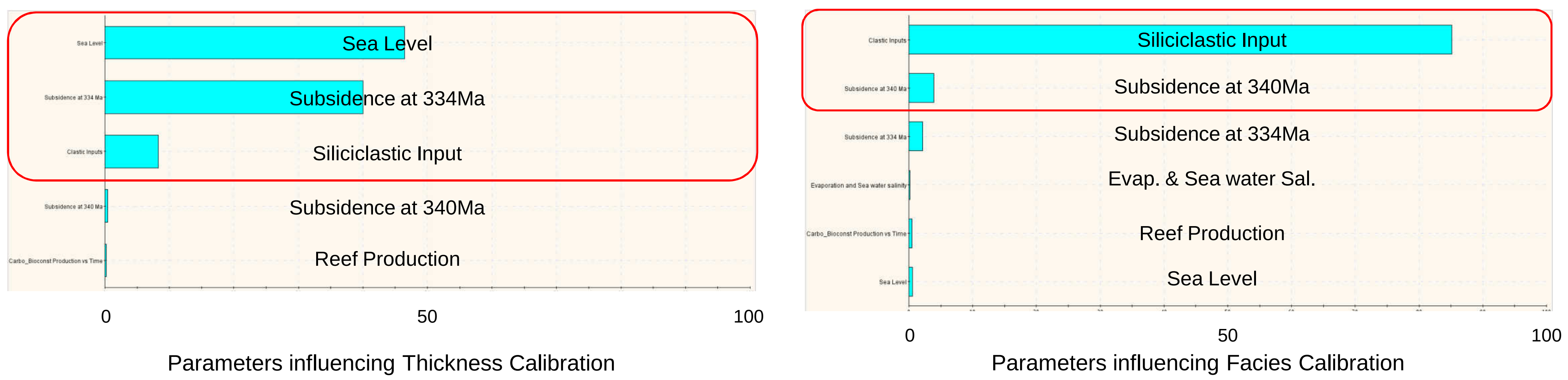


Figure 33: Parameters' influence on map thickness calibration results (left) and on well facies calibration results (right).

It should be underlined that the primary uncertainties can be reduced by acquiring modern 3D seismic data since subsidence has influence on both calibration indicators.

Insights on the well facies calibration indicator

As previously mentioned, only one well – P-91 Saint Paul – penetrated Windsor Group. Because of its location this well is not representative of the entire Sydney Basin. This is why two synthetic wells have been extracted from the reference model (Figure 34; See Pl. 7.1.5 for the reference model). Their positions have been selected according to the stratigraphic record of the basin. One is located at the F-24 North Sydney well position. In this area, outcrops and data tend to demonstrate that the Windsor Group is represented by thick salt, which is also what was observed in the stratigraphic modelling results. Another well (named Basin Well) has been extracted in the southeast part of the block, in an area where the salt is expected to be very thick as suggested by salt diapirs. The extracted logs are used as observed data for calibration computation. Note that these two locations (1 & 2) are pseudo wells created to assist the calibration process.

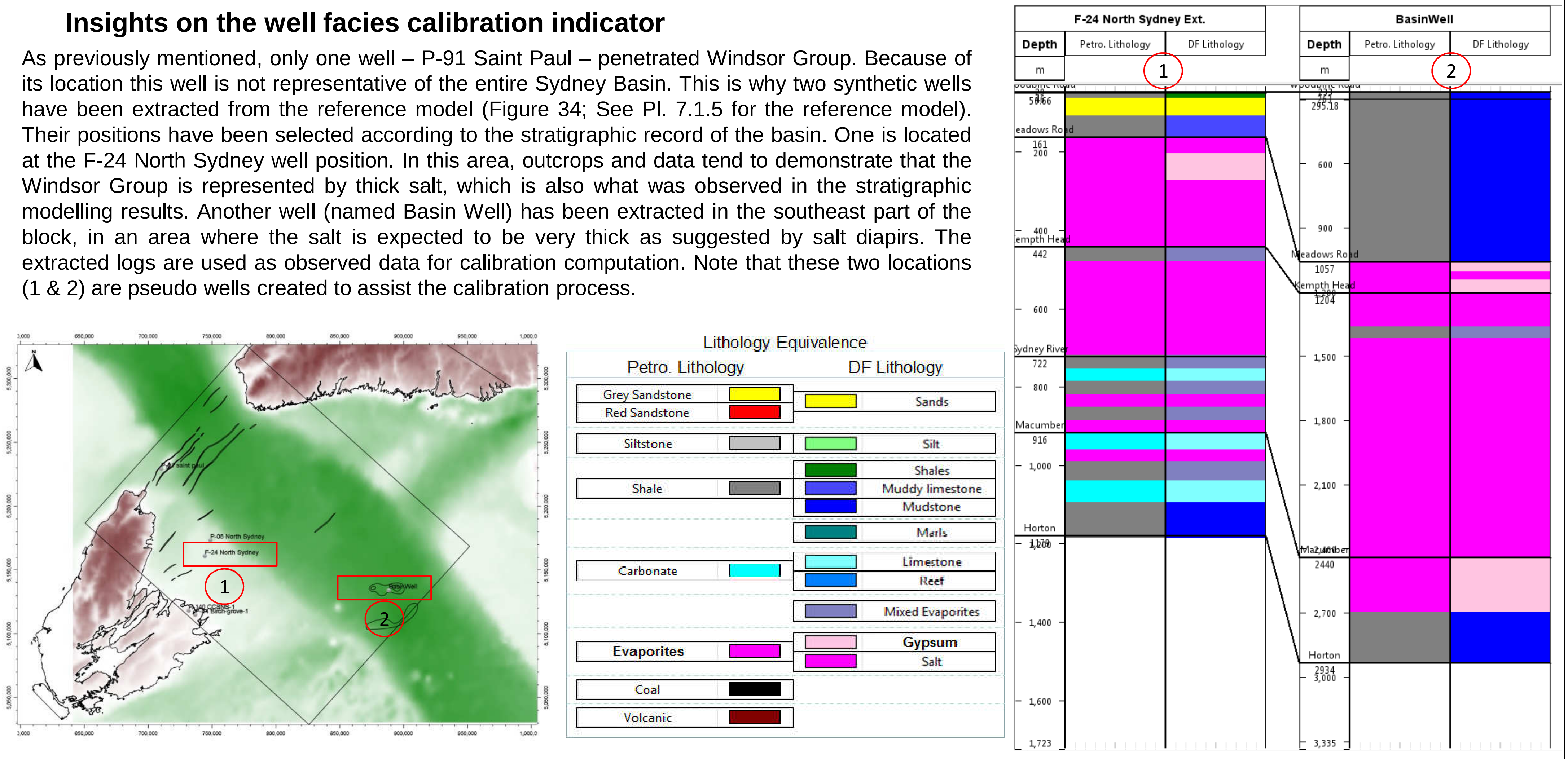


Figure 34: Synthetic wells positions and extracted logs.

Independent sensitivity analyses have been completed on the facies calibration indicator for each well (Figure 35). These analyses reveal that for the synthetic wells, subsidence parameters are the main influential factors (respectively 30% for subsidence at 340Ma for F-24 and 60% for subsidence at 334Ma for Basin Well) contrary to the P-91 well whose most influential parameter is siliciclastic input at 90%. If we exclude the Cabot Fault area, subsidence appears to be the main driving factor on facies calibration at the basin scale, whereas at Cabot it is a combination of clastic input and subsidence. This is well represented in Figure 36.

In Figure 36, simulation 54 has a high calibration value but general facies trends are not represented. This is contrary to simulation 1 (reference model) and simulation 56 whose thickness calibration is less good but facies trends are more accurate.

Because of its particular location, P-91 represents only a part of Sydney Basin's geological history. Therefore a good calibration of the well is necessary but not sufficient. This is why it is highly important in this study to add calibration wells at locations where we can assume that the reference model is closest to the geological model.

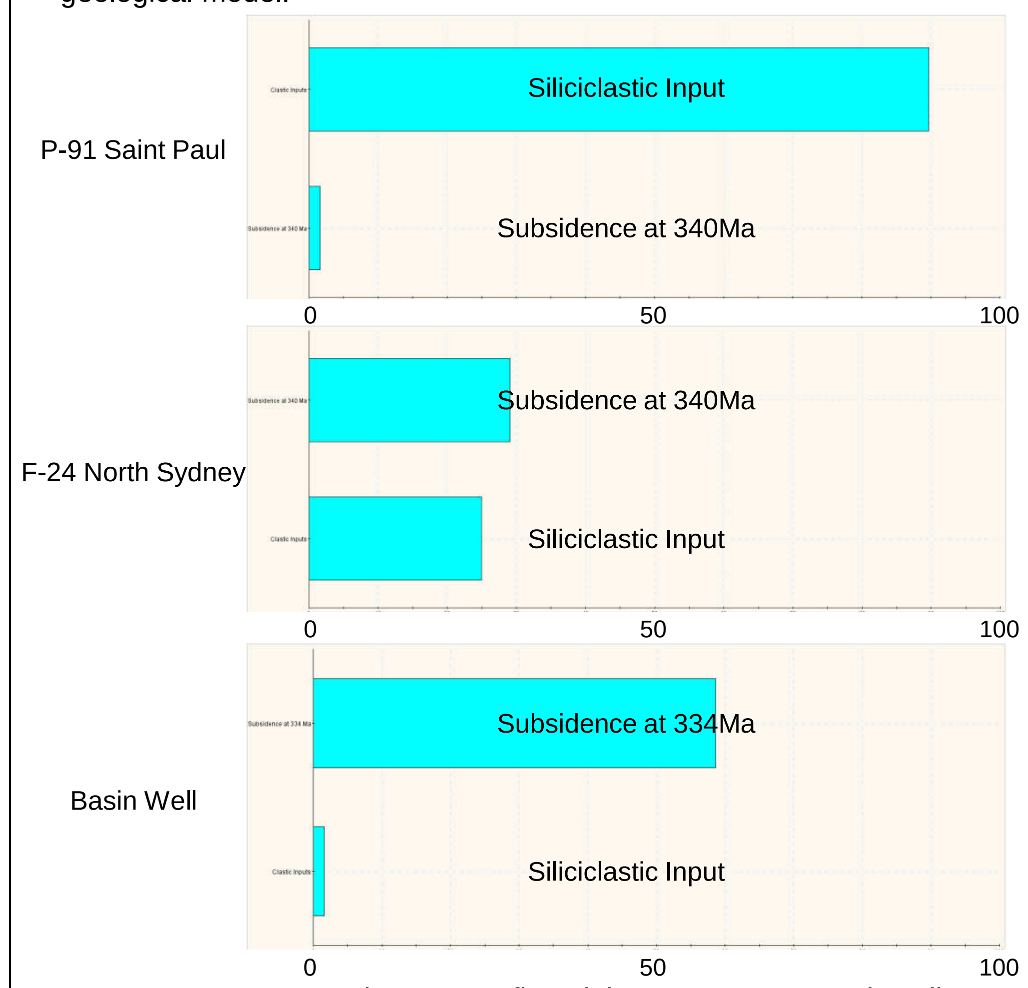


Figure 35: Influential parameters on each wells.

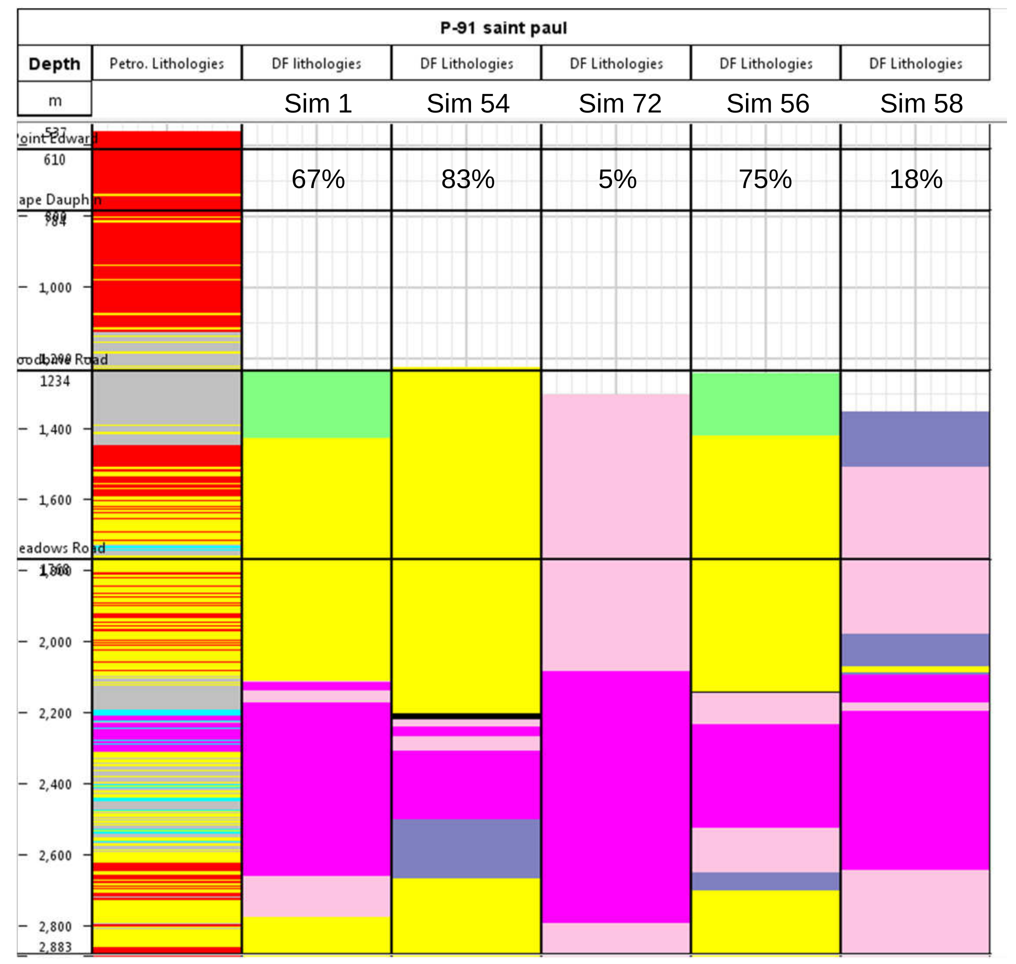


Figure 36: Different simulated logs extracted from several simulations with their facies calibration values.

CougarFlow® Multi-Realizations Results

Salt thickness confidence

Of 103 simulations run, 83 were validated in terms of calibrations by both calibration indicators. From this set of simulations, statistical maps can be computed to assess the seal capacity and integrity of the Middle Windsor interval. From this panel of simulations, two types of confidence properties will be provided:

- A mean salt thickness map of the Middle Windsor and its associated standard deviation,
- A 3D block representing salt occurrence within the Middle Windsor highlighting possible leakage areas.

Salt thickness confidence for the Middle Windsor

The mean salt thickness map and its associated standard deviation map (Figure 37) permit an evaluation of the seal capacity and integrity of the Middle Windsor. Only this formation is considered as an effective regional seal since it comprises the main massive salt deposits.

From computed maps, seal capacity and integrity appear good to excellent across most of the Sydney Basin; mean salt thickness ranges from 200m to 1100 m with a normalized standard deviation at 25% of the salt thickness. Exceptions are observed around actual onshore limits and around the Cabot Fault area where salt thicknesses are good but the standard deviation is higher than 100% of the salt thickness. It should be noted that fault activity from Middle Carboniferous to present is not taken into account in our models and can degrade seal integrity. It is also important to note that salt deposits outcrop along the shore of Nova Scotia which supports the assessment of lower risk (but outcrop information cannot be included in the calculations).

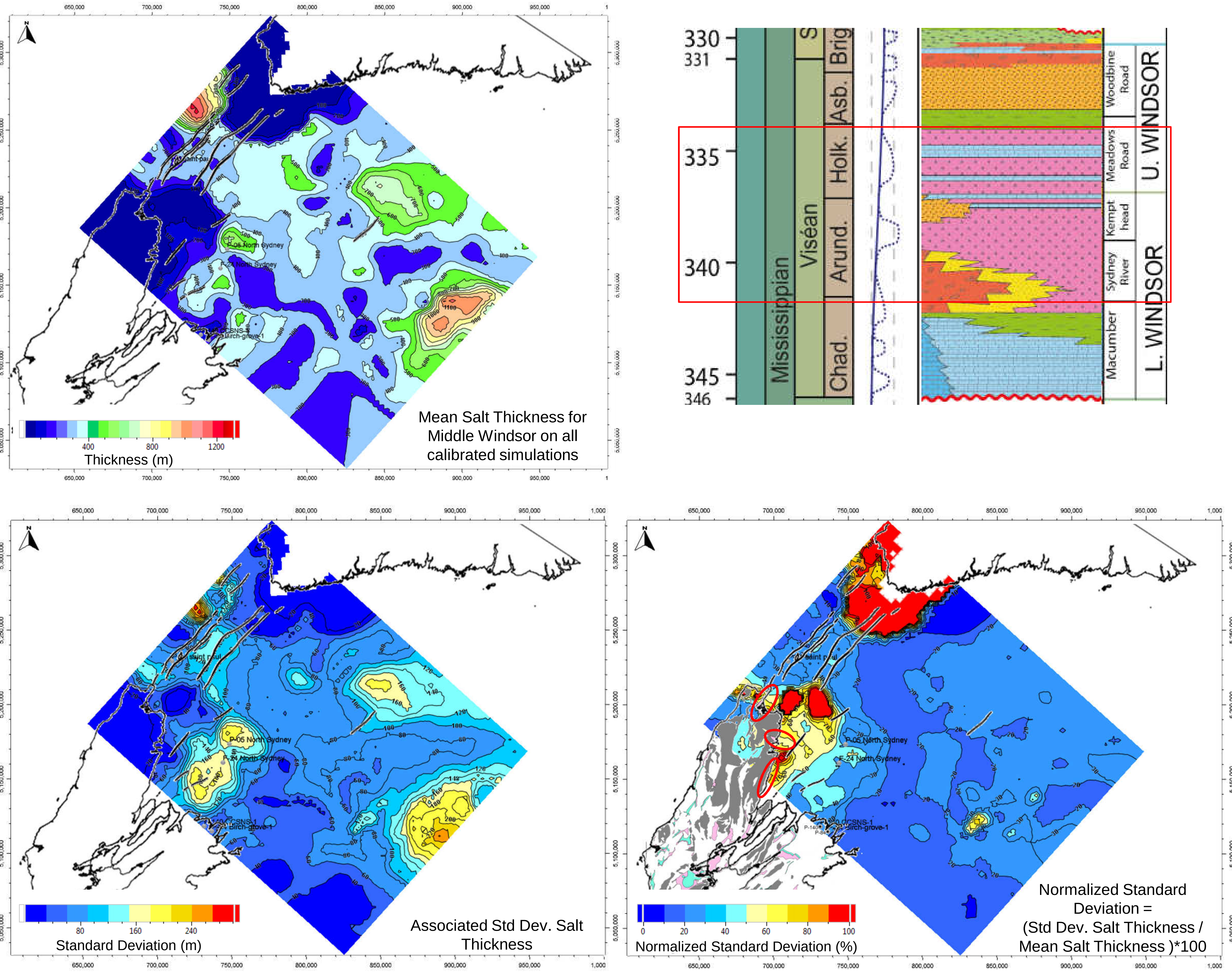
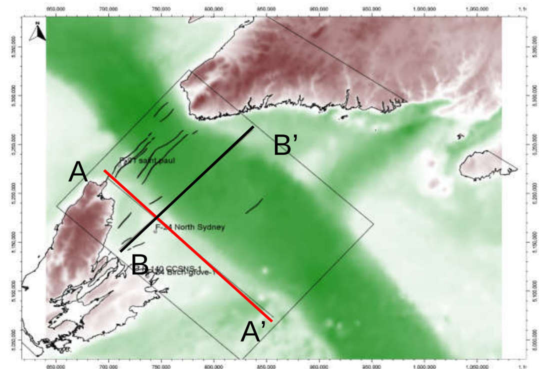


Figure 37: Mean salt thickness map (top left hand corner), associated standard deviation map (bottom let hand corner) and associated normalized standard deviation map (bottom right hand corner); on the last map red ellipses highlight Windsor salt outcrops.

Salt occurrence confidence

A 3D block assessing salt occurrence for the Middle Windsor was computed from the 83 calibrated models. To produce this block, the presence of salt was tested in each corresponding cell of all calibrated blocks. When salt is present at a cell, a salt counter is incremented by one. When all blocks are screened, results are weighted by the total calibration simulation number. This method allows the creation of a 3D block evaluating the salt occurrence confidence on a scale varying from low to high risk.

Extracted sections of the Middle Windsor interval are displayed in Figure 38. Seal capacity appears good as salt deposits are continuous and massive across most of the Sydney Basin.



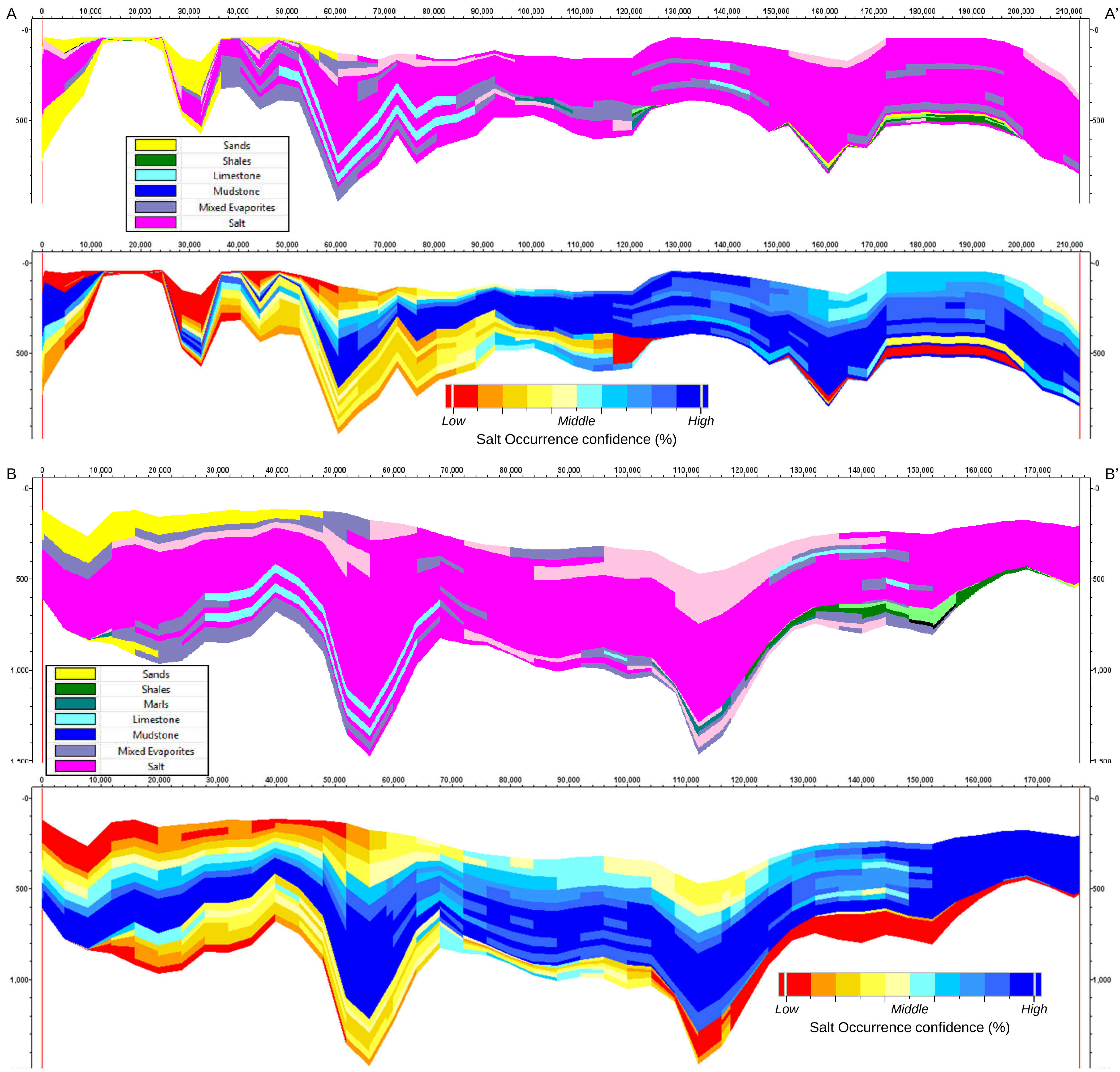


Figure 38: Facies (upper) and salt occurrence confidence (lower) sections extracted along strike (top – AA') and dip (bottom – BB') in Sydney Basin for the Middle Windsor Group.

CougarFlow® Multi-Realizations Results & Conclusions

Salt occurrence confidence

Salt occurrence confidence 3D block allows assessment of the possible leakage areas of the Middle Windsor seal (Figure 39).

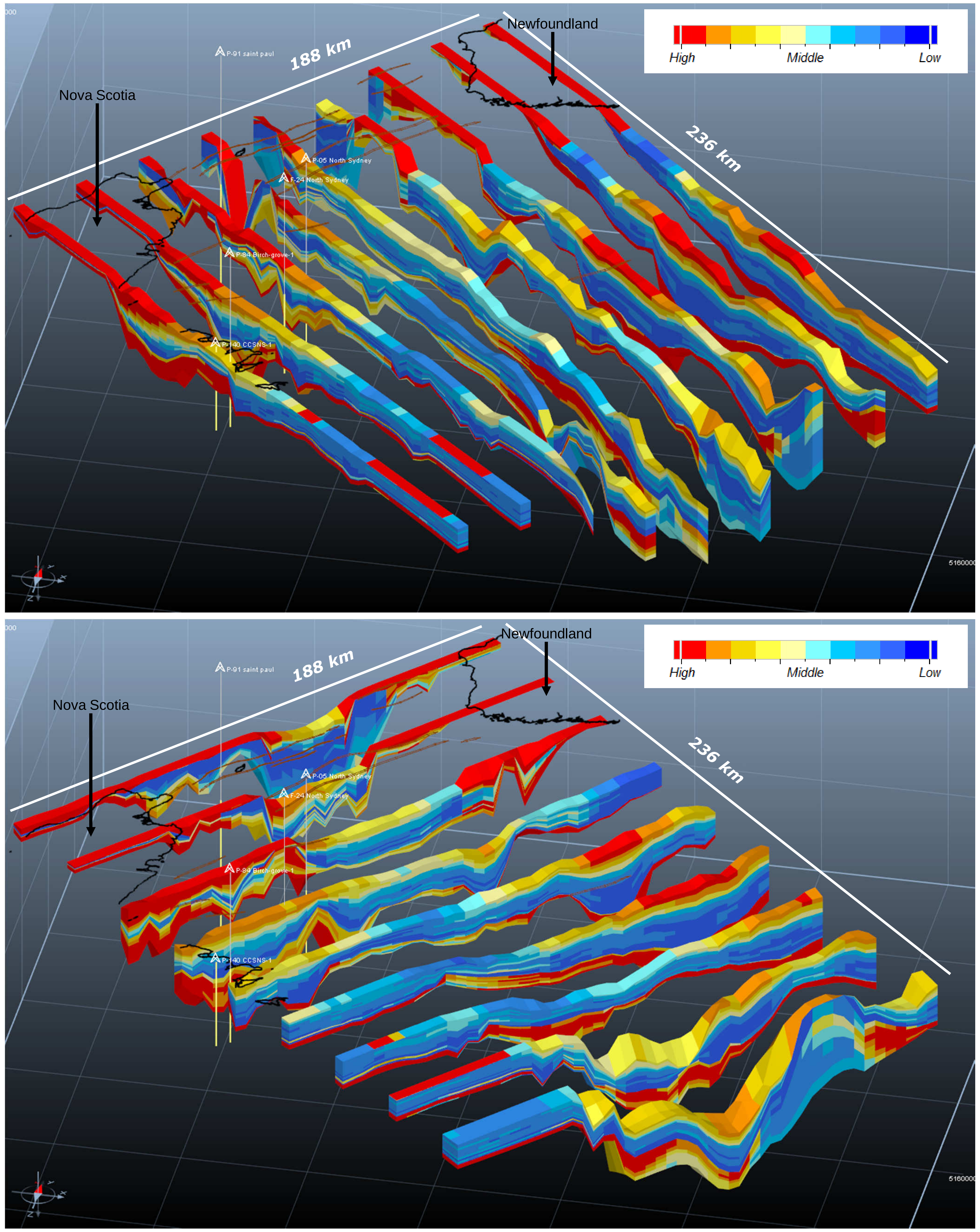


Figure 39: Salt occurrence confidence 3D block fence diagram along strike (top) and along dip (bottom); Northwestern area is the one presenting the highest risk of leakage. Red = high relative risk, blue = low relative risk

Stratigraphic modelling and multi-realizations conclusions

To conclude, the Windsor Group presents a good regional capacity especially in its Middle Windsor interval (Figure 40 & 41). Leakage areas are assessed in the northwestern part of the block around actual onshore Newfoundland and Nova Scotia. Nevertheless, onshore Nova Scotia presents a lower risk as Windsor salt outcrops can be observed and these observations cannot be directly included in the modelling.

The main limit of the modeling to predict seal capacity and integrity is that the DionisosFlow model spans only the Visean stage from the early Carboniferous. Fault activity, specifically due to motion on the Cabot Fault, could affect the seal characteristics from Middle Carboniferous to present and this would not be captured in the present modeling work.

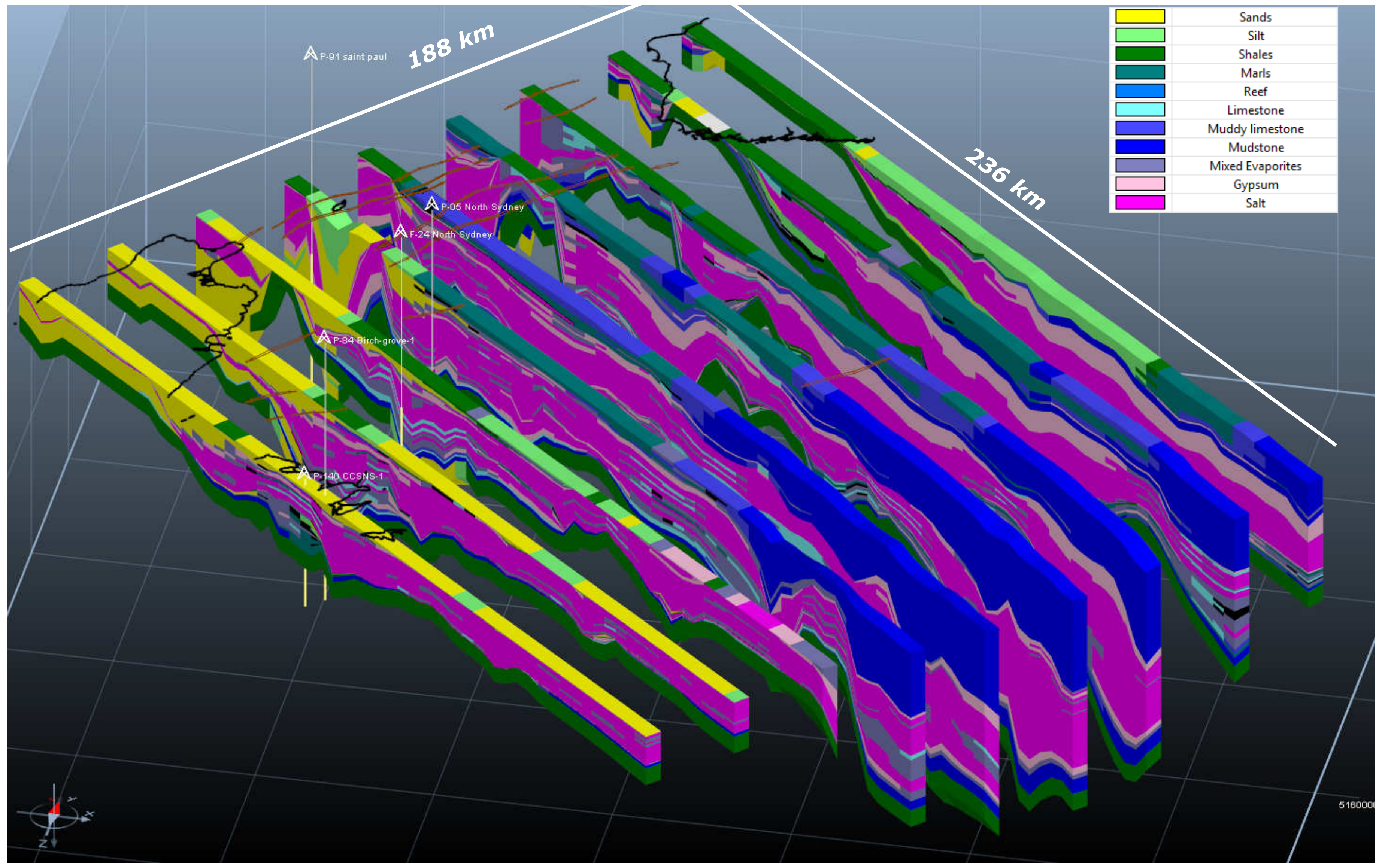


Figure 40: 3D fence diagram of lithofacies distribution for Windsor interval

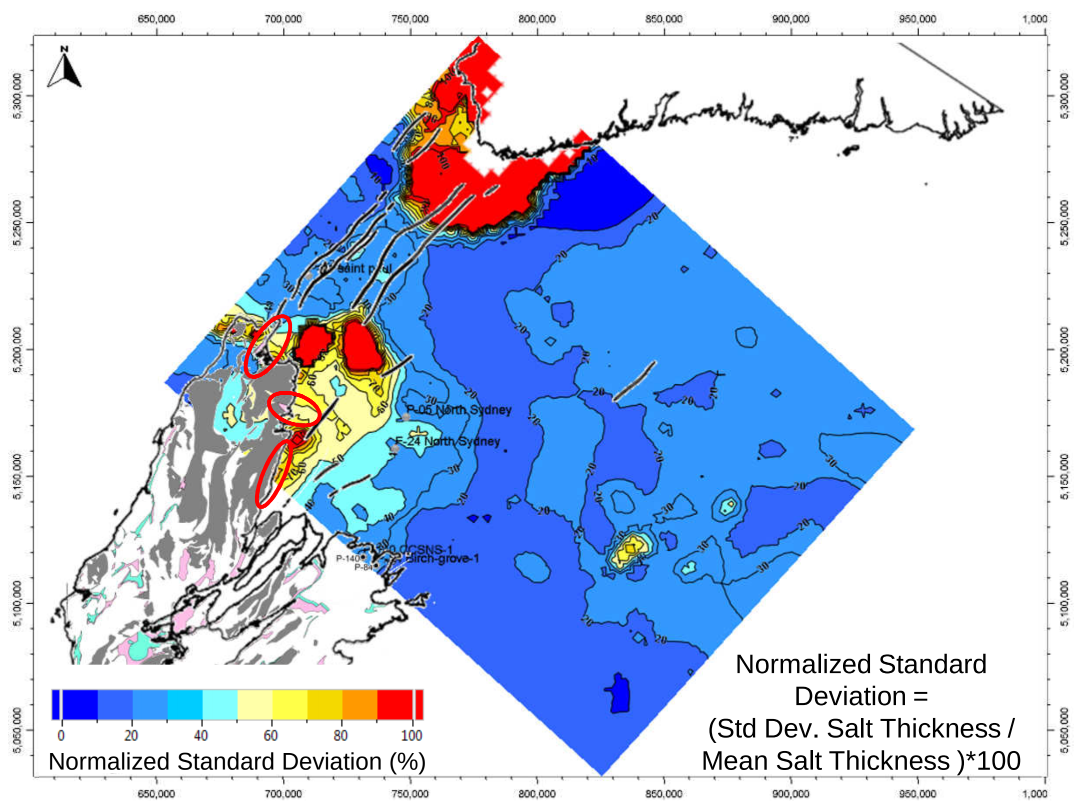


Figure 41: Normalized standard deviation of salt thickness for Middle Windsor interval highlighting high risk areas northwestward.

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