International Journal of Engineering & Technology, 7 (4.35) (2018) 143-147

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



A Review of Stratigraphic Foward Models (Sfm) for Carbonate Platform

Redwan Rosli[1]*, Michael C. Poppelreiter[2], Siti Nur Fathiyah Jamaludin[3]

[1,2]South East Asia Carbonate Research Laboratory (SEACaRL), Universiti Teknologi PETRONAS
[3]Department of Geoscience, Universiti Teknologi PETRONAS
**Corresponding author E-mail: redwanrosli@outlook.com*

Abstract

Stratigraphic forward modelling (SFM) is a numerical method that simulates the key factors that control depositional processes. A few models have been developed over years for different geological environment (fluvial, turbidite and carbonate). The model for carbonate system is particularly more complex compared to others. This is due to fact that carbonate system is controlled by the interplay between carbonate productivity, eustasy, subsidence/uplift. Carbonate platform's morphology also strongly influenced by hydrodynamic factors (Wind and Waves). SFM has been used to test the hypothesis on factors that controlled the evolution of carbonate platforms. This technique also a reliable tool for hydrocarbon exploration and development. SFM has been used to predict carbonate facies distribution, petrophysical properties, and architecture of carbonate platforms. In this review paper, four SFMs namely CARB3D+, GPM CARBONATE, DIONISOS, SEDPAK are discussed.

Keywords: *carbonate platform; hydrocarbon exploration tool; stratigraphic forward model (SFM)*

1. Introduction

Stratigraphic forward modelling is a numerical experiment that applies various algorithms to simulate geological processes such as sediment supply and subsidence. This tool is helpful in predicting sedimentary facies and stratigraphic architecture away from well data and poor quality data(Warrlich et al., 2008)(Griffiths et al., 2012)(Ku Shafie & Madon, 2016). SFM also has been used to improve seismic sequence stratigraphy modelling and help to improve reservoir characterization (Madhoo et., 2016). Basically, SFM requires input parameters that describe the geological processes and initial conditions before deposition: 1) initial topography/surface, 2) subsidence/ uplift rate, 3) eustasy curve, 4) carbonate production rate, 5) Hydrodynamic input (waves and current for sediment transportation and rework). If there is evidence of subaerial exposure from geological data, the additional input requires is the surface lowering rate. A recent focus in SFM on Carbonate Platform is to develop a tool that can predict the diagenetic overprint on the carbonate platform (Al-Helal et., 2012)(Lanteaum et al., 2016). The diagenetic processes for carbonate system are complex and not a straight-forward processes.

2. Application of Stratigraphic forward Modelling in Hydrocarbon Exploration

Stratigraphic forward modelling (SFM) is a promising and helpful tool for hydrocarbon exploration. Geoscientists are having difficult time to characterize the reservoir properties due to poor and limited data. Low resolution of seismic data and sometimes poor quality due to gas chimney rise a problem to determine the reservoir facies and its associated properties. SFM also had been used to improve seismic facies interpretation (Cacas et al., 2008)(Lanteaum et al., 2016). The high resolution of sequences from SFM helps to improve the interpretation of poor quality of seismic data. Therefore, SFM can be used to help geoscientists to have better understanding on the formation and properties distribution of hydrocarbon reservoirs. SFM is built with an algorithm to simulate the distribution and re-worked of sediments. Subsequently, predict the facies distribution. The algorithm classifies the facies of carbonate rock based on Dunham (1962) classification. The carbonate facies in SFM is assigned based on the ratio of coarse and fine sediments.

Carbonate reservoirs are susceptible to diagenetic modification. Porosity and permeability of carbonate is highly influenced by diagenetic processes such as dissolution, karstification and cementation. Karst prediction on seismic is sometimes misleading. The dendritic pattern in seismic appeared to be similar as the seismic noise pattern (Chung, Ting, & AlJaaidi, 2011). SFM are able to simulate the karstification processes by considering the dissolution of carbonate mineral during the subaerial exposure event. Dionisos has been used to predict the karst on Luconia carbonate platform and the result is promising (Uli et al., 2017). The karst prediction using SFM can provide better guidance for well drilling to prevent the well lost. Prediction of karst also helpful for reservoir development plan. Karst provide a conduit for water to flow and caused un-even flow of hydrocarbon throughout the reservoir. Uneven fluid contact in Jintan gas field in Central Luconia is suspected because of the karst (Rabani et al., 2014).

SFM programs such as Carb3d+ has coupled the sedimentological and diagenetic forward modelling. Built-in algorithm has been developed to govern the principle of resident time for each different diagenetic environment (figure 1) and subsequently predict the porosity and permeability distribution. Due to limited well data and core available, there has been difficulty in prediction of porosity and permeability distribution. SFM is able to calculate the porosity and permeability based on the percentage of coarse and

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

fine sediments. The built-in algorithm also takes into account of compaction and dissolution of carbonate minerals to calculate final value of porosity. A porosity-permeability (poro-perm) correlation such as Lucia (1995) is used to calculate permeability. Thus, the SFM is an alternative method to determine the permeability distribution.

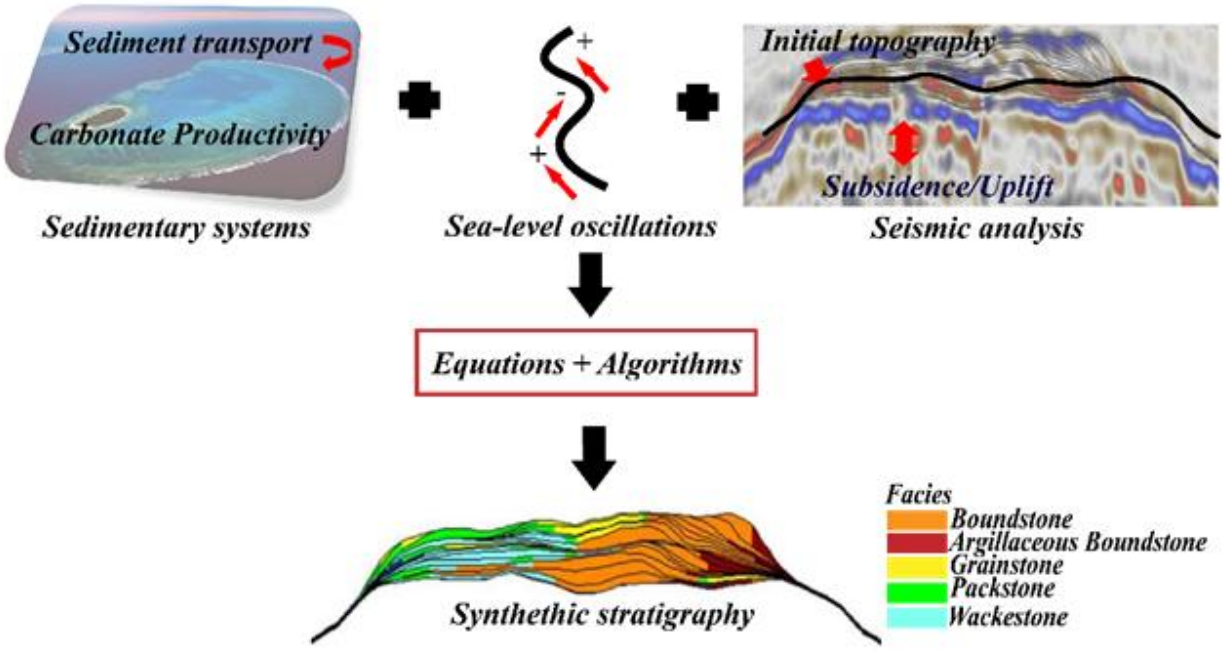


Fig. 1: Workflow of stratigraphic forward modelling. Figures are taken and modified from ("Google image," 2018) and (Uli et al., 2017).

3. Methodology

The objective of this paper is to review a few SFMs that can be used to model carbonate system. This technique shows a promising potential to be an essential tool in hydrocarbon recovery and for academic purposes. The information in this review is obtained from books, conference proceedings, and journals

4. Stratigraphic forward Models for Carbonate Platform

4.1. Carb3d+

Carb3d+ is a process-based forward model, developed by the University of Bristol and Royal Holloway University of London. The model is governing by algorithms that use to simulate the physical processes of fluid flow, sediment distribution and reworked. It capable to model 3D sedimentological process and early diagenetic processes (Paterson et al., 2006). In Carb3d+, the carbonate factories are divided into four; reef factory, margin factory, interior factory and pelagic factory (Smart et al., 2011). These factories represent the realistic carbonate production as can be observed in modern carbonate platform. The algorithm is based on closed system and conservation of mass developed by Waltham (1992) and Hardy & Waltham (1993). The sediment production is governed by Eq.1 and Eq. 2 as below:

$$P_d = P_{max} \exp\left(-\frac{d}{D_{light}}\right)\left[1 - \exp\left(-\frac{d}{D_{wave}}\right)\right] \quad (1)$$

Where P_d is depth dependent of production; D_{light} is fall-off depth when the production is zero; P_{max} is maximum production; D_{wave} is waves energy computed from maximum depth. The equation above is only applying for reef and margin factory. Meanwhile, for interior and pelagic factory is programmed to be independent of depth. The overall equation used to incorporate the sediment production, transport and deposition is function of wave and current climate is described as below:

$$\frac{\delta h}{\delta t} = \left[P_f + P_c + P_r\right] - \left[\frac{\delta F_f}{\delta_x} + \frac{\delta F_c}{\delta_x}\right] + \left[V_S + V_C\right] \quad (2)$$

Where p is production of sediments (f = fine, c = coarse, r = reef), F is transported sediment flux, x is horizontal distance, V_S is vertical velocity due to subsidence and V_C is velocity due to compaction.

The key advantage of Carb3d+ is it able to simulate the marine and meteoric diagenetic processes. The program predict the distribution of hydrozones and capture the residence time by considering the sea level change, rainfall and hydraulic conductivity (Berra et al., 2016). Diagenetic modelling in Carb3d+ considered only three minerals, namely low-magnesium calcite (LMC), aragonite and dolomite (Smart et al., 2011). High-magnesium calcite (HMC) is excluded due to it is highly unstable mineral and assumed it does not affect the porosity distribution. The diagenesis processes are simulate based on residence time of each hydrological zones; phreatic, vadose, mixing zone and marine. Therefore, the software is able to predict the porosity and permeability changes due to diagenetic processes, such as early meteoric dissolution and cement precipitation.

Carb3d+ does not include the influx of siliciclastic sediment. The introduction of siliciclastic into a carbonate system is important as it one of the controlling factor on the carbonate platform morphology as can be seen in Central Luconia province. The intercalation of siliciclastic influx and carbonate produced the wing morphology (Kosa, Warrlich, & Loftus, 2015).

4.2. GPM Carbonate

GPM (Geological Process Models) is built based on modelling algorithms by Tetzlaff & Harbaugh, (1989). Similar to others SFM, carbonate production in GPM is based on depth-dependent

relationship. The relationship of growth rate is given by equation from Bosscher & Schlager (1992) as below:

$$S_L = \frac{\tanh(I_0 e^{-kz})}{\tanh(\frac{I_0}{I_k})} \quad z > 1 \tag{3}$$

Where S_L is stress function due to water depth; I_0 is the light irradiance at the surface; I_k is the saturating light irradiance. The effect of waves energy in controlling the growth rate of coral reef also included in GPM Carbonate. Coral reef growth is decrease to zero when wave energy dissipated less than 2 W/m2 (Hill et al., 2009). Similar as in Carb3d+, this algorithm allowed us to include the wave energy as realistic controlling factor on coral reef growth as can be observed on modern reef platform (Munk & Sargent, 1948). When the wave energy is low is indicating of calm environment. This will allow the terrigenous sediment to settle down and will suffocate the coral reef. In GPM Carbonate, the effect of the nutrients on carbonate production can be tested. The model presumed the nutrients supply is related to waves turbulence (Tetzlaff at al., 2014). The carbonate production not only influenced by presence of sunlight, nutrients and temperature, but also the calcium carbonate supersaturation in the sea water (Hill et al., 2009). GPM Carbonate has included the
effect of carbonate supersaturation. Supersaturation of carbonate is controlled by the residence time. Hill et al., (2009) stated that "the carbonate is removed from a parcel of water by organic and inorganic processes, the amount of carbonate in that parcel of water decreases unless it is replenished". Demicco & Hardie, (2002) has found that supersaturation of carbonate decreasing with time. Therefore, if the environment is restricted and no re-supply of the carbonate, such as in back reef and lagoon, the carbonate production is decrease exponentially with time.

4.3. Dionisos

Diffusion Oriented-Normal and Inverse Simulation of Sedimentation (Dionisos) is a 3D forward model developed by the Institut Francais du Petrole. It is based on diffusion model (Granjeon & Phillip, 1999). This model is used the deterministic approach to describe physics of sediment transportation. Two set of equations; transport law and continuity equation are applied in this software to model sediment transportation process. The equations used are able to simulate the interplay between the long-term and short-term factors that affect the sedimentary processes (Granjeon & Phillip, 1999). The sediment supply equation is a function of channel depth, water velocity and channel slope. Even though, the Eq. 4 below computed for continental areas, the equation has been tested valid for marine environment as well (Granjeon & Phillip,1999).

$$Q_{sed} = \alpha\tau^{2/3} = \alpha\rho g d S \sqrt{\tfrac{1}{2}\rho C_x \mu^2} = [\alpha\rho g d S \sqrt{\tfrac{1}{2}\rho C_x}\,]\mathrm{d}\mu\mathrm{S} \tag{4}$$

Where Q_{sed} is sediment flow rate, τ is shear stress, ρ is density of water, g is gravity, d is channel depth, S is the channel slope, μ is viscosity of water and C is dimensionless Reynold number. To differentiate sediments from different environment, the diffusion the diffusion coefficient, K is used. The value of K is a function of water depth as given by Eq. 5 as below:

$$K = \alpha\rho g \sqrt{\tfrac{1}{2}\rho C_x} \tag{5}$$

Similar to other SFM, sediment production is controlled by subsidence rate, climate, and topography elevation. In situ carbonate production rate is defined as a function of water depth and the siliciclastic flow. The software is capable to simulate the intercalations between carbonate and clastic sediment. Therefore, it capable to produce a carbonate-wing geomorphology and also to simulate the demise of the carbonate platform due to environmental stress caused by siliciclastic influx. However, the algorithms are still need to be improved to simulate the realistic interaction of siliciclastic and carbonate production. Figure 2 show an attempt by Hanif (2016) to build a carbonate platform model of "Christmas tree" morphology.

4.4. SEDPAK

Sedpak is a 2D stratigraphic forward modelling developed by University of South Carolina. The program traced the evolution of sedimentary architecture as clastic sediments deposited, in-situ car bonate growth and the re-worked of carbonates sediments. The Sedpak model is based on geometric model that applies the principle of mass and energy balance (Strobel et al., 1989) (Kendall et al., 1991). The program utilising simple geometric rule that follow gradient and stacking pattern of the stratigraphic layers. The carbonate production in Sedpak is controlled by wave energy, amount of clastic sediments and the lagoon damping (restriction of the waves or nutrient supply into the lagoons) (Strobel et al., 1989).
However, Sedpak has several limitations. It can only simulate 2-dimensional sedimentological processes. Therefore, ineffectively model sediments distribution, erosion and re-worked. Sedpak also does not incorporate the wind-driven energy for carbonate sediment production and distribution. Wind-driven energy is known as one of the key factor in controlling the evolution of carbonate platform, especially for the coral-dominated carbonate platform.

5. Conclusion

Stratigraphic forward modelling is process-based model simulation technique. The input parameters are based on the carbonate depositional system and structural history of the platform. Therefore, the accuracy of the model is based on our understanding of the depositional history of the carbonate platform. SFM is not an ultimate tool for hydrocarbon exploration. But, the integration of SFM with seismic, well logs and core data surely help to reduce the uncertainty in reservoir modelling workflow.

Acknowledgement

We would like to thank the South East Asia Carbonate Research Laboratory (SEACaRL) for permission to present and publish this paper as part of forward modelling project.

References

[1] Al-Helal, A., Whitaker, F. F., & Xiao, Y. (2012). Reactive transport modeling of brine reflux : Dolomitization , anhydrite precipitation , and porosity evolution. *Journal of Sedimentary Research*, *82*, 196–215. https://doi.org/10.2110/jsr.2012.14

[2] Berra, F., Lanfranchi, A., Smart, P. L., Whitaker, F. F., & Ronchi, P. (2016). Forward modelling of carbonate platforms: sedimentological and diagenetic constrains from an application to a flat-topped greenhouse platfrom (Triassic, Southern Alps, Italy). *Marine and Petroleum Geology*. https://doi.org/10.1016/j.marpetgeo.2016.10.011

[3] Bosscher, H., & Schlager, W. (1992). Computer simulation of reef growth. *Sedimentology*, *39*(3), 503–512. https://doi.org/10.1111/j.1365-3091.1992.tb02130.x

[4] Cacas, M. ., Laigle, J. M., Albouy, E., & Sulzer, C. (2008). Integrating stratigraphic modelling and seismic interpretation: two practical examples. *Petroleum Geoscience*, *14*(3), 253–261. https://doi.org/10.1144/1354-079308-762

[5] Chung, E. K. Y., Ting, K. K., & AlJaaidi, O. (2011). Karst Modeling of a Miocene carbonate build-up in Central Luconia, SE Asia: Challenges in seismic characterization and geological model building. *International Petroleum Technology Conference*, 1–6.

https://doi.org/10.2523/IPTC-14539-MS
[6] Demicco, R. V, & Hardie, L. A. (2002). The "carbonate factory: revisited: a reexamination of sediment production functions used to model deposition on carbonate platform. *Journal of Sedimentary Research*, (72), 849–857.
[7] Dunham, R. J. (1962). Classification of carbonate rocks according to depositional texture. In *Classification of carbonate rocks: American Association of Petroleum Geologists Memoir* (pp. 108–121).
[8] Google image. (2018). Retrieved June 9, 2018, from https://i.pinimg.com/originals/c7/e8/e4/c7e8e40c8cf916d476615db1fbbaef81.jpg
[9] Granjeon, D., & Joseph Phillip. (1999). Concepts and applications of a 3D multiple lithology,diffusive model in stratigraphic modelling. In J. W. Harbaugh, W. W. Lynn, E. C. Rankey, R. Slingerland, G. R. H., & E. K. Franseen (Eds.), *Numerical experiments in stratigraphy:recent advances in stratigraphic and sedimentologic computer simulations* (pp. 197–210). Tulsa: SEPM Special Publication 62.
[10] Griffiths, C. M., Seyedmehdi, Z., Salles, T., & Dyt, C. (2012). *Stratigraphic forward modelling for South West Collie Hub*.
[11] Hanif, M. (2016). Process driven approach for the improvement of facies property modelling. In *Third EAGE Intergrated Reservoir Modelling Conference* (pp. 1–5).
[12] Hardy, S., & Waltham, D. A. (1993). Computer modelling of tectonics,eustasy and sedimentation using the Macintosh. *Geobyte*, *7*, 49–52.
[13] Hill, J., Tetzlaff, D., Curtis, A., & Wood, R. (2009). Modeling shallow marine carbonate depositional systems. *Computers and Geosciences*, *35*(9), 1862–1874. https://doi.org/10.1016/j.cageo.2008.12.006
[14] Kendall, C. G. S. C., Strobel, J., Cannon, R., Bezdek, J., & Biswas, G. (1991). The simulation of the sedimentary fill of basins. *Journal of Geophysical Research*, *96*(B4), 6911–6929. https://doi.org/10.1029/90JB01406
[15] Kosa, E., Warrlich, G. M. D., & Loftus, G. (2015). Wings, Mushrooms, and Christmas trees : The carbonate seismic geomorphology of Central Luconia , Miocene – present , offshore Sarawak , northwest Borneo. *AAPG Bulletin*, *99*(11), 2043–2075. https://doi.org/10.1306/06181514201
[16] Ku Shafie, K. R., & Madon, M. (2016). A review of stratigraphic simulation techniques and their applications in sequence stratigraphy and basin analysis. *Bulletin of the Geological Society of Malaysia*, *54*(November 2008), 81–89. https://doi.org/10.7186/bgsm2008014
[17] Lanteaum, C., Fournier, F., Borgomano, J., & Pellerin, M. (2016). Coupled stratigraphic and diagenetic forward modelling as input to seismic simulation for a better understanding of carbonate reservoirs. In *Second Conference on Forward Modelling of Sedimentary Systems*. Trondheim, Norway.
[18] Lucia, F. J. (1995). Rock-Fabric / Petrophysical Classification of Carbonate Pore Space for Reservoir Characterization, *9*(9), 1275–1300. https://doi.org/10.1306/7834D4A4-1721-11D7-8645000102C1865D
[19] Madhoo, H., Acevedo, A., Tetzlaff, D., & Tveiten, J. (2016). Combining forward stratigraphic modelling with seismic reconstruction to improve reservoir characterization. In *Second Conference on Forward Modelling of Sedimentary Systems*. Trondheim, Norway. https://doi.org/10.3997/2214-4609.201600382
[20] Munk, W. H., & Sargent, M. C. (1948). Adjustment of Bikini Atoll to ocean waves. *Transactions, American Geophysical Union*, *29*(6).
[21] Paterson, R. J., Whitaker, F. F., Jones, G. D., Smart, P., Waltham, D., & Felce, G. (2006). Accommodation and sedimentary architecture of isolated icehouse carbonate platforms : insights from forward modeling with CARB3D+. *Journal of Sedimentary Research*, *76*, 1162–1182. https://doi.org/10.2110/jsr.2006.113
[22] Paterson, R. J., Whitaker, F. F., Smart, P., Jones, G. D., & Oldham, D. (2008). Controls on early diagenetic overprinting in icehouse carbonates : insights from modeling hydrological zone residence times using CAR3D+. *Journal of Sedimentary Research*, *78*, 258–281. https://doi.org/10.2110/jsr.2008.029
[23] Rabani, M. N., Adams, E., Ryba, A., Harwijanto, J., Warrlich, G., Fui, L. H., … Berhad, S. S. (2014). An integrated approach to understand the remaining potential and ultimate hydrocarbon recovery of a giant carbonate gas field , offshore Sarawak, Malaysia. *Offshore Technology Conference Asia*.
[24] SEDPAK v.4.1 Help System. (n.d.). Retrieved from http://sedpak.geol.sc.edu/doc/help/index.html
[25] Smart, P. L., Felce, G. P., Oldham, D., Cooper, K., Whitaker, F., Flory, R., & Wang, D. (2011). *A users guide (CARB3D + v3.4): A forward model for predicting carbonate sedimentology and diagenesis*.
[26] Smart, P., Waltham, D., Felce, G., Wang, D., Oldham, D., & Whitaker, F. (2011). CARB3D+ v3.4: A forward model for predicting carbonate sedimentology and diagenesis program description and function.
[27] Strobel, J., Cannon, R., Kendall, C. G. S. ., Biswas, G., & Bezdek, J. (1989). Interactive (SEDPAK) simulation of clastic and carbonate sediments in shelf to basin settings. *Computers & Geoscience*, *15*(8), 1279–1290. https://doi.org/10.1016/0098-3004(89)90092-7
[28] Tetzlaff, D., & Harbaugh, J. . (1989). *Computer simulation of clastic sedimentary processes, van Nostrand-Renold series in Mathematical Geology*. Plenum Publishing.
[29] Tetzlaff, D. M., Tveiten, J., Salomonsen, P., Christ, A., & Athmer, W. (2014). Geologic process modeling. *IX Congreso De Exploración Y Desarrollo De Hidrocarburos*, (November), 155–174. Retrieved from http://www.iapg.org.ar/congresos/2014/conexplo/
[30] Uli, D. ., Mithani, A. ., Ali, K., Abu Mansur, R., Masoudi, R., Tewari, R. D., … Lee, Y. (2017). Integrated carbonate field management using forward stratigraphic modelling approach : Case study of a field in Central Luconia. In *SPE/IATMI Asia Pacific Oil & Gas Conference and Exhinition*. Jakarta. https://doi.org/10.2118/186339-MS
[31] Waltham, D. (1992). Mathematical modeling of sedimentary basin processes. *Marine and Petroleum Geology*, *9*(3), 265–273. https://doi.org/10.1016/0264-8172(92)90075-p
[32] Warrlich, G., Bosence, D., Waltham, D., Wood, C., Boylan, A., & Badenas, B. (2008). 3D stratigraphic forward modelling for analysis and prediction of carbonate platform stratigraphies in exploration and production, *25*, 35–58. https://doi.org/10.1016/j.marpetgeo.2007.04.005

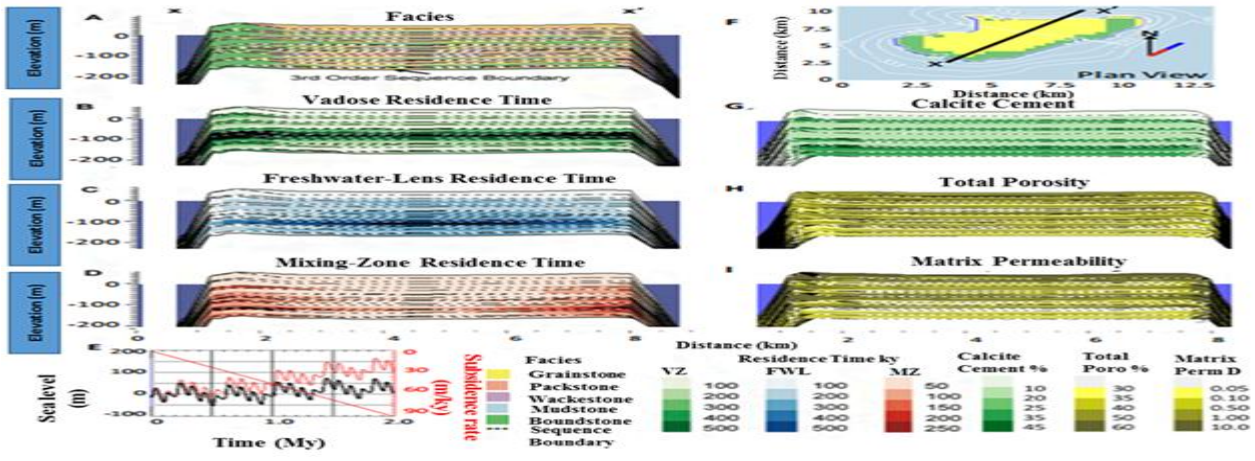


Fig. 2: CARB3D+ model based on Natuna platform. CARB3D+ simulate the diagenetic overprint based on residence time for each hydrozone. Subsequently, predict cement precipitation. Adapted from (Paterson at al., 2008).

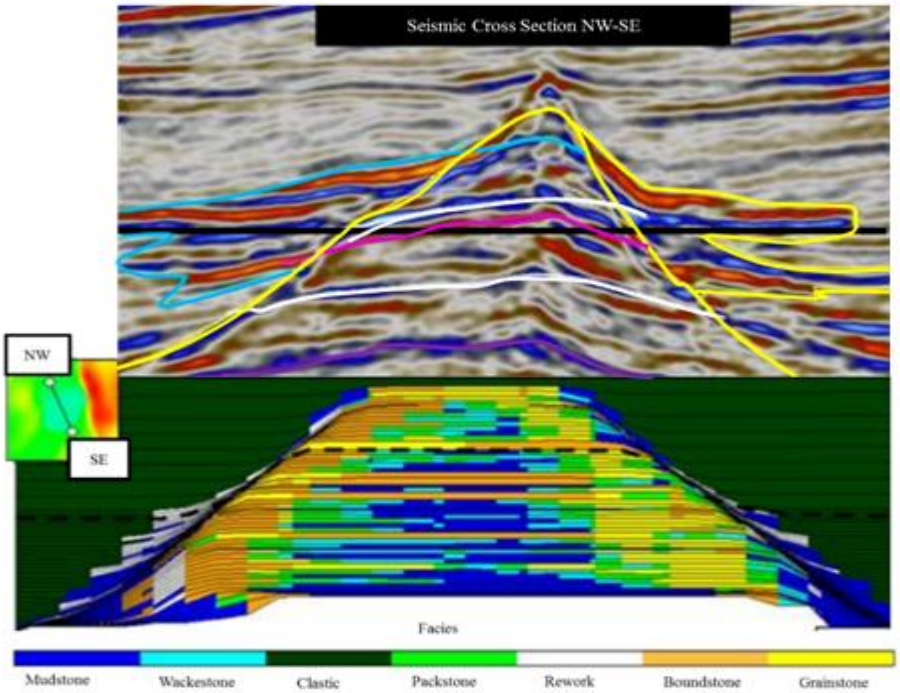


Fig. 3: SFM model of the 'Christmas Tree' carbonate platform as compared with the seismic section. Modified from (Hanif, 2016).Even though the SFM model does not perfectly similar with seismic morphology, but this attempt show the SFM is a promising tool that can be used to model such carbonate morphology.

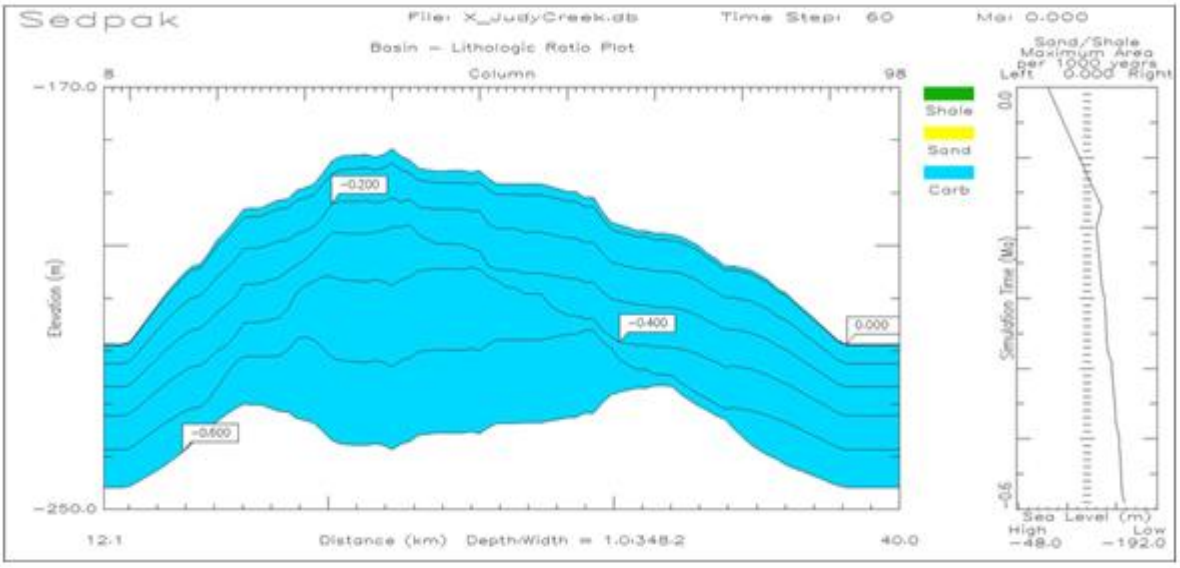


Fig. 4: Sedpak simulation of Judy Creek reef complex indicate the build-up phase (aggradation) due to rising of sea level. Figure is taken from example case in Sedpak program ("SEDPAK v.4.1 Help System," n.d.)