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Interactive comment on “Porosity and Permeability Prediction through Forward Stratigraphic Simulations Using GPM™ and Petrel™: Application in Shallow Marine Depositional Settings” *by* Daniel Otoo and David Hodgetts

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I appreciate the suggestions provided by the reviewer. Our responses will follow the format in which the reviewer’s comments were presented.

NB: Lines will be referred to as “L” in our response. General Comments (GC)

GC1: A paragraph with a detailed description of how GPM works would be beneficial

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to readers. This would fit well within the section title “Process Modeling in GPM”.

Response 1: Additional information on how geological processes in GPMTM operate have been included. Below are the additions:

Steady Flow Process The steady flow process in GPM model flows that change slowly over a period; e.g. rivers at normal stage, and deltas. The steady flow process best depicts sediment transport scenarios where flow velocity and channel depth do not vary abruptly. The steady flow process settings can be specified to fit a task in the steady flow pane of the “run sedimentary simulation” dialog box in Petrel software (2017.1 version and above). To attain stability in the simulator before running the full simulation (i.e. entire depositional period), it is advisable to undertake preliminary runs to ascertain the appropriateness of the source intensity and flow behaviour. For steady flow, a boundary condition must be specified at the edges of the model. In an open flow system, negative integers (i.e. values below zero) should be assigned to the edges of the hypothetical paleo-surface to allow water to enter and leave the simulation area. Further information on the steady flow settings can be located in the GPM user manual (i.e. Guru in the Petrel software).

Unsteady Flow Process The unsteady flow process simulates flow that are periodic, and run for a limited time; example, in turbidites where velocity of flow and depth changes abruptly over time. The unsteady flow process involves fluid elements that are affected by gravity, and by friction against the hypothetical topographic surface. A previous study on the use of unsteady flow process for stratigraphic simulation is outlined in Otoo and Hodgetts, (2019).

Diffusion Process The diffusion process replicates sediment erosion from areas of higher slope (i.e. source location), and deposition to lower slope sections of the model area. Sediment dispersion is carried out through erosion and transportation processes that are driven by gravity. The diffusion process follows an assumption that sediments are transported downslope at a proportional rate to the topographic gradient; therefore making fine grained sediments easily transportable than coarse grained sediments. The diffusion process is controlled by two parameters; (i) diffusion coefficient, which controls the strength of the diffusion, and (ii) diffusion curve that serves as a unitless multiplier in the algorithm. The mathematical equation for the diffusion geological process is: $\partial z/\partial t$=kâĹĞ^{2}z, where z is topographic elevation, k the diffusion coefficient, t for time, and âĹĞ^{2}z the laplacian.

Sediment Accumulation This involves the deposition of sediment using an areal source location. In the GPMTM software, sediment source can be set to a point location or considered to emanate from a whole area. For example, where a lithology is interpreted to be uniformly distributed, the sediment accumulation process can replicate such depositional scenarios. The areal input rates (in mm/yr) for each sediment type must be specified in the settings. Specifying the areal rates for each sediment is important because the software is configured to use the value of the surface at each cell in the model and multiplies it by a value (i.e. value from a unitless curve) at each time step in the simulation to estimate the thickness of sediments accumulated or eroded from the cell.

GC2: Statistical validation of why the number of modelling scenarios were chosen would be good to include. For this to be reproducible (which should be the aim), anyone that reads this should have a clear idea as to why 20 scenarios were chosen so this method can be repeated in other studies.

Response 2: A major limitation in the FSM approach is that initial boundary conditions at the time of deposition, which is required for the simulation, are unknown. In our opinion, a better means to evaluate the stratigraphic scenarios selected should be the capacity of their resultant stratigraphic-based porosity and permeability property model to match known data. An initial simulation (labelled figure 6a) was undertaken to see if the outcome will mimic the depositional pattern observed in the seismic section (figure 3b). The 20 scenarios were derived by using different input parameters with Figure 6a as guide.

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GC3: I would advise the authors to not mention any ‘future studies’ or further work. This manuscript should stand alone and showcase the modelling methods presented rather than putting a final statement about what they want/are going to do in the future.

Response 3: The suggestion will be discussed, and appropriate considered, and the necessary corrections made in the manuscript.

Line Comments (LC)

L15: The appropriate word “accommodation” will be used henceforth.

L6-10: The statement has been corrected to read “Typically, reservoir modeling tasks require continued property modification until an a appropriate match to known subsurface data is obtained. However, acquisition of subsurface datasets is costly, thus restricts data collection and subsurface modeling condition; hence reducing our perspective of reservoir property variation and its impact on fluid behaviour”

L16: The new statement now reads “Reservoir modeling techniques with the capacity to integrate forward stratigraphic simulation outputs with stochastic modeling techniques for subsurface property modeling will improve reservoir heterogeneity characterization, because they more accurately produce geological realism than the other methods (Singh et al. 2013)”.

L41: The geological processes referred to as “tides” and “riverine” have been replaced with Tidal and Fluvial processes respectively.

L73: The statement has been changed into “ Datasets include 3-D seismic data, and a suite of 24 wells that consist of formation pressure data, core data, and sedimentological logs”

L76: Additional statement have been added. This reads “Grain size, sediment matrix and the degree of sorting will typically drive the volume of void created, and therefore the porosity and permeability attributes”.

L105-109: The statement has been changed into “Sediment deposition, and its response to post-depositional sedimentary and tectonic processes are significant in the ultimate distribution of subsurface lithofacies units. To attain stratigraphic outputs that fall within the depositional architecture interpreted from the seismic data, the input parameters were varied (see Table 2)”.

L164: Figure 4d is the hypothetical topographic surface that was used to generate the “best fit” stratigraphic model in Figure 5d. So figure 5d as used in the manuscript is the appropriate figure.

L164-166: The statement has been reviewed into “This is because, when compared to depositional description in studies such as Folkestad and Sature (2006); kieft et al., (2011), it produced a stratigraphic sequence that mimics the depositional sequence in the shallow marine depositional environment under study”

L176-178: This has been corrected into “For example, shoreface lithofacies units were characterized using medium-to-coarse grained sediments, which accumulates at proximal distance to the sediment source. In contrast, mudstone units are associated to fine grained sediments that accumulate at distal section of the simulation domain”.

L180-183: In line with the reviewer’s comment, the following changes have been made: “The statement here has been changed to now read “In previous studies on the Sleipner Øst, and Volve field (e.g. Equinor, 2006; Kieft et al., 2011), Shoreface deposits were identified to make up the best reservoir units, whilst lagoonal deposits formed the worst reservoir units. Using this as guide, shoreface sandstone units and mudstone/shale units in the forward stratigraphic model were characterized as best and worst reservoir units respectively”.

L195-205: Specific to L205, the sentence with respect to the fault directions has been modified into “The prominent orientation of faults (I-direction) within the model area trends generally in a N-S and NE-SW direction, so the “I-direction” was set to the NNE-SSW direction to align the grid cells”.

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L211-212: The statement has been revised into “Vertical layering on the other hand defines the thicknesses and orientation between the layers of the model. Layers in this context describes significant changes in particle size or sediment composition in a geological formation. Using the vertical layering scheme makes it possible to honour the fault framework, pillar grid and horizons that have been derived”.

L215-218: The statement has been changed into: “ Upscaling: involves the substation of fine grid cells with coarser grid cells. This is done to assign property values to cells in order to evaluate which discrete value suits each a selected data point. One advantage of the upscaling procedure is to make the modeling process faster”.

L223-225: The statement has been revised into “The original petrophysical model has a grid dimension of 108 m x 100 m x 63 m, and is compressed by 75.27% of cell size (from an approximated original cell size 143 m x 133 m x 84 m)”.

L230-233: The statement will now read, “For option 2 the best-fit forward stratigraphic model was populated with porosity, and permeability attributes using the stratigraphic orientation captured in the seismic data (i.e. NE-SW; 240âĄř) to control property distribution trends. Porosity and permeability were populated into the model by using the petrophysical modeling tool under property modeling process in PetrelTM”.

L237-239: Modification has been made to the statement. New statement is “Ten synthetic wells (SW), ranging between 80 m and a 120 m in total depth (TD) were positioned in the forward model to capture the vertical distribution of porosity-permeability at different sections of the stratigraphic model”. L253-257: As suggested, Fig. 5 has been modified to indicate the maximum flooding surfaces (MFS) in the forward stratigraphic model. Its orientation has also been changed into landscape format (Figure 5).

L258: References have been added as suggested. The new statement is “This is consistent with real-world scenario where sediment supply matchup with accommodation generated as a result of the relative constant sea level rise within a period (e.g. Muto

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and Steel, 2000; Neal and Abreu, 2009)".

L262-270: The suggestions have been taken on board, and the necessary corrections will be done.

L272: According to the petrophysical evaluation report of the Volve field by Equinor, porosity in the reservoir is between 0.17-0.30. Vertical sampling in some selected models show more porosity values within this range (i.e. 0.17-0.30). This sentence is to illustrate how the FSM approach could generate outputs that are consistent with known data. I however, agree that more explained is required in the statement. The entire statement will be modified into "The vertical distribution (Figure 12) of porosity in selected model realizations shows a large set of porosity values that range between 0.18 – 0.24. This output is consistent to porosity figures captured in the petrophysical evaluation of the Volve field (Equinor, 2016)".

L274-275: The entire statement has been reviewed into ". In view of the limitation in making variations within a simulation run in GPMTM, the forward stratigraphic-based model was derived with an assumption that variogram parameters, stratigraphic inclination within zones are constant in each simulation run. In contrast, the original petrophysical model involve other measured attributes within the stratigraphic zone, hence the variations noted in Table 5b".

L277-281: The statement has been re-arranged into "Typically, a petrophysical model like the Sleipner Øst and Volve field model will take into account other sources of data. For example, data from a special core analysis (SCAL) will improve the reservoir petrophysics assessment. On the basis that the FSM approach did not involve these additional information from the formation, it is reasonable to suggest that the forward stratigraphic-based porosity and permeability models have been adequately conditioned to known subsurface data".

L295-297: The entire statement has been amended into "As indicated in other studies, (e.g. Allen and Posamentier, 1993; Ghandour and Haredy, 2019) sequence stratigraphy is vital in the characterization of lithofacies in shallow marine settings. Aimed at replicating stratigraphic sequence formation in 3-D, the forward stratigraphic modeling approach in GPMTM provide a good framework to analyse petrophysical property variations in a reservoir".

L314-315: The statement has been revised into "In reality, sediment deposition into a geological basin is also controlled by mechanical and geochemical processes that tend to modify a formations petrophysical attributes (Warrlich et al. 2010). Therefore, using different geological processes and initial conditions to generate depositional scenarios, will help to produce a best fits stratigraphic framework of the reservoir under study".

Table Comments The correction has been done as suggested. Please see updated table 1 in the supplement file section. Figure Comments Figure 4, 5, 7 & 12: The figures have been changed into a landscape orientation to make them more visible. Figure 6: A key has been provided to this figure.

Please also note the supplement to this comment:
https://gmd.copernicus.org/preprints/gmd-2020-37/gmd-2020-37-AC2-supplement.pdf

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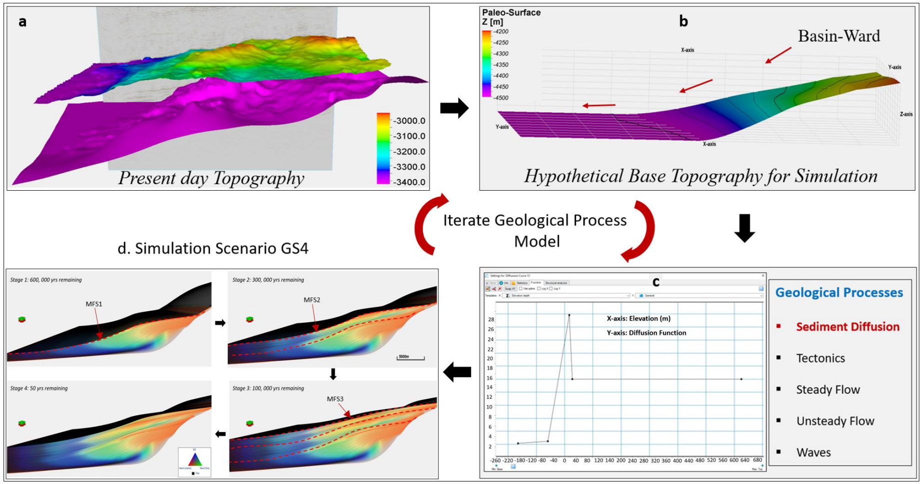

Figure 5.

Fig. 1.

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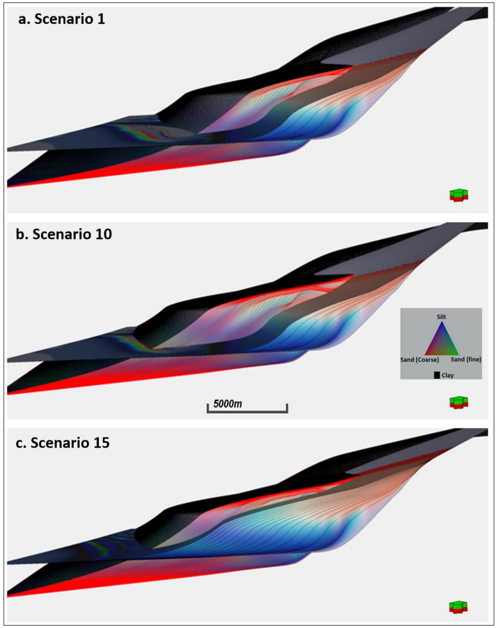

Figure 6.

Fig. 2.

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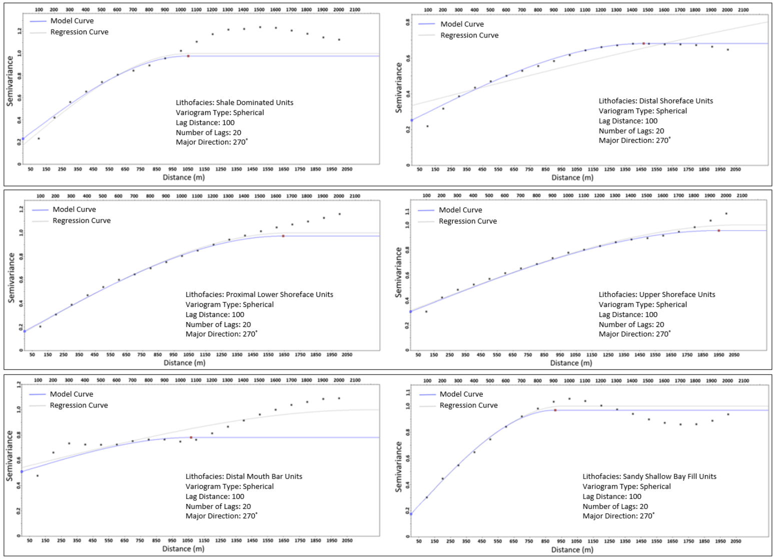

Figure 10.

Fig. 3.

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