Modelling intra-parasequence reservoir heterogeneity with a process-mimicking algorithm: a case study from the Kenilworth Member, Blackhawk Formation

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This work aims to show how parasequence and intra-parasequence sedimentary heterogeneity can be captured in a reservoir model by a newly developed process mimicking algorithm. It accomplishes such a task by capturing sedimentary features of potential reservoir importance observed in the K4 parasequence outcrop. The presented workflow builds upon a previous identification and correlation of parasequences across a reservoir, and as a result highlights the importance of the concept of parasequences and their identification for reservoir zoning and modelling.

Abstract: Wave dominated, shallow marine siliciclastic successions form some of the most prolific oil and gas reservoirs worldwide, where individual parasequences comprise the main flow units. Within parasequences, these reservoirs have been traditionally modelled as simple shore-parallel facies belts, given their reputation as simple reservoirs with subtle spatial heterogeneity in petrophysical properties. However, there are many documented cases in which intra-parasequence scale heterogeneities can have a relevant impact in reservoir behavior. Some of these heterogeneities, for example clinoforms associated with bedset boundaries, are difficult to capture with current reservoir modelling algorithms. The newly developed GEOPARD algorithm provides a rule-based approach that can capture the intra-parasequence scale heterogeneity typical of this type of reservoir. In this paper, we use the very well-known outcrops of the wave-dominated succession of the K4 parasequence of the Kenilworth Member, Utah, USA, to test the ability of the algorithm to reproduce geometries of reservoir interest. Having previous studies as reference, facies and bedset boundary geometries are mapped using virtual outcrops. The GEOPARD algorithm is then presented and used to match the geometries mapped in the outcrop, and the results are used to compare model and outcrop in detail. Most importantly, the logic used to mimic geological processes with the rule-based approach of the presented algorithm is discussed. The results and discussion of this study highlight the importance of this new approach to reservoir modelling that has the potential to provide fast and robust models for many different types of reservoirs beyond the shallow marine realm.

INTRODUCTION

Shallow marine siliciclastic successions, and particularly shoreface and wave dominated delta deposits, form some of the most prolific oil and gas reservoirs worldwide (Howell et al., 2008a; Ringrose and Bently, 2021). Examples include reservoir units of the North Sea (Brent and Humber Groups, e.g. Richards and Brown, 1986; Howell et al., 1996; Husmo et al., 2003); onshore United States (e.g., Galloway et al., 2000); and Tertiary delta systems of Southeast Asia (e.g., Hodgetts et al., 2001; Ainsworth, 2005). They are also known for having very high recovery factors (Tyler and Finlay, 1991), which make them also especially good candidates for CCS (e.g. Jackson et al., 2022).

In the case of shoreface and wave-dominated delta reservoirs, parasequences usually comprise the main flow units in the reservoir (e.g. Reynolds et al., 2016). Within parasequences, facies have been traditionally modelled as shore-parallel belts (MacDonald and Aasen, 1994; Howell et al., 2008a; Eide et al., 2014, Ringrose and Bently, 2021). However, there are documented cases in which a range of sedimentological features at an intra-parasequence scale can act as baffles or barriers to fluid flow under specific conditions (Ainsworth, 2010; Eide et al., 2014; Hampson et al., 2008; Hampson et al., 2015; Isla et al., 2021), most notably clinoforms (*sensu* Hampson, 2000) related to bedset boundaries (*sensu* Van Wagoner et al., 1990).

Attempts to provide a method that can rapidly and easily handle modelling intra-parasequence, shallow marine clinoforms in a subsurface scenario are scarce. Howell et al., (2008b) experimented with an inclined grid solution to model the deltaic deposits of the Ferron Sandstone. Sech et al., (2009) used a surface-based method to reproduce the detailed architecture of shoreface deposits at the K4 parasequence in outcrop. Graham et al., (2015) provided an algorithm that takes a geometric approach to construct clinoform surfaces between two bounding surfaces. These procedures are complicated and expert-based solutions, lacking a simple way to do this which is tailored to shoreface environments and their controls.

The GEOPARD algorithm provides a rule-based modelling solution to shoreface and wave dominated delta reservoirs (Aarnes et al., 2024, *submitted for publication*). This approach has the potential to rapidly deliver realistic reservoir models that capture a range of intra-parasequence features key to reservoir geometry and heterogeneity. The so-called 'rules' are simplifications of geological processes that are incorporated in the modelling algorithm. This is inspired by the event-based or process-mimicking approach of Pyrcz et al. (2009, 2012). With a rule-based approach, physical processes are being mimicked and not actually reproduced. On the one hand, this approach allows keeping computational requirements accessible and even more importantly, it allows conditioning to observational (i.e. well) data. On the other hand, it demands that the algorithm results are validated against geometries observed in the geological record, and especially in outcrop successions, where more control on rock geometry is available.

The aim of this study, therefore, is to test the ability of GEOPARD to produce an accurate reservoir model based on outcrops of a well-known shoreface unit. This is done by (1) characterizing the sedimentary features that would have had implications on fluid flow had they been in a reservoir (features of reservoir interest) in the outcrop succession of the K4 parasequence in the localities of Battleship and Gunnison buttes, Utah, USA; (2) identifying the geological processes that have been interpreted to generate the observed features with significant impact on reservoir performance, (3) creating static reservoir models of the outcropping rock succession using the GEOPARD algorithm (4) comparing the outcrop to the reservoir model, and (5) discussing how GEOPARD mimics geological processes with a rule-based approach and its advantages and disadvantages.

GEOLOGICAL SETTING AND STUDY AREA

The shoreface deposits of the K4 Parasequence of the Blackhawk Formation (Taylor and Lovell, 1995) were accumulated in the shallow waters of western margin of the Western Interior Seaway, USA (. 1B), during the Campanian stage of the Upper Cretaceous (Young, 1955). The Sevier Orogen, located to the west of the study area, provided an abundant sediment source which was transported to the shoreline by fluvial systems though up to 150 km of alluvial plain (Hampson et al., 2012). The area had a warm and humid climate at a paleolatitude of approximately 40° N (Davies et al., 2005, 2006), resulting in coastal plains with abundant vegetation and the frequent formation of peat swamps, preserved as coal seams (Howell et al., 2003).

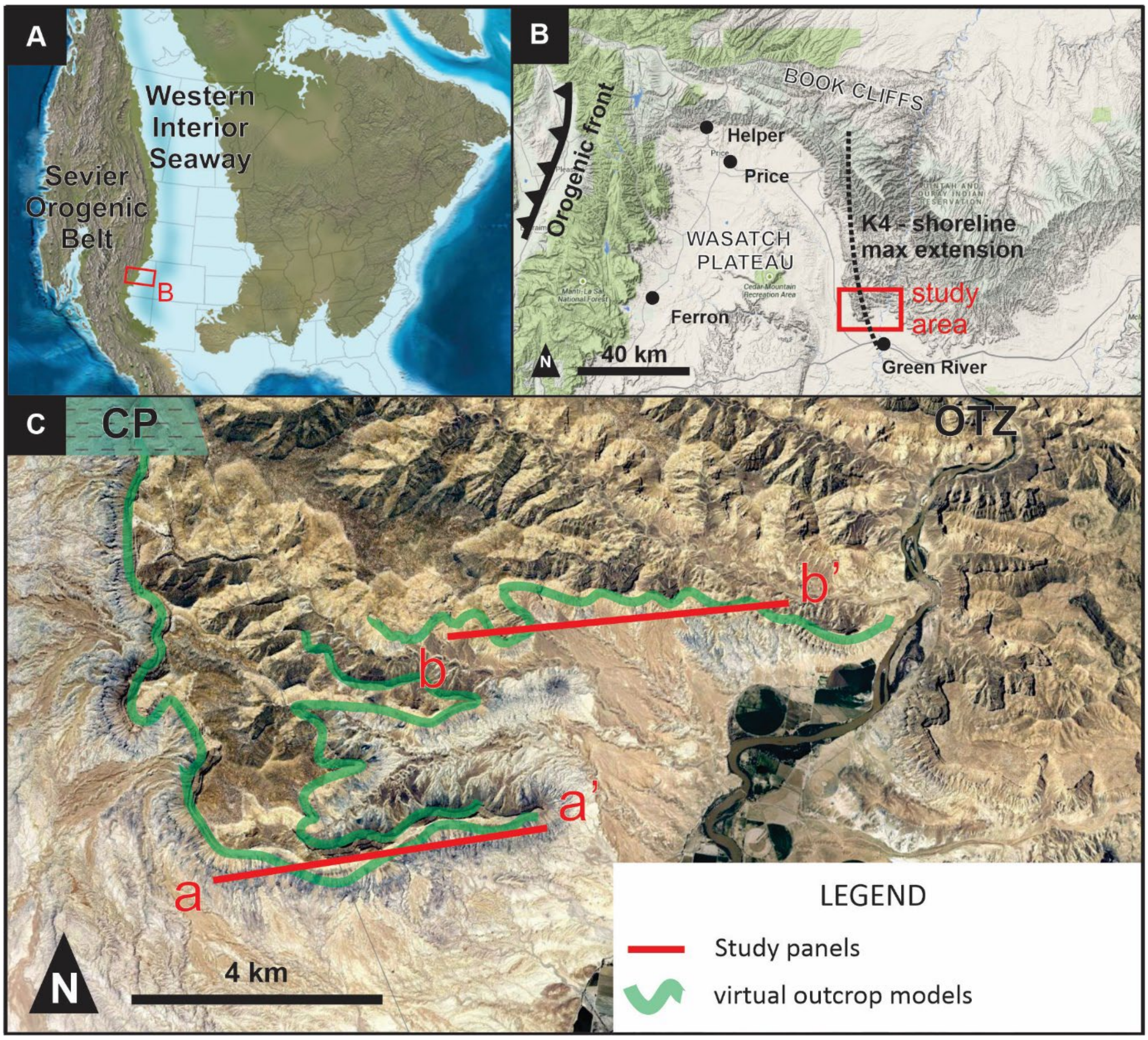

Figure 1. A) Western Interior Seaway map for the Campanian (Scotese, 2014). B) present day topographic map of western Utah, USA, indicating the easternmost extent of the Campanian orogenic belt which was the sediment source, and the maximum extent of the K4 parasequence palaeoshoreline. C) Oblique view of the study area, showing the extent of the available virtual outcrops and the study sections (Imagery © Google 2024).

Shorefaces developed in the seaway's western margin prograded eastward due to excess sediment supply, before being punctuated by transgressive episodes. These progradational-retrogradational cycles resulted in the formation of 'sandstone tongues' which are intercalated with offshore deposits of the Mancos Shale. The K4 parasequence comprises one of such progradational retrogradational cycles. Ammonite zone dating in the offshore deposits allowed Howell et al., (2003) to estimate the average time represented by these parasequences to be in the order of 70-80 Kyr (3,5 Myr/46 stratigraphic events). The same authors calculated a simple average subsidence rate of 0,15 mm/yr for the unit, which is relatively low for a foreland basin, but still moderate in general terms. We can therefore broadly classify this example as moderate accommodation, high supply, in a late foreland basin setting with a warm and humid climate.

For this study, we have selected a specific outcrop of a shoreface unit belonging to the Blackhawk Formation, close to the locality of Green River, Utah, USA, given its combination of accessibility, great understanding through abundant previous studies, availability of virtual outcrop models and field data, and position and down-dip orientation with respect to the interpreted paleoshoreline. In this outcrop, lateral transitions from coastal plain, to shoreface, to offshore transition facies have been identified within the K4 Parasequence across a composite 12 km long section from the Battleship to Gunnison Buttes (Fig. 1). These transitions are explained by the lateral passage from proximal to distal locations in the ancient coastal system (Hampson, 2000; Eide et al., 2014; Sech et al., 2009).

FEATURES OF RESERVOIR INTEREST IN THE K4 PARASEQUENCE

Changes in Facies Thickness Down Depositional Dip

Shoreface facies, and particularly the upper shoreface facies, are the key reservoir in most wave-dominated shallow marine deposits (Fig. 2C). This is also the case in the K4 parasequence, where shoreface sands have high porosity and permeability good vertical and lateral connectivity, while offshore transition and coastal plain facies associations have marginal reservoir properties (Sech et al., 2009, Eide et al., 2015). As a result, thickness variations of shoreface facies are key to reservoir geometry, and a feature of reservoir interest to be captured by our model. Downdip variations in shoreface sandstone thickness in the K4 have been documented since early studies (Young, 1955; Pattison, 1995; Taylor and Lovell, 1995; Hampson, 2000). Most of these studies mentioned repeatedly how shorefaces facies of the Blackhawk formation wedge out distally into shelf facies. However, downdip shoreface thickening has also been recorded (Hampson, 2000; Eide et al., 2014, Ainsworth et al., 2017). For instance, shoreface thickness passes from around 15 meters in

Lila Canyon to up to 40 meters in Battleship Butte, which is relatively more distal (Fig. 4 in Hampson, 2000).

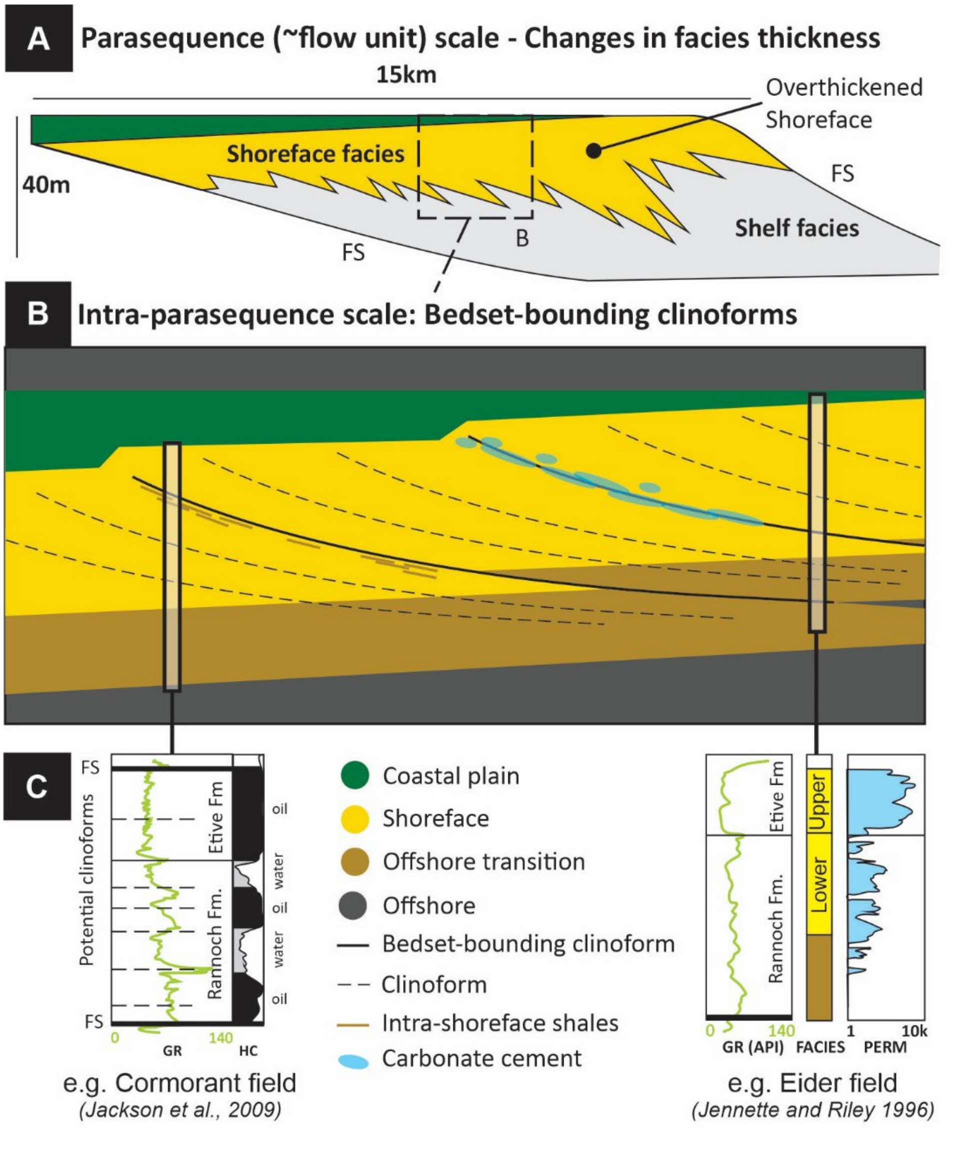

Figure 2. Sketches of sedimentary features that can have significant impact on reservoir behavior and have been observed in the K4 parasequence. A) Sketch redrawn from Ainsworth et al., 2017; their Figure 21I, showing a schematic cross section that illustrates the down-dip overthickening of shoreface facies as a result from the transition from low- to high-accommodation conditions. B) Sketch illustrating intra-parasequence heterogeneities, emphasizing bedset-bounding clinoforms and the features that can be associated with them, like intra shoreface shales or carbonate cement. C) Logs from two fields that penetrate the Brent Group in the North Sea, showing the relationship between

facies and petrophysical properties (Eider field log) and the relationship between potential clinoforms and oil saturation (HC) after 20yrs waterflooding (Cormorant field log).

Different interpretations for the downdip thickness variations of the K4 parasequence shoreface at Battleship Butte have been presented. One such interpretation is suggested by Hampson (2000) who based on the facies distribution, the sharp base of the shoreface and other regional observations, interprets the shoreline trajectory of the parasequence in the study area. He links this interpreted shoreline trajectory of successive normal and forced regressions (presented in detail in Hampson and Storms, 2003 and Hampson et al., 2008; their Fig. 7) to the generation of an overthickened shoreface (see 'Comparison with Regional Sequence Stratigraphic Context' Hampson, 2000). A second explanation is presented by Eide et al., (2014) linking downdip thickening of shoreface to a combination of (i) exposure of the shoreline to stronger waves as it prograded into deeper and more exposed waters, coinciding with (ii) vertical stacking of bedsets linked to a bedset boundary that records a 5-meter relative sea level rise. Finally, a third explanation is presented by Ainsworth et al., (2017, 2020). They have gathered information from many parasequences, including the K4, and analyzed the positions of maximum sandstone thickness. Their results show that maximum sandstone thickness occurs at a sandstone to parasequence thickness ratio of approx. 0.5 (Ainsworth et al., 2017) and suggest that this is the result of load-induced compactional subsidence of shelfal mud. As mud is compacted, the shoreface deposits are lowered and more space is created and eventually filled in shallow waters, giving a result an overthickened shoreface (Ainsworth et al., 2020).

Bedset boundaries were defined by Van Wagoner et al., (1990) as surfaces of nondeposition or erosion that bound concordant and shallowing upwards successions of genetically related beds within parasequences (*i.e.* bedsets). Hampson (2000) identified a large number of intra-parasequence discontinuities in the K4 in the study area, that he refers to as clinoforms and equates them to bedset boundaries (Hampson, 2000; p. 327). Here, we will focus on the intra-parasequence discontinuity surfaces that record a landward facies shift (but no landward dislocation of the shoreline) i.e., the 'non-depositional discontinuity surfaces' of Hampson (2000) and 'bedset-bounding clinoforms' of Eide et al., (2014). These have major potential to act as buffers of barriers within a parasequence or flow unit (Fig. 2; Sech et al., 2009; Jackson et al., 2009), given that they can be associated to an increased proportion of intra-shoreface muds (Eide et al., 2014) and/or carbonate cement (Hampson et al., 2015). In addition, since they are related to landward shift of facies belts, they modify the reservoir geometry and the distribution of the highest quality facies, i.e. they dislocate the base of the shoreface and the upper shoreface (Sech et al., 2009, Eide et al., 2014).

The generation of bedset boundaries has been typically linked to either very low magnitude relative sea level rise, changes in sediment supply or changes in wave regime, but the three triggering mechanisms are usually very difficult to discriminate (Sømme et al., 2008; Hampson and Storms, 2003). In the Blackhawk Formation, it is generally agreed that the main control over bedset boundary formation is changes in sediment supply, with small-scale sea level rise or wave regime change as smaller contributors (Howell et al., 2003). In the study area however, Hampton (2000) linked the generation of 'non-depositional intra-parasequence discontinuities' to changes in wave regime, based on regional data that suggest very linear coastlines. He linked those changes in regime either to autogenic or allogenic processes depending on the along-strike extension of the surfaces. However, later authors like Eide et al., (2014) have linked at least one bedset boundary of the K4 to relative sea level rise, since it is related to a steep change in shoreline trajectory and coastal plain thickness. This study also highlights the presence of wave dominated deltas in parts of the succession, which hints that sand supply could also be a key factor in bedset boundary generation in the area.

METHODS

Outcrop Mapping

Using the Virtual outcrops of the SAFARI database, the major features of reservoir interest in the K4 parasequence were mapped over the virtual outcrops using Lime software (Fig. 3). Following the methodology of Eide et al. (2014), parasequence-bounding flooding surfaces, facies belt boundaries and bedset-bounding surfaces were identified in the outcrops. These contacts were projected into two panels, which are oriented N75-255°. The two panels are connected correlating a pair of interpreted bedset boundaries that are observed in both panels and in an outcrop between them (Fig. 3). The strike of this pair of bedset bounding surfaces is N150-330°. If we assume an average progradation direction of N60°, normal to the strike of the bounding surfaces and agreeing with previous studies (e.g. Hampson and Storms, 2003), then the orientation of the panels is nearly parallel to proximal-distal direction. Flattening was carried out with the 2D unfolding tool using the top flooding surface as datum.

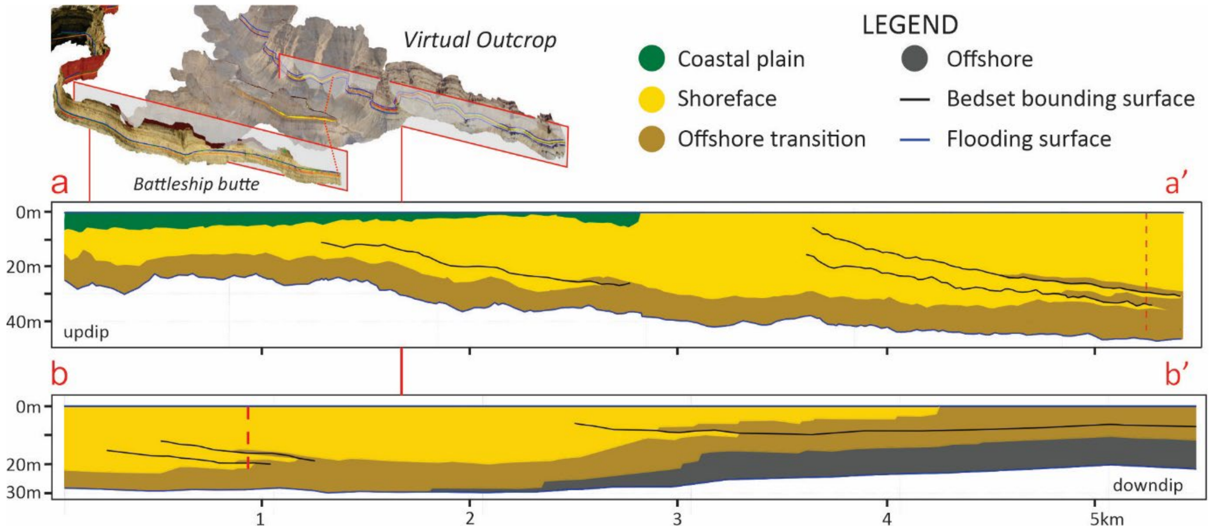

Figure 3. Study panels that result from features mapped in the virtual outcrops projected into a flat surface perpendicular to the bedding orientation. Emphasis is given in features that are of reservoir interest at this scale: facies belts distribution and clinoforms associated with bedset boundaries. A pair of closely spaced clinoforms are used for correlation between the two panels (see text for details).

The GEOPARD Algorithm

The GEOPARD algorithm is designed to mimic a stage of shoreface progradation at the parasequence scale. This follows the logic that the corresponding deposits at this scale are expected to define a flow unit in a reservoir, and most likely will represent also a zone in a reservoir model. Bedsets are chosen as the main geological object to represent the dynamics of this shoreface progradation, since they represent relatively small pulses of progradation in which most controlling parameters remain constant (Fig. 4A). At the end of one run, the algorithm gives a succession of prograding bedsets up to a certain point in space given by the user. This allows for sufficient flexibility to represent trends as the shoreface progrades, like changes in shoreface thickness, shoreline trajectory or progradation direction. It also allows the representation of typical internal heterogeneities along its boundaries, like cemented intervals, mudstone or siltstone beds, while being able to mimic changes in their spacing, slope orientation, etc.

Bedsets and their boundaries may or may not be recognized in cores or wireline logs. Their correlation from well to well carries a large uncertainty, even in very closely spaced wells. Therefore, even if the user may identify and condition the model to bedset boundary observations in wells, the key conditioning parameter in the wells is facies. We have considered that bedsets and their boundaries will be a stochastic component in most, if not all, reservoir facies models. The interest behind modelling bedsets is that they represent discrete events in shoreface progradation, that allow us to have the flexibility to mimic the processes that govern facies distributions and surfaces of reservoir importance. Further details of the algorithm are presented in a separate paper (Aarnes et al., 2024, *submitted for publication*).

The input values that the algorithm asks for can be separated between the ones that are fixed for each run, and the ones that can vary around the 3D volume of the model (Fig. 4B). On the first category we have: (i) progradation direction of the system; (ii) initial sea level (iii) and stop location (or maximum shoreline advance). On the second, we will have (i) shoreface and offshore transition zone depths (ii) length of the bedset (iii) slope at the upper shoreface and at the shelf (iv) progradation and aggradation magnitude of bedsets (v) retreat (*i.e.* erosion and/or vertical shift assigned to bedset boundaries) and finally (vi) intra-bedset shoreface depth variation. The first three inputs of the second category define the shoreface-shelf profile, while the last three are more related to the shoreline trajectory and geometry of facies belts and bedsets.

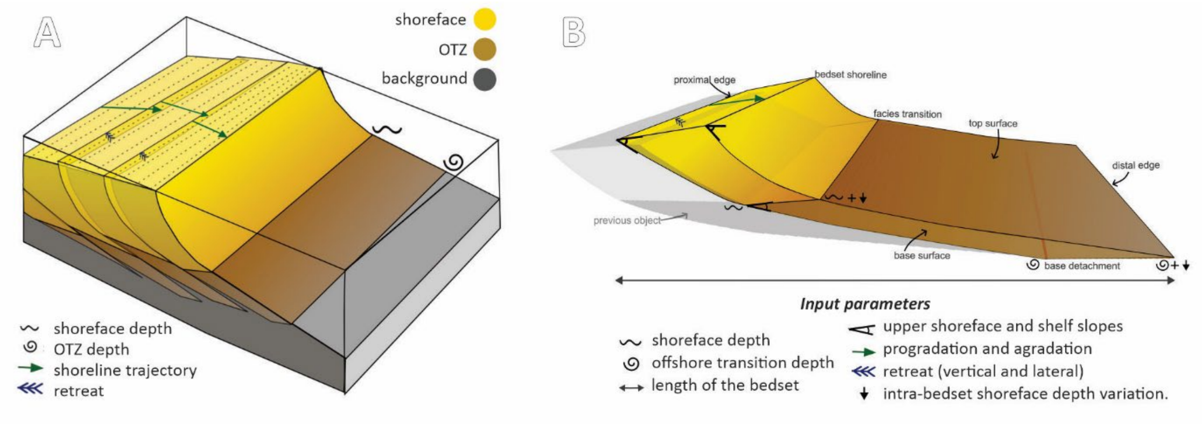

Figure 4. Geopard modelling algorithm (modified from Aarnes et al., 2024, submitted for publication). A) Conceptual model, consisting of a prograding succession of bedsets with shoreface and offshore transition (OTZ) facies within. While bedsets are formed during progradation, their boundaries are formed during retreat (i.e. erosion or non-deposition) episodes. B) Parametrization of a bedset element by the GEOPARD algorithm. The geometrical elements indicated in the sketch are informed with the parameters that are listed below the sketch.

Modeling Approach

With the sections imported in RMS®, GEOPARD was used with an iterative approach to try to match the sections. Starting from a standard, moderate accommodation, high supply, configuration, and giving and approximate location for maximum shoreline advance, input parameters were modified until the geometries observed in the outcrop section were matched. GEOPARD was integrated into an RMS® workflow to rapidly import each new version. The choice of input parameters was manual, and therefore, it intended to follow the logic behind the presented conceptual models from previous studies. We have as a result generated two GEOPARD models: A and B. Model A corresponds to the combination of the conceptual models of Eide et al., (2014) and Ainsworth et al., (2020), while Model B corresponds to the conceptual model of Hampson (2000) and Hampson and Storms (2003). The final inputs and resulting geometries of those models are presented and discussed further below.

Comparison Strategy

As explained previously, we have separated features of reservoir interest identified in the K4 into (i) changes in facies thickness down depositional dip, which control reservoir geometry, and (ii) clinoforms associated with bedset boundaries, which are a main control on internal heterogeneity. Changes in facies thickness down depositional dip were analyzed using 5 virtual logs measured from the outcrop sections, spaced every 2 km. The positions of those logs are relative to the point of maximum shoreface thickness. These were compared to facies thickness produced by GEOPARD in the same locations. For bedset boundaries, we have analyzed their (i) dip angle relative to the top flooding surface, (ii) average spacing and (iii) apparent landward shift at the base of the shoreface. These are measured in the same way in a fence across the models generated by GEOPARD, and the values are compared.

RESULTS (COMPARISON TO OUTCROP)

Downdip Facies Thickness Variations

Down-dip thickness changes in facies described by previous studies in the area are clearly observed in the outcrop section and in the virtual logs (Fig. 5). In the most up-dip sector, coastal plain deposits are thick, around 6 m, while shoreface deposits have a medium thickness of around 10 m, and offshore transition deposits cannot be observed in their full thickness, since their base is not preserved. 4 km further down-dip, coastal plain deposits gradually wedge out, as shoreface deposits thicken considerably, reaching a maximum thickness of around 35 m. If we go again 4 km down-dip of this point, shoreface deposits wedge out completely, and offshore transition deposits with a total thickness of 12 m are recorded.

When comparing the outcrop sections and virtual logs to a section across the models generated by GEOPARD, the variations in thickness are reproduced successfully in both models (Fig. 5). To match coastal plain thickness, adjustments were made in the parameters that affect shoreline trajectory: aggradation and vertical retreat values versus progradation and lateral retreat values. The considerable thickness increment of the shoreface in the middle part of the section was matched in two ways: Firstly, by a combination of two parameters: Higher aggradation value, that leads to vertical stacking of bedsets, and most importantly, by a considerable increment in shoreface depth values in this sector from 7 to 27 meters (Fig. 5B).

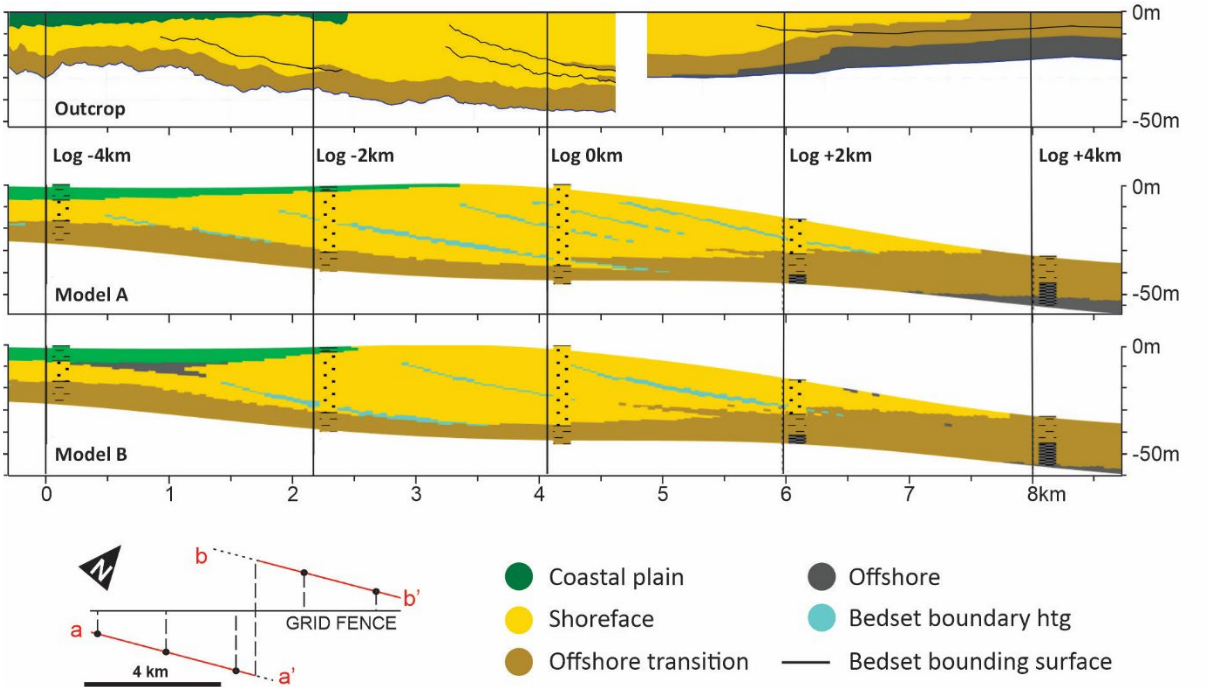

Figure 5. Sections comparing results. The top section shows the facies and bedset boundary distribution identified in the outcrop panels (Fig. 3). The middle section shows Model A results, and the lower section shows Model B results. The 5 virtual logs extracted from outcrop are projected into the models below for comparison (see text for details and discussion).

Bedset Boundaries

The apparent landward shift of the base of the shoreface (Table1) averages 460 m in the 6 outcrop measurements, ranging from 250 to 880 m (two bedset boundaries were measured in both sections, 3 km away, to capture their along-strike variability). The models match these values by tuning the variation in shoreface depth within bedsets, and in some of the cases also by adding subtle sea level rise during bedset boundary formation (vertical retreat), an element that is present in the conceptual model by Eide et al., (2014) and Hampson and Storms (2003). Model A produces 7 bedset boundaries from which only 5 record facies shift at their boundaries. Average landward shift at the base of the shoreface in model A was 410 m, ranging from 105 to 830 m. Model B produces 8 bedset boundaries, and 4 of those have facies shift at their boundaries. The average landward shift in model B was 430 m, ranging from 105 to 830 m.

Slope angle of bedset boundaries is compared at the lowermost shoreface, where such surfaces are best expressed (Isla et al., 2021). The slope recorded in the outcrop, calculated using the K4 flooding surface as datum, is on average 0.4°, ranging from 0.45° to 0.2°. To match the angles from the outcrop, the key input needed was a base angle of 0.6° to 1°, with an increment of 0.1 to 0.3° in the top slope. The models A and B then generate an average slope of 0.4° in the lower shoreface, ranging from 0.5° to 0.3° (Table1)

Bedset boundary spacing is measured at the lower boundary of shoreface, again because of the good expression of surfaces a that depth. The outcrop shows a wide variability at the exposed section, since two of the bedset boundaries are very close to each other (200 m apart; Fig. 5; Km 4 to 5 in section a-a') while the rest are widely spaced (2 km apart). In average, the spacing is 1480 m in the outcrop. We have emulated this average in the models by setting a progradation trend with values from 1000 to 2000 m (and retreats at bedset boundaries from 50 to 400 m). We have therefore decided to match average values, but alternatively we could have had very small and very large bedsets as well. The final spacing average is 1440 m in model A and 1280 in Model B (Table1).

		Outcrop	**Model A**	**Model B**
Landward facies shift	Av	460	410	430
	Max	880	830	630
	Min	240	105	260
	N	6	5	4
Spacing	Av	1480	1440	1280
	Max	2620	3830	3390

	Min	230	424	130
	N	4	6	6
Dip angle	Av	0.4	0.4	0.4
	Max	0.5	0.5	0.5
	Min	0.2	0.3	0.3
	N	5	5	4

Table 1. Bedset boundaries characterization for outcrop and GEOPARD models.

DISCUSSION

Conceptual Models of the K4 Shoreface

We have shown that we can match the geometries from the outcrop with two models that are based on different interpretations of the outcrop. Model A corresponds to the conceptual models of Eide et al., (2014) and Ainsworth et al., (2020), while B corresponds to the conceptual model of Hampson (2000) and Hampson and Storms (2003). It is worth noting that in the second case, we found that having a single sea level fall episode followed by a subsequent relative sea level rise (with a higher magnitude than scenario of model A), was the simplest way to emulate the geometry observed in outcrop. This is different to the very complex and detailed shoreline trajectory consisting of several rises and falls that the authors have interpreted, but it allows us to represent the broader geometries of reservoir interest while following their concept.

If both models fit well to available data, and we can represent features of reservoir interest, why would it be important to identify and model the two scenarios? Relative sea level rises and falls would be expected to impact systems regionally, linked to eustatic sea level and uplift/subsidence (refs). Wave base and compaction however can change in short distances and are therefore more local (refs). As a result, identifying the forcing factors has implications in along-strike or more regional predictions. Even if in our modelling area there’s no apparent difference, it is important to note that GEOPARD can model both scenarios. In the base of model A, if compaction or wave base changes spatially, then wave base can be introduced as a 2D or even 3D trend.

From the point of improvement of the conceptual models available for the K4, the process mimicking model at this point cannot provide evidence to select a more likely scenario. It is far more straightforward however, to match observed outcrop geometries with model A, provided that it can be proven that an increment in wave base and the effect of compaction can adequately explain for the full magnitude of shoreface thickening in the area.

Process Mimicking

In the previous sections we described how we changed parameters to make our models match the outcrop geometries, but we still need to discuss now how these parameters and the rules they are applied in, were intended to mimic geological processes.

The known processes of gradual fair-weather wave depth increment (Eide et al., 2014) and autocompaction (Ainsworth et al., 2020) presented in the introduction, were mimicked by GEOPARD by increasing shoreface depth with a spatial trend. The logic behind that link is that fair-weather wave base increment makes the shoreface deeper, and so does mud compaction, since as the shoreface is lowered by its own weight the new available space filled by more shoreface sands. Shoreface depth input parameter can be given as a 1D, 2D or 3D trend (in the presented case study a 1D trend was used, parallel to progradation direction) and as a result, each successive bedset has a deeper shoreface than the previous. This reproduces the expected shoreface downdip thickening geometry observed in so many examples in outcrop besides the K4 parasequence (Ainsworth et al., 2020).

Relative sea level rise and fall as the shoreline progrades were mimicked using the aggradation input parameter. It is important to note that this has a clear impact on bedset shape. Shoreface thickness will increase with relative sea level rise and decrease with relative sea level fall (Fig. 5, see difference between model A and B from 0 to 2 kms).

The relatively more abrupt processes that form bedset boundaries were mimicked by a combination of methods. Bedset boundaries that generate a landward facies shift by changes in sediment supply rate (e.g. an avulsion in the coast plain) or changes in wave climate (e.g. wave direction or intensity) were mimicked by shoreface deepening within a bedset and lateral retreat parameters. We support this choice since sediment supply in the coast and fair-weather wave base impact directly the depth of the shoreface, while also in some cases triggering coastal erosion during bedset boundary formation (Sømme et al., 2008; Hampson and Storms, 2003). Bedset boundaries that generate landward facies shift by subtle sea level rise are mimicked by the vertical retreat parameter. This means that if the bedset boundary was triggered by relative se level rise, the next bedset will have an elevated position with respect to the previous. The two ways to generate landward facies shift at bedset boundaries generate different geometries in the model.

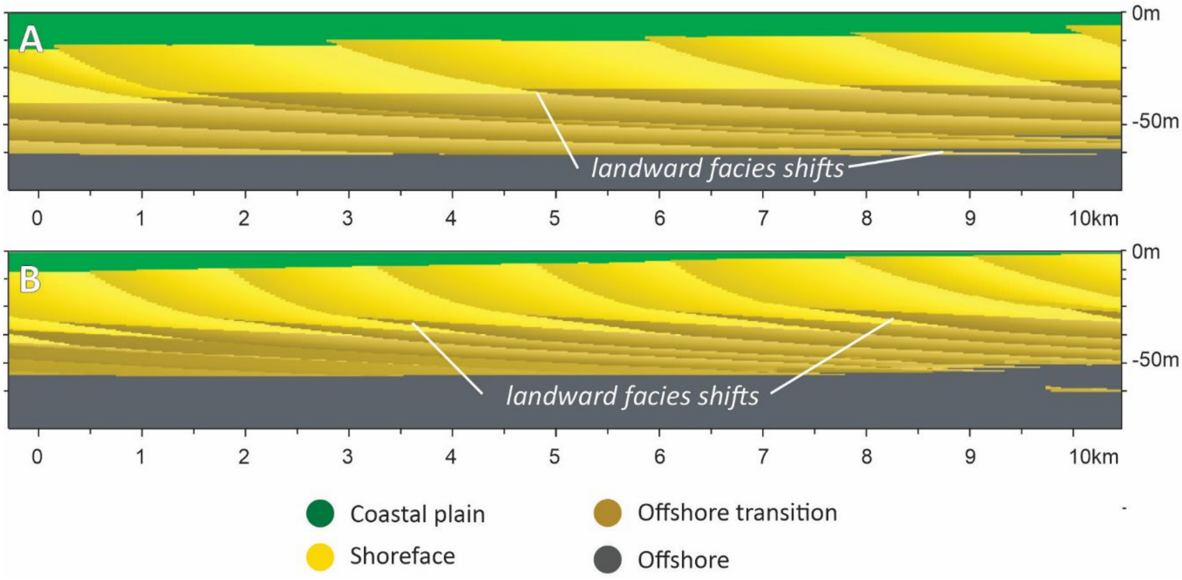

Figure 6. Process mimicking of the formation of bedset boundaries. A) Imitation of bedset boundaries caused by subtle sea level rise. B) Imitation of bedset boundaries caused by changes in sediment supply to the coastline.

It is also important to highlight that the GEOPARD model generates also many bedset boundaries that do not record a landward facies shift. These have been also identified in the geological record (e.g. erosive discontinuities of Hampson, 2000) and explained in numerical models (Storms and Hampson, 2005). Even if these adhere to the classic bedset boundary definition by Van Wagoner et al., (1990) they are instead usually referred in the literature simply as shoreface clinoforms or shoreface discontinuity surfaces (Hampson, 2000; Sech et al., 2009).

Even if shoreface clinoforms (compared to typical bedset boundaries) have a lower impact as reservoir heterogeneities, we believe that their representation in the rule-based model is desirable. Having many smaller bedset elements in a model allows for a greater flexibility to match known data and to apply spatial trends in input parameters, like progradation, aggradation, shoreface depth, etc. At a first glance, having many bedsets might seem like a too complicated model, that has many objects of limited reservoir interest. However, we want to highlight that bedsets are not expected to be correlated or even identified by GEOPARD users. They are instead the main modelling elements used in the background to mimic the process and produce a reservoir model that captures realistic geometries.

A comparison to traditional methods is a key aspect to test the added value of using this method. The most typical algorithm used for wave-dominated shallow marine reservoirs is arguably the truncated gaussian simulation (Ringrose and Bently, 2021). At a first glance, the user does not need a much more elaborate conceptual model and input data to model with GEOPARD compared to truncated gaussian. Both need a progradation direction, a notion of shoreline trajectory, depth of facies belts, etc. Differently from truncated gaussian, GEOPARD asks for inputs related to the expected slopes in the shoreface and shelf. As we have explored in this study however, this comes with the advantage of representing internal heterogeneities typical of wave dominated shallow marine reservoirs, that are known to have considerable impact on oil recovery on certain scenarios (Jackson et al. 2009). In addition, GEOPARD can represent complex reservoir geometries like landward facies shifts at bedset boundaries. Both these features are poorly represented by truncated gaussian and represent a clear advantage of GEOPARD. A proper comparative analysis and discussion between methods are, however, beyond the scope of this study and will be presented in future papers.

CONCLUSIONS

This study has tested the ability of the GEOPARD algorithm to reproduce features of reservoir interest observed in a wave-dominated shallow marine succession, at a scale typical of most geocellular reservoir models.

Previous studies of the well-known outcropping succession of the K4 parasequence of the Kenilworth Member (Blackhawk Formation) in Green River, Utah, USA, were consulted to select the features of reservoir interest that the models aimed to capture. Downdip facies thickness variations and clinoforms associated with bedset boundaries, were chosen as the key features that respectively control reservoir geometry and internal heterogeneity in the shoreface of the K4 parasequence. Interpretations of the formative processes of these features were also taken from previous studies.

Using virtual outcrops, the selected geological features were successfully identified, mapped, and projected into panels. The GEOPARD modeling philosophy was briefly introduced and the main input parameters that the user can modify were presented. GEOPARD was then used to reproduce downdip facies thickness and bounding surface geometries with an iterative approach and the results were compared quantitatively with the outcrop. Two models were generated following contrasting conceptual models from previous studies. One model considers subtle relative sea level rise, while the second considers a combination of relative sea level fall and rise. For both models, down-dip thickness variations of facies belts, emphasizing on shoreface facies, were matched down to meter accuracy at the position of the virtual logs. GEOPARD models were also successful in accurately matching average bedset boundary slope, spacing, and magnitude of landward facies shift.

GEOPARD was able to match outcrop's facies and bedset boundary geometries following two different conceptual models, likely indicating that both are viable at the scale of analysis and particularly at our study sections. However, we have discussed how these two scenarios would produce very different results at a regional scale. Most importantly, the logic followed to reproduce geological processes was discussed. We have shown how long-term wave base variations, compaction, and relative sea level rise and fall can be mimicked by trends in shoreface depth and aggradation parameters. Similarly, we have shown how processes at bedset boundaries can be mimicked with retreat and intra-bedset shoreface depth variation parameters. Finally, we have highlighted how having higher number of smaller scale bedset objects allows the algorithm much more flexibility to match reservoir geometries and heterogeneities.

Following the analysis and discussions presented in this study, we believe that GEOPARD has a big potential to be used as a quick and robust method for modeling reservoirs of wave dominated shallow marine origin. Future studies will focus on comparing closely the results and inputs needed from GEOPARD and traditional algorithms like truncated gaussian simulation. Furthermore, this rule-based methodology has a big potential to mimic processes and reproduce geometries from other sedimentary systems.

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