Forward modelling as a method for predicting the distribution of deep-marine sands: an example from the Peira Cava Sub-basin

TOR EVEN AAS1,3,*, RICCARDO BASANI2, JOHN HOWELL1 & ERNST HANSEN2

1CIPR, University of Bergen, Allegaten 41, Bergen, 5007 Norway
2Complex Flow Design, Trondheim, Norway
3Present address: Statoil ASA, Svanholmen 8, Stavanger, Norway
*Corresponding author (e-mail: toevaa@statoil.com)

Abstract: The aerial extent, thickness and internal distribution of grain-size are key, bed-scale controls on turbidite reservoir performance. Process-based modelling provides a method for predicting both the sandbody thickness and the grain-size distribution within the bed. The goal of the current study is to test such an approach on the Annot Sandstone in the Peira Cava Sub-basin in SE France, and determine whether the process-based model can reliably recreate the bed characteristics observed in the outcrop. Turbidity currents were modelled using a commercially available software solution called MassFlow3D that is based on computational fluid dynamics. The goal of the current study was to accurately replicate a single bed (termed MU5). To achieve this goal, the base of the basin was structurally restored and then a simplified simulation of the beds below MU5 was generated using four flow events in order to recreate the bathymetry on to which MU5 was simulated. Several versions of MU5 were simulated with different input parameters for the flow, and the results were compared with the observed thickness and grain-size distribution from the outcrop. The study suggests that process-based modelling has the potential to be a useful tool in reservoir modelling.

Supplementary material: Multi-phase flow modelling of transport, deposition and erosion of sediments is available at http://www.geolsoc.org.uk/SUP18719.

Sandstones deposited by gravity-driven processes in deep-water settings act as important hydrocarbon reservoirs in many basins around the world (Weimer et al. 2000; Prather 2003; Hurst et al. 2005; Mayall et al. 2006). Globally turbidite reservoirs contain over 78 billion barrels of oil with significant volumes yet to find (Weimer & Pettingill 2007). Predicting reservoir properties and how they vary away from the wellbore in such systems is traditionally done by studying analogous outcrops (Nilsen et al. 2007).

At the scale of individual beds the petrophysical characteristics and hence hydrocarbon reservoir properties are controlled by the depositional processes (e.g. Barker et al. 2008) and an understanding of turbidite depositional process can be used to predict reservoir properties and how they vary away from the wellbore.

Numerical simulations of flow using computational fluid dynamics have been developed to shed light on flow parameters which are difficult or impossible to deduce from experimental and field studies such as detailed density and turbulent kinematic energy distributions (Janocko et al. 2013). While the conceptual knowledge developed from the analysis of seismic and outcrop data has seen remarkable progress in recent years (Mulder & Alexander 2001; Hadler-Jacobsen et al. 2007; Schwab et al. 2007; Dykstra & Kneller 2009; Duller et al. 2010), the fundamental science of sediment transport and deposition based on controlled experiments and direct observations of natural flows has been hampered by scaling issues and practical problems in measuring the most important parameters (Meiburg & Kneller 2010). The method has been widely applied in the engineering branches of fluid mechanics but has thus far been little used in sedimentological research and reservoir studies in a fully 3D numerical scheme. All of the principal hydraulic properties of the flow (e.g. velocity, density, sediment concentration, apparent viscosity, turbulence intensity and bottom shear stress) and its responses to topography can be continuously monitored in three dimensions over the whole duration of the turbidity current. Using deterministic process-based simulations it is possible to recreate the flow events that deposited a basin fill. Numerical simulations for gravity flow phenomena have been around for a long time. After pioneering work in the 1960s (Komar 1969), 1970s (Harbaugh 1970; Komar 1973, 1977) and 1980s (Tetzlaff & Harbaugh 1989 and references herein), various 2D
and 3D studies have been published in which numerical models have been calibrated to physical models (Groenenberg et al. 2009), natural events (Pirmez & Imran 2003; Dan et al. 2007; Salles et al. 2008; Abd El-Gawad et al. 2012) or geomorphological features (Fagherazzi & Sun 2003; Cartigny et al. 2011; Kostic et al. 2010; Kostic 2011), or based on extensive outcrop data (Groenenberg et al. 2010). Waltham et al. (2008) utilized numerical flow modelling on to one specific palaeosurface to investigate potential entry points for the flows. The resulting deposits were matched to existing well-data. Similarly Aas et al. (2010a, b) utilized the software MassFLOW-3D from Complex Flow Design to numerically simulate gravity flows on to multiple palaeosurfaces in an attempt to identify the palaeosurface that best matched observed datapoints. Janocko et al. (2013) used MassFLOW-3D to demonstrate that flow parameters and depositional features from laboratory experiments could be recreated by the software and, similarly, Basani et al. (in press) successfully recreated results from a laboratory experiment by Baas et al. (2004).

Process-based models of deep-water systems are highly sensitive to the input parameters used in the model setup, not least the bathymetric surfaces across which the flows are simulated. Therefore reconstructing palaeobathymetry is a critical part of the modelling workflow (Waltham et al. 2008; Aas et al. 2010a, b), which is typically based on backstripping and structural restoration of present-day rock volumes. The 3D restoration of palaeosurfaces is now a well-documented process (Buddin et al. 1997; Williams et al. 1997; Rouby et al. 2000; Yin & Groshong 2006; Waltham et al. 2008; Roberts et al. 2009; Aas et al. 2010a, b). Buddin et al. (1997), Williams et al. (1997), Rouby et al. (2000) and Yin & Groshong (2006) focused on structural restoration techniques, while Roberts et al. (2009) studied the temporal development of palaeosurfaces and palaeobathymetry on a large basin scale.

The aim of the current paper is to utilize numerical process-based flow modelling to predict bed geometry and grain-size distribution in a single deep-marine sandstone bed from the Peïra Cava sub-basin of SE France. A base-case simulation was performed as well as several additional simulations to highlight the effects of input parameters on flow simulation. The available surface at the onset of modelling was the base surface for the basin-fill while the targeted sandstone bed is located within the basin-fill. Therefore initial flow simulations were performed to model the basin-fill up to the targeted sandstone bed with the aim of creating a palaeoseafloor that could be used for modelling this bed. The model was allowed to compact and bend through flexing after each flow simulation had deposited a new sediment volume. The results were compared with data from the outcrop. The Peïra Cava sub-basin is part of the Annot Sandstone system (Elliott et al. 1985; Ravenne et al. 1987; Pickering & Hilton 1998; Sinclair 2000; Apps et al. 2004; Ford & Lickorish 2004; Joseph & Lomas 2004; and references herein), which is a well-exposed, deep-water system that is commonly used as an analogue for turbidite reservoirs deposited in small mini-basins (Moares et al. 2004). This approach is of potential interest to the petroleum industry with regards to both exploration and reservoir management.

**Study area: Peïra Cava sub-basin**

The deep-marine Eocene–Oligocene Annot Sandstone that crops out around the village of Peïra Cava (SE France) has been well studied (Bouma 1962, 1990; Stanley et al. 1978; Bouma & Coleman 1985; Ravenne et al. 1987; Stanley 1993; Hilton 1994; Pickering & Hilton 1998; Amy 2000; Amy et al. 2000, 2004, 2007; McCaffrey & Kneller 2001; Shanmugam 2002; Joseph & Lomas 2004; Lee et al. 2004). The outcrop extends for 10–12 km in a north–south direction and 8–10 km in a west–east direction (Fig. 1) and reveals a c. 1.2 km-thick Annot Sandstone succession. The sub-basin is defined by a syncline with a north-plunging fold axis and is believed to have been sourced along a north-dipping slope from the south (Amy et al. 2007). Initial studies interpreted the outcrop as a canyon–fan system (Stanley et al. 1978; Bouma & Coleman 1985; Ravenne et al. 1987; Bouma 1990; Stanley 1993), while more recent interpretations suggest that these are sheeted sands deposited in a confined basin (Hilton 1994; Pickering & Hilton 1998; Amy 2000; Amy et al. 2000, 2004, 2007; McCaffrey & Kneller 2001). This interpretation is based on observable onlap relationships of the Annot Sandstone on to the basin margins; the numerous thick mudcaps associated with individual beds suggest the trapping of flows within the basin and bi-directional palaeocurrent data suggest deflection of turbidity currents away from confining topography (McCaffrey & Kneller 2001). A depositional model proposed by Amy et al. (2007) suggests that proximal scour-and-fill facies are located close to a hydraulic jump zone in the south, and that a transitional zone separates these deposits from the more sheet-like beds towards the north.

Amy et al. (2007) demonstrated that the turbidite beds are mainly sheet-like in shape and extend throughout the observed portion of the sub-basin. Extensive data collection (stratigraphic sections and photomosaics) were used to correlate beds between known datapoints along most of the western and southeastern parts of the outcrop.
These authors identified 18 key marker units (MU1 near the base of the succession through MU18 near the top of the succession) based on their greater thickness and/or position within a distinct bed package. Marker unit 5 (MU5), which is the focus of the current study, is an easily recognizable 8–18.5 m-thick sandstone bed. It is the lowermost marker unit that can be confidently correlated throughout the basin. See Amy et al. (2007) for a full review of the sedimentology of the Peïra Cava sub-basin.

The uppermost part of the basin fill is thought to have been eroded as no clear evidence for fill and subsequent spill out of the basin or the presence of stratigraphy post-dating the Annot Sandstone has been observed (Amy et al. 2007). After the deposition of the Annot Sandstone, the Peïra Cava sub-basin was overridden by emerging thrust sheets from the east (Elliott et al. 1985; Apps et al. 2004) followed by subsequent erosion and uplift.

**Methodology and rationale**

This work set out to model a specific sandstone bed (Marker Unit 5, MU5) within the Annot Sandstone basin fill through deterministic process-based modelling. Such modelling is surface-based and thus requires a seafloor to represent the base of the bed. The Base Annot Sandstone surface was mapped and structurally restored following the process described in Aas et al. (2010b). Process-based modelling was then used to simulate early fill of the basin and generate the surface at the base of the MU5 bed. Modelling within the study was thus carried out at two resolutions.
(1) Relatively coarse process-based flow simulations initially introduced on to the base Annot Sandstone surface and associated modelling of compaction and isostatic bending of the model. The aim was to create a seafloor surface that could be used for the subsequent modelling of the MU5 bed.

(2) Finer, bed-scale, process-based flow simulation of the MU5 bed with the aim of matching as well as possible the variations in thickness and grain-size distributions from the field data. Several additional flow simulations for MU5 were performed with different flow parameter inputs in order to investigate their influence on the resulting deposits.

At the onset of flow simulations the model created in the current study included two surfaces from Aas et al. (2010b). These authors recreated a number of different palaeobathymetric surfaces for the base of the Annot Sandstone succession at Peira Cava. Based on process-based flow simulations, their ‘Surface 7’ was the palaeobathymetry which provided the best fit to the gross basin fill (Fig. 2). This surface has been used as the initial seafloor in this study (Fig. 3a). The other surface from Aas et al. (2010b) that was used was their Top Basement surface. Top Basement represents the boundary between sediments that will compact upon burial (above this surface) and rigid basement that will not compact upon burial (below this surface). This defines a volume between Top Basement and base Annot Sandstone that is modified by compaction as the basin fill is deposited, which in turn affects the bathymetry.

In the real world the surfaces respond dynamically through consolidation, compaction and flexural subsidence as mass is introduced on to the top of the model through deposition. A full dynamic approach was not possible in the available software so in the forward modelling this is captured in a stepwise manner in which each step includes the addition of a rock volume through process-based flow simulations performed in MassFLOW3D, followed by modelling of instantaneous isostatic response and compaction of buried mass performed in 3DMove. This is believed to be a reasonable approximation since deposition by mass flows is virtually instantaneous.

3DMove utilizes compaction curves from Sclater & Christie (1980), which describe the mechanical reduction in pore-space upon burial. Based on well data from the North Sea, they calculated the exponential reduction of pore-space towards depth for four different lithologies: sand, shale, sand and shale combination, and carbonate. Thus the rock volumes present between the surfaces of the model were assigned parameters based on their lithology (Table 1). 3DMove classifies rock volumes as load, intermediate and basement. When a load is introduced, the intermediate volume (or volumes) compacts instantly while the basement volume and the load volume do not compact. When a new load is introduced on to the top of the model, the old load is re-defined as an intermediate volume that compacts. All surfaces in the model change shape after a load is introduced owing to the combined effects of isostatic response and compaction of the intermediate volume or volumes.

Phase 1 modelling

Process-based flow simulations are extremely time-demanding and computationally expensive. Therefore it is not practical to simulate every single one of the vast number of individual beds that are present below MU5. This part of the stratigraphy could have been simulated in MassFLOW-3D as one very thick volume of sediment, but such an approximation would probably be too simplistic as the isostasy and compaction modelling would have been treated as a single step: this sediment volume would be classified as a rigid load volume in
3DMove that will not compact until it is buried by another volume that is classified as load. Thus the effects of dynamic compaction and compensational stacking on the evolving surface topography would have been severely underestimated.

As an intermediate case the stratigraphy below MU5 was subdivided into individual stratigraphic intervals that are defined by the five marker beds (MU1–MU5). That way they could be correlated and quality controlled with the available sedimentary logs (Amy et al. 2007) and the large-scale geometries of the basin fill were honoured. The intervals between MU2 and MU4 were very thin and were combined into a single interval so the total package was modelled in four steps which are detailed below.

Table 1. Surfaces used for forward modelling and initial porosity and compaction factor applied to the individual volumes

| Surfaces          | Surface origin     | Lithology underneath surface | Initial porosity | Compaction factor |
|-------------------|--------------------|------------------------------|------------------|-------------------|
| MU5               | Forward modelling  | Sand                         | 0.49             | 0.27              |
| MU4               | Forward modelling  | Sand and shale               | 0.56             | 0.39              |
| MU2               | Forward modelling  | Sand and shale               | 0.56             | 0.39              |
| MU1               | Forward modelling  | Sand and shale               | 0.56             | 0.39              |
| Base Annot Sandstone | Aas et al. (2010b) | Shale                        | 0.63             | 0.51              |
| Basement          | Aas et al. (2010b) | Crystalline                  | 0                | 0                 |

The Basement and Initial Seabed are the surfaces available at the onset of forward modelling. Loads 1–4 and MU5 surfaces are resulting surfaces from forward modelling.
During the first step of forward modelling the stratigraphy from the base Annot Sandstone surface and up to MU1 is modelled. The process-based flow simulation adds a new discrete volume on top of the base Annot Sandstone surface, and the top of this volume is defined by a new surface (MU1). These two surfaces along with the basement surface mentioned earlier are then exported from MassFLOW-3D and imported into 3DMove, in which the flexural response and compaction as a result of added load from flow simulation are calculated. For this modelling the volume between the base Annot Sandstone surface and MU1 is defined as rigid load, while the volume between the Base Annot Sandstone surface and the Top basement surface is compacted. After this modelling the three surfaces are exported out of 3DMove and imported back into MassFLOW-3D.

During the second step of forward modelling, the rock volume between MU1 and MU2 is modelled through flow simulations. At this stage the model comprises the Top Basement surface, the base Annot Sandstone surface and the MU1 surface. The flow simulation deposits a new volume that is defined by the MU2 surface. The model, now comprising four surfaces, is exported from MassFLOW-3D to 3DMove. The volumes between surfaces MU1 and MU2 are defined as rigid load and the volumes between surfaces MU1 and base Annot Sandstone, and surfaces base Annot Sandstone and Top Basement, are compacted as an effect of added load. The surfaces in the model are subsequently imported back into MassFLOW-3D.

Steps 3 and 4 of the forward modelling are performed in a similar manner to steps 1 and 2. After the stepwise forward modelling of phase 1 is complete, a process-based version of the MU5 seafloor is available. The model at this point comprises six surfaces: MU5, MU4, MU2, MU1, base Annot Sandstone and Top Basement.

Results from the forward modelling of the basin-fill interval between Base Annot Sandstone and MU5 were compared with two sedimentary logs from the field (Amy et al. 2007, sections 2 and 7; Fig. 3). In these the present-day thicknesses are 290 and 310 m. All of the Marker Units are present in section 7, whereas MU1–MU4 are either not present or cannot be correlated southward to section 2 (Fig. 3). Therefore the cumulative thickness of all four flow simulations was compared with both sections 2 and 7; in addition the thickness of each depositional unit was also compared with section 7.

The field data are the present-day thickness of compacted sediment, whereas the results from the flow simulations in MassFLOW-3D have not yet experienced the compaction from several kilometres of overburden and are in an uncompacted state. Thus, in order to be able to compare the simulation results and field data, an estimation of the uncompacted thickness at time of deposition for the latter was performed. Two assumptions were made: (1) maximum burial depth for the MU5 bed at these two locations from the surface model from Aas et al. (2010b) was indicated to be 3500 m in the area of section 7 and 3000 m in the vicinity of section 2; and (2) compaction curves from Sclater & Christie (1980) are representative of the overall Peı¨ ra Cava basin-fill compacted as a sandy shale lithology. Following these assumptions the cumulative, uncompacted thickness for the basin-fill below MU5 is approximately 740 m in section 7 and 420 m in section 2 (Table 3).

Phase 2 modelling

The phase 2 flow simulation was performed on the output MU5 seafloor surface from the Phase 1 forward modelling with the aim of creating a version of the MU5 (Marker Unit 5) bed that could be used to predict thickness and grain-size distribution trends away from known datapoints. The MU5 bed was chosen for modelling because it is the lowest bed in the basin-fill succession that can be traced reliably throughout the area. The reason for applying this method on the MU5 as opposed to one of the thinner, more commonly observed sandbeds is founded in field-data reliability. The Peı¨ ra Cava outcrop is partially covered by vegetation, and visual correlation of the thinner individual sandbeds between well-exposed areas is not possible, while the MU5 can be observed continuously along the southeastern, southern and western parts of the outcrop. Thus the available field data from MU5 are thought to be reliable. Since MU5 is laterally extensive across the entire outcrop, there are six datapoints on thickness and grain-size distribution from across the outcrops.

MU5 is present in six out of the seven available stratigraphic logs (Amy et al. 2007), and these datapoints were used to constrain the input parameters for the flow simulation. Its present thickness varies from 8 to 18.5 m and, excluding section 3, the thickness is consistent between 8 and 12 m. In all six logged sections there is an absence of internal siltstone or claystone layers. Where this sand is exposed in the field and including five of the datapoints, the sandbed is normally graded (Amy et al. 2007). The exception is section 3, where the upwards-finishing trend is interrupted by upwards coarsening about 6 m from the base of the bed. In this work this is simply thought to be the amalgamation of the MU5 bed and a sandbody associated with an earlier flow. Thus the MU5 bed is between 8 and 12 m thick in all the available datapoints (Table 5).

Assuming the burial depth for MU5 was 3000 m, a number obtained from the back-stripping model
used by Aas et al. (2010b), the porosity is thought to be 22% in its present compacted state (Sclater & Christie 1980). The calculated thickness at time of deposition is expected to have been 10–15 m (Table 5). This thickness estimate is applied in combination with the expected aerial extent of MU5, given by the base-MU5 ancient seabed (Fig. 7c), to calculate the sediment volume required for the flow simulation.

The amount (in volume percent) of each grain-size in the six datapoints (Table 5, Fig. 8) was based on the logs from Amy et al. (2007). Clay, silt and very coarse sands are absent within MU5. A thin layer of gravel less than 0.5 m was observed locally at the base of section 4. These particle sizes were not included in the flow simulation.

**MassFLOW-3D**

The flow modelling was undertaken using MassFLOW-3D™, which is a computational fluid dynamic-based software package for the numerical simulation of the physical equations describing fluid flow and sediment transport in turbidity currents. Flows are simulated on a structural restored, back-stripped and decompacted palaeobathymetry. Given that confinement, tilting and topography are key parameters for the development of turbidity currents and their deposits, particular attention was given to recreating by-pass, fill-spill and deflection phenomena, documented in the outcropping succession (Amy et al. 2007; Aas et al. 2010b). The fluid motion of a sediment gravity flow in MassFLOW-3D™ is simulated by solving the fully 3D transient Reynolds-averaged Navier–Stokes equations by a finite-volume–finite-differences method in a fixed Eulerian rectangular grid. The suspension of mono- or poly-disperse, non-cohesive sediment is treated as a continuous phase and its variable spatial volumetric concentration is calculated. The effects of flow turbulence are simulated using the renormalization-group model, in which the equation constants are derived explicitly. This model is thought to be superior to the commonly used k–ε model in that it describes more accurately low-intensity turbulence in liquid flows. The drift velocity (velocity needed to compute the transport of sediments owing to drift relative to the fluid phase) of suspended particles is approximated by a non-linear multiphase model, allowing the deposition of larger and faster drifting sediment to be simulated more accurately. Particle interactions in suspension (hindered settling, particle collisions and interlocking of grains) are approximated by the Richardson–Zaki correlation (Richardson & Zaki 1954). Erosion, settling and lifting of sediment particles are calculated in terms of tensors superimposed on the sediment advection with the turbulent fluid. Entrainment (re-suspension, erosion) of sediment from the bed into the flow is calculated with the Mastbergen & Van den Berg (2003) model in which the critical Shields parameter is predicted using the Shield–Rouse equation (Guo 2002). The erosion model also accounts for particle armouring by using the Egiazaroff formula (Kleinhans 2002). The rolling and saltating motion of larger sediment near the packed bed interface (bedload transport) is predicted according to the Meyer-Peter & Müller (1948) sediment transport equation. The governing equations describing these separate modules can be found in Basani et al. (in press) and in the Supplementary material.

**Forward modelling**

The forward modelling was performed in two phases. The aims for phase 1 were to model the basin fill below bed MU5 to create a seafloor surface that could be used for more detailed forward modelling of the MU5 bed. For phase 2 modelling the aims were to model in more detail the thickness and grain-size distribution of the MU5 bed.

Some of the input parameters were common for both phases of forward modelling. The source point and direction of the flow were similar. The width and height of the flow at the onset of flow simulation were set to 1500 and 108 m, respectively. The flow simulations were performed on the same numerical grid that comprised 32 cells in the west–east direction, 55 cells in the north–south direction and 350 cells in the vertical direction. The input cells vary in size and an overview is given in Table 2. For the sake of compaction and modelling of isostatic response in 3DMove, standard values of 2.7 g cm−3 for the crust and 3.3 g cm−3 for the mantle were assigned. The crust was modelled to bend when loads were added and the stiffness of the plate was described by a constant value of 20 km for the elastic thickness as indicated by Ford et al. (1999).

All flow simulations were initially performed on to seafloor that could be eroded into using standard parameters from the literature (see Supplementary material). The results from the simulation of the MU5 bed showed too much erosion and the best match to the outcrop was obtained when scour by the flow was inhibited. The final MU5 bed simulations were performed without erosion, this is discussed further below. Input parameters for the forward modelling are shown in Table 3.

**Phase 1 forward modelling**

Flow 1: base Annot Sandstone–MU1. The simulated flow 1 was introduced on to the restored base Annot Sandstone palaeosurface, which shows a
general deepening towards the north punctuated by a series of smaller depocentres that are separated by highs (Fig. 2). The flow was point-sourced from the south with an initial velocity of 8 m s\(^{-1}\) and the total sediment/particle volume concentration set to 20%. Flow 1 was modelled as a sustained flow with a flow continuity of 45 h. The goal was to match the initial thickness estimated from the observed thickness between Base Annot Sandstone and the MU1 bed at logged sections 6 and 7.

After the flow simulation was complete the deposited volume (Fig. 4a) was used as a load to flex and compact the underlying volume between the Base Annot Sandstone and Basement surfaces. As a result, the MU1 surface generated from the flow simulation (Fig. 4b) changed shape (Fig. 4c).

Flow 2: MU1–MU2. Flow 2 aimed to capture the basin-fill interval MU1–MU2. It was simulated as a sustained flow with a total duration of 8.3 h (30 000 s) while the other input parameters were the same as for Flow 1 (Table 3). The aim of flow was to match the estimated 44 m depositional thickness of this interval at section 7 (Table 4). After flow simulation was complete the deposited MU1–MU2 volume (Fig. 5a) was added on top of the model as load, allowing for further flexure and compaction of the volumes Base Annot Sandstone–MU1 and Top Basement–Base Annot Sandstone. As a result the MU2 surface from flow simulation (Fig. 5b) changed shape (Fig. 5c).

Flow 3: MU2–MU4. Flow 3 input parameters were similar to the two previous flows with the exception of flow duration, which was set to 22 h (72 000 s) (Table 3). Flow 3 aimed at capturing the estimated depositional thickness of the interval MU2–MU4 at section 7, which was 125 m. The volume deposited from flow simulation (Fig. 6a) was subsequently added on to the model as load, which allowed for further flexure and compaction of the volumes MU1–MU2, Base Annot Sandstone–MU1 and Top Basement–Base Annot Sandstone. As a consequence the MU4 surface from flow simulation (Fig. 6b) changed shape (Fig. 6c).

Flow 4: MU4–MU5. Flow 4 was run to represent the interval between MU4 and MU5, and the input parameters were similar to those used previously with the exception being the flow duration set to 28 h (10 100 s) (Table 3). The estimated depositional thickness at section 7 was 160 m. As previously the deposited volume from flow simulation (Fig. 7a) was added on to the model as load with resulting compaction of underlying volumes and flexure of surfaces. The MU5 surface from flow simulation (Fig. 7b) became the MU5 seafloor surface (Fig. 7c) after this last modelling.
Phase 2 forward modelling

Flow 5: MU5 bed. The four particle sizes used for MU5 flow simulation were: 80 \( \mu \text{m} \) (very fine sand), 200 \( \mu \text{m} \) (fine sand), 400 \( \mu \text{m} \) (medium sand) and 1 mm (coarse sand). The proportion of each grain-size within the input volume of sediment that was used for simulation was defined within the range estimated from the six datapoints (Table 5): 35% very fine sand, 35% fine sand, 20% medium sand and 10% coarse sand. All input parameters can be found in Table 3.

Input parameter sensitivity

Seven flow simulations of the MU5 bed were run to investigate the effects that some of the main input parameters had on the depositional thickness and grain-size distribution. Changes in source point location, sediment concentration, initial velocity and grain composition were tested for (Table 3).

Results

The cumulative thickness of sediment deposited from the first four flows at the location of section 7 was 755 m (flow 1, 450; flow 2, 15; flow 3, 125; flow 4, 165), which is a good match with the target thickness of 739 m (Table 4). Similarly at section 2 the cumulative deposited thickness from flows 1–4 was 440 m (flow 1, 200; flow 2, 10; flow 3, 100; flow 4, 130), which is within 10% of the target of 410 m (Table 4). Flow 1 effectively filled in the deepest accommodation in the north and an overall southerly backstepping pattern is observed. The stepwise compaction of the basin fill and underlying Blue Marl after each flow shows that there is slightly greater accommodation created in the northern part of the basin. At the time of MU5 deposition there was still topography on the Peïra Cava basin seafloor.

The results of the first two flows (Base Annot Sandstone–MU1 and MU1–MU2) show a good

Table 4. Comparison of deposited thicknesses from flow simulations and outcrop data for the basin-fill below the MU5 bed

| Flow no. | Basin-fill interval   | Section 2 thickness (m) | Section 7 thickness (m) |
|----------|-----------------------|-------------------------|-------------------------|
|          |                       | Outcrop Depositional Simulated | Outcrop Depositional Simulated |
| 1        | Base Annot Sandstone–MU1 | NA 200 | 280 405 450 |
| 2        | MU1–MU2               | NA 10  | 30 44 15 |
| 3        | MU2–MU4               | NA 100 | 90 130 125 |
| 4        | MU4–MU5               | NA 130 | 110 160 165 |
| Total    |                       | 280 410 | 440 510 739 755 |

The initial thickness is the estimated depositional thickness using curves from Sclater & Christie (1980).
match with the observed thickness in the field. The interval is 449 m, which is a good match to the expected 465 m at section 7 (Table 4). There was, however, significant erosion associated with flow 2 (Fig. 5), which resulted in too thin deposits (10–15 m) around section 7 (Table 4). This suggests that the erosion is too aggressive, possibly owing to the lack of clay in the model (see below); however, since the total thickness for the two units showed a good match, the models were retained.

The detailed simulation of MU5 deposited a sandbody that is laterally extensive throughout the basin (Fig. 8). The thickness varies from 0 m where the sand onlaps the confinement to 33 m in the centre of the basin. In section 2 the simulated thickness is 7.5 m, which compares favourably to a decompacted thickness of the actual bed of 10 m. In section 7 the simulated thickness is 14 m and the decompacted, observed thickness is 15 m (Table 5). The only poor match is section 3, where the MU5 bed is 13 m thick, compared with 4 m from the flow simulation (Table 5).

Testing sensitivities to the input parameters was undertaken with an additional seven simulations.

Fig. 5. Results from flow 2 forward modelling. (a) Map showing areas of erosion and depositional thickness from the flow simulation of the interval MU1–MU2. The red areas show very thin deposition, non-deposition or erosion into the sediments from the underlying flow 1. (b) Map showing the new uncompacted MU2 seabed generated by flow 2. (c) Map displaying the updated MU2 seabed after compaction. This surface became the input seabed surface for step 3 modelling.

Fig. 6. Results from flow 3 forward modelling: (a) thickness map of sediment deposited during flow 3; (b) MU4 uncompacted seabed from flow modelling of the interval MU2–MU4; and (c) compacted MU4 seabed that was used as input for flow modelling of the MU5 seabed in step 5.
The results of these are summarized in Figures 9–13. The additional bed simulations all show that, although there are variations in thickness, the overall geometry of the bed remains similar, that is, the presence of local thickening around sections 1 and 2 and the thickest part east of sections 3 and 4 followed by the area between sections 5 and 7 (Fig. 8). For example, the bed from the simulation using 1 m s\(^{-1}\) as initial velocity is up to 22 m thick while the comparable number for the 4 m s\(^{-1}\) deposit is 50 m, which is the thickest recorded bed (Fig. 8).

The spatial distribution of each particle size is summarized in Figures 9–13. For the base-case flow simulation the distribution of grain-sizes from the flow simulation matches the hard data very well at section 7 in the north where very fine and fine particles comprise 100% of the outcrop (Table 5). The simulation shows a content of 99.9% fine and very fine particles with the remaining 0.1% comprising medium size particles (Table 5). The distribution in section 6 also matches the flow simulation results, both for the medium fraction and for the combined amount of very fine and fine particles (Table 5). The flow simulation results for the more proximal section 2, which is closer to the inbound slope, are dominated more by coarse and medium grains, as observed in the outcrop. However the actual values show slightly too much medium and coarse material (60% modelled v. 35% observed) and conversely too little fine and very fine particles (40% modelled v. 65% observed).

The ancient thicknesses are calculated using equation from Sclater & Christie (1980) assuming burial depth around 3000 m. The distribution of grain-sizes for sections 1–7 is shown for the outcrop data and simulation results. See Figure 2 for location of sections.

### Table 5. MU5 bed: present thickness, ancient thickness, flow simulated thickness and comparison of simulated thickness and ancient thickness are shown

| Datapoint                        | Section 2 | Section 3 | Section 4 | Section 5 | Section 6 | Section 7 |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Thickness at outcrop (m)         | 8         | 12        | 11        | 11        | 8         | 12        |
| Thickness at time of deposition (m) | 10        | 15        | 13.5      | 13.5      | 10        | 15        |
| Thickness from flow simulation (m) | 7.5       | 4         | 16        | 12        | 7         | 14        |
| Error (%)                        | -25       | -73       | 19        | -11       | -30       | -7        |
| Fraction very fine sand, outcrop | 0.18      | 0         | 0.23      | 0.25      | 0.67      | 0.58      |
| Fraction very fine sand, flow simulation | 0.10      | 0.35      | 0.15      | 0.45      | 0.15      | 0.34      |
| Fraction fine sand, outcrop      | 0.47      | 0.77      | 0.23      | 0.42      | 0.17      | 0.42      |
| Fraction fine sand, flow simulation | 0.30      | 0.15      | 0.13      | 0.55      | 0.7       | 0.65      |
| Fraction medium sand, outcrop    | 0.23      | 0.08      | 0.41      | 0.17      | 0.16      | 0         |
| Fraction medium sand, flow simulation | 0.35      | 0.13      | 0.45      | 0         | 0.15      | 0.01      |
| Fraction coarse sand, outcrop    | 0.12      | 0.15      | 0         | 0.15      | 0         | 0         |
| Fraction coarse sand, flow simulation | 0.25      | 0.37      | 0.2       | 0         | 0         | 0         |

The ancient thicknesses are calculated using equation from Sclater & Christie (1980) assuming burial depth around 3000 m. The distribution of grain-sizes for sections 1–7 is shown for the outcrop data and simulation results. See Figure 2 for location of sections.
Fig. 8. The thickness of the deposit from flow simulations of the MU5 bed is shown for all the scenarios tested. Note that the colour scale is not case-specific.
Fig. 9. The distribution of coarse sand grains from flow simulations of the MU5 bed is shown for all the scenarios tested.
Fig. 10. The distribution of medium sand grains from flow simulations of the MU5 bed is shown for all the scenarios tested.
Fig. 11. The distribution of fine sand grains from flow simulations of the MU5 bed is shown for all the scenarios tested.
Fig. 12. The distribution of very fine sand grains from flow simulations of the MU5 bed is shown for all the scenarios tested.
In the more intermediately placed sections 3 and 4, a similar trend with slightly too much medium and coarse sand particles and too little very fine and fine sand particles is also seen (Table 5). The poorest match with regards to distribution of particle size is found in section 5 (Table 5) located distally along the western edge of the basin. At this location the flow simulation deposited only fine and very fine particles, while medium and coarse sand particles should account for 33% of the thickness (Table 4). The base-case simulation results display a general trend where the deposit is dominated by coarse particles from section 3 and southwards centrally in the basin (Fig. 9). Medium-sized particles are pronounced along the flanks of the basin south of section 3 as well as the area between sections 3, 5 and 6 (Fig. 10). The distribution pattern of fine (Fig. 11) and very fine (Fig. 12) particles shows high concentrations locally in small areas around section 2, along the flanks of the basin and, very pronounced, the large distal area involving sections 5–7 and the far end of the basin.

The sensitivity runs present a complex picture with regards to grain-size distribution locally at the six datapoints (Fig. 13). For the coarse particles it is clear that the denser (15% sediment concentration) and the faster (4 m s\(^{-1}\) initial velocity) flows completely dominate the outcrop in sections 3 and 4 while the slower (1 m s\(^{-1}\) initial velocity) flow recorded lower readings than the base-case. The coarse fraction is less than 0.15 for all simulations in sections 5–7. The greatest deviation from the base-case for the medium sized grains is observed in the 1 m s\(^{-1}\) flow that dominates the deposit in section 3 and 4. Conversely the 4 m s\(^{-1}\) flows recorded very low contents of medium particles in sections 2–4. In the more distal datapoints, sections 5–7, it was the 4 m s\(^{-1}\) flow that recorded significantly higher values than the base-case, whereas the other runs were more in line with the base-case. For the fine and very fine particles the sensitivity run results are scattered around the base-case results for the most proximal datapoint, section 2. For the more intermediate sections 3 and 4 the sensitivity results were comparable to, or lower in content than, the base-case simulation. In particular the 15% sediment concentration run showed very limited amounts of fine and very fine particles. For the distal datapoints, sections 5–7, the sensitivity runs are similar to the base-case with fractions of 0.8 and higher. The only outlier is the 15% sediment concentration case, which recorded 0.6 at section 6.

The map view comparison for the distribution of individual grain-sizes can be seen for all of the simulations in Figures 9–12. The clear pattern is that the sensitivity runs show very similar distributions to that seen in the base-case.

**Discussion**

The goal of the study was to use process-based forward modelling to simulate the deposition of a single bed (MU5 of Amy et al. 2007) within the fill of the Peira Cava Basin. A base-case result that provided a reasonable match for both the spatial distribution of both bed thickness and grain-size was established, and seven alternative runs were performed to highlight the influence on some of the key input parameters of the flow simulation. The latter is significant as the flow parameters of ancient flows are virtually unconstrained, and the number of input parameter combinations is infinite. Thus such a deterministic approach should involve several scenarios and their influence on the result.

Flows 1–4 were run with the target of creating a seafloor on to which the MU 5 bed simulations could be performed, and this part of the forward modelling is highly relevant to sub-surface datasets of limited seismic resolution. In such cases details of the basin-fill are typically not imaged and the most relevant reflector to use might be the base of the basin-fill. Thus some initial modelling is required before modelling of a specific bed can be performed.

The results from flow 2 (MU1–MU2), which was a relatively small flow, showed locally cut scours up to 40 m deep. The erosional and bypass features are more pronounced in proximal and intermediate parts of the basin than in the distal end of the basin where small-scale erosion and non-deposition are observed on the flanks (Fig. 5a). This pattern fits well with the observation at the outcrop where scours are commonly observed in the proximal part as opposed to the distal end. The amount of erosion observed locally in the distal part – up to 40 m – is greater than observed at the outcrop. It is likely that the chosen input for this flow, and the three other flows in phase 1 modelling (sediment concentration = 20% and initial velocity = 8 m s\(^{-1}\)), caused these flows to be too energetic in the proximal and intermediate parts of the basin. These parameters were chosen to speed up the computing time to free up more time for the MU5 bed modelling. Alternatively the amount of erosion may reflect the lack of clay material in the model runs. Cohesive clays within the flows and more importantly in the mudstone intervals between them would provide intervals that were resistant to erosion by subsequent flows. These were not included directly in the modelling because MassFlow-3D does not deal with cohesive forces in the flow. As the thicknesses for flows 1–4 matched the control data from sections 2 and 7 it was decided to proceed with the produced data.

The base-case modelling of the MU5 bed produced a very good match for the thickness at the
Fig. 13. The distribution of grain size for each flow simulation run of the MU5 bed in the six available datapoints from the outcrop. The location of each datapoint can be found in Figure 10.
datapoints (Fig. 13). Away from the datapoints the results predict sand thickening up to 33 m in the central parts of the basin between sections 3 and 4, and up to 27 m in the north between sections 5 and 7 (Fig. 8). This pattern was prevalent for all the sensitivity runs performed for the MU5 bed (Fig. 8), which strengthens the robustness of the predicted thickness pattern. The central parts of the Peı¨ ra Cava basin are not exposed and the significance of these data is that they suggest that the sheeted MU5 bed more than doubles in thickness. Had the MU5 bed been a reservoir in the subsurface buried at intermediate or greater depth (>1500/2000 m) it almost certainly would have been below seismic resolution. In this case the six available datapoints would have been the only indicator of the thickness distribution with consistent readings between 10 and 15 m. In such a case this work adds potentially valuable prediction of thickness distribution of the reservoir sand.

The simulated grain-size distributions show a clear pattern where the coarse and medium-sized particles are the dominant components of the deposit in the proximal and intermediate parts of the outcrop (Figs 9 & 10). It was expected that the ‘high energy’ flows (4 m s\(^{-1}\) initial velocity and 15% sediment concentration) and the flow with higher content of medium and coarse particles would transport coarse particles even further than the base case, which was confirmed by the simulations. None of these cases, however, managed to transport any significant amounts into the truly distal parts of the basin around and north of section 7. Similarly the medium-sized particles are also not carried the full distance into the distal parts of the basin (Fig. 10), but are mostly concentrated in the centrally in the intermediate part of the basin and along the basin margin in the proximal parts. Thus the results here propose a sorting of medium and coarse particles in the proximal to intermediate parts of the basin. The 4 m s\(^{-1}\) flow is the flow that shows the most limited deposition of coarse grains in the proximal part relative to the deposition in the more intermediate part of the basin, which is suggesting that this flow is more bypassing than the other runs in this area.

The two datapoints with the poorest match between simulations and outcrop are sections 3 and 5. At section 3 the simulated thicknesses are all too low (Fig. 11), whereas for section 5 the deposited fractions from simulation are finer grained than in the real world (Fig. 11). It is likely that these discrepancies are due to the geometry of the generated surface on to which the MU5 bed was simulated (Fig. 7c). With the modelled surface MU5 is located in the distal part of the basin that is fairly flat, and this basin configuration makes it unrealistic to expect any profound difference in the grain-size distribution between sections 5 and 7. In reality section 7 lacks coarse and medium particles, whereas these are present at section 5. Thus it is proposed here that section 5 was probably located in the end of a topographic low that has enabled the flow to maintain its energy and ability to transport these two coarsest fractions into this area. All of the simulations deposited a bed that is too thin at the location of section 3, and this is also probably related to the shape of the generated surface used for MU5 bed simulations. Section 3 is located on the slope of the topographic feature extending from south of section 2 towards section 3. Thus section 3 is not located favourably for receiving thick deposits. Had the datapoint been shifted 200–300 m towards the east, the simulated thickness would have been in accordance with the deposited thickness. This demonstrates how sensitive this approach is to the shape of input surfaces.

The first attempts to simulate the MU5 bed were performed with the sediment scour model turned on in order to include the effects of erosion. The results failed to match the outcrop as localized erosion took place in proximal parts and as far into the basin as the section 3 area. Further, the flows seemed to maintain competence so that they were able to transport coarse particles into the distal parts of the basin. It is speculated that the reason for this could be that the inbound slope was too steep. Modifying the inbound slope was beyond the scope of this work and it was assumed that the MU5 base surface could not be eroded into. This simplification was not in conflict with field data as no erosive base is observed for the MU5 throughout the outcrop.

**Conclusion**

The work here has demonstrated a process-based forward-modelling methodology to simulate a single turbidite bed as part of a basin-fill succession. The approach was tested on a sandstone bed MU5 which forms part of the 1300 m-thick fill of the Peı¨ ra Cava Basin in SE France. The inputs for a single model run are bathymetry, height of flow, width of flow, density of flow, initial flow velocity, sediment concentration and grain-size distribution. The goals of the simulation were to recreate the thickness and grain-size distribution of the studied bed within a series of success criteria, which included a reasonable match to the outcrop at a series of control points.

The first stage of the modelling was to recreate the pre-MU5 stratigraphy (steps 1–4) in order to capture the bathymetry on to which the MU5 bed was deposited. This was done with four composite flow events and the cumulative deposited thickness
of the four flows matched the observed thickness in the control points, which were the criteria at the onset of modelling.

Detailed modelling of the specific MU5 bed resulted in a base case that showed a good match to the thickness at datapoints from the outcrop. With regard to the distribution of grain-sizes at the same datapoints, the results were encouraging for the coarse and medium-sized particles, and less robust for the very fine and fine grain-sizes. Seven other flow simulations were performed to highlight the influence of input parameters on the deposited thickness and grain-size distribution.

A key aspect of obtaining a good match to the observed thicknesses and grain-size trends within the real world was the degree of erosion associated with the flows. The software typically overestimated the degree of erosion and the best match was achieved when erosion in the underlying bed was restricted. This is either because the models lack cohesive clay, either within the beds or as hemipelagic layers between events, or because the inbound slope is too steep. The necessity to manually limit flow scour highlights the importance of cohesive beds, especially within confined basins where thick mud caps on top of beds are common. 

This work shows that, while the broad depositional trend is obtained with the majority of simulation runs, the finer detail of the results varies greatly. Some aspects of the simulation set, such as the thickening of the bed in the central parts of the outcrop, occur in all of the runs, across the range of sensitivities, but others are less robust. The application of process-based modelling is in its infancy and it is possible that detailed results are so sensitive to the initial conditions of a set of parameters that cannot be constrained that it will never be possible to model every bed within a basinfill succession. However, the results also illustrate that a number of outcomes are robust across a range of input parameters and these can, therefore, be given a higher degree of confidence when considering the uncertainty space within which the reservoir exists.

Statoil ASA is thanked for kindly funding the publication costs.

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