Abstract

As hydrocarbons become scarcer, submarine channelised slope systems have become a focus of exploration due to their reservoir potential. Outcrops of both levee-confined (Unit C) and entrenched (Unit D) channel systems are exposed in the Permian Fort Brown Formation, Karoo Basin, South Africa and have been extensively studied and interpreted. Full coring and logging of six research boreholes behind the outcrop surface has produced a comprehensive dataset including oriented borehole images.

Directional features from FMS borehole image logs can be subdivided into direct (cross-bedding and climbing ripples) and indirect (erosion- and amalgamation surfaces and syn-sedimentary faults) palaeoflow indicators. The distribution of these indicators is analysed qualitatively and statistically per well and per (sub)unit to arrive at a solid palaeoflow reconstruction. Distributions of features in unconfined external levee deposits yield the most unambiguous results, whereas levee- or valley-confined features display a higher level of scattering.

A borehole-confined, pseudo-2D and a well- and outcrop-confined 3D facies model are built to test the incorporation of the palaeoflow reconstruction. Erosion surface dip azimuths help to locally constrain (sub)unit bounding surfaces. The palaeoflow reconstruction serves to constrain the orientation of data analysis on conceptual facies models and to assign realistic orientations to the representation of multi-point facies patterns. Application of a multi-point statistics (MPS) algorithm maximises use of the available dataset and therefore yields the best results.

The approach used is thought to be applicable to analogous channelised slope systems and is designed to work with a subsurface dataset.
First and foremost, I would like to thank my supervisor, Stefan Luthi (Delft University of Technology), for offering me the opportunity to do this research project, including a both interesting and exciting excursion/fieldwork in South Africa and a poster presentation at the Annual Convention & Exhibition of the American Association of Petroleum Geologists (AAPG) in Houston, USA. The STRAT group of the University of Liverpool running the SLOPE project is thanked for providing the data and support I needed to conduct my research, especially Emma Morris, David Hodgson and Rufus Brunt. Tiago Agne de Oliveira (Petrobras) has kindly provided realistic petrophysical data of reservoir analogues to use in future research.

Peter Schlicht (Schlumberger), Xiaoxi Wang (Delft University of Technology) and Stefan Luthi were great company during the excursion and adventures we had in the Tanqua-Karoo, South Africa. Peter Schlicht has also been very helpful in suggesting how to model channelised slope systems in Petrel. Furthermore, I am very grateful to Emma Morris, George Jones and Laura Edwards (University of Liverpool) for making me feel so much at home during the fieldwork in and around Laingsburg, South Africa. In slightly over one week, Emma Morris has given me an idea of the fieldwork that lies at the base of the SLOPE project, including the sometimes frustratingly poor outcrop quality and the hard work that has gone into describing and interpreting the outcrops. I had a great time!

I would like to thank Remco Groenenberg and Geertje Strijker (Delft University of Technology) for their help in designing my poster presentation for the AAPG conference. My visit to Houston would not have been the same without Kyle Brandon Spaulding and Danny Sutton (Steven F. Austin State University) showing me around from day one onwards and Leah Guillory’s hospitality.

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1. Introduction

As hydrocarbons are becoming scarcer and oil prices are rising, the focus of exploration has expanded to more complex reservoirs. Channelised slope systems have drawn the attention of the petroleum industry over the past decade (e.g. Lerat et al., 2007; Roggero et al., 2007), but are difficult to characterise and produce due to their complicated architecture. Sub-seismic heterogeneities cannot be deterministically modelled due to a lack of data and hydrocarbons are compartmentalised or flow in tortuous pathways when produced.

To bridge the gap between seismic and well data, system analogues are extensively studied throughout the world to derive a conceptual architecture (e.g. Cronin et al., 2000; Hickson and Lowe, 2002; Beaubouef, 2004; Kane et al., 2007, 2009; Hodgson et al., 2011; Flint et al., 2011). Understanding the geometries and distributions of architectural elements helps to better appreciate subsurface datasets and to arrive at more realistic reservoir models.

The SLOPE project is run by the Stratigraphy Group of the Department of Earth and Oceanic Sciences, Liverpool University, U.K. with support from, amongst others, the Delft University of Technology, the Netherlands, and Stellenbosch University, South Africa. It aims to analyse outcrops of slope systems in the Karoo Basin, South Africa (Fig. 1). The project is sponsored by a consortium of companies in the oil- and gas industry.

![Fig. 1: Geological map of the Western Cape Province, South Africa, showing the southwest Karoo Basin and the Tanqua- and Laingsburg (marked by the red rectangle) depocentres. 'L' marks the town of Laingsburg (Flint et al., 2011).](image)

This research project is a contribution to phase 3 of the SLOPE project, focussing on the comprehensive dataset of the Unit C and D mid- to lower-slope channel systems in the Permian Fort Brown Formation, located in the Laingsburg depocentre near the town of Laingsburg (Fig. 1). The dataset encompasses a detailed description and interpretation panel of the CD ridge outcrop on the
southern limb of the Baviaans Syncline (Fig. 2) and interpreted core and log data from six research boreholes drilled behind the outcrop surface.

Fig. 2: Aerial photograph showing the Baviaans Syncline and the studied CD ridge outcrop (red ellipse) west of the town of Laingsburg, South Africa (Kolenberg, 2011).

The aim of this research project is to use directional features picked from Formation Micro-Scanner (FMS) images (Kolenberg, 2011) to constrain the architecture of the channelised slope systems in static facies models. To achieve this, the directional features will be used as input for a palaeocurrent reconstruction, assessing the value of each different dip set. Subsequently, the palaeocurrent reconstruction will be used to help orientate the data analysis and multi-point facies patterns that lie at the basis of stochastic facies modelling. This is done in both a borehole-confined, pseudo-2D configuration and in a 3D configuration including the outcrop interpretation panel as an artificial seismic cross-section. Both sequential indicator simulation (SIS) and multi-point statistics (MPS) algorithms are tested to build stochastic facies models. The results of the different modelling approaches will be evaluated to find an optimal method. Finally, the exportability of the methodology to analogous (subsurface) channelised slope systems will be discussed.
2. Geology

2.1 Geological setting

The tectonostratigraphy of southern Africa is related to the development of western Gondwana (e.g. Flint et al., 2011). Located along the southern margin of Gondwana, it underwent two first-order episodes of both compression and extension as summarised by De Wit and Ransome (1992a):

i) the Pan-Gondwanean convergence circa 650 ± 100 Ma, associated with the fusion of greater proto-Gondwana (of which North America may have been part). The Pan-African/Braziliano age fold belt is the major manifestation of this episode;
ii) the late Proterozoic to early Paleozoic extension circa 500 ± 100 Ma, related to the break-up of greater proto-Gondwana. This resulted in the formation of a passive rift margin along the southern edge of Gondwana;
iii) the late Paleozoic convergence circa 300 ± 100 Ma (Fig. 3), related to the assembly of Pangea. The Hercynian or Variscan age fold belt is the major manifestation of this episode;
iv) the mid to late Mesozoic extension circa 150 ± 50 Ma, related to the break-up of Pangea and Gondwana, with the subsequent opening of the southern oceans. The major igneous provinces along the southern margins of Gondwana seem to be related to this episode.

Fig. 3: Map showing the geodynamics of early Permian Gondwana and the extent of the Karoo basin (MKB) as part of a series of interconnected marine basins. Modified from Faure and Cole (1999).

From the early Paleozoic to early Mesozoic, the Cape and Karoo basins formed within the interior of Gondwana (Tankard et al., 2009). The Early Ordovician to Early Carboniferous Cape basin subsided in an extensional setting. Its sedimentary infill comprises approximately 8 km of dominantly shoreline
to shallow marine deposits on top of the Precambrian basement. The top of this Cape Supergroup is marked by a >25 Ma unconformity caused by regional uplift (Fig. 4a).

Northward subduction at the southern margin of Gondwana led to late-Hercynian thrusting and folding of the Cape Fold Belt (CFB) (Fig. 1). Amongst others, De Wit and Ransome (1992a,b) and Cole (1992) considered that the Late Carboniferous to Early Jurassic Karoo basin developed as a retroarc foreland basin associated with the formation of the CFB, possibly complemented by buckling (Cloetingh et al., 1992), thinning and thermal weakening of the lithosphere (Visser, 1992). More recent studies, however, show that basin infill up to the Early Triassic does not comply with this interpretation (Flint et al., 2011) and suggest that the CFB is Triassic in age (Tankard et al., 2009). Instead, dynamic topography caused by subduction-induced mantle flow (Burgess and Moresi, 1999) is now believed to have dominated early subsidence of the Karoo basin (Tankard et al., 2009).

The Karoo basin unconformably overlies the laterally offset Cape basin to the south and Precambrian basement rocks to the north (Tankard et al., 2009). It developed as part of a series of interconnected marine basins (Paraná, Beacon and Bowen basins) along the southern margin of Gondwana (Fig. 3) and comprises approximately 5.5 km of deep marine to terrestrial (fluvial) deposits (Flint et al., 2011; Fig. 4). This Karoo Supergroup is overlain by Jurassic continental flood basalts associated with the breakup of Gondwana (Tankard et al., 2009).
2.2 Stratigraphy of the Karoo Supergroup

The base of the Karoo Supergroup is marked by the Late Carboniferous glacial deposits of the Dwyka Group up to 800 m thick (Flint et al., 2011; Fig. 4a). The upper Dwyka Group displays two occurrences of volcanic tuff, probably derived from a southern magmatic arc related to the ongoing subduction at the southern margin of Gondwana (Cole, 1992).

In the Early Permian, the ice sheets retreated and gave way to a marine transgression, the onset of Ecca Group deposition (Cole, 1992; Fig. 4a). The maximum flooding surface (MFS) of the last deglaciation sequence marks the base of the Prince Albert Formation (Tankard et al., 2009), which consists of shallow-marine carbonates and pelagic sediments (Flint et al., 2011). The overlying Whitehill Formation accumulated under anoxic conditions and forms a distinctive black carbonaceous claystone (Cole, 1992; Flint et al., 2011). The Collingham Formation contains dark carbonaceous claystones interbedded with thin-bedded turbidites and volcanic ash beds (Flint et al., 2011).

The distinctive Matjiesfontein chert marker bed within the Collingham Formation is an important correlation aid for the overlying Tanqua and Laingsburg depocentres, which display a different stratigraphy in the upper part of the Ecca Group. In the Laingsburg depocentre, the distal basin-floor Vischkuil Formation conformably overlies the Collingham formation and represents the onset of a long-term feeder system from the southwest (Fig. 4b). As this system prograded to the northeast, the deposits in the Laingsburg Formation include a proximal basin-floor fan and a base of slope system (Units A and B, respectively; Fig. 4b). Progradation continued during the deposition of the Fort Brown Formation, which grades from a lower to middle slope system (Units C and D; Fig. 4b,c) to a middle to upper slope system (Units E, F and G; Fig. 4b). The Waterford Formation displays further progradation with a prodelta system (Unit H) base overlain by shelf-edge delta and shelf deposits. It marks the top of the Permian Ecca Group (Flint et al., 2011).

The Beaufort Group conformably overlies the Ecca Group and represents a non-marine basin-filling phase (Fig. 4a). It comprises sediments that were mainly deposited in lacustrine, fluvial and floodplain environments and is capped by Jurrassic continental flood basalts (Tankard et al., 2009).

2.3 Architecture of the lower-middle slope system (Units C and D of the Fort Brown Fm.)

The focus of this research is on Units C and D of the Fort Brown Formation (Fig. 4c), which are exposed over a 900 km² area around the town of Laingsburg (Flint et al., 2011). The study area, named CD ridge, stretches 5 km WNW-ESE along the southern limb of the post-depositional Baviaans syncline (Fig. 2) and displays Units C and D as two temporally separate lower to middle slope channel-levee systems, described in detail by Hodgson et al. (2011).

The hemipelagic claystone separating Units B and C holds a sharp-based and sharp-topped fine-grained sandstone unit up to 5 m thick and lying approximately 25 m below the base of Unit C (in areas where the base is non-erosional; Fig. 4c and Fig. 5). Flint et al. (2011) interpreted this B/C
interfan unit as an intraslope distributary lobe complex, which implies that it is laterally extensive and can provide a good reference datum for log correlation.

Hodgson et al. (2011) identify the eastern exposure of Unit C (Fig. 5a,c) as comprising a non-channelised facies and architectural association. Two regional-scale internal mudstone units subdivide Unit C into three sub-units (C1, C2 and C3; Fig. 4 and Fig. 5). C1 and C2 form a wedge that thins in an eastward direction, while C3 and the internal mudstone units maintain a relatively constant thickness regionally. The geometry, sedimentary facies distributions and location adjacent to channelised deposits (towards the west) lead Hodgson et al. (2011) to interpret the eastern exposure of Unit C as external levee (Kane and Hodgson, 2011). The base of C1 has the characteristics of a lobe and C3 is interpreted as either an external levee or a submarine lobe fringe (Hodgson et al., 2011).

In the western exposure of Unit C (Fig. 5a,b), a C2-aged composite erosion surface cuts through C2, C1 and further down through the B/C interfan, confining a 90 m thick channelised association (Hodgson et al., 2011). It comprises at least seven remnant unorganised channel complexes which exhibit asymmetrical cross-sections and facies distributions. The earliest complexes display lateral stepping trends while the youngest complex is vertically stacked. Adjacent to this complex, thin-bedded, very fine-grained sandstones and siltstones fine and thin away from the channel complex. These are interpreted by Hodgson et al. (2011) as internal levee deposits (Kane and Hodgson, 2011). Although some erosion occurs in underlying sediments, most of the channel complexes are bound by external levees and therefore Unit C is classified as a levee-confined channel system (Hodgson et al., 2011).

A 21 m thick hemipelagic mudstone separates Units C and D (in areas where the base is non-erosional), truncated along with the entire Unit C stratigraphy by a >100 m deep asymmetrical composite erosion surface of the Unit D channel system (Hodgson et al., 2011; Fig. 5a). Outside this incision, a non-channelised association resembles that of Unit C and is interpreted as external levee
deposits (Kane and Hodgson, 2011). The erosion surface has a steep western margin and less steep eastern margin and holds a channelised association on top of a relatively flat base. The oldest channel-complex fills overlie this base in the easternmost part of system and younger deposits exhibit westward lateral stepping, which contributed to the deepening and widening of the incision (Hodgson et al., 2011). The youngest channel complexes are symmetrical and vertically stacked along the western margin. Adjacent to the east of these complexes is a 50 m thick succession of tabular thin-bedded siltstones and very fine-grained sandstones onlapping the eastern margin. Hodgson et al. (2011) interpreted this succession as internal levee (Kane and Hodgson, 2011). Conduit abandonment is evident from the mudstone fill down to approximately 25 m from the top of the external levee crests. As the composite erosion surface confines the bulk of the channel complexes, Hodgson et al. (2011) classified Unit D as an entrenched or valley-confined channel system.

Hodgson et al. (2011) concluded that Units C and D share a common stacking pattern of component channels and proposed a four-stage model for the channel-levee system evolution (Fig. 6). The asymmetry of the Unit D valley-confined channel system is interpreted to indicate a degree of sinuosity with the more sand-prone steeper margins and thicker external levees being the outer banks to channel bends, showing similarity to outcrop analogues (Khan and Arnott, 2011) and physical experiments (Kane et al., 2010).

Fig 6: Schematic cross-sections and planform maps illustrating the four-stage model for submarine channel-levee system evolution. (1) Reduced accommodation (due to a fall in equilibrium profile) initiates deposition of coarse-grained sediments with local lobe deposition, focusing flow as constructional levees develop. (2) Slope degradation and sediment bypass with an unorganised channel system confined by external levees and/or a composite erosion surface. (3) Increased organisation of component channels at grade leads to lateral stacking and widening of the composite erosion surface. (4) As high accommodation is established, component channels are vertically stacked and internal levees develop (Hodgson et al., 2011).
3. Data and Methodology

3.1 Dataset and earlier work

The dataset for this research project consists of a detailed outcrop interpretation panel (Fig. 7), detailed core descriptions of six research boreholes drilled behind the outcrop surface (Fig. 7) and interpreted wireline logs from five of these boreholes, including Formation Micro Scanner (FMS) borehole images. Establishing this dataset was part of the SLOPE 2 and 3 projects.

3.1.1 Outcrop log correlation and interpretation panel

Researchers from the University of Liverpool conducted a comprehensive outcrop study at the CD ridge as part of the SLOPE 2 project. Projecting closely spaced (20-50 m) sedimentary log sections onto a vertical plane and establishing a firm correlation by walking out individual beds resulted in a structure-corrected correlation panel. Detailed study and description of the lithofacies lead to a subdivision into facies associations of genetically related lithofacies. Interpretation of the depositional setting, geometry and relative position of these facies associations resulted in the identification of different architectural elements in the depositional system (Table 1). By applying this classification to the structure-corrected correlation panel, a cross-section of the depositional system architecture was obtained (Fig. 7). The results of this study have been published by Flint et al. (2011), Kane and Hodgson (2011) and Hodgson et al. (2011).

<table>
<thead>
<tr>
<th>Lithofacies association (genetic architectural element)</th>
<th>Simplified lithofacies association (model-architectural element)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive sandstone (channel-axis)</td>
<td>0: Massive sandstone (channel)</td>
</tr>
<tr>
<td>Mudstone conglomerates (rip-up clasts)</td>
<td></td>
</tr>
<tr>
<td>Thin-bedded sand- and siltstones (channel margin)</td>
<td>1: Thin-bedded sand- and siltstones (channel margin)</td>
</tr>
<tr>
<td>Thin-bedded sand- and siltstones (internal levee)</td>
<td>2: Thin-bedded sand- and siltstones (internal levee)</td>
</tr>
<tr>
<td>Thin-bedded sand- and siltstones (basal/normal/top external levee)</td>
<td>3: Thin-bedded sand- and siltstones (external levee)</td>
</tr>
<tr>
<td>Thin-bedded sand- and siltstones (lobe fringe)</td>
<td></td>
</tr>
<tr>
<td>Fine-grained dominated slump</td>
<td>4: Slump</td>
</tr>
<tr>
<td>Sandstone slump</td>
<td></td>
</tr>
<tr>
<td>Mudstone (intra-unit condensed interval shale)</td>
<td>5: Mudstone</td>
</tr>
<tr>
<td>Mudstone (interfan shale)</td>
<td></td>
</tr>
<tr>
<td>Massive sandstone (slope lobe)</td>
<td>6: Massive sandstone (slope lobe)</td>
</tr>
</tbody>
</table>

Table 1: Relation between lithofacies associations and interpreted genetic architectural elements distinguished in the interpretation panel (Fig. 7) and the simplified subdivision used for modelling (including colours).
Fig. 7: (a) Map view of the CD ridge outcrop on the southern limb of the Baviaans syncline near the town of Laingsburg, South Africa. Location of the research boreholes is indicated by red dots. (b) Outcrop interpretation panel displaying architectural elements (see legend). Note the vertical exaggeration. Research boreholes are projected onto the panel.
3.1.2 Core interpretation

As part of the SLOPE 3 project, six research boreholes located approximately 200-400m behind the outcrop surface (Fig. 7) and perpendicular to the structural dip were drilled and fully cored. Each borehole intersects the entire succession of Units C and D and total depth (TD) lies below the B/C interfan. The cores are of excellent quality and were slabbed and photographed at the national core storage facility of the Council for Geosciences near Pretoria. Ph.D. student E.A. Morris (University of Liverpool) studied the cores in great detail, producing a sedimentological core description at a mm-scale. Recorded data include bed thickness, grain size, colour, sedimentary structures, bioturbation and diagenetic features. Interpretation of the core description resulted in the identification of facies associations and genetic architectural elements (Table 1), linking the core description to the outcrop interpretation panel.

3.1.3 GR/Sonic logs and interpretation

Schlumberger ran a wireline logging operation using an offshore logging unit and slimhole wireline logging tools in five of the six research boreholes (borehole BAV2 was not reamed to the required diameter). The drilling mud was replaced by water prior to logging in order to obtain a higher data quality.

The Gamma Ray (GR) tool records natural gamma radiation and is mainly used to distinguish between sandstone and mudstone and for depth matching between different logging runs. The depth of investigation is approximately 20-30 cm into borehole wall and the vertical resolution is 25-30 cm. The GR response in the research boreholes ranges from 100 API (clean sandstones) to 250 API (mudstones) and show good repeatability.

The Sonic tool emits an acoustic signal and records its travelling time through the formation. It is mainly used to measure porosity, although in this case most formation porosity is lost due to deep burial. The sampling interval in the research boreholes is approximately 15 cm and compressional velocities range from 4200-5400 m s⁻¹.

Kolenberg (2011) compared GR and Sonic tool responses to their depth-corresponding lithofacies associations (from core interpretation) and found typical ranges for the main architectural elements. She concluded that five genetic architectural elements can be distinguished from a combination of GR and Sonic tool readings (Fig. 8).

3.1.4 Formation Micro Scanner logs, classification and interpretation

As part of the wireline logging operation, Schlumberger ran a slim-hole Formation Micro Scanner (FMS) in the five logged research boreholes. The FMS records high-resolution formation resistivity, producing oriented resistivity images of the borehole wall. In the 4.5 inch research boreholes, the borehole wall coverage is approximately 69 %, the vertical resolution 1 cm and the azimuthal accuracy roughly 10 °.
Fig. 8: Cross-plot of GR and Sonic log values, exhibiting typical ranges for the main architectural elements of the depositional system (Table 1). EL: external levee, CM: channel margin (Kolenberg, 2011).

Kolenberg (2011) processed the raw wireline log data (GR, Sonic and FMS) using the Schlumberger GeoFrame 4.4 software package. The raw dataset was first loaded into the program, after which the inclinometer and accelerometer data were quality checked using the GPIT Survey module. The BHGeol Formatter module served to convert the data to the required file format, after which BorElD made basic corrections to the FMS data (logging-speed correction, tool response averaging and correction and voltage correction). The BorNor module produced static (absolute resistivity scale over the entire interval) and dynamic (local resistivity scale adjustment for enhanced contrast) normalisations of the FMS data.

In a normal processing routine, an automated picking algorithm in the BorDip module detects and picks planar features in the FMS borehole images, allowing computation of corresponding dips and azimuths. Kolenberg (2011) hand-picked all planar features (Table 2), yielding a more reliable identification and evaluation. Planar and non-planar features (Table 2) identified in the FMS borehole images were compared and validated against the detailed core interpretation to establish a robust classification of dip sets. The BorView module derived dips and azimuths for all picks, presented as tadpole logs (Appendix A).

As the research boreholes are drilled perpendicular to the structural dip, the derived dip and azimuthal data have to be corrected to reconstruct the orientation at the time of deposition. The SediView module calculates the structural dip based on the dip and azimuth of bed boundaries, which are assumed to have been deposited close to horizontally in shales. Subtraction of the derived structural dip from the dip and azimuth data in all dip classes yields the original orientations (Appendix A, B and C).

Typical suites of features on the FMS borehole images combined with GR/Sonic value ranges (Fig. 8) were assigned to lithofacies associations and genetic architectural elements (Kolenberg, 2011; Table
Validation against the core description and interpretation resulted in a reasonably good correlation. Kolenberg (2011) concluded that five main lithofacies associations (genetic elements) can be confidently identified using typical features on FMS borehole image logs combined with GR/Sonic logs: (1) massive sandstone (channel axis or slope lobe), (2) thin-bedded sand- and siltstones (channel margin), (3) thin-bedded sand- and siltstones (internal levee), (4) thin-bedded sand- and siltstones (external levee) and (5) mudstones (inter- and intra-unit shales).

Table 2: Overview of the identified planar and non-planar features encountered in the FMS borehole images. Planar features are subdivided into sedimentological and structural features. 1: used for structural dip correlation, 2: possible palaeoflow indicators (modified from Kolenberg, 2011).

<table>
<thead>
<tr>
<th>Planar features</th>
<th>Dip class</th>
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<tbody>
<tr>
<td>Sedimentary origin</td>
<td>Bed boundaries(^1)</td>
</tr>
<tr>
<td></td>
<td>Erosion surfaces(^2)</td>
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<tr>
<td></td>
<td>Cross-bedding(^2)</td>
</tr>
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<td></td>
<td>Climbing ripples(^2)</td>
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<td></td>
<td>Amalgamation surfaces(^2)</td>
</tr>
<tr>
<td>Structural origin</td>
<td>Syn-sedimentary faults(^2)</td>
</tr>
<tr>
<td></td>
<td>Faults</td>
</tr>
<tr>
<td></td>
<td>Fractures</td>
</tr>
<tr>
<td>Non-planar features</td>
<td>Syn-sedimentary folds/slumps(^2)</td>
</tr>
<tr>
<td></td>
<td>Load-cased bed boundaries</td>
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<tr>
<td></td>
<td>Volcanic ash beds/drapes</td>
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<td>Concretions</td>
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<td>Injectites</td>
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<td></td>
<td>Breccias</td>
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</table>

3.2 Palaeoflow reconstruction from log-derived directional features

Six dip classes are analysed to form a palaeoflow reconstruction: (1) cross-bedding, (2) climbing ripples, (3) erosion surfaces, (4) amalgamation surfaces, (5) syn-sedimentary faults and (6) syn-sedimentary slump folds (Table 2). A second quality check of the directional features considers the certainty of identification of the features on the FMS borehole image and fit of the dip-picking sinusoids (Fig. 9). The best picks are classified as three-star dips (Appendix B), which are the main input for the palaeoflow reconstruction. A two-star dip group (Appendix C) is composed to generate a larger population in case of inconclusive results from the three-star dips only. The selected dips are grouped according to their corresponding (sub-)unit.

It should be noted that palaeocurrents in submarine channel-levee systems are not unidirectional but vary with system evolution, flow regime, and location within the system (Fig. 10). The channel thalweg can be highly sinuous with currents climbing obliquely out onto the associated internal levee and spilling over its crest. Channel-belt topography and deflection from the inner external levee also influence and scatter confined overbank flow directions. Unconfined overbank flow causes a more unidirectional flow over the outer external levees (Fig. 10). Channel-levee system evolution can
change the main palaeoflow orientation of the entire channel belt. These temporal and spatial variations are recognised and described by e.g. Kane et al. (2006, 2009), Dykstra and Kneller (2009) and Kane and Hodgson (2011).

Fig. 9: Examples of rejected, 2-star and 3-star features on the FMS borehole image logs. Classification is based on certainty of identification of the feature and on fit of the dip-picking sinusoid.

Fig. 10: Plan view and cross-section of a submarine channel-levee system. Light grey: channel, intermediate grey: inner levee, dark grey: external levee. (a) Unconfined overbank flow and its associated current vectors. Note the narrow range of palaeoflow directions. (b) Current vectors associated to confined overbank flow. Note the more than 180 ° range in palaeocurrent directions climbing out of the highly sinuous channel and the flow deflection from the inner external levee (modified from Kane and Hodgson, 2011).
Cross-bedding foresets and climbing ripples are considered direct palaeoflow indicators as their dip azimuth is directly related to the local current direction at the time of deposition. The manifestation of these indicators on FMS borehole images differs from their visual appearance in the field and in cores and is interpreted by Kolenberg (2011).

Kolenberg (2011) found that cross-bedding is difficult to reliably identify on the FMS borehole images. The high resistivity of sand-prone deposits causes insufficient contrast on the FMS borehole images to recognise detailed sedimentary structures. Convex-up laminae similar to hummocky cross-stratification are interpreted as low-angle cross-bedding (Mulder et al., 2009) and are easier to identify. However, these cross-beds only rarely form planar features and their geometry causes a bimodal (up- and down-current) distribution of measured dip azimuths (Fig. 11).

Climbing ripples are difficult to recognise in sand-prone intervals, but can be easily identified when clay laminae are present in the ripple troughs. The en-echelon stacking pattern of these troughs causes a resistivity contrast on the FMS borehole images dipping in the up-current direction (Luthi et al., 2006; Fig. 12).

The direct palaeoflow indicators are visualised in stereonet plots (Appendix B and C) which display both dip and azimuthal data in one overview. Data are presented per well and grouped into (sub-)units to differentiate between spatial and temporal variations in palaeocurrent directions. A qualitative analysis of the stereonet plots not only attempts to reconstruct palaeoflow directions, but also to recognise the relation between locally different current directions (Fig. 10).
A quantitative, statistical analysis of the direct palaeoflow indicators is performed by assuming the azimuth data are normally distributed around a mean (palaeoflow) direction $\theta_\mu$. The 0/360 ° (or 0/2 $\pi$) discontinuity in the circular function of angular data implies that simple arithmetic averaging results in an erroneous value for the mean. Instead, a double-pass method applies to the calculation of $\theta_\mu$ for a population $n$ of azimuths $\theta_i$ ($i = 1, ..., n$). Note that the factor $n^{-1}$ cancels out in the calculation of $\theta_\mu$:

$$\theta_\mu = \tan^{-1}\left(\frac{s_a}{c_a}\right)$$

where

$$s_a = n^{-1} \sum_{i=1}^{n} \sin \theta_i$$

$$c_a = n^{-1} \sum_{i=1}^{n} \cos \theta_i$$

The standard deviation indicates the dispersion of azimuths around $\theta_\mu$. Yamartino (1984) derived a reliable estimator for the standard deviation $\sigma_\theta$ of wind directions, which is applicable to any kind of angular data:

$$\sigma_\theta \approx \sin^{-1}(\varepsilon) \left[1 + \left(\frac{2}{\sqrt{3}} - 1\right) \varepsilon^2\right]$$

where

$$\varepsilon = \sqrt{1 - (s_a^2 + c_a^2)}$$

A theoretical maximum error of this estimation is derived by assuming an oscillation in opposite directions, resulting in $s_a = c_a = 0$ and therefore:

$$\varepsilon = \sqrt{1 - ((0)^2 + (0)^2)} = 1$$

$$\sigma_\theta \approx \sin^{-1}(1) \left[1 + \left(\frac{2}{\sqrt{3}} - 1\right) (1)^2\right] = \frac{\pi}{2} \frac{2}{\sqrt{3}} = \frac{\pi}{\sqrt{3}}$$

For two equally common angles (as is the case with bi-directional data) an exact value for the standard deviation can be derived from $\varepsilon$:

$$\sigma_\theta = \sin^{-1}(\varepsilon) = \sin^{-1}(1) = \frac{\pi}{2}$$

The resulting theoretical maximum error is 15.5 %, but testing against Monte Carlo generated cases yielded results within a ± 2 % error (Yamartino, 1984).
3.2.2 *Indirect palaeoflow indicators*

Erosion surfaces, amalgamation surfaces, syn-sedimentary faults and syn-sedimentary slump folds are classified as indirect palaeoflow indicators. When interpreted correctly, their dip and azimuth distribution can help to derive the main palaeocurrent direction (Fig. 13).

![Schematic representation of the relation between various indirect palaeoflow indicators to the main palaeocurrent direction (red arrow). Note that only directional features associated with the channel belt are shown. ES: erosion surface (black pointer); AS: amalgamation surface (green pointer); SF: syn-sedimentary fault (purple pointer); SD: syn-sedimentary slump fold (brown pointer).](image)

Erosion surfaces are easy to identify on the FMS borehole images and play an important role in deriving the orientation of channel and channel-system incisions. However, in thin-bedded successions, where they are commonly sub-parallel to bed boundaries, they are difficult to distinguish (Kolenberg, 2011). Channel erosion surfaces dip towards the channel axis, perpendicular to the thalweg current direction. Composite erosion surfaces dip towards the channel-belt axis, perpendicular to the general palaeoflow direction (Fig. 13). Towards the base of the channel-belt, the dip of the composite erosion surface is a representation of the down-slope system profile.

Identification of amalgamation surfaces on FMS borehole images is difficult due to the commonly sand-prone environments in which they form, although many are recognised on the *CD ridge* outcrop. Resistivity contrasts from small mudclasts provide a means to recognise these features (Kolenberg, 2011). The appearance of amalgamation surfaces is common in massive channel sandstones. Abreu et al. (2003) state that the lateral migration of individual channels within a channel complex produces laterally amalgamated channel complexes with varying degrees of internal amalgamation. Lateral amalgamation occurs in the inner bends of sinuous channels, similar to what is observed in fluvial point bars (Abreu et al., 2003; Arnott, 2007; Dykstra and Kneller, 2009). As the inner bend migrates towards the channel axis and down-current, lateral amalgamation features are expected to display dip directions ranging from perpendicularly towards to the channel...
axis to along the palaeoflow direction (Fig. 13) Amalgamation of vertically stacked channel complexes probably yields a dip range similar to that of erosion surfaces.

Syn-sedimentary faults stand out relatively well on the FMS borehole images and display steep dips. They often are accompanied by slumping and brecciation and complicate the interpretation of other sedimentary features (Kolenberg, 2011). Syn-sedimentary faults occur on relatively steep and unstable topography, either on the slope (dipping towards the basin) or into a channel or channel system (perpendicular to the channel-axis or system orientation; Fig. 13). They are often accompanied by syn-sedimentary slumps.

The orientation of syn-sedimentary slump folds is measured from the fold axis, resulting in dip directions opposite to the slump direction. Slumps are easy to recognise on FMS borehole images and form substantial deformed units, often several meters thick (Kolenberg, 2011; Fig. 14). As slumps are accompanied by syn-sedimentary faults and dip in the opposite direction, it is expected that they either dip towards the palaeoslope or away from the channel-axis or system orientation (Fig. 13).

Like the direct palaeoflow indicators, the indirect indicators are visualised in stereonet plots (Appendix B and C). Data are presented per well and grouped into (sub-)units to accurately locate their position within the system architecture. Understanding how each indicator class is formed aids in deriving the palaeocurrent direction.

![Fig. 14: Schematic representation of a syn-sedimentary slump block in a borehole (Kolenberg, 2011).](image)

### 3.3 Data correlation and facies modelling

The main aim of this research project is to use the palaeoflow reconstruction based on FMS borehole images as an added constraint for submarine channel-levee system modelling. The Schlumberger Petrel 2009.1 software package is used to establish a correlation between available data and to test various modelling approaches. The modelling workflow applied should be applicable to analogous (subsurface) datasets, e.g. in hydrocarbon reservoir modelling.

#### 3.3.1 Model input positioning and correlation

The positioning of the structure-corrected interpretation panel and wells is complicated as their respective UTM coordinates are measured in a structurally-deformed setting in the field. In order to accurately place the input data whilst honouring their original spatial relation, implementation of a
relative coordinate system is required. This coordinate system should be based on the structural correction of one or multiple reference surfaces, e.g. the B/C interfan.

In this research project, positioning of the input data is simplified by assuming that the UTM coordinates of the logged section- and well tops approximate their original lateral relation. Subdividing the interpretation panel into approximately 500 m wide segments facilitates off-linear placement, honouring the UTM coordinates more accurately. The B/C interfan serves as a reference surface for the vertical correlation of the input data as it represents a laterally extensive and approximately horizontally deposited slope lobe that is identified in all wells but BAV1a. The relatively flat, non-erosional base of Unit D (interpreted as external levee in BAV1a) ties this well to the other input data.

For each of the six boreholes, all well data (wireline logs, interpreted directional features, core interpretation and facies interpretation) are depth matched based on the GR log response to avoid discrepancies. Seismic-scale unit boundaries (base B/C interfan, base Unit C, base Unit D and top Unit D) are picked and correlated between the wells, forming so-called well tops (Appendix A). The same seismic-scale unit boundaries are traced on the outcrop interpretation panel to serve as an analogue for the interpretation of a seismic line.

3.3.2 Model definition

Two model configurations are defined in this research project: (1) a pseudo-2D model only constrained by borehole data and (2) a 3D model constrained by borehole data and the outcrop interpretation panel. The borehole-constrained model serves to evaluate different approaches to inter-well facies modelling. As the research boreholes are aligned approximately perpendicular to the system orientation, this pseudo-2D correlation will eliminate the influence of facies variability in the direction parallel to the system orientation. The 3D model incorporates facies variability in all directions and can be validated by the outcrop interpretation panel, which at the same time serves as an input for seismic-scale unit boundaries.

The bounding polygon for the pseudo-2D grid is constructed tightly around the six research boreholes (Fig. 15). Where an erosion surface represents a seismic-scale unit boundary, its dip and azimuth are assigned to the corresponding well top. This creates local dip/azimuth constraints which in addition to the z-values (depth) of the well tops help to create more realistic unit-bounding surfaces between the wells.

The polygon bounding the 3D grid broadly encloses the boreholes and the channel-belt sections on the interpretation panel (Fig. 15). The traced unit boundaries on the interpretation panel and information on the main palaeocurrent direction in addition to the input used in the well-constrained model further constrains the creation of unit-bounding surfaces, resulting in oriented unit-bounding surfaces.

The model grid for both model configurations encompasses grid cells measuring 50 x 50 m laterally and 1 m in height. The unit-bounding surfaces or horizons subdivide the grid into zones denoted by
the associated unit name (Fig. 16). Each zone will be modelled individually as facies distributions vary per zone.

![Fig. 15: Bounding polygons of the pseudo-2D grid around the six research boreholes (small) and the 3D grid around the six research boreholes and the interpretation panel (big). Coloured circles indicate outcrop logs and research boreholes, north is upwards.](image1)

![Fig. 16: Unit-bounding surfaces of the 3D model configuration. Colours indicate depth, grid has 200 m intervals, arrow indicates north.](image2)

### 3.3.3 Facies distribution analysis

Facies data from the well-log and core interpretation provide a ground truth in (subsurface) facies modelling and are used to establish vertical and lateral facies relationships, depending on well spacing and facies-architecture complexity. To simplify the modelling process, the facies associations are limited to seven genetic elements (Table 1) before upscaling them to the two model configurations. The Petrel 2009.1 property-modelling workflow includes data analysis of upscaled properties, including facies.

A conceptual facies model for each zone is normally based on the architecture of outcrop analogues (e.g. Cronin et al., 2000; Hickson and Lowe, 2002; Beaubouef, 2004; Kane et al., 2007, 2009; Hodgson et al., 2011; Flint et al., 2011) and unit-specific information such as palaeoflow directions, basin setting and palaeoslope topography. The conceptual models for Units C and D are rendered onto a coarse grid and form the basis for data analysis and establishing 2- and 3D facies trends (Fig. 17).
The vertical facies relationships are analysed for each unit in a vertical proportion curve. This curve quantifies the proportion of each genetic element as a function of the height. A thickness frequency analysis of the genetic elements in the boreholes composes a histogram of their specific thicknesses. The lateral and vertical variations are captured in variograms. As the wells are approximately aligned and can thus only provide information in one lateral direction, the variograms for the 3D model are based on the conceptual models. This is done by mimicking the architecture of the interpretation panel in 2D and building this out in 3D based on knowledge of analogous systems.

A training image represents the geometry of genetic elements whilst being stationary over the entire image. It is required to encompass all elements completely but should not be too large. A multi-point facies pattern quantifies the relationships between the facies in all three dimensions in a search tree.

### 3.3.4 Facies modelling approaches

In this complex facies architecture, the six research boreholes do not provide sufficient data for a deterministic modelling approach. Instead, two stochastic approaches are applied to the facies modelling in the pseudo-2D and 3D grids: (1) sequential indicator simulation (SIS) and (2) multi-point facies simulation (MPS).

SIS applies vertical proportion curves, thickness frequency histograms and oriented facies-distribution variograms to stochastically model a facies distribution. Each cell is assigned a facies probability function from which a value is picked stochastically. The algorithm can be aided by 2D trends (or 3D trends when the vertical proportion curves are ignored), quantifying the spatial probability distribution for each genetic element. In this case, the trends are based on the conceptual models, but in a subsurface setting they can be derived from e.g. seismic attributes.

MPS depends on multi-point facies patterns to stochastically model a facies distribution. The value assigned to each cell depends on multiple other cells according to the according facies probability from the search tree. The algorithm is aided by 3D trends, quantifying the spatial probability for each genetic element. Like the 2D trend surfaces, the 3D facies trends are based on the conceptual models. In subsurface modelling they can also be derived from e.g. seismic attributes.
4. Results

4.1 Palaeoflow reconstruction

As the palaeocurrent direction of subsequent submarine channel-levee systems may vary, the reconstruction discriminates between (sub-)units (Fig. 18). The analysis of individual dip classes considers the spatial variation in dip direction within the system architecture based on their formational mechanism. The analysis focusses primarily on three-star features and only considers two-star data in the absence of a reliable population of the former.

![Legend](image)

**Fig. 18:** (Sub-)unit subdivision in stereonet plots.

4.1.1 Cross-bedding

Three-star cross-bedding features only appear in BAV1a, twelve of which are in Sub-unit C3 and three in Unit D (Appendix B.1 and D.1a). Two-star cross-bedding dip-picks are more abundant (Appendix C.1 and D.1b) and will be used for the cross-bedding based palaeoflow analysis in other wells and (sub-)units where available. As the distribution of cross-bedding features is bimodal (in view of the hummocky nature of the cross-beds), its analysis aims to derive a palaeocurrent orientation rather than a direction.

Sub-unit C1 cross-bedding is only encountered in BAV6, which displays five two-star features (Appendix C.1f). The dips appear to be distributed along a NE-SW orientation in external levee deposits.

Sub-unit C2 cross-bedding only manifests itself in BAV6 (Appendix C.1f), where all four two-star features dip in a general NE direction in external levee deposits. Statistical analysis (valid as there seems to be a unimodal distribution) yields a mean azimuth of 52 ° with a relatively low standard deviation (\(\sigma_\theta = 26^\circ\) for \(n = 4\); Appendix D.1b). Hence, C2 cross-bedding indicates a NE-SW palaeocurrent orientation in BAV6.

BAV1a contains three-star cross-bedding features in Sub-unit C3 external levee deposits, all in a relatively uniform SSW direction and with dips ranging approximately 0-10 ° (Fig. 19). Statistical analysis (Appendix D.1a) yields a mean azimuth of 206 ° with an exceptionally low standard deviation (\(\sigma_\theta = 25^\circ\) for \(n = 12\)) for this apparently unimodal distribution. A single two-star cross-bedding
feature is encountered in BAV6 external levees dipping northward. In conclusion, the general palaeocurrent direction in C3 is oriented NNE-SSW in external levee deposits in both BAV1a and BAV6.

Fig. 19: Three-star cross-bedding features in BAV1a. Units in degrees, legend as Fig. 18, background colour (red) indicates dip class.

Unit D comprises three three-star features in its external levee deposits in BAV1a, oriented roughly N-S (Fig. 19). As this population is relatively small, thirteen Unit D two-star cross-bedding dips in BAV1a around an approximately NNE-SSW orientated axis are also considered (Appendix C.1b). In the absence of three-star cross-bedding picks, two-star features are considered in the other wells except BAV6, where no cross-bedding features were selected. Dips in BAV3 channel margin deposits seem to be scattered in all directions (Appendix C.1c) whereas those in BAV4 exhibits dips spread over roughly 170 ° in a generally SW direction (Fig. 20). Statistical analysis (Appendix D.1b) results in a mean azimuth of 229 ° with an acceptable standard deviation ($\sigma_\theta = 52 °$ for $n = 12$). BAV5 contains only two features in internal levee deposits dipping roughly westward (Appendix C.1e).

4.1.2 Climbing ripples

The occurrence of detectable climbing ripples is rare and only two three-star climbing ripple dips have been identified, both in BAV1a (Appendix B.2 and D.2a). Fourteen two-star climbing ripple picks are distributed over all wells but BAV6. The measured-dip distribution for climbing ripples is unimodal in an up-current direction.

BAV1a contains one three-star and three two-star climbing-ripple features in Sub-unit C2 channel-margin deposits (Appendix B.2b and Fig. 21, respectively). The former dips in a NE direction, whereas
the latter are roughly aligned in a NE-SW orientation, possibly indicating a palaeoflow reversal in these directions. None of the other wells contain C2 climbing ripple features.

Fig. 20: Three- and two-star cross-bedding features in BAV4. Units in degrees, legend as Fig. 18, background colour (red) indicates dip class.

Fig. 21: Three- and two-star climbing-ripple features in BAV1a. Units in degrees, legend as Fig. 18, background colour (blue) indicates dip class.
Sub-unit C3 contains only one (three-star) climbing ripple dip, located in $BAV1\alpha$ external levee deposits and dipping to the SSW (Fig. 21). This single indicator suggests a NNW palaeoflow direction in C3.

Unit D is represented by two-star dips in $BAV3$, $BAV4$ and $BAV5$, all of which are found in channel margin deposits. Climbing ripple features in $BAV3$ and $BAV5$ (three in total) dip towards the east, indicating a westward palaeoflow. $BAV4$ dips are spread approximately 100 ° in a generally SW direction, indicating a NE palaeocurrent direction (Fig. 22).

![Fig. 22: Three- and two-star climbing-ripple features in $BAV4$. Units in degrees, legend as Fig. 18, background colour (blue) indicates dip class.](image)

### 4.1.3 Erosion surfaces

Erosion surfaces are the most common of all dip classes and serve as an indirect palaeoflow indicator as well as a local dip and azimuth constraint for unit-bounding surface modelling. As the erosion surfaces dip towards the channel or system axis, the palaeocurrent direction is expected to be perpendicular to the orientation of the dips.

Sub-unit C1 erosion surfaces are only selected in $BAV6$, where they dip in a generally southward direction (Appendix B.3f and C.3f) in external levee deposits. The two-star features seem to be aligned in a NNE-SSW orientation, passing the central axis of the stereonet plot on the eastern side. The palaeoflow at this location was possibly towards the east.

Erosion surface features in C2 are exposed in $BAV1\alpha$ and $BAV6$ in channel axis/margin and external levee deposits, respectively. In $BAV1\alpha$ they are oriented in a roughly N-S orientation, although this is
not unambiguous (Appendix B.3b). The orientation in BAV6 is clearer and runs NNE-SSW (Appendix C.3f).

The erosion surfaces in Sub-unit C3 only form a reliable population in BAV1a, where a combination of three- and two-star features align along a NNE-SSW orientation in external levee deposits (Appendix C.3b). Palaeoflow is thought to have been perpendicular to this orientation.

Unit D comprises three-star erosion surfaces in all wells and its population only needs complementation by two-star dips in BAV1a, exhibiting a N-S orientation in external levee deposits (Appendix C.3b). The orientations in BAV3, BAV4 and BAV5 are NNW-SSE in channel axis/margin deposits (Fig. 23 and Appendix B.3c,e). The orientation in the BAV6 internal levee deposits is roughly N-S (Appendix B.3f).

![Three-star erosion surfaces in BAV3](Fig. 23: Three-star erosion surfaces in BAV3. Units in degrees, legend as Fig. 18, background colour (grey) indicates dip class.)

### 4.1.4 Amalgamation surfaces

Amalgamation surfaces have only been selected in Sub-unit C2 and Unit D, all of which in channel sands (Appendix B.4). The dips of the amalgamation surfaces range from perpendicular to the channel axis to the palaeocurrent direction.

Sub-unit C2 amalgamation surfaces only appear in BAV1a, where they form an ‘arrow-head formation’ pointing towards the north (Fig. 24). This might indicate a palaeocurrent towards the north, but when the two-star features are also considered a north-eastward palaeoflow direction seems to fit the distribution better.
The amalgamation surfaces of Unit D occur in BAV4 and BAV5 (Appendix B.4c,d) and do not show a conclusive pattern. All dips are less than 10° from horizontal and dip southward in BAV4 (Appendix B.4c) and oriented approximately NE-SW with a bias towards the NW in BAV5 (Appendix B.4d).

4.1.5 Syn-sedimentary faults

Only Sub-unit C2 and Unit D hold selected syn-sedimentary faults, but due to the nature of these features, they are also recognised in the inter-unit mudstones. They dip in the direction of the sloped topography on which they are likely to have formed. In the (sub-)units, this is perpendicular to the channel or system axis, whereas the dip in the inter-unit mudstones is probably basinward.

Syn-sedimentary faults in Sub-unit C2 are selected in BAV1a (Fig. 25) and BAV6 (Appendix B.5f). In the channel deposits in BAV1a, fault dips are aligned roughly NW-SE with a bias of low-angle dips to the SW. In the external levee deposits in BAV6, the dips all seem to be oriented southward.

In Unit D, picked in BAV3, BAV4 and BAV5, the dips seem to be oriented roughly NW-SE for the former two wells (Appendix B.5c and B.5d) rotating to a N-S orientation in BAV5 (Appendix B.5e), all in channel deposits.

Syn-sedimentary faults selected in the DE inter-unit mudstone display a large scatter with a subtle bias towards the SW (Appendix B.5a). Only one two-star syn-sedimentary fault dip has been identified in the BC and CD shale each, dipping towards the SW and the north, respectively (Appendix C.5a).
4.1.6 Syn-sedimentary slump folds

Syn-sedimentary slump folds are only recognised in Unit D and the DE inter-unit mudstone. As three-star features are rare (Appendix B.6a), a combination of three- and two-star dips is analysed (Appendix C.6). There seems to be no dominant dip direction or orientation in either Unit D or the DE inter-unit mudstone, deeming the syn-sedimentary slump folds ineffective for the palaeoflow reconstruction.

4.1.7 Overall palaeoflow reconstruction

The only palaeoflow indicators found in Sub-unit C1 are the cross-bedding features and erosion surfaces in BAV6 external levees (Table 3). The cross-bedding suggests a NE-SW palaeoflow orientation, but the erosion surfaces display a range that does not fully comply with this interpretation. This uncertainty translates in a range of possible palaeocurrent directions roughly between NE to eastward.

Table 3: Sub-unit C1 palaeocurrent interpretations per research borehole. CB: cross-bedding, CR: climbing ripples, ES: erosion surfaces, AS: amalgamation surfaces, SF: syn-sedimentary faults, SD: syn-sedimentary slump folds.

<table>
<thead>
<tr>
<th>C1</th>
<th>BAV1a</th>
<th>BAV3</th>
<th>BAV4</th>
<th>BAV5</th>
<th>BAV6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>NE-SW</td>
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<tr>
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<td>ES</td>
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<td>AS</td>
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<td>SD</td>
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</table>
Sub-unit C2 contains palaeoflow indicators in BAV1a and BAV6, on either ends of the Unit D composite erosion surface (Table 4). In the channel deposits of BAV1a, climbing ripples are the only direct palaeoflow indicators, but they suggest alternation of the palaeocurrent direction between NE and SW. The erosion surfaces and syn-sedimentary faults in this well seem to support this orientation. The distribution of the amalgamation surface dips could comply with this interpretation. Two-star cross-bedding features are the direct palaeoflow indicators in BAV6 external levee deposits and indicate a NE-SW orientation with a large spread. Erosion surfaces indicate a more E-W orientation, as do the syn-sedimentary faults. Based on the basin setting and the palaeocurrent directions of the other Unit C sub-units, it is concluded that the main palaeoflow was in a NE direction. The palaeoflow on the external levees in BAV6 was slightly oblique to the main direction (Fig. 10), roughly towards the ENE.

Table 4: Sub-unit C2 palaeocurrent interpretations per research borehole. CB: cross-bedding, CR: climbing ripples, ES: erosion surfaces, AS: amalgamation surfaces, SF: syn-sedimentary faults, SD: syn-sedimentary slump folds.

<table>
<thead>
<tr>
<th>C2</th>
<th>BAV1a</th>
<th>BAV3</th>
<th>BAV4</th>
<th>BAV5</th>
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Cross-bedding, climbing ripples and erosion surfaces in BAV1a and BAV6 are the palaeoflow indicators for Sub-unit C3 (Table 5). The direct palaeoflow indicators in BAV1a show a consistent NNE palaeocurrent direction (approximately 025°) whereas the erosion surfaces are indicate a roughly ENE-SWS orientation. The single directional feature in BAV6 is a two-star cross-bedding feature indicating a roughly N-S orientation, which complies with the NNE palaeocurrent direction in BAV1a.

Table 5: Sub-unit C3 palaeocurrent interpretations per research borehole. CB: cross-bedding, CR: climbing ripples, ES: erosion surfaces, AS: amalgamation surfaces, SF: syn-sedimentary faults, SD: syn-sedimentary slump folds.

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Unit D directional features are selected in all wells with varying reliabilities (Table 6). In BAV1a external levee deposits, cross-bedding dependably indicates a NNE-SSW palaeocurrent orientation. The only other directional feature class in this well, the erosion surfaces, is inconclusive but could support the cross-bedding interpretation. A single two-star climbing ripple in BAV3 channel deposits indicates a deviant westward palaeoflow, but this might be the result of the large range in flow directions in a confined overbank flow regime (Fig. 10). The erosion surfaces and the syn-sedimentary faults display an ENE-WSW and NE-SW orientation, respectively. Direct palaeoflow indicators in BAV4 consistently show an average NE palaeocurrent direction (approximately 050°),
but with a relatively large spread in directions. The syn-sedimentary faults confirm this direction, whereas the amalgamation- and erosion surfaces indicate a more ENE direction. BAV5 direct palaeoflow indicators again show a westward palaeocurrent direction, but their quality and population renders them unreliable. Three-star erosion surfaces show a more reliable ENE-WSW orientation and the syn-sedimentary fault features suggest an E-W orientation. Erosion surfaces are the only palaeocurrent indicators in BAV6, indicating an E-W orientation, which is interpreted in its context as the result of an eastward palaeoflow.


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### 4.2 Facies models

The derived palaeocurrent directions are mainly used in combination with the conceptual facies models to form 3D facies trends. They are also used to orientate variograms and the multi-point facies patterns. Furthermore, individual erosion surfaces at (sub-)unit boundaries are used to locally constrain the dip and azimuth of the unit bounding surfaces.

#### 4.2.1 Borehole-constrained, pseudo-2D facies models

The unit-bounding surfaces were modelled using convergent interpolation (default in Petrel 2009.1) confined by their corresponding well-top depths and locally constrained by the dip and azimuth of corresponding erosion surfaces. This yields a generally good resemblance to the shape of the unit-bounding surfaces on the outcrop interpretation panel, whilst smoothing out details below a lateral resolution smaller than that of the well spacing.

The borehole-constrained sequential indicator simulation (SIS) model (Fig. 26) is based on the vertical proportion curves of the facies found in the research boreholes and the oriented variograms derived from the upscaled facies logs. It is not guided by 2D- or 3D facies trends (the algorithm can only use 2D trend surfaces when vertical proportion curves are applied). Unit C in the model resembles the architecture and facies proportions on the outcrop interpretation panel, although lateral continuity is exaggerated, especially for the channel facies (Fig. 26). This is most likely due to the fact that only three research boreholes intersect Unit C facies and hence the data analysis is based on very widely spaced data. The modelled Unit D displays a realistic distribution of internal levee, slump and channel margin facies both vertically and laterally. The proportion of external levee and channel-axis facies seems to be underrepresented and less realistically positioned (Fig. 26). The poor channel-axis facies
distribution might be due to the fact that no single well intersects the vertical stack of component channels, resulting in a lower borehole facies proportion.

Fig. 26: Borehole-constrained, pseudo-2D sequential indicator simulation model (WNW-ESE, Fig. 14). Units in meters, colour legend as in Table 1, red lines indicate research borehole locations.

The multi-point statistics (MPS) model (Fig. 27) uses multi-point facies patterns derived from training images to model facies relationships. It is aided by 3D facies trends based on the conceptual models. In Unit C, the channel facies display a more realistic distribution and geometry than in the SIS model, although channel-margin facies seem to be underrepresented and internal levee deposits seem to be distributed randomly throughout the unit (Fig. 27). The lateral continuity of the external levee and shale facies seems to be lost in the facies architecture and the vertical resolution is poor compared to the SIS model (Fig. 26). Unit D displays a generally good distribution of channel-axis deposits, although some false occurrences appear in the top of the unit. Similarly to Unit C, the channel-margin deposits are underrepresented, as are slump deposits. The internal levee facies seem to be realistically distributed, but the external levee deposits appear randomly in the upper part of the unit (Fig. 27).

Fig. 27: Borehole-constrained, pseudo-2D multi-point statistics model (WNW-ESE, Fig. 14). Units in meters, colour legend as in Table 1, red lines indicate research borehole locations.

4.2.2 3D facies model

The unit-bounding surfaces in the 3D model are confined by well top depths and the seismic scale traced surfaces on the outcrop interpretation panel. The bases of Unit C and D were modelled by assigning their surface depth to that of the closest known point using an oriented search radius (in
which the orientation depends on the palaeocurrent direction, which determines the orientation of the composite erosion surface). This results in a locally accurate representation of these bases, but cannot be applied realistically when data density is low or when the composite erosion surface displays a high degree of sinuosity or a non-linear geometry. It is also unable to take the local dips and azimuths of the well tops into account.

The variograms for the SIS model (Fig. 28) are based on the conceptual models in order to capture the spatial relationships between the different facies. Instead of vertical proportion curves from the upscaled facies logs, the distribution of genetic elements is guided by 3D probability volumes. For Unit C, this resulted in an excellent representation of the channel facies, although channel-margin facies are underrepresented and appear at erroneous locations. The shale seems to be distributed almost randomly throughout the unit, which might be solved by adding its 3D trend map. The lateral continuation of the internal and external levee facies is too short (Fig. 28). Unit D displays a realistic distribution of internal and external levee facies, but its channel facies is interrupted by internal levee facies towards the east of the vertical stack of composite channels. Slump facies almost do not occur in the model, whereas they form a significant proportion of the facies suite in the outcrop interpretation panel (Fig. 28).

The MPS model (Fig. 29) uses the same multi-point facies pattern as is used in the borehole-constrained, pseudo-2D model, aided by 3D facies trends for channel sands, internal and external levees and shales. Compared to the other models, Unit C exhibits the best resemblance to the outcrop interpretation panel, although channel-margin deposits are underrepresented (as is the case in the pseudo-2D MPS model; Fig. 29). Unit D is also best represented in this 3D MPS model, even though the distribution of channel-axis and external levee deposits is dissimilar to that of the outcrop interpretation panel. The vertically stacked channel sands in the west are separated by sheets of internal levee deposits and isolated patches of channel sand appear randomly throughout the internal levee deposits. West of the incision, all internal levee deposits should be external levee instead (Fig. 29).
Fig. 29: Borehole- and panel-constrained 3D multi-point statistics model (WNW-ESE, Fig. 15). Units in meters, colour legend as in Table 1.
5. Discussion

5.1 Palaeocurrent indicators and reconstruction

Kolenberg (2011) picked dip features from the FMS images and classified them according to their appearance and corresponding core interpretation, aided by other well-log data to establish the environment of deposition. Although the FMS provides oriented images with a 1 cm vertical resolution which can be used to identify various features, the principal identification should come from core interpretation if available. When cores do not span the entire logged interval, they should be used to calibrate the FMS image interpretations. This approach is already commonly applied to similar well data (e.g. Samuel et al., 2003; Luthi et al., 2006).

In this research project, the selection of three- and two-star dips is solely based on their manifestation in the FMS image logs. One criterion is the certainty of a feature appearing in the image, mainly dependent on the contrast which is highest in the dynamic normalisation of the FMS data. The second condition is the fit of the hand-picked sinusoid to the actual image. The classification of the features by Kolenberg (2011) is assumed to be reliable enough to use without additional quality checking. However, integrating these two steps might result in a more consistent classification and rating.

Cross-bedding and climbing ripples are identified as direct palaeoflow indicators, although the former only provides an orientation of the palaeocurrent. This implies that the bimodal distribution of cross-bedding azimuths should always be interpreted in the light of other palaeoflow indicators. In case of such a bimodal distribution, a quantitative statistical analysis as described in this report does not yield correct results, but should be modified to an oriented 180° range mirroring the features outside this range and reconsidering the calculation of the standard deviation, accordingly. Note that in cases where cross-bedding is represented by a unimodal distribution, the original quantitative analysis still holds. Climbing ripples are unimodal by definition, but three-star features occur less frequently. In some cases, the distribution of climbing ripples seems to be bimodal (Appendix B.2b and Appendix C.2b), which is either caused by palaeoflow reversals, ripples climbing down bar-like topographies or incorrect interpretation of the features.

The indirect palaeoflow indicators are related to the palaeocurrent direction by analysis of the geometry of their occurrence. Erosion surfaces are the most common and their analysis can thus be based on generally reliable populations of three-star features. The distribution of erosion surface dips is close to what was expected, although some up-current dips are also encountered. These can possibly be contributed to the cut-banks of channel bends (Dykstra and Kneller, 2009) or even to the high sinuosity of the channels. Amalgamation surfaces are only found in channel deposits and display distributions that are susceptible to various interpretations, which implies they should merely play a role in validating results from other palaeoflow indicators. Syn-sedimentary faults display a distribution confirming expectations and should therefore be considered as valuable input for the palaeoflow reconstruction. Syn-sedimentary slump folds are scarcely recognised and do not display a clear dominant orientation in their distribution, which renders them useless in this palaeoflow reconstruction.
The data clearly show a larger spread in palaeoflow directions within channel facies and internal levees compared to the external levees, similar to what has been recognised in the field by Kane and Hodgson (2011). Dykstra and Kneller (2009) quantify the divergence of local channel axis orientations from the main palaeoflow direction up to 133° in the analogous Rosario Formation of Baja California, Mexico, which can be attributed to a relatively high sinuosity of the channels. Kane et al. (2007) also describe opposing palaeocurrents suggesting deflection from the confining incision or levee crest, possibly explaining the palaeoflow reversals seen in the climbing ripple orientations. Palaeocurrent directions outside the levee crests in the external levees seem to be oriented more uniformly down-slope, representing unconfined overbank flows (Dykstra and Kneller, 2009; Kane and Hodgson, 2011). As the external levees display a wedge-shaped geometry, this flow is slightly divergent from the main palaeocurrent direction (Kane and Hodgson, 2011; Fig. 10). Provided that a reliable population of directional features can be identified, a reconstruction of the main palaeoflow direction should preferably be based on their relatively uniform distribution in the external levees. The influence of local topography on the unconfined flows (Kane et al., 2007) should be considered in this analysis and the distribution of palaeoflow direction within the confines of the levee crests should comply with the reconstruction.

A process similar to sequential Gaussian simulation (SGS) could be applied to generate a palaeocurrent vector for each cell, even for each indicator specifically. This implies generating a direction probability distribution for each cell and drawing a random point from this distribution. The contribution of each indicator should be weighted according to reliability, but establishing a quantification of the factors requires more research.

5.2 Modelling approach

Well-top depths, dip and azimuth data from erosion surfaces and traced interpretation panels (analogous to a 2D seismic interpretation) are the input parameters on which the seismic scale unit-bounding surfaces are based in this research project. Convergent interpolation and the ‘assign to closest point’ algorithm are used to arrive at realistic representations of the unit boundaries for the pseudo-2D and 3D models, respectively. However, only convergent interpolation incorporates the dip and azimuth data and should therefore be favoured over the latter algorithm. The ‘assign to closest point’ algorithm is merely used in this specific case to avoid unrealistic averaging in areas with a low input density and because it can be guided by an oriented search ellipse (oriented according to the palaeoflow reconstruction). In exploration and appraisal scenarios, 2D and 3D seisms combined with the well data would be considered the main input for unit boundaries. Shallow 2D seisms performed by Nakajima et al. (1998) in the active Toyoma deep-sea channel-levee complex, Japan Sea, contain enough detail to identify composite erosion surfaces, levee geometries and even large scale slumping. Samuel et al. (2003) even distinguish boundaries on a sub-unit scale, e.g. reincision surfaces, in high-resolution 3D seismic data of incised deep-marine slope channels in the Nile Delta, Egypt. High-resolution 3D seisms of the partially levee-confined Girassol Field, Angola, also clearly display sub-unit scale boundaries (Lerat et al., 2007).

Modelling of architectural elements is based on the well interpretation, conceptual models and probability distribution functions. The former of these should be considered reasonably accurate,
especially with the available core interpretations validating the entire interval. All facies models should therefore honour the well data. The conceptual models are based on the outcrop interpretation panel (e.g. facies proportions, local architecture), detailed interpretations of Units C and D in the CD ridge outcrop (Flint et al., 2011; Hodgson et al, 2011) and analysis of the architecture of submarine channel-levee systems by Kane and Hodgson (2011). Instead of hand-drawing the conceptual models, utilisation of a process-based simulator could be considered. Information on e.g. the nature and supply of sediments, change in accommodation space and palaeotopography can be incorporated in such a model. Ultimately, the conceptual models are used for the data analysis and multi-point facies patterns on which the facies modelling is based.

The probability distribution functions are primarily based on the outcrop interpretation panel combined with well data. In exploration and appraisal scenarios, seismic attributes can form the basis for realistic probability distributions (Lerat et al., 2007). Especially high-resolution 3D seismic volumes can yield valuable information on the distribution of facies associations and are therefore highly recommended in the analysis of similar submarine channel-levee complexes. Roggero et al. (2007) even successfully apply history matching based on 4D seismic attributes from the Girassol Field, offshore Angola to further constrain facies distributions.

In the well-constrained pseudo-2D model, the sequential indicator simulation (SIS) seems to yield better results than the multi-point statistics (MPS) algorithm when compared to the outcrop panel. This is mostly due to the fact that SIS makes optimal use of the vertical facies distribution functions and interpolates between the wells, whereas MPS only honours the wells and uses a combination of the multi-point facies pattern and less accurate probability distribution functions for the interpolation. However, as the required inter- and extrapolation of the available data in the 3D model is much larger, MPS performs significantly better than SIS. The variograms and vertical facies distribution functions only capture facies relationships, whereas MPS can model facies patterns. In reservoir modelling of complex reservoirs such as submarine channel-levee systems, MPS should therefore be preferred over SIS, provided that the training images are realistic and probability distribution functions are reasonably accurate. Furthermore, MPS modelling can be further constrained by creating a vector field from the palaeocurrent reconstruction to orientate the facies patterns locally. This functionality is already available in the Petrel 2009.1 modelling software and could be streamlined for optimal results.

All models have been assessed qualitatively based on their resemblance to the outcrop interpretation panel. This resemblance could be quantified by assigning ‘most-of’ values to a grid on the interpretation panel and comparing its match to a cross-section through the model grid.

5.3 Analogy to similar submarine channelised slope systems

This research encompasses both the levee-confined and entrenched submarine channelised slope systems of Units C and D, respectively. However, the deposits are composed of relatively fine-grained sediments compared to analogous systems, although a number of subsurface analogues is reported to comprise similar-sized sediments. Galloway and Hobday (1996) state that systems developing with coarser sediments have a higher width/depth-ratio, a lower sinuosity and levee height and relatively
less steep and stable slopes, showing similarities with fluvial systems. Outcrop analogue studies seem to confirm these statements, e.g. in the Rosario Formation, Baja California, Mexico (Kane et al., 2007, 2009), the Cerro Toro Formation, southern Chile (Beaubouef, 2004), the Juniper Ridge Conglomerate, Coalinga, California (Hickson and Lowe, 2002) and the Kirkgeçit Formation, eastern Turkey (Cronin et al., 2000). However, the processes and stages in which these systems evolve are generally the same (e.g. Hickson and Lowe, 2002; Kane et al., 2009; Khan and Arnott, 2011; Hodgson et al., 2011) and hence the directional feature analysis on which this research is based should be applicable. It should be noted that the coarser-grained material could make identification of the different directional features on the FMS images more difficult as most of its contrast comes from the finer-grained material. This hold especially for climbing ripples, which are identified from the clay laminae on their lee-side.

The methodology of this research project focuses on data that would be available in actual reservoirs, lacking outcrop data and fully cored wells. It should therefore be applicable in hydrocarbon reservoir exploration and appraisal scenarios of similar submarine channel-levee systems such as those in West Africa, Brazil and the Gulf of Mexico. Provided that seismic data, cores and well logs including FMS images are available, this approach can further constrain facies models for such reservoirs.
6. Conclusions and Recommendations

6.1 Conclusions

Kolenberg (2011) identified and picked various directional features from FMS images in research boreholes, some of which are used to reconstruct palaeoflow directions within the levee-confined and entrenched submarine channelised slope systems of Units C and D of the Permian Fort Brown Formation, Karoo Basin, South Africa. After ranking the individual dip features based on quality and reliability, they are subdivided into direct and indirect palaeoflow indicators.

Cross-bedding and climbing ripples directly represent the palaeocurrent orientation or the up-stream direction, respectively:

- Cross-bedding is found to either dip up- or down-current and therefore only provides information on the orientation of the palaeoflow through a bimodal distribution in the stereoplots;
- Climbing ripples are scarcer and form a unimodal up-current distribution which can be statistically analysed to find a mean palaeoflow direction and a standard deviation. The unimodal distribution is easily recognisable on stereoplots.

Erosion surfaces, amalgamation surfaces and syn-sedimentary faults provide information on palaeoflow directions through analysis of their respective dip and azimuth distributions in stereoplots:

- Erosion surfaces are most common and are generally distributed on a line perpendicular to the main palaeoflow direction and passing the stereoplot axis with a slight down-current bias. They define the local dip and azimuth of corresponding surfaces;
- Amalgamation surface distributions are less conclusive as dips range from perpendicular to down-current and because they generally occur in fairly sinuous channel facies;
- Syn-sedimentary faults display a distribution similar to that of the erosion surfaces, but form less reliable populations as they do not occur with the same frequency.

Syn-sedimentary slump folds seem to be randomly distributed and are therefore not used in the palaeoflow reconstruction.

The palaeocurrent reconstruction combines all indicators to establish a solid interpretation of the palaeoflow direction per well and per (sub-)unit. From the results, it is apparent that the scatter in palaeocurrent directions is significantly higher within the levee or valley confinement than in the unconfined external levees. This is caused by channel sinuosity, lateral migration and stacking and possibly converging flow from the levee or valley slopes. Provided that the slight divergence from the main palaeocurrent direction and the influence of local topography are taken into account, the palaeoflow indicators in unconfined deposits yield the most reliable results.
Seismic-scale unit-bounding surfaces are generated for both the borehole-confined pseudo-2D and the 3D models using convergent interpolation aided by dip and azimuth data from erosion surfaces corresponding to well-top depths. An oriented ‘assign to closest point’ algorithm is used in two cases for more realistic results, but this approach is not preferred. In reservoir modelling scenarios, 2D and 3D seismics would be considered the main input for these surfaces.

Conceptual facies models for the submarine channelised slope systems in Units C and D are based on the outcrop interpretation panel, detailed interpretations of the units and general knowledge on typical system architecture from literature. These models form the basis for data analysis and multi-point facies patterns and should accurately represent the system architecture and facies proportions. The palaeoflow reconstruction is used to orientate variograms and the multi-point facies patterns.

Facies associations in the borehole-confined pseudo-2D model were modelled using sequential indicator simulation (SIS) and multi-point statistics (MPS). The former is based on data analysis performed on the well-log and core interpretation, whereas the latter uses multi-point facies patterns. In this case, the SIS model yields the most realistic results in which the vertical proportion curves seem to play a major role. The MPS model merely uses the wells as a constraint and is aided by oriented probability distribution functions, which in this case leads to a less realistic representation.

The 3D model incorporates both the well data and the outcrop interpretation panel and extrapolates the data over larger distances in all directions. The SIS model is based on data analysis performed on the conceptual models and aided by facies probability distribution functions. However, as the MPS model is based on the same conceptual models and distribution functions and is able to accurately mimic facies patterns, it yields the most realistic results.

In reservoir modelling scenarios, MPS modelling therefore should be preferred as it yields realistic results and can be aided by both facies probability distribution functions (based on 3D seismic attributes) and vector fields based on local palaeocurrent reconstructions. It is thus able to use all the available information to more accurately represent the channelised slope system.

Although many analogous submarine channelised slope systems are coarser grained, the fundamental processes and stages behind their formation and deposition are similar. The larger grain size implies that there may be more cross-beds, but coarser-grained sediments make identification of directional features on FMS images more complicated. The general approach in using directional features to further constrain submarine channelised slope systems tested in this research project is thought to be applicable to subsurface data in analogous reservoirs.

6.2 Recommendations

The identification and classification of directional features, aided and supported by core interpretations, should be integrated with the ranking of their quality and reliability. This prevents unreliable features or features with an uncertain identification from being incorporated in the population of high quality dips. In the current approach, no information on the quality and reliability
of the features is gathered from the identification process, as this was performed by a predecessor. Care should also be taken to devise a more objective classification of high quality dips instead of the reasonable subjective qualitative identification in this research. Provided that a sufficient population of directional features is available, a relation between depth or facies association and dip azimuth could be investigated instead of grouping entire (sub-)units together. This could help to identify a possible rotation of the palaeoflow during the deposition of a single (sub-)unit or provide a better understanding of palaeoflow directions in different modes of deposition. As such, it can be the frame for a 3D model of directional data. However, it should be noted that in all cases a distribution of indicators should be considered instead of single features. A process-based modelling approach could be considered to arrive at a more accurate conceptual model. This could yield a more realistic representation than a hand-drawn conceptual model and could incorporate information on e.g. sediment size, accommodation space and palaeotopography. As the conceptual model forms a keystone in the entire modelling approach, this could significantly improve the realism of the eventual facies models. The palaeoflow reconstruction should not only be used to orientate data analysis or multi-point facies patterns, but also to define the palaeocurrent direction locally. This can already be done using the available Petrel 2009.1 software package by producing a vector field which locally orientates the MPS patterns. This could be done by implementing a technique similar to sequential Gaussian simulation (SGS), taking the 0/360° discontinuity into account. In order to further test the approach used in this research project, it could be applied to the dataset of a well-documented subsurface reservoir analogue, such as those in West Africa, Brazil or the Gulf of Mexico. Provided that an equivalent dataset contains FMS image logs and a standard log suite, core descriptions and a high-resolution 3D seismic volume, this should result in improved facies models and possibly new ideas of how to incorporate directional features from FMS borehole image logs in reservoir model enhancement.
List of References


Appendix A – Well-log correlation and interpretation, including tadpole logs

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A.1: BAV1a well-log correlation and interpretation. Columns: MD: measured depth (m); C1: calliper 1 (inch), C2: calliper 2 (inch); GR: gamma ray (API); Sonic: compressional velocity (m s⁻¹); dip and azimuth of three-star directional features displayed as tadpoles (red: cross-bedding, blue: climbing ripples, black: erosion surfaces, green: amalgamation surfaces, purple: syn-sedimentary faults); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (dark green: C1, green: C2, light green: C3, red: D).
A.2: BAV2 well-log correlation and interpretation. Columns: MD: measured depth (m); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (purple: B/C interfan, green: C2, red: D).
A.3: BAV3 well-log correlation and interpretation. Columns: MD: measured depth (m); C1: calliper 1 (inch), C2: calliper 2 (inch); GR: gamma ray (API); Sonic: compressional velocity (m s\(^{-1}\)); dip and azimuth of three-star directional features displayed as tadpoles (black: erosion surfaces, purple: syn-sedimentary faults, orange: syn-sedimentary slump folds); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (purple: B/C interfan, red: D).
A.4: BAV4 well-log correlation and interpretation. Columns: MD: measured depth (m); C1: calliper 1 (inch), C2: calliper 2 (inch); GR: gamma ray (API); Sonic: compressional velocity (m s⁻¹); dip and azimuth of three-star directional features displayed as tadpoles (black: erosion surfaces, green: amalgamation surfaces, purple: syn-sedimentary faults, orange: syn-sedimentary slump folds); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (purple: B/C interfan, red: D).
A.5: BAVS well-log correlation and interpretation. Columns: MD: measured depth (m); C1: calliper 1 (inch), C2: calliper 2 (inch); GR: gamma ray (API); Sonic: compressional velocity (m s⁻¹); dip and azimuth of three-star directional features displayed as tadpoles (black: erosion surfaces, green: amalgamation surfaces, purple: syn-sedimentary faults); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (purple: B/C interfan, red: D).
A.6: BAV6 well-log correlation and interpretation. Columns: MD: measured depth (m); C1: calliper 1 (inch), C2: calliper 2 (inch); GR: gamma ray (API); Sonic: compressional velocity (m s\(^{-1}\)); dip and azimuth of three-star directional features displayed as tadpoles (black: erosion surfaces, purple: syn-sedimentary faults); core description; genetic architectural element; model-architectural element; MD. Horizontal lines indicate (sub-)unit boundaries (purple: B/C interfan, dark green: C1, green: C2, light green: C3, red: D).
Appendix B – Stereonet plots of three-star directional features

The stereonet plots indicate azimuthal degrees on the outer circular axis and the dip from horizontal on the horizontal axis. Note that the dip range is not equal for all directional features. Features are indicated by coloured dots where colour denotes (sub-)unit subdivision (see below). The background colour indicates the dip class (red: cross-bedding, blue: climbing ripples, black: erosion surfaces, green: amalgamation surfaces, purple: syn-sedimentary faults, orange: syn-sedimentary slump folds).

### B.1 Cross-bedding

B.1a: Stereonet plot of three-star cross-bedding features in all wells.
B.1b: Stereonet plot of three-star cross-bedding features in BAV1a.

B.2 Climbing ripples

B.2a: Stereonet plot of three-star climbing ripple features in all wells.
B.2b: Stereonet plot of three-star climbing ripple features in BAV1a.

B.3 Erosion surfaces

B.3a: Stereonet plot of three-star erosion surface features in all wells.
B.3b: Stereonet plot of three-star erosion surface features in BAV1a.

B.3c: Stereonet plot of three-star erosion surface features in BAV3.
B.3d: Stereonet plot of three-star erosion surface features in BAV4.

B.3e: Stereonet plot of three-star erosion surface features in BAV5.
B.3f: Stereonet plot of three-star erosion surface features in BAV6.

B.4 Amalgamation surfaces

B.4a: Stereonet plot of three-star amalgamation surface features in all wells.
B.4b: Stereonet plot of three-star amalgamation surface features in BAV1a.

B.4c: Stereonet plot of three-star amalgamation surface features in BAV4.
B.4d: Stereonet plot of three-star amalgamation surface features in BAV5.

B.5 Syn-sedimentary faults

B.5a: Stereonet plot of three-star syn-sedimentary fault features in all wells.
B.5b: Stereonet plot of three-star syn-sedimentary fault features in BAV1a.

B.5c: Stereonet plot of three-star syn-sedimentary fault features in BAV3.
B.5d: Stereonet plot of three-star syn-sedimentary fault features in BAV4.

B.5e: Stereonet plot of three-star syn-sedimentary fault features in BAV5.
B.5f: Stereonet plot of three-star syn-sedimentary fault features in BAV6.

B.6 Syn-sedimentary slump folds

B.6a: Stereonet plot of three-star syn-sedimentary slump fold features in all wells.
B.6b: Stereonet plot of three-star syn-sedimentary slump fold features in BAV3.

B.6c: Stereonet plot of three-star syn-sedimentary slump fold features in BAV4.
Appendix C – Stereonet plots of three- and two-star directional features

The stereonet plots indicate azimuthal degrees on the outer circular axis and the dip from horizontal on the horizontal axis. Note that the dip range is not equal for all directional features. Features are indicated by coloured dots where colour denotes (sub-)unit subdivision (see below). The background colour indicates the dip class (red: cross-bedding, blue: climbing ripples, black: erosion surfaces, green: amalgamation surfaces, purple: syn-sedimentary faults, orange: syn-sedimentary slump folds).

(CSub-)unit subdivision in stereonet plots

C.1 Cross-bedding

C.1a: Stereonet plot of three- and two-star cross-bedding features in all wells.
C.1b: Stereonet plot of three- and two-star cross-bedding features in BAV1a.

C.1c: Stereonet plot of three- and two-star cross-bedding features in BAV3.
C.1d: Stereonet plot of three- and two-star cross-bedding features in BAV4.

C.1e: Stereonet plot of three- and two-star cross-bedding features in BAV5.
C.1f: Stereonet plot of three- and two-star cross-bedding features in BAV6.

C.2 Climbing ripples

C.2a: Stereonet plot of three- and two-star climbing ripple features in all wells.
C.2b: Stereonet plot of three- and two-star climbing ripple features in BAV1a.

C.2c: Stereonet plot of three- and two-star climbing ripple features in BAV3.

C.2e: Stereonet plot of three- and two-star climbing ripple features in BAV5.
C.3 Erosion surfaces

C.3a: Stereonet plot of three- and two-star erosion surface features in all wells.

C.3b: Stereonet plot of three- and two-star erosion surface features in BAV1a.
C.3c: Stereonet plot of three- and two-star erosion surface features in BAV3.

C.3e: Stereonet plot of three- and two-star erosion surface features in BAV5.

C.3f: Stereonet plot of three- and two-star erosion surface features in BAV6.
C.4 Amalgamation surfaces

C.4a: Stereonet plot of three- and two-star amalgamation surface features in all wells.

C.4b: Stereonet plot of three- and two-star amalgamation surface features in BAV1a.
C.4c: Stereonet plot of three- and two-star amalgamation surface features in BAV4.

C.4d: Stereonet plot of three- and two-star amalgamation surface features in BAV5.
C.5 Syn-sedimentary faults

C.5a: Stereonet plot of three- and two-star syn-sedimentary fault features in all wells.

C.5b: Stereonet plot of three- and two-star syn-sedimentary fault features in BAV1a.
C.5c: Stereonet plot of three- and two-star syn-sedimentary fault features in BAV3.

C.5e: Stereonet plot of three- and two-star syn-sedimentary fault features in BAV5.

C.6 Syn-sedimentary slump folds

C.6a: Stereonet plot of three- and two-star syn-sedimentary slump fold features in all wells.

C.6a: Stereonet plot of three- and two-star syn-sedimentary slump fold features in BAV3.
C.6c: Stereonet plot of three- and two-star syn-sedimentary slump fold features in BAV4.

C.6d: Stereonet plot of three- and two-star syn-sedimentary slump fold features in BAV5.
Appendix D – Statistical analysis of direct palaeoflow indicators

D.1 Cross-bedding

D.1a: Statistical analysis of three-star cross-bedding features

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<th>BAV1a</th>
<th>BAV3</th>
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D.1b: Statistical analysis of three- and two-star cross-bedding features

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D.2 Climbing ripples

D.2a: Statistical analysis of three-star climbing ripple features

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D.2b: Statistical analysis of three- and two-star climbing ripple features

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