Constraining the sedimentology and stratigraphy of submarine intraslope lobe deposits using exhumed examples from the Karoo Basin, South Africa

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Abstract

Intraslope lobe deposits provide a record of the infill of accommodation on submarine slopes and their recognition enables the accurate reconstruction of the stratigraphic evolution of submarine slope systems. Extensive exposures of discrete sand-prone packages in Units D/E and E, Fort Brown Formation, Karoo Basin, South Africa, permit analysis of the sedimentology and stacking patterns of three intraslope lobe complexes and their palaeogeographic reconstruction via bed-scale analysis and physical correlation of key stratal surfaces. The sand-prone packages comprise tabular, aggradationally to slightly compensationally stacked lobe deposits with constituent facies associations that can be attributed to lobe axis, lobe off-axis, lobe-fringe and distal lobe-fringe environments. Locally, intraslope lobe deposits are incised by low aspect ratio channels that mark basinward progradation of the deepwater system. The origin of accommodation on the slope for lobe deposition is interpreted to be due to differential compaction or healing of scars from mass wasting processes. The stacking patterns and sedimentary facies arrangement identified in this study are distinct from those of more commonly recognised basin-floor lobe deposits, thereby enabling the establishment of recognition criteria for intraslope lobe deposits in other less well exposed and studied fine-grained systems. Compared to basin floor lobes, intraslope lobes are smaller volume, influenced by higher degrees of confinement, and tend to show aggradational stacking patterns.

Keywords

intraslope lobes; submarine slope; slope topography; facies stacking pattern; facies variability; Karoo Basin

1. Introduction

Basin floor lobe deposits are the dominant component of submarine fan successions and criteria for their recognition are well established (e.g., Harms, 1974; Hartog Jager et al., 1993; Sixsmith et al., 2004; Pyles, 2008; Prélat et al., 2009, 2010; Pyles and Jenette, 2009; Kilhams et al., 2012; Etienne et al., 2012; Burgreen and Graham, 2014). By contrast, the characteristics of intraslope lobes, which are also referred to as perched lobes (Plink-Björklund and Steel, 2002; Prather et al., 2012a) or transient fans (Adeogba et al., 2005; Gamberi and Rovere, 2011), which form in areas of slope accommodation, are poorly defined (Fig. 1). Intraslope lobes have been identified in several subsurface geophysical studies based on multibeam bathymetric data, CHIRP profiles and seismic imaging (2D and 3D). Documented examples include studies from the Gulf of Mexico (Prather et al., 1998; Fiduk et al., 1999; Pirmez et al., 2012; Prather et al., 2012b), the Niger Delta continental slope offshore Nigeria (Adeogba et al., 2005; Li et al., 2010; Barton, 2012; Prather et al., 2012a), the Lower Congo Basin, offshore Angola (Oluboyo et al., 2014), the Algarve Margin, offshore Portugal (Marchès et al., 2010), the Gioia Basin, southeastern Tyrrhenian Sea (Gamberi and Rovere, 2011; Gamberi et al., 2011) and the Baiyun Sag, South China Sea (Li et al., 2012).

The geophysical expression of intraslope lobes is described as layered (high amplitude reflectors) to transparent seismic facies by most authors (Booth et al., 2003; Adeogba et al., 2005; Li et al., 2012), though Marchès et al. (2010) report cases that are represented by chaotic seismic reflectors. These seismic facies have been interpreted as channel-lobe systems and associated mass transport deposits, respectively. Different mechanisms are invoked to explain the development of intraslope accommodation needed for intraslope lobe deposits to form, including tectonics (Marchès et al., 2010; Li et al., 2012), mud diapirism (Adeogba et al., 2005), halokinesis (Booth et al., 2003; Oluboyo et al., 2014) or slide scars (Morris et al., 2014a). Several commonly observed features of intraslope lobes are considered as diagnostic indicators: 1) a smaller lateral extent and lower aspect ratio than basin floor lobes (Plink-Björklund and Steel, 2002; Deptuck et al., 2008); 2) common evidence for incision due to their transience that is linked to a lower base level on the basin floor (Adeogba et al., 2005; Flint et al., 2011; Barton, 2012; Prather et al., 2012b) or to slope profiles that are not in equilibrium (Ferry et al., 2005); 3) association with mass transport complexes (MTCs) (Adeogba et al., 2005; Gamberi and Rovere, 2011; Li et al., 2012); 4) deposits delimited by onlap and downlap terminations (Booth et al., 2003; Li et al., 2012); 5) prevalence of coarse sand sediment that is deposited in response to hydraulic jumps due to a break-in-slope related to a stepped slope profile (Komar, 1971; Ferry et al., 2005); and 6) mounded or tabular morphologies (e.g., Oluboyo et al., 2014).

Intraslope lobes are important features in the reconstruction of the evolution of the slope and the analysis of sediment dispersal patterns, and indicate the presence of an uneven slope profile during deposition. Although attempts have been made to determine the importance of submarine slope deposits within a source-to-sink system (Eschard et al., 2004), intraslope lobes have rarely been identified in outcrop studies (Plink-Björklund and Steel, 2002; Sinclair and Tomasso, 2002; Beaubouef et al., 2007; Figueiredo et al., 2010; Bernhardt et al., 2012; van der Merwe et al., 2014). Therefore, the sub-seismic depositional architecture of intraslope lobes can be considered as one of the missing pieces in understanding the stratigraphic record of deep-marine systems and their preserved successions.

Extensive fieldwork carried out in the Laingsburg depocentre of the Karoo Basin, South Africa (e.g., Grecula et al., 2003a; Sixsmith et al., 2004; Di Celma et al., 2011; Flint et al., 2011; Hodgson et al., 2011; Brunt et al., 2013a; Morris et al., 2014b; van der Merwe et al., 2014), has established the stratigraphic and palaeogeographic framework in detail and enables the identification of lobes that were deposited in a slope setting. In this study, we focus on a more detailed characterisation of some of the intraslope lobes of the Karoo Basin. Specific objectives are: 1) to determine the characteristic facies associations and anatomies of the intraslope lobes in the study area; 2) to compare their characteristics with those of basin floor lobes; and 3) to discuss the origin of the transient slope accommodation. The establishment of recognition criteria for the identification of intraslope lobes will help reduce uncertainties in the interpretation of depositional environments observed in core and outcrop where the palaeogeographic context is not clear.

2. Geological and Stratigraphic Settings

The evolution of the Karoo Basin has long been associated with a magmatic arc and the tectonics of a fold-thrust belt (Cape Fold Belt; Fig. 2a), thus characterising it as a retroarc foreland basin (Visser and Prackelt, 1996; Visser, 1997; Catuneanu et al., 1998). Recent studies (e.g., Tankard et al., 2009) suggest that an early phase of subsidence enabled a basin fill that pre-dates the initiation of the Cape Orogeny, and was induced by dynamic topography. This topography is thought to have been derived from the coupling of mantle flow processes to distant subduction of the palaeo-Pacific Plate (Pysklywec and Mitrovica, 1999).

The Laingsburg depocentre is located in the south-western part of the Karoo Basin and adjacent to the present-day Cape Fold Belt (Flint et al., 2011). The stratigraphic unit of study is the Fort Brown Formation of the Ecca Group, which is exposed along the limbs of large, post-depositional folds (Fig. 2b). The Fort Brown Formation is a 400 m-thick submarine slope succession (Di Celma et al., 2011; Flint et al., 2011; Hodgson et al., 2011) that overlies the Laingsburg Formation, a 550 m-thick sand-rich basin floor and base-of-slope succession (Sixsmith, 2000; Grecula et al., 2003a, 2003b; Sixsmith et al., 2004; Brunt et al., 2013b). The Fort Brown Formation is divided into Units C to G (Flint et al., 2011; van der Merwe et al., 2014). These sand prone-units are each separated by regional hemipelagic claystones that locally include additional thin (1-15 m-thick) intercalated sand-prone units informally referred to as interfans (B/C interfan and D/E interfan) (Grecula, 2003a; Hodgson et al., 2011). The sequence stratigraphy of the Fort Brown Formation has been proposed by Flint et al. (2011) to comprise two composite sequence sets, the lower one containing units B/C, C and D and the upper one containing units D/E, E and F. Each individual unit represents a lowstand sequence set, with subunits. For example Unit E is divided into Subunits E1, E2, and E3 based on the occurrence of claystone layers of regional mapped extent. Each subunit is interpreted as a lowstand systems tract. In this framework, the regional claystones that separate the units are interpreted as associated transgressive (TST) and highstand (HST) sequence sets and the equally widespread claystones between sub-units are interpreted as combined transgressive and highstand systems tracts that record the deep-water expression of maximum flooding surfaces (Flint et al., 2011). Limited chronostratigraphic age control in the Fort Brown Formation (McKay et al. 2015) precludes establishment of the duration of depositional sequences.

This study focuses on two areas. Exposures of the Unit D/E interfan and Subunit E1 in the NW area of Zoutkloof (Fig. 2b) have been interpreted previously as lobes that formed in a slope setting (Figueiredo et al., 2010), but have not been hitherto characterised in detail. Four correlation panels were constructed (Zoutkloof S, Zoutkloof N, Roggekraal and Roggekraal N) to illustrate down-dip and strike variations in the successions. Unit E2 in the Geelbek area (Fig. 2b) comprises tabular sand-rich deposits, which, based on a detailed regional dataset, are interpreted to be intraslope lobes that formed above a stepped slope profile up-dip of a ramp dominated by sediment bypass (van der Merwe at al., 2014). The existence of these intraslope lobe deposits demonstrates the location and timing of slope accommodation and can be used to constrain the stratigraphic evolution of the Laingsburg submarine slope system.

3. Methodology and Dataset

For this study, 125 measured sections (each ranging from 3 to 36 m in length and totalling 2.8 km in cumulative thickness) were logged at 1:50 scale in the field, recording grain size, sedimentary structures and the nature and extent of bounding surfaces. In the Zoutkloof area (Fig. 2b,d), 80 sedimentary logs and 422 palaeocurrent measurements from ripple lamination and climbing-ripple lamination were collected over three large, adjacent fold limbs to reconstruct the large-scale geometries of exhumed intraslope complexes (Fig. 2b). In the south-eastern study area (Geelbek area; Fig. 2b,e), 45 sedimentary logs and 173 palaeoflow measurements were collected from ripple lamination, climbing ripple lamination and tool marks along an oblique dip section. In areas of specific interest, 11 additional detailed short sections were measured and correlated (Fig. 2e). This has permitted the development of a detailed sedimentological model to account for facies distributions and small-scale geometries. Correlation panels for the Geelbek area are hung from the regional claystones separating subunits E2 and E3. The Zoutkloof correlation panels are hung from the base of Unit D/E that overlies a regional claystone above Unit D.

4. Facies associations

Six facies associations (FA) are identified based on inferred sedimentary processes and depositional environment. Five of the six facies associations represent particular lobe sub-environments (lobe axis, lobe off-axis, lobe fringe and distal lobe fringe) and have been modified from Prélat et al. (2009) according to the observed facies in the intraslope lobe deposits. FA1-5 represent lobe axis to lobe distal fringe, whereas FA 6 represents hemipelagic background sedimentation.

4.1 FA 1: Thick-bedded sandstone

Observations. This facies association is dominated by structureless, 0.7 to 2.5 m-thick beds of lower to upper fine-grained sandstone that commonly contain parallel lamination with some lenticular mudstone chips (mm-sized) aligned parallel to the laminae. Overall, beds are moderately to well sorted. Most beds lack grading, though weak normal grading is observed towards the tops of some beds that consist of 2 to 10 cm-thick caps of mica-rich, moderately sorted silty sandstone. Intraformational mudclasts are rarely observed at bed bases. Bed bases are sharp, loaded or erosive and can preserve tool marks. Bed amalgamation is common and can lead to > 10 m-thick packages of structureless sandstones (high-amalgamation zones; Fig. 3a). Amalgamation surfaces are indicated by discontinuous layers of mudclasts or subtle grain size breaks.

Amalgamated sandstone packages can overlie surfaces that truncate underlying strata by up to 5 m. These surfaces are mantled with thin layers of mudstone clast conglomerates. Thick-bedded sandstones show tabular geometries. They are laterally extensive for up to 6 kms.

Interpretation. Thick-bedded, structureless and amalgamated sandstones with weak normal grading are interpreted to be the deposits of high-density turbidity currents (Kneller and Branney, 1995) with high aggradation rates (Arnott and Hand, 1989; Leclair and Arnott, 2005; Talling et al., 2012). Their geometries, thickness and facies conform to lobe- or channel-axis settings (e.g., Prélat et al., 2009; Brunt el al., 2013a).

4.2 FA 2: Medium- to thin-bedded structured sandstone

Observations. This facies association comprises lower fine- to very-fine-grained, normally graded sandstone beds that are well sorted. Bed thicknesses range from 0.1 to 0.7 m. Sedimentary structures present include planar lamination, wavy lamination, current-ripple lamination and climbing-ripple lamination (Fig. 3b). Climbing-ripple lamination can be observed with supercritical angles of climb whereby stoss sides are preserved. The majority of beds contain two or more of these sedimentary structures. A common pattern is the vertical repetition of climbing-ripple laminations that are transitional to wavy laminations. Ripple foresets can be draped by thin (<0.1 cm thick) silty laminae. Individual beds can preserve multiple flow directions. Carbonaceous material and mud chips are dispersed in the sandy matrix. Bed bases are sharp or loaded. Medium- to thin-bedded sandstones show tabular geometries and can be traced for kms down-dip and in strike section.

Interpretation. This facies association is interpreted to be deposited by low-density turbidity currents in a lobe off-axis setting. Bedforms such as planar lamination and current-ripple lamination are produced beneath dilute turbulent flows, which rework sediment along the bed (Allen, 1982; Southard, 1991; Best and Bridge, 1992). Beds with opposing palaeocurrent indicators suggest reflection and deflection of the flow (Edwards et al., 1994). Beds with repeating patterns of climbing-ripple and wavy lamination are interpreted to indicate highly unsteady flow behaviour due to either long-lived surging or collapsing flows (Jobe, 2012).

4.3 FA 3: Interbedded thin-bedded sandstones and siltstones

Observations. This facies association comprises thin-bedded (0.01 to 0.2 m), very-fine-grained sandstone interbedded with sandy siltstone and coarse to fine siltstone. Sandstone beds show planar, current-ripple or wavy lamination, whereas siltstone beds commonly display planar lamination with rare isolated starved ripple forms at their base where there is a sand component to the siltstone (Fig. 3c). Contacts between sandstone and siltstone beds are sharp, undulating or loaded. Stoss-side preservation of climbing ripple lamination in sandstone beds is observed in 2D, and ripple geometries are locally preserved as sigmoid-shaped bedforms where 3D observations are possible (see Fig. 12b in Kane and Hodgson, 2011,). Commonly, interbedded sandstones and siltstones form stacked, aggradational packages up to 5 m thick, which internally show no discernible trends in grain size or bed thickness. Individual packages dominantly comprise ripple and climbing-ripple laminated sandstones in their lower part and planar laminated sandstones in their upper part.

Interpretation. Ripple lamination formed due to reworking by dilute turbulent flows with moderate aggradation rates, whereas climbing-ripple lamination is indicative of high aggradation rates (Allen, 1971; Allen, 1982; Southard, 1991). Ripple and planar laminated packages correspond with T_C and T_D divisions of Bouma (1962). This facies association is interpreted as a combination of deposition from sluggish, small-volume flows (Jobe et al., 2012) and flows that underwent rapid deceleration that led to high rates of sediment fallout. This implies that some flows were responding to changes in confinement, similar to flows that undergo expansion and rapid deposition when exiting channel confinement (e.g., Morris et al., 2014b). Observed facies and thicknesses of this facies association conform to an interpretation of a lobe-fringe setting.

4.4 FA 4: Bipartite beds

Observations. Bipartite sand-prone beds (0.01 to 1.5 m thick) are composed of a lower and upper division. The well sorted lower division that comprises relatively clean, structureless sandstone with low mud content. The upper division comprises poorly sorted mica-rich argillaceous sandstone that contains sand grains that are coarser than in the lower division, and varied proportions of subangular to subrounded mudstone clasts (mm to cm sized), mudstone chips and carbonaceous material (plant fragments) (Fig. 3d). Mudstone clasts show no preferred orientation. Typically, the boundary between the lower and upper divisions is gradational. Bed bases are sharp, whereas bed tops can be undulose.

Interpretation. Bipartite beds are interpreted to be the result of a juxtaposition of a high-density turbidity current and a genetically linked cohesive debris flow - a type of hybrid bed (Haughton et al., 2009). Several authors have identified an increase in the number of turbidites with linked debrites in distal parts of basin floor lobes (e.g., Ito, 2008; Hodgson et al., 2009; Talling et al., 2012; Grundvåg et al., 2014). Therefore, bipartite beds are interpreted to be deposited in lobe-fringe settings.

4.5 FA 5: Thin- bedded siltstone

Observations. Thin-bedded (sandy), fine- to coarse-grained siltstones (0.05 to 0.1 m) form metre-scale packages with rare thin (>0.05 m), very fine-grained sandstones that are well sorted (Fig.

3e). Typically, beds are structureless or planar laminated and some incorporate mudstone chips (up to 20% of the bulk volume). Some sandy siltstone beds show isolated starved ripple forms at their base. Thin-bedded siltstones can show minor bioturbation.

Interpretation. Siltstone deposits are interpreted as the preserved products of dilute turbidity currents in distal lobe-fringe settings. Structureless beds are attributed to direct suspension fallout (Bouma, 1962), whereas planar laminated beds are produced by traction (Stow and Piper, 1984; Mutti, 1992; Talling et al., 2012).

4.6 FA 6: Regional claystone

Observations. Homogenous intervals of (silty) claystone (Fig. 3f) are up to 22 m thick. Layers of concretions are common and tend to be associated with distinct horizons in the deposits. Claystone intervals are laterally extensive for tens of kilometres, except where eroded by channelised flows. Thin (<10 cm) ash layers and thin-bedded (mm-scale) graded siltstone units are locally intercalated with the claystones.

Interpretation. Claystones are interpreted as hemipelagic background deposits. Where mapped over large areas, they mark episodes of sediment starvation to the deep basin, and are interpreted to contain the deep-water expression of maximum flooding surfaces (e.g., Flint et al., 2011). Such packages therefore serve as useful correlation intervals.

5. Architecture

Unit D/E and Subunits E1 and E2 of the Fort Brown Formation have been recognized as tabular, sand-prone units within the submarine slope succession (Grecula et al., 2003b; Figueiredo et al., 2010). Flint et al. (2011) placed these packages into the overall sequence stratigraphic framework and van der Merwe et al. (2014) confirmed their palaeogeographic position on the slope. For the first time, the distribution of architectural elements and facies associations of these units are presented and discussed.

The identification of architectural elements is based on cross-sectional geometry, spatial extent, distribution of sedimentary facies and bounding surfaces marked by abrupt changes in facies (Fig. 4). Interpreted architectural elements include lobe deposits, channel-fills and drapes (Fig. 4).

5.1 Zoutkloof area

Unit D/E. Unit D/E is a tabular sandstone package, informally referred to as an interfan (Flint et al., 2011), with a basal interval of interbedded siltstones and very fine-grained sandstones and a sharp top (Fig. 4a). The spatial extent of Unit D/E is limited to the Zoutkloof and Roggekraal study area (81 km^2; Figueiredo et al., 2010). Overall, palaeocurrent direction is to the ENE, but climbing ripple-laminated sandstones at Zoutkloof S show some readings to the west (Figs. 5, 6). Unit D/E is thickest (10 m) in the Zoutkloof N and Roggekraal areas where it comprises amalgamated thick-bedded structureless sandstones (FA 1) (Fig. 5). Across strike to the south (Zoutkloof S), a 6 m heterolithic package (FA 3) sharply overlies very fine- and fine-grained structured sandstones (FA 2). Unit D/E is not observed 6 km along strike to the south, which constrains the southward (lateral) pinch-out (Fig. 6). Across strike to the north (Roggekraal North; Fig. 4b), a 7 m-thick succession of structured sandstone (FA 2) is sharply overlain by structureless sandstones (FA 1).

Interpretation. Overall, the axis of Unit D/E is in the Zoutkloof N and Roggekraal areas, with more off-axis and fringe deposits in the south and north. The stratigraphic changes in facies in the Zoutkloof S and Roggekraal N areas suggest that Unit D/E comprises at least two lobes, and therefore represents a lobe complex (*sensu* Prélat et al., 2009). The lower lobe extends further south than the upper lobe, with lobe off-axis deposits (FA 2) overlain by lobe-fringe deposits (FA 3) in Zoutkloof S and lobe off-axis deposits (FA 2) overlain by lobe-axis deposits (FA 1) in Roggekraal N (Fig. 5) suggesting a minor compensational stacking pattern. The lobe axes are amalgamated in the central part of the study area.

The westward palaeocurrents in deposits in Zoutkloof S are interpreted to indicate rapid deposition of turbidity currents deflected and reflected off seabed topography at the fringes of the intraslope lobe (Fig. 6). There is no evidence of incision into the Unit D/E deposits and no deposit of this age directly down-dip has been recognized (van der Merwe et al., 2014). The abandonment of Unit D/E suggests that either the sediment routing system avulsed outside of the study area or sand-grade sediment supply ceased prior to the complete infill of the slope accommodation.

Subunit E1. E1 is separated from Unit D/E by a 10 m thick mudstone, and has a basal ~0.5 m-thick interval of interbedded mudstone, siltstone and very fine-grained sandstone. The dominant palaeoflow is to the E, which is consistent with regional trends, whereas some deposits show palaeoflow to the W in the Zoutkloof S area (Figs. 5, 6). Where thickest (14 m), E1 is characterised by structureless amalgamated sandstones (FA 1) and structured sandstones (FA 2). In Roggekraal N, to the north where E1 is 8 m-thick, 3 packages are identified by sharp contacts with thin-bedded siltstones (FA 5) units. The lowermost unit is dominated by heterolithic deposits (FA 3), the middle is dominated by FA 1, and the upper is dominated by FA 2 (Fig. 4b). In contrast, to the south at Zoutkloof S, E1 is thinner (5 m) and comprises heterolithic packages (FA 3) and thin-bedded siltstones (FA 5). E1 is not observed 6 km along strike to the south, which constrains the southward (lateral) pinch-out (Fig. 6). Locally, E1 is truncated by erosion surfaces from multiple stratigraphic levels (Figueiredo et al., 2010, 2013;) (E1, E2, E3 and Unit F;, Fig. 6). Erosion surfaces within E1 cut down up to 10 m and are overlain by thick-bedded sandstones that have low aspect ratios (10:1 to 15:1;

Fig. 4). Younger erosion surface commonly have higher aspect ratios (20: 1 to 35: 1; Fig. 5) and are overlain by thin bedded, and locally tightly folded, sandstones and siltstones (Figueiredo et al., 2010, 2013), but sand-filled younger channel-fills are also observed.

Interpretation. In Roggekraal N, thin siltstone packages that abruptly separate three axis and off-axis packages indicate the existence of three lobes in the lobe complex (Fig. 4). The distribution of the lobe axis and off-axis deposits, and the lobe fringe and distal fringe deposits of the individual lobes, suggest an aggradational to slightly compensational stacking pattern. Deviation from the regional palaeocurrent trend in Zoutkloof S is interpreted to indicate deflection and reflection of turbidity currents off seabed topography. Erosion surfaces overlain by sandstones are interpreted as W-E and NW-SE oriented channel-fills.

5.2 Geelbek area

Subunit E2. Subunit E2 comprises three packages based on thickness trends, facies distribution, bounding surfaces and palaeocurrents measurements (Figs. 7a-d, 8). The mean palaeocurrent direction is to the E, but with local variations (Fig. 8). The base of the lower package, E2A, consists of heterolithic deposits (FA 3) overlain by FA 1 and FA 2 beds with abundant dm-scale erosion surfaces (Fig. 9a). Commonly, medium-bedded, structured sandstones (FA 2) display more than one sedimentary structure vertically and laterally (planar lamination, ripple lamination and climbing-ripple lamination). Lateral facies transitions in individual beds include ripple-, through wavy-, to planar-lamination, which occur over tenss of metres lateral extent.

In some beds, palaeocurrent measurements from stoss-side preserved climbing ripple-lamination can display ENE palaeocurrents in the lower section whereas the upper section preserves palaeocurrents to the WSW (e.g., Marker bed 1 (Mb1), see Fig. 7-9a). Typically, these beds are thickest in the east and thin westward in an up-dip direction. Sedimentary structures change in the direction of thinning from stoss-side preserved climbing-ripple lamination, through planar lamination with isolated current-ripple forms, to planar laminated sandstones. The bases of some beds with bi-directional palaeocurrents (e.g., Marker bed 2 (Mb2), see Fig. 9a) truncate underlying bedding with siltstones that display soft-sediment deformation structures (Fig. 7b).

The middle package, E2B, is defined by a stepped basal erosion surface that incises 6 m into E2A (Fig. 8). The overlying sediments comprise highly amalgamated thick-bedded sandstones (FA 1) with rare planar lamination on bed tops (Fig. 8). These pass into more clearly stratified but internally structureless fine-grained sandstones close to the (oblique) margin of the cut and can be traced out for over a km away beyond the basal scour surface, where E2B overlies

E2A concordantly (Fig. 7c). Palaeocurrents from grooves indicate an overall ENE-WSW flow direction (Fig. 8).

The upper E2C division is the most laterally extensive of Subunit E2 and the boundary with E2B is marked by a thin siltstone horizon (~10 cm; FA 5; Fig. 7d). It comprises basal bipartite beds (FA 4) in its proximal (westerly) section and is largely made up of medium-bedded, structured sandstones (FA 2) that overlie the highly amalgamated sandstones of E2B (FA 1). Thin-bedded deposits (FA 3 and FA 5) are rare. Palaeocurrents measured from current- and climbing-ripple lamination indicates an easterly flow direction (Fig. 8). In the west, beds are structureless (FA 1), with rare ripple lamination showing easterly palaeocurrents. Structureless sandstone beds onlap westward onto the underlying claystone, overstepping the E2A and B deposits (Fig. 8). Commonly, the onlapping beds show pinching and swelling close to the onlap surface as well as evidence of erosion (rip-up clasts, truncation). Clastic injectites are abundant in the mudstone that underlies the sandstone onlap (Fig. 9b).

In the underlying claystone that separates Units D and E, a distinctive 0.4 m-thick intraformational clast-rich bed is used as a local marker bed. The sandstone bed and bounding claystones are present in western part of the outcrop. However, they terminate abruptly eastward against a steep surface overlain by a thin-bedded coarse siltstone and silty claystone succession below where the overlying E2 attains its maximum thickness (Fig. 8). The thin-bedded siltstone unit forms a discrete ~30 m-thick unit that thins out over ~700 m to the east; by contrast, the western edge is steep and abrupt (Fig. 8).

Interpretation. The high sand-content and tabular geometry, the underlying and overlying channel-levee systems (e.g., Brunt et al 2013b), and the downdip change to thin-bedded turbidites led van der Merwe et al. (2014) to interpret E2 as an intraslope lobe in the Geelbek area. The three divisions of E2 in Geelbek are interpreted here as lobe deposits that stack to form a lobe complex. In E2A, sandstones beds with bidirectional palaeocurrents and up-dip thinning are interpreted to indicate deflection of the flow column (Edwards et al., 1994). Soft-sediment deformation was triggered either through instability on the open erosional slope or through dewatering due to deposition of overlying strata. This range of features is consistent with a confined setting at the onset of the filling of slope accommodation. The amalgamated deposits of E2B are interpreted to be deposited in a scoured lobe-axis setting. The scour-fill interpretation is preferred to a channel-fill interpretation because no mudstone clast conglomerate facies is observed, the geometries of the structureless sandstone beds are tabular and can be walked out for ~1.5 km away, and the erosion surface shallows in the direction of main palaeocurrent direction. E2C is the most laterally extensive of the subunits. Lack of bidirectional palaeocurrent indicators and dominance of climbing-ripple laminated medium-bedded sandstones indicates a relatively unconfined phase of deposition. Overall, the depocentre of successive E2 lobe deposits shifts slightly to the W (up slope; Fig. 9). These findings conform to subsurface observations made in the Gulf of Mexico indicating temporal evolution of the locus of sedimentation (Prather et al., 2012b).

6. Discussion

6.1 Mechanisms of slope accommodations

Typically, submarine slope systems are dominated by sediment bypass (e.g., Beaubouef et al., 1999; Gardner et al., 2003; Romans et al., 2009; Hodgson et al., 2011). For lobate bodies to deposit on the submarine slope low gradient areas of high accommodation must be present. Here, the origin of this accommodation is discussed.

The formation of the intraslope lobe complexes of Unit D/E and Subunit E1 in a similar location, albeit slightly offset, demonstrates the presence of accommodation on Zoutkloof part of the palaeoslope through multiple depositional sequences. In the Zoutkloof area, there is no evidence of slide scars, syn-sedimentary tectonic or diapiric deformation of the seabed, or underlying mass transport complexes that could form an area of high accommodation (Figueiredo et al., 2010). However, in the underlying successions (Units A-D) the Zoutkloof area represents an overall off-axis position with abundant silt-prone deposits (levees and lobe fringes), and the main slope channel-levee systems to the south (e.g., Grecula et al., 2003 a; Sixsmith et al., 2004; Figueiredo et al., 2010) feeding sand-prone basin-floor lobe complexes to the east and north east (Di Celma et al., 2011; van der Merwe et al., 2014). Therefore, slope accommodation at Zoutkloof is interpreted to be the result of differential compaction of the underlying fine grained stratigraphy relative to the more sand-rich underlying stratigraphy to the south (Figueiredo et al., 2010) and east (van der Merwe et al., 2014).

The geometries of architectural elements, palaeocurrent measurements, and facies distributions in Subunit E2 indicate a depositional setting that evolved from highly- to weakly-confined. E2A deposited on the partially healed accommodation (Fig. 10) and beds show evidence for flow deflection and reflection. E2B deposits show a slightly different main palaeocurrent direction and formed above an erosion surface that cuts into E2A and shallows downdip (Fig. 10). E2C shows onlap against the open slope when the accommodation was infilled (Fig. 10).

At the regional-scale, sedimentary features in the Geelbek area have been shown to form part of a step in a stepped slope profile with a ramp and sediment bypass ~ 2 km basinward of this area (van der Merwe et al., 2014). A large slide scar has been interpreted at the top of the underlying Unit D in this locality (Brunt et al., 2013b). In this study, an abrupt facies change from claystones with a clast-rich sandstone marker bed to a 30 m-thick asymmetric wedge of thin-bedded siltstone (Fig. 8) in strata underlying Subunit E2 has been identified. This is interpreted to indicate the presence of a W-E oriented slide scar that formed near the step-to-ramp transition area prior to the initiation of Unit E, but was only partially healed, and could have modified and amplified the accommodation for the E2 intraslope lobe complex (Fig. 10).

6.2 Diagnostic criteria for intraslope lobe deposits

The identification of key characteristics of intraslope lobes compared to basin floor lobes can aid their identification in less well constrained subsurface and outcrop datasets (Fig. 11a). Geometries and architecture have been compared using published data from basin floor lobes in the Karoo Basin (Fan 3, Tanqua depocentre, Prélat et al., 2009; Unit A, Laingsburg depocentre, Prélat and Hodgson, 2013) with intraslope lobes of Units D/E and E (Table 1).

6.2.1 Dimensions

The lobe complexes are 6 to 10 km wide, 15 to 25 km long and 10 to 15 m thick. In volume, they are an order of magnitude smaller than dimensions of basin floor lobe complexes quoted in Prélat et al. (2010), which are 10 to 30 km wide and 30 to 100 m thick.

6.2.2 Lobe stacking patterns

Lobes stack to form lobe complexes (Deptuck et al., 2008; Prélat et al., 2009), and the patterns of stacking of lobes within such complexes provide an insight into the degree of confinement

(Deptuck et al., 2008; Straub et al., 2009). Generally, an aggradational to slightly compensational style of stacking is observed within intraslope lobes of the Fort Brown Formation (Fig. 11). This characteristic is also identified from subsurface studies of recent deepwater systems (Ferry et al., 2005; Barton, 2012). In contrast, basin floor lobes exhibit markedly compensational styles of stacking, indicative of relatively unconfined settings (Prélat et al., 2009; Straub et al., 2009; Groenenberg et al., 2010).

6.2.3 Sedimentary facies and features

Intraslope lobe-axis deposits share similar facies associations with basin floor lobes (e.g., Prélat et al., 2009). Off-axis deposits of intraslope lobes are characterised by an abundance of medium bedded ripple- and climbing ripple-laminated sandstones (Fig. 11). Successions of climbing-wavy-climbing lamination or ripple-wavy-ripple lamination are indicative of highly unsteady flows with high rates of sediment fallout. Individual beds can preserve ripple forms and climbing ripple-lamination that yield palaeoflow directions oriented at a high angle or even opposite to each other (Fig. 11), indicating deflection and reflection of the turbidity current during sedimentation. Commonly, basin floor, lobe fringe deposits contain numerous bipartite beds (Hodgson, 2009), and these are relatively rare in intraslope lobe fringe deposits. Erosion surfaces mantled with mudclasts are more common in intraslope lobe axis and lobe off-axis deposits than in basin floor lobe systems because proximity to channels and flow confinement leads to more entrainment of fine-grained substrate. Basin floor lobes also display erosion surfaces in the lobe axis, leading to amalgamation of thick-bedded sandstones by removal of intervening thin beds (Stephen et al., 2001; Prélat et al., 2009). However, erosion surfaces in basin floor lobes are more subtle than in the intraslope lobes. In basin floor lobe systems, facies transitions occur over several kilometres, both frontally and laterally (e.g., Prélat et al., 2009; Groenenberg et al., 2010), whereas in intraslope lobe systems, facies transitions occur over shorter distances (typically over 10+ m), as observed in Unit E2 in the Geelbek area (Fig. 9).

6.2.4 Sand percentage

Overall, intraslope lobe deposits are characterised by a higher percentage of sandstone than basin floor lobe deposits because sand becomes trapped preferentially in areas where available accommodation is limited compared to flow depth (Brunt et al., 2004). If the flow height is greater than the relief of the confinement then the upper fine-grained part of the flow can be stripped, which will increase the proportion of sand that is accumulated (Sinclair and Tomasso, 2002; Prather et al., 2012b). Basin floor lobes of Unit A have an average sandstone percentage of 60% , with >80% in lobe axes and < 40% in distal lobe fringe settings (Prélat et al., 2009); intraslope lobes of Unit D/E and E show an average of 75% sandstone, with >90% in lobe axes and <50 % sandstone in lobe fringes (Table 1, Fig. 11b).

6.2.5. Incision of intraslope lobes by channels

Commonly, intraslope lobes are incised by channels (e.g., Adeogba et al., 2005). Incision of the E1 lobe complex by low-aspect-ratio channel systems of different ages, including E1-aged channels, indicates that when the accommodation had been filled, slope channel systems could develop in response to a lower base level. This indicates that slope accommodation in this area was transient. This is supported by the identification of thick basin floor lobe complexes of Unit E age farther into the basin by van der Merwe et al. (2014).

7. Conclusions

Three exhumed intraslope lobe complexes, constrained by stratigraphic and geographic position based on extensive and detailed correlation and mapping in the Laingsburg depocentre, Karoo Basin, were studied to establish their sedimentological and stratigraphic characteristics.

In the study area, intraslope lobe complexes are a 6 to 10 km wide and extend 15 to 25 km in down-dip directions; areal extent is controlled by the area over which slope accommodation was generated. The deposits are sandstone-rich and lack significant siltstone. Stacking patterns are aggradational to slightly compensational depending on the amount of confinement. The lobe axis is dominated by thick-bedded, amalgamated sandstones. The lobe off-axis mainly comprises medium-bedded climbing-ripple laminated sandstones. The lobe fringe is characterised by ripple- and climbing ripple-laminated sandstones that can show flow deflection and reflection, and are interbedded with siltstones. Lateral and vertical facies changes occur over tens of metres and demonstrate highly variable, unsteady depositional flows that interacted with, and were governed by, underlying sea-bed topography and surrounding confinement. Two mechanisms are identified for the development of accommodation on the Karoo slope: differential compaction and scars formed by mass wasting processes. The presence of intraslope lobe complexes supports regional interpretations that the slope of the Laingsburg depocentre developed a series of steps. These sub-seismic-scale observations and interpretations provide possible analogues to sub-surface examples identified on geophysical data for which information relating to detailed internal sedimentary architecture is not available.

The development of sedimentological and stratigraphic recognition criteria for identification of intraslope lobes will permit improved reconstruction of the stratigraphic evolution of continental margins. However, the depositional architecture will vary across systems depending on the mechanism responsible for slope accommodation, the areal extent of the accommodation, and the ratio of flow size and the degree of confinement.

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Figure Captions

Table 1. Comparison chart of the main sedimentological and stratigraphic characteristics of intraslope lobes and basin-floor lobes.

Fig. 1. Principal features of a stepped deep-water system. Two mechanisms to generate accommodation on the slope are shown: generation of a slope step due to tectonic faulting and above a scar of a mass transport complex (MTC).

Fig. 2. (A) The Laingsburg depocentre is located inboard of the Cape Fold Belt. Black square indicates the area of study. Satellite images taken from Google Earth. (B) Location of detailed study areas: Roggekraal and Zoutkloof in the North, Geelbek in the South. White squares indicate the zoom-in areas in (D) and (E). Shading corresponds to colours of boxes in C. (C) Schematic stratigraphic log sections of the Fort Brown Fm., Laingsburg Fm. and Waterford Fm. (Flint et al., 2011). Units D/E and E are highlighted by the black square. (D) Detailed view of the Zoutkloof and E) Geelbek study areas. White lines indicate outcrop exposure, black dots indicate positions of logged sections, and black boxed areas of detailed correlation panels (Figure 7).

Fig. 3. Representative photographs of sedimentary facies observed in the Zoutkloof area. (A) Thick-bedded amalgamated sandstones of the lobe axis (FA 1). Geologist for scale (1.6 m). (B) Climbing ripple-laminated, medium bedded, fine-grained sandstones, with some stoss-side preservation, in lobe off-axis (FA 2). Camera lens cover for scale. (C) Heterolithic packages of thin-bedded sandstones and siltstones in the lobe fringe (FA 3). Logging pole (0.5 m) with 10 cm gradations as scale. (D) Hybrid bed (FA 4). Camera lens cover as scale. (E) Siltstone package with intercalated sandstones (FA 5). Logging pole (2 m) with 10 cm gradations as scale. (F) Silty claystones (FA 6). Geologist for scale (1.6 m).

Fig. 4. Representative photographs and correlation panel of the intraslope lobe complexes of Unit D/E and E1 in the Zoutkloof area

and correlation panel for the Roggekraal N area. (A) Coarsening- and thickening-upward at the base of the intraslope lobe deposits in Unit D/E. Logging pole with 10 cm gradations as scale. (B) Roggekraal N correlation panel showing siltstone intervals that separate individual lobes in Subunit E1 and the two lobes of Unit D/E. Dashed red line represents erosion surface (C) Tabular geometries of Unit D/E and Subunit E1 in the Zoutkloof N area. The sand-prone units are separated by a ~11 m thick mudstone. (D) E1 channels cut down through E1 lobes and into the underlying claystone (Zoutkloof N).

Fig. 5. Correlation panels for Unit D/E and Subunit E1 in the Zoutkloof area. Overall axis of the lobe complexes of Unit D/E and Subunit E1 is located in the Roggekraal and Zoutkloof N areas. Towards the north and south lateral facies transitions can be observed and correspond to lobe off-axis and lobe fringe deposits. Note incision of Subunit E1 by younger channel-fills.

Fig. 6. Simplified palaeogeographic reconstruction of (1) Unit D/E and (2) overlying Subunit E1 in the Zoutkloof area. Flows show evidence for deflection and reflection.

Fig. 7. Representative photographs of the intraslope complex in the Geelbek area. (A) Bed showing climbing-ripple lamination with opposing flow direction patterns. Camera lens cover as scale. (B) Deformed mudstone interlayer with flames. Camera lens cover as scale. (C) E2B overlies E2A outside of the basal scour surface. Camera lens cover as scale. (D) E2B and E2C are separated by a thin

(0.1 to 0.2 m thick; indicated by orange overlay) siltstone interval. Geologist (1.6 m) as scale.

Fig. 8. Correlation of subunit E2 in the Geelbek area. Panel is hung from hemipelagic claystone between E2 and E3. Black boxes (A-D) indicate areas shown in detail in Figure 9. Note siltstone wedge within the mudstone interval which is interpreted to partially fill a slide scar.

Fig. 9. Details of the Geelbek correlation panel. (A) Detailed correlation panel of E2A. (B) Injected mudstone below E2A with geologist as scale. (C) Detailed correlation panel of the E2C onlap zone. 'a' marks amalgamation surfaces, 'E' erosion surfaces. (D) Example graphic log through high-amalgamation zone of E2B overlain by well bedded, structured sandstone beds of E2C.

Fig. 10. Simplified palaeogeographic reconstruction of subunit E2 in the Geelbek area. (1) slide removeshemipelagic claystone and marker bed 3 (MB3). Surface is steep in the west and shallows to the east. (2) thin-bedded siltstone beds partially infill scar, which is also draped by hemipelagic mudstone. (3) deposition of confined sediments of E2A. (4) E2B locally scours into E2A. (5) onlap of E2C deposits to the west. Slope feeder channels are not exposed in the field and therefore not displayed.

Fig. 11. (A) Block diagram showing the key recognition criteria of intraslope lobes. Aggradational to slightly compensational stacking patterns; onlap combined with injection onto mud-prone slope;

highly amalgamated zones in the lobe complex axis; subtle confinement leads to fringes that show aggradational stacking; high degree of confinement leads to preservation of beds with evidence of flow deflection, erosional based beds and abrupt facies changes; climbing-ripple lamination is the dominant facies of the lobe-off axis; incision by low-aspect-ratio channels that originate in the same unit as the intraslope lobes; more lobe deposits can be found down-dip on the basin-floor or on steps basinward on the slope. (B) Simplified logs of typical thicknesses and stacking patterns from lobe axis to lobe fringe (downdip and laterally) in intraslope lobes that are observed over a few kilometres. Note position of the schematic logs from fringe (1) to axis (4) in (A).