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SPECIAL

Submarine slope degradation and aggradation and the stratigraphic evolution of channel–levee systems

D. M. HODGSON[1]*, C. N. DI CELMA[1,2], R. L. BRUNT[1] & S. S. FLINT[1]

[1]*School of Environmental Sciences, University of Liverpool, Liverpool, L69 3GP UK*

[2]*Present address: School of Science and Technology, Geology Division, University of Camerino, Camerino, 62032 Italy*

**Corresponding author (e-mail: hodgson@liv.ac.uk)*

Two seismic-scale submarine channel–levee systems exposed in the Karoo Basin, South Africa provide insights into slope conduit evolution. Component channel fills in a levee-confined channel system (Unit C) and an entrenched channel system (Unit D) follow common stacking patterns; initial horizontal stacking (lateral migration) is followed by vertical stacking (aggradation). This architecture is a response to an equilibrium profile shift from low accommodation (slope degradation, composite erosion surface formation, external levee development, sediment bypass) through at-grade conditions (horizontal stacking and widening) to high accommodation (slope aggradation, vertical stacking, internal levee development). This architecture is likely common to other channel–levee systems.

Supplementary material: A detailed correlation panel (presented schematically in Figure 2) is available at www.geolsoc.org.uk/SUP18456.

Submarine slope channel–levee systems are major geomorphological features (kilometres wide and hundreds of metres deep) on present-day continental margins, which act as conduits for the transfer of large volumes of coarse-grained sediment to the deep oceans, particularly during sea-level lowstands (Covault & Graham 2010). Channelized parts of the systems record erosional and depositional processes, in contrast to genetically related levee deposits, which preserve a more complete depositional record. Changes in channel system planform and cross-sectional geometry down slope can be well constrained (e.g. Pirmez *et al.* 2000; Babonneau *et al.* 2002; Labourdette 2007). Subsurface seismic datasets of filled submarine channel systems indicate stratigraphic complexity and a large proportion of low-amplitude seismic facies that suggest significant fine-grained components of the fills (e.g. Mayall *et al.* 2006; Deptuck *et al.* 2007). Sedimentary facies distribution is best constrained by outcrop studies (e.g. Gardner *et al.* 2003; Schwarz & Arnott 2007; Figueiredo *et al.* 2010); however, these examples can be biased towards sand-prone fills of small systems owing to exposure constraints. Furthermore, at outcrop it is challenging to demonstrate conclusively that thin-bedded successions adjacent to channel systems are levee deposits and genetically related to the development and fill of the channels. Here, the detailed analysis of two seismic-scale exhumed late Permian submarine slope channel–levee systems that crop out in the Laingsburg area of the SW Karoo Basin is documented (Fig. 1a and b). Their architecture, depositional environments, and stratigraphic evolution are presented and merit close consideration as analogues to modern and ancient channel–levee systems.

Geological setting and stratigraphy. The Karoo Basin evolved from a retroarc basin with subsidence owing to mantle flow (Permian) to a foreland basin (Triassic) (Tankard *et al.* 2009). In the Laingsburg depocentre, a 1.4 km thick Permian progradational basin floor to upper slope succession is well exposed (Flint *et al.* 2011; Fig. 1). The lithostratigraphic units of the Fort Brown Formation under investigation here, Units C and D, are interpreted to represent the deposits of lower to middle slope setting.

The study area, the south Baviaans ridge, runs for 5 km NW–SE with strata dipping and younging to the NE on the southern limb of a post-depositional syncline (Figs 1c and 2). Initial field investigations identified two broad sedimentary facies and architectural associations: (1) channelized, with a complicated stratigraphy of closely spaced, cross-cutting erosion surfaces overlain by mudstone clast conglomerates, amalgamated fine-grained sandstones, mass-flow deposits (chaotic and folded strata), and thin-bedded ripple laminated beds that locally fine and thin onto erosion surfaces; (2) non-channelized, with a simple stratigraphy comprising mudstones, tabular, planar laminated siltstones, and climbing ripple laminated very fine- and fine-grained sandstones (Fig. 2). More than 200 measured sections were collected (20–50 m lateral spacing), with single beds and erosion surfaces walked out during the logging to establish a robust stratigraphic correlation (Fig. 2). The basal datum for the sedimentary logs is a thin (>1–4 m) but extensive fine-grained sandstone unit, the B–C interfan, which is overlain by *c*. 30 m of mudstone to the base of Unit C (Fig. 2).

Unit C stratigraphy and environment of deposition. At the NW and SE ends of the south Baviaans ridge (Fig. 2), Unit C is 45 m thick and comprises the non-channelized association. Two regionally mapped (>500 km^2) internal mudstone units, one near the base (lower C mudstone, 2 m thick) and one near the top (upper C mudstone, 8 m thick) divide Unit C into three sub-units (C1, C2 and C3; Fig. 2). Unit C1 is the most sandstone-prone part of Unit C in non-channelized areas, and fines and thins upward to the lower C mudstone (Fig. 2). Where C1 is thickest (15 m thick) metre-scale cross-stratified bedforms and climbing ripple laminated beds cut by metre-scale scours mantled with mudstone clast conglomerates are common. In the SE part of the outcrop, Unit C2 thins to the east from 30 m to <5 m over a distance of 6 km away from an erosional contact with a channelized association (Fig. 2). The average grain size and bed thickness of the succession fines and thins in the same direction. The mudstone between the B–C interfan and Unit C maintains the same thickness regionally, which indicates that C1 and C2 form a wedge. The geometry, sedimentary facies distributions and location adjacent to channelized stratigraphy support an interpretation of the Unit C non-channelized deposits as an external levee (Kane & Hodgson 2011). The geometry, grain size, and tractional bedforms with evidence of rapid deposition cut by energetic currents suggest that the basal part of C1 is a lobe (Prélat *et al.* 2009). C3 is a 5–10 m thick regionally developed package of thinly bedded sandstones and siltstones

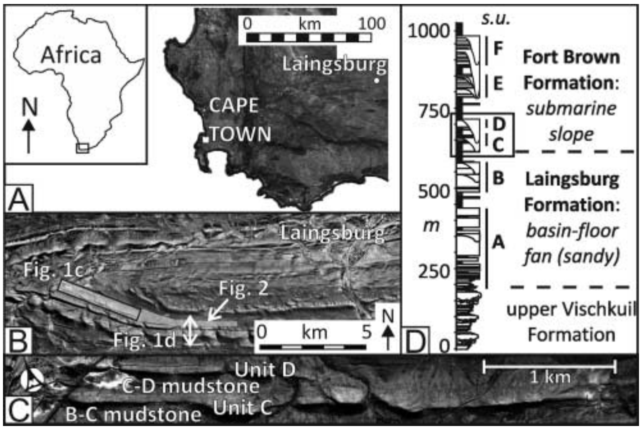

Fig. 1. (**a**) Location map of study area in southwestern South Africa near the town of Laingsburg. (**b**, **c**) Aerial photographs of the Baviaans syncline and the south Baviaans ridge study area, SW of Laingsburg. (**d**) Simplified sedimentary log showing the stratigraphic context of Units C and D in the Fort Brown Fm. s.u., stratigraphic unit.

that overlies the upper C mudstone, and is interpreted as a submarine lobe fringe or external levee. C3 is overlain by the 21 m thick C–D mudstone. The lower and upper C mudstones record periods of regionally reduced sand supply, suggesting that they are related to relative rises in sea level (Flint *et al.* 2011).

At the NW exposure of the Baviaans ridge, the same C1 and C2 stratigraphy is cut by an erosion surface that marks the boundary between the non-channelized and channelized associations. This erosion surface is C2 in age as the lower C mudstone is truncated but C3 and the upper C mudstone are not (Fig. 2). The erosion surface confines a 90 m thick channelized association. The surface is composite, as several erosion surfaces merge together onto it. Palaeocurrent directions from cross-lamination and sole marks indicate mean palaeoflow toward the NNE. The original width of the channel system was between 2 and 3.3 km (Fig. 2).

A hierarchy of erosion surfaces is identified in the Unit C channel system based on the scale of incision surfaces, stacking patterns, and the distribution of sedimentary facies (e.g. Abreu *et al.* 2003; Fig. 2). Typically, channel-scale erosion surfaces are *c.* 100–200 m wide and *c.* 10–20 m deep, although most channel fills are remnant bodies owing to repeated cycles of cut and fill. A common facies transition within single channel fills is from a channel axis association of amalgamated fine-grained sandstone and mass-flow deposits, to a channel margin association of stratified thin-bedded ripple laminated sandstone and siltstone beds that thin and onlap (with a depositional dip) onto an erosion surface. Where several channels stack in a similar pattern and are filled with similar sedimentary facies, the larger channelized feature that is bounded by a composite erosion surface (*c.* 300–500 m wide and *c.* 30–50 m deep) is termed a channel complex (e.g. Abreu *et al.* 2003).

Sub-unit C2 comprises at least seven remnant channel complexes. The oldest preserved channel complex remnants are found at the deepest point of the composite erosion surface. They are characterized by closely spaced erosion surfaces and their fills comprise chaotic deposits, highly amalgamated, medium- to thick-bedded fine-grained sandstones, and mudstone clast conglomerates that onlap directly onto the C2 composite erosion surface. No clear stacking pattern is identified, which suggests an unorganized channel network. Erosional remnants of younger complexes are laterally offset, showing an eastward then westward stepping trend (Fig. 2). Complete channel and channel-complex fills are rare but exhibit a roughly asymmetrical cross-section and sedimentary facies distribution. The youngest channel complex in Unit C is 300 m wide and 40 m thick with vertically stacked sandstone-dominated component channel fills. Adjacent to this channel complex and within the main composite erosion surface, the stratigraphy comprises thin-bedded, very fine-grained sandstones and siltstones that show gradual fining and thinning away from the channel-complex fill. These are interpreted as internal levee deposits as they are not confined by channel-complex scale erosion surfaces, but are within the main C2 composite erosion surface (Fig. 2). The internal levee built above, and likely merged with, the external levees (Kane & Hodgson 2011; Fig. 2). Unit C is classified as a levee-confined channel system as most of the channel complexes are bound by adjacent external levee deposits (Fig. 2).

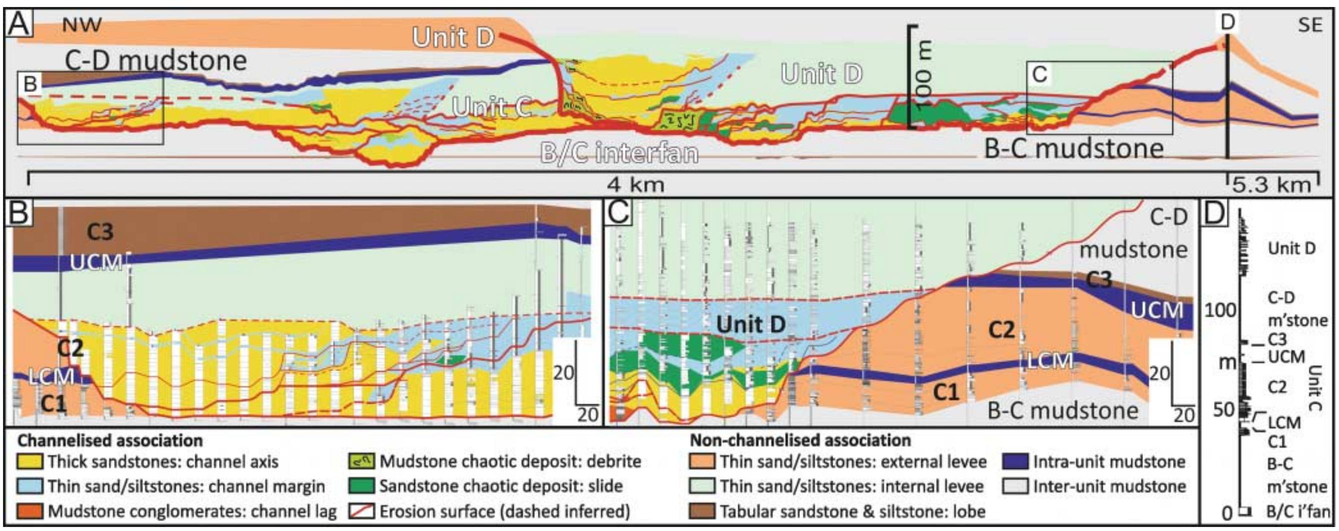

Fig. 2. (**a**) Schematic correlation panel based on physical correlation of *c.* 200 closely spaced logged sections. The panel demonstrates that an entrenched submarine channel–levee system (Unit D) partially removed an older levee-confined submarine channel–levee system (Unit C) above a horizontal datum (B–C interfan). (**b**, **c**) Insets of the NW and SE margins of Unit C with the detailed stratigraphy labelled (see (**a**) for location). (**d**) A measured section from the south Baviaans ridge study area (see (**a**) for log location). UCM, upper C mudstone; LCM, lower C mudstone.

Unit D stratigraphy and environment of deposition. The 21 m thick mudstone between Units C and D, and the whole of the Unit C stratigraphy are truncated at two places along the Baviaans ridge by a 2 km wide and >100 m deep erosion surface (Fig. 2). This defines the Unit D channel system, which is characterized by a complicated stratigraphy with multiple erosion surfaces and abrupt sedimentary facies changes (Fig. 2). Outside the main incision surface thin-bedded siltstone-prone tabular non-channelized deposits overlie the C–D mudstone. These non-channelized deposits share characteristics with non-channelized deposits of Unit C. Thick (0.2–0.5 m) climbing ripple laminated fine-grained sandstone beds at the base of successions fine and thin upward and laterally away from the channel system fill to thin-bedded siltstone-prone deposits. Relative to the constant thickness of the underlying C–D mudstone, Unit D non-channelized deposits form wedges that taper away from the Unit D channelized deposits, and are interpreted as external levee deposits (Fig. 2). The maximum thickness of the western and eastern external levee deposits is 70 m and 40 m respectively.

The Unit D channelized association is confined to an asymmetrical erosion surface that passes into the adjacent external levee deposits (Kane & Hodgson 2011). The erosion surface is composite and younger than the base external levee, and has a steep western margin (*c*. 80°), a less steep eastern margin (*c*. 25°), and a relatively flat base that is oriented subparallel to the mudstone beneath Unit C (Fig. 2). Cross-cutting erosion surfaces allow age relations of the fill to be deduced. The oldest deposits lie above the easternmost part of the main erosion surface and exhibit numerous erosional surfaces cutting to the west and east, overlain by mass-flow deposits, thick mudstone clast conglomerates and structureless amalgamated fine-grained sandstones (Fig. 2). Younger channel-complex fills directly overlying the main erosion surface preserve a clear westward stepping horizontal stacking pattern that indicates multiple cycles of cut and fill and lateral migration that locally deepened and widened the base of the channel system (Fig. 2). In contrast, the youngest channel complexes are vertically stacked and comprise symmetrical sandy channel fills that are bounded by the main composite erosion surface to the west, and tabular thin-bedded very fine-grained sandstones and siltstones to the east. The two distinct channel stacking patterns, horizontal and vertical, are separated stratigraphically by several argillaceous mass-flow deposits close to the steep western margin (Fig. 2).

Only *c*. 20% of the Unit D channel system fill is sandstone. A 50 m thick succession of tabular thin-bedded siltstone and very fine-grained sandstone beds adjacent to the youngest channel complexes is not confined by a channel complex scale surface, but is contained within the main composite erosion surface (Fig. 2). This sedimentary facies is a significant portion of the channel–levee system fill and is interpreted to represent internal levee deposits (Kane & Hodgson 2011). The composite erosion surface remained underfilled during the backfill and abandonment of the conduit as the top surface of fill is 20–30 m below the external levee crests. Unit D is classed as an entrenched channel–levee system because the component channel complexes are confined by a composite erosion surface that extends palaeobathymetrically below the base of Unit D-aged external levee deposits.

Discussion

Stratigraphic evolution. Units C and D share a common stacking pattern of component channel fills following development of composite erosion surfaces. Based on the observations of the sedimentary facies distributions and depositional architecture of Units C and D, a four-stage model for the channel–levee system evolution tied to accommodation change is proposed (Fig. 3). Accommodation on the submarine slope is the gap between the sediment surface (the background slope surface) and the equilibrium profile (the slope profile of no net erosion or deposition) (Pirmez *et al.* 2000; Kneller 2003). The gradient of the equilibrium profile responds to changes in the volume and composition of turbidity currents, and the position of base level.

Stage 1. A fall in the equilibrium profile reduces accommodation, which initiates deposition of coarse-grained sediment with local deposition of lobes where there is accommodation (Fig. 3). Flows at a point on the slope become focused as constructional external levees develop (Fig. 3).

Stage 2. Local gradients will decrease through slope degradation and the formation of a composite erosion surface, confinement of an unorganized channel system and significant bypass of coarse-grained sediment (Fig. 3). There is limited preservation of channel fills toward the base of the composite erosion surface (Fig. 3).

Stage 3. When the base of the channel system is at grade with the equilibrium profile there is no net deposition or erosion.

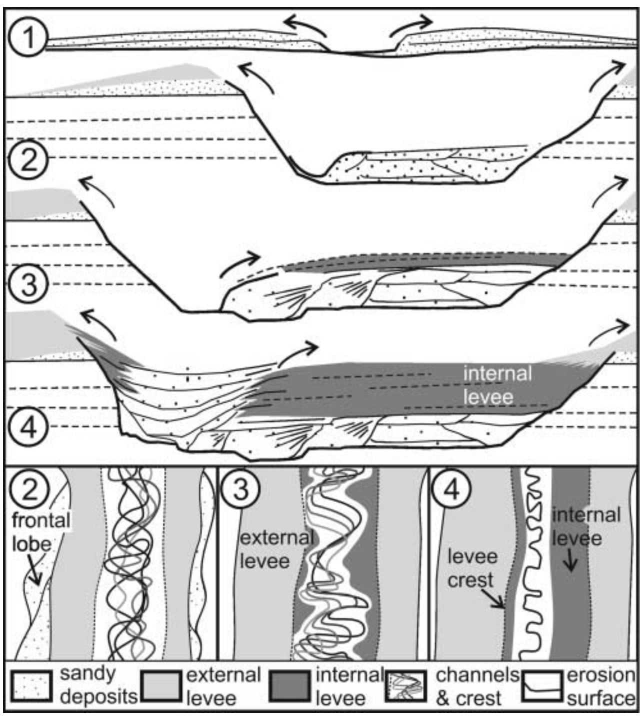

Fig. 3. Schematic cross-sections and planform maps to illustrate the evolution of submarine channel–levee systems during a cycle of accommodation change based on observations and interpretations from the south Baviaans ridge. 1 and 2: low accommodation drives initial localized lobe deposition, followed by slope degradation and sediment bypass with confinement by external levee development and/or erosion and unorganized channelization. 3: at grade there is increased organization of component channels (horizontal stacking) and widening of the composite erosion surface. 4: high accommodation is established, which leads to slope aggradation with vertical stacking of component channels and internal levee development.

Laterally migrating channels, which indicate increased organization of component channels, will further modify and widen the composite surface of the channel system and erode external levee deposits (Fig. 3).

Stage 4. A rise in the equilibrium profile increases accommodation, which allows aggradation of component channel fills, which are confined by flows that deposit inside the composite constructional and/or degradational confinement surface (internal levees) (Fig. 3). Internal and external levees may merge as the channel system fills (Fig. 3).

Channel-form asymmetry and stacking patterns. The cross-cutting erosion surfaces and stacking pattern of channel and channel-complex fills indicates repeated episodes of erosive flushing (cutting), channel filling, and channel migration, such that a complete cross-section preservation of a channel form is rare. Commonly, the geometries and sedimentary facies distributions within complete channel and channel-complex fills in cross-section are asymmetrical, with a low gradient margin (<10°) overlain by dipping thin beds and a high-gradient margin (15–20°) overlain by amalgamated sandstone. A marked asymmetry to the fill of the Unit D entrenched submarine channel system is also present, as indicated by aggradational channel and channel-complex axes against the steeper western valley wall with thicker external levee deposits on this side of the cut. This asymmetry at multiple scales is interpreted to indicate a degree of sinuosity, with the sand-prone steeper margins being the outer banks to channel bends. Channel and channel-complex stacking pattern has a primary control on the preservation of sedimentary facies in the channel system. The initial horizontal stacking in Units C and D promotes the preservation of thin-bedded channel margin sedimentary facies during later channel migration and system widening. In contrast, sandstone-prone channel axes and outer bank deposits are preserved in vertical stacking patterns during channel aggradation.

Conclusions. Correlation of some 200 closely spaced logged sections demonstrates that a levee-confined submarine channel system (Unit C) was partially removed by a younger entrenched submarine channel system (Unit D, Fig. 2). The two systems provide a high-resolution record of the evolution of channel–levee systems with similar geometric patterns, cross-sectional configurations and scale normally recorded only in seismic reflection datasets (e.g. Abreu *et al.* 2003; Deptuck *et al.* 2007; Labourdette 2007), which typically lack either stratigraphic and lithological control or have resolution limitations. The depositional architecture preserved is interpreted to be controlled by cycles of accommodation change in response to changes in the slope equilibrium profile (Kneller 2003). Low accommodation drives initial slope degradation and sediment bypass with initiation of external levee construction locally (lobes). Unorganized channelization early in the history of the channel–levee system passes to horizontal stacking of channel fills. Lateral migration of component channels modifies and widens the composite surface and erodes external levee deposits. Increased accommodation leads to slope aggradation with vertical stacking of component channels and internal levee development, and ultimately system abandonment. The resultant stratigraphy is complicated but not random. This may be part of an allogenically modulated record of waxing then waning sediment supply (and flow magnitude) during a base-level cycle, which may be common to many other submarine channel–levee systems (e.g. McHargue *et al.* 2011).

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References

Abreu, V., Sullivan, M., Pirmez, C. & Mohrig, D. 2003. Lateral accretion packages (LAPs): An important reservoir element in deep water sinuous channels. *Marine and Petroleum Geology*, **20**, 631–648.

Babonneau, N., Savoye, B., Cremer, M. & Klein, B. 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. *Marine and Petroleum Geology*, **19**, 445–467.

Covault, J.A. & Graham, S.A. 2010. Submarine fans at all sea-level stands: Tectono-morphologic and climatic controls on terrigenous sediment delivery to the deep sea. *Geology*, **38**, 939–942, doi:10.1130/G31081.1.

Deptuck, M.E., Sylvester, Z., Pirmez, C. & O'Byrne, C. 2007. Migration–aggradation history and 3D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope. *Marine and Petroleum Geology*, **24**, 1–28.

Figueiredo, J., Hodgson, D.M., Flint, S.S. & Kavanagh, J.P. 2010. Depositional environments and sequence stratigraphy of an exhumed Permian mud-dominated submarine slope succession, Karoo Basin, South Africa. *Journal of Sedimentary Research*, **80**, 97–118, doi:10.2110/jsr.2010.002.

Flint, S.S., Hodgson, D.M., *et al.* 2011. Depositional architecture and sequence stratigraphy of the Karoo basin floor to shelf edge succession, Laingsburg depocentre, South Africa. *Marine and Petroleum Geology*, **28**, 658–674.

Gardner, M.H., Borer, J.M., Melick, J.J., Mavilla, N., Dechesne, M. & Wagerle, R.N. 2003. Stratigraphic process-response model for submarine channels and related features from studies of Permian Brushy Canyon outcrops, West Texas. *Marine and Petroleum Geology*, **20**, 757–787.

Kane, I. & Hodgson, D.M. 2011. Submarine channel levees: nomenclature and criteria to differentiate subenvironments. Exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Laingsburg Fm. (Permian), Karoo Basin, S. Africa. *Marine and Petroleum Geology*, **28**, 807–823.

Kneller, B. 2003. The influence of flow parameters on turbidite slope channel architecture. *Marine and Petroleum Geology*, **20**, 901–910.

Labourdette, R. 2007. Integrated three-dimensional modeling approach of stacked turbidite channels. *AAPG Bulletin*, **91**, 1603–1618.

Mayall, M., Jones, E. & Casey, M. 2006. Turbidite channel reservoirs—key elements in facies prediction and effective development. *Marine and Petroleum Geology*, **23**, 821–841.

McHargue, T., Pyrcz, M.J., *et al.* 2011. Architecture of turbidite channel systems on the continental slope: patterns and predictions. *Marine and Petroleum Geology*, doi:10.1016/j.marpetgeo.2010.07.008.

Pirmez, C., Beaubouef, R.T., Friedmann, S.J. & Mohrig, D.C. 2000. Equilibrium profile and base level in submarine channels: examples from Late Pleistocene systems and implications for the architecture of deep-water reservoirs. *In:* Weimer, P., Slatt, R.M., *et al.* (eds) *Deep-water Reservoirs of the World: Gulf Coast Society of the Society of Economic Paleontologists and Mineralogists Foundation, 20th Annual Research Conference*, 782–805.

Prélat, A., Hodgson, D.M. & Flint, S.S. 2009. Evolution, architecture and hierarchy of distributary deep-water deposits: a high-resolution outcrop investigation from the Permian, Karoo Basin, South Africa. *Sedimentology*, **56**, 2132–2154, doi:10.1111/j.1365-567 3091.2009.01073.x.

Schwarz, E. & Arnott, R.W.C. 2007. Anatomy and evolution of a slope channel-complex set (Neoproterozoic Isaac Formation, Windermere Supergroup, southern Canadian Cordillera): implications for reservoir characterization. *Journal of Sedimentary Research*, **77**, 89–109.

Tankard, A.J., Welsink, H., Aukes, P., Newton, R. & Stettler, E. 2009. Tectonic evolution of the Cape and Karoo basins of South Africa. *Marine and Petroleum Geology*, **26**, 1379–1412.

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