# Modelling the architecture of distal sand-rich lobe deposits: an example from Fan 2, Skoorsteenberg Formation, Tanqua Karoo, South Africa

by

**Rochelle Steyn** 



Thesis presented in partial fulfilment of the requirements for the degree of Master of Science

at

Stellenbosch University

Department of Geology, Geography and Environmental Studies

Supervisor: Dr H. de V. Wickens Co-supervisor: Dr D. Hodgson

March 2009

## Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

17 February 2009

Copyright © 2009 Stellenbosch University

All rights reserved

#### Abstract

Fan 2, one of five submarine fan systems of the Tanqua fan complex in the south-western Karoo Basin, South Africa, is subdivided into Lower, Middle and Upper units. Here, detailed analysis of the internal architecture and distribution of lithofacies associations of Middle Fan 2 facilitated the 3-D visualisation of the sedimentological and stratigraphical changes towards the pinch-out.

Middle Fan 2 is interpreted to be a lower-fan, sand-rich terminal lobe, comprising three sandstone-lobe elements, separated by two siltstone interlobe elements. It is fed by a distributary channel that is hypothetically positioned to the west-southwest of the study area. The sandstone-lobe elements pinch out downdip to the north-east and updip to the south-southwest in the study area. The consecutive pinch out of lobe elements to the north-east indicates a progradational stacking pattern similar to the entire lobe complex.

Palaeocurrent analysis and the interpretation of isopach maps indicate that the transport direction of Middle Fan 2 was in a north-easterly direction. The fringes of the lobe and the distribution of internal elements (channels, amalgamated sheets and sheets) show a finger-like geometry in plan-view, in contrast to simple radial-lobe bodies that are commonly envisaged.

Six lithofacies subdivisions were used in this study, namely massive sandstone, ripple cross- and parallel-laminated sandstone, massive siltstone, ripple cross- and parallel-laminated siltstone, organic-rich co-genetic beds and claystone. Co-genetic beds are interpreted as linked debrites, found predominantly in the areas populated by amalgamated sheets, indicating a depositional area of higher velocity and energy. The locations of the measured vertical profiles containing co-genetic debrites are in the shape of a debrite-prone fringe. The co-genetic debrites could not be traced out laterally from profile to profile as they are discontinuous and commonly pinch out within ten to fifteen metres.

#### Acknowledgements

I would like to express gratitude to my project supervisors, Dr H. de V. Wickens and Dr D. Hodgson, for all their help and encouragement over the last two years – it would have been impossible to complete this thesis without you. I would also like to thank my administrative supervisors, Dr R. van den Berg and Dr D. Mikes, for being willing to step in at the last minute and for ensuring that everything ran smoothly from the departmental side.

Thank you to everyone in the Department of Geology, University of Stellenbosch, for taking an interest and for always being willing to lend a helping hand, especially Loxie Conradie, who was a ray of sunshine on many a cloudy day. Thanks also go to the Strat Group, Department of Earth and Ocean Sciences, University of Liverpool, for allowing me to take part in the Lobe project and for organising the funding for this thesis.

A big thank you goes to Jody Frewin from PetroSA for spending hours and hours checking and rechecking my Petrel chapters and ensuring I extracted the most out of my field data and the computer programme. Thank you also to Bryan Cockrell from Schlumberger South Africa for giving me a Petrel crash course and for organising a copy of the programme for use at the University of Stellenbosch.

I would also like to express thanks to Amandine Prélat, Nick Drinkwater and Eric Scott for their advice on field work, thesis work and finding work in the real world. I also wish to thank Frank Willemse for allowing me to stay in his house on Kleine Gemsbok Fontein and thank you to the Inverdoorn staff for rescuing me from a couple of sticky situations.

Finally, I'd like to thank my family and friends, both near and far, for believing in me and keeping me motivated through the hard times and having fun with me in the good times. You'll always have a place in my heart!

# **Table of Contents**

2.2.1.1. Leveed channels	51
2.2.1.2. Levee deposits	52
2.2.1.3. Distributive channels	52
2.2.1.4. Lobes	53
2.2.2. Hierarchy	53
Chapter 3	57
3. Lithofacies description	58
3.1. Lithofacies 1: Massive sandstone	58
3.2. Lithofacies 2: Parallel- and ripple cross-laminated sandstone	ə63
3.3. Lithofacies 3: Massive siltstone	66
3.4. Lithofacies 4: Parallel- and ripple cross-laminated siltstone	66
3.5. Litofacies 5: Organic-rich co-genetic beds	68
3.6. Lithofacies 6: Massive claystone	69
Chapter 4	71
4. Data manipulation and presentation	72
4.1. 1-D	72
4.2. 2-D	72
4.3. 3-D	75
4.3.1. Introduction	75
4.3.2. Aims	77
4.3.3. Model size	79
4.3.4. Petrel workflow	80
4.3.4.1. Data input	82
4.3.4.2. Surfaces	86
4.3.4.3. Isopach (thickness) maps	90
4.3.4.4. Static model grids	96
4.3.4.5. Upscaling of facies	96
4.3.4.6. Correlation panels	97
4.3.4.7. Facies modelling attempts	103
4.3.5. Results and discussion	110
Chapter 5	120
5. Stratigraphy and architectural elements	121
5.1. Stratigraphy	121
5.2. Architectural elements	122

5.2.1. Channel elements	123
5.2.2. Sheet elements	125
5.3. Correlation panels	127
5.4. Lobe geometry	141
5.5. Sequence stratigraphy	145
5.5.1. Introduction	145
5.5.2. The Tanqua sub-basin	145
5.5.3. Middle Fan 2	146
Chapter 6	148
6. Palaeocurrent analysis	149
6.1. Introduction	149
6.2. Flute casts	149
6.3. Groove casts	150
6.4. Ripple cross-lamination ("Rib and furrow")	150
Results	151
Chapter 7	154
7. Depositional model	155
Chapter 8	160
8. Discussion and conclusions	161
Aims and results:	161
9. References	166
Appendix A Poster presented at the AAPG conference in Cape	• Town, 26 –
29 October 2008	177
Appendix B	182
PowerPoint presentation given at PetroSA on 18 June 2008	182
Appendix C	189
Isopach maps using the Kriging algorithm and convergent interpola	ation with
polygon A (A and B on Figure 101 to Figure 105) and convergent i	nterpolation
with polygon B (C and D on Figure 101 to Figure 105)	189

# Table of Figures

Figure 1: Simplified geological map of South Africa (A), the Western Cape (B)
and the Tanqua sub-basin (C) (Geological map of South Africa, Council for
Geoscience, 2000; Tanqua sub-basin map after Van der Merwe, 2003)19
Figure 2: A Google Earth image showing the location of the study area (in
yellow) and the farm names (in white) (Google, 2007)20
Figure 3: Geological map showing the outcrop distribution of Fans 1 to 5 in
relation to each other. Fan 2 is indicated in red (after Wickens & Bouma,
2000)23
Figure 4: Isopach and palaeocurrent indicators for Lower, Middle and Upper
Fan 2 (from Rozman, 2000)24
Figure 5: Depositional model for Fan 2 (from Johnson <i>et al.,</i> 2001)25
Figure 6: A reconstruction of the outline of Fan 2 (from Hodgson <i>et al.,</i> 2006).
Figure 7: 1:50 000 ArcView map shows the localities of the 91 vertical profiles
in the study area (green dots), farm names and boundaries (grey) and 20 m
interval contours (brown)
Figure 8: Karoo, Paranà, Beacon and Bowen Basins in response to accretion
tectonics along the southern margin of Gondwana (from De Wit & Ransome.
1992)
Figure 9: Illustration of the Cape-Karoo succession (from Wickens, 1994)33
Figure 10: Illustration to highlight the differences between transport and
deposition of turbidity currents and debris flows (from Shanmugam, 2000)37
Figure 11: Turbidite divisions as proposed by Lowe, Bouma and Shanmugam
(from Shanmugam, 2000)
Figure 12: Panorama photomontage of the pinch out of the debritic part of a
co-genetic bed (A) with two close-ups (B&C) of the same photographed at the
Fan 2 type locality where it forms part of profile R00A
(34H0399360/UTM6373789, on the farm Kleine Gemsbok Fontein 72). Image
A further shows 4, the pinch-out of the debrite; 3, the underlying massive
sandstone; 2, the debrite; and 1, the overlying sandstone. The outcrop is
viewed towards the east45

Figure 13: Four main depositional settings for deep-water sands (from Stow & Figure 14: A sand-rich submarine fan system that originated from a point source (from Reading & Richards, 1994; Stow & Mayall, 2000). ......47 Figure 15: A mud-rich submarine fan system that originated from a point source (from Reading & Richards, 1994; Stow & Mayall, 2000). ......47 Figure 16: Fine-grained submarine fan subdivided into three end-members Figure 17: Depositional model developed using Fans 1 – 4 of the Tanqua fan Figure 18: Illustration of architectural elements found in submarine fans, including mounds and lobes, contourite drifts and sheets, and drapes (from Stow & Mayall, 2000)......50 Figure 19: Illustration of architectural elements found in submarine fans, including surfaces, gradient changes, slides and slumps, canyons and channels, and levees (from Stow & Mayall, 2000). .....51 Figure 20: Hierarchy of compensational stacking of composite lobes (from Deptuck et al., 2008)......54 Figure 21: Hierarchical interpretation of Fan 2 illustrating the lobe complex, lobe, lobe-element and bed (outcrop viewed towards the west; located on the farm Drie Fontein 87, near vertical profile R88, 34H0396579/UTM6367977).55 Figure 22: Hierarchy for turbidite systems (modified after Mutti & Normark, 1987; Prélat *et al.*, in review)......56 Figure 23: Load casts (arrow) at the base of a massive sandstone bed (1.2 m Jacob's staff for scale, vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72). .....59 Figure 24: Groove casts at the base of a massive sandstone bed (head of Jacob's staff for scale, vertical profile R42, 34H0397661/UTM6374647, on the farm Kleine Gemsbok Fontein 72). .....60 Figure 25: A plant fragment imprint (arrow) encased in a massive sandstone bed (vertical profile R39, 34H0398211/UTM6374607, on the farm Kleine Gemsbok Fontein 72). .....60 Figure 26: Secondary calcareous concretion (arrow) in a massive sandstone bed (vertical profile R01B, 34H0399413/UTM6373810, on the farm Klein Gemsbok Fontein 72). .....61 Figure 27: A claystone rip-up clast (arrow) in a massive sandstone bed (1.2 m Jacob's staff for scale; vertical profile R00C, 34H0399356/UTM6373839, on the farm Klein Gemsbok Fontein 72). .....61 Figure 28: Casts of feeding burrows (arrows) in the pelitic top of the underlying turbidite (vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72). .....62 Figure 29: Parallel-laminated sandstone bed (arrow) (vertical profile R05B, Figure 30: Ripple cross-lamination (arrow) found in the upper half of a sandstone bed (vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72).....65 Figure 31: Soft-sediment deformation due to loading in an area of parallel lamination (vertical profile R85, 34H0398427/UTM6373891, on the farm Kleine Riet Fontein 88). .....65 Figure 32: Alternating layers of 1) coarse-grained siltstone, 2) very finegrained sandstone, 3) sand injection into underlying siltstone, and 4) massive fine-grained siltstone (vertical profile R00C, 34H0399356/UTM6373839, located on the farm Kleine Gemsbok Fontein 72).....67 Figure 33: Parallel-laminated coarse-grained siltstone (vertical profile R05B, 34H0399263/UTM6374071, located on the farm Kleine Gemsbok Fontein 72). Figure 34: Co-genetic bed composed of underlying massive sandstone and an overlying dark-weathering organic-rich siltstone (arrow, 1.2 m Jacob's staff for scale; vertical profile R00A, 34H0399360/UTM6373789, located on the farm Kleine Gemsbok Fontein 72).....69 Figure 35: Blue-weathering silt-rich claystone (1.2 m Jacob's staff marked in 10 cm increments for scale; vertical profile R13, 34H0398427/UTM6373891, located on the farm Kleine Gemsbok Fontein 72).....70 Figure 36: Hand-drawn representation of vertical profile R00A (34H0399360/UTM6373789) at a scale of 1:50 cm. The notations "R00-A-B" and "R00-A-T" refer to the base and top of the vertical profile, respectively. .73

Figure 37: Vertical profile R00A (34H0399360/UTM6373789) compiled in
CorelDraw format superimposed on its associated photopanel74
Figure 38: Vertical profiles R01A, R01B, R00A, R00B, R00C and R02
represented as a correlation panel in CorelDraw74
Figure 39: Vertical profile R00A (34H0399360/UTM6373789) compiled in DSL
format showing the representation of facies used in the legend on the right. 76
Figure 40: Tabular representation of Virtual Reality Geological Studio (DSL)
facies
Figure 41: Petrel-generated image of profile R00A
(34H0399360/UTM6373789) showing the DSL input data (a), Petrel facies (b),
the model-generated facies up-scaled into the grid (c), the DSL facies legend
(d) and the Petrel facies legend (e)78
Figure 42: Location of data points (pink dots) and polygons A (yellow) and B
(green)
Figure 43: Petrel workflow diagram81
Figure 44: Thickness and GPS coordinate data (m) for measured vertical
profile R00A (34H0399360/UTM6373789)83
Figure 45: An Excel spreadsheet containing GPS and thickness data for
profiles R00A to R27 and surfaces Base 3/Top B, Base B/Top 2 and Base
2/Top A
Figure 46: Data for surface Base 2/Top A imported from a text file into Petrel.
Figure 47: Line diagram illustrating elements, zones and surfaces used in
Petrel
Figure 48: Surface of lobe-element 2 done using the Kriging algorithm87
Figure 49: Surface of lobe-element 2 done using convergent interpolation and
polygon A
Figure 50: Surface of lobe-element 2 done using convergent interpolation and
polygon B
Figure 51: Isopach map for sandstone-lobe element 1 calculated from
surfaces generated using Kriging interpolation and polygon A90
Figure 52: Isopach map for siltstone inter-lobe element A calculated from
surfaces generated using Kriging interpolation and polygon A91

Figure 53: Isopach map for sandstone-lobe element 1 calculated from Figure 54: Isopach map for siltstone inter-lobe element A calculated from surfaces generated using convergent interpolation and polygon A......92 Figure 55: Isopach map for sandstone-lobe element 1 using convergent Figure 56: Isopach map for siltstone inter-lobe element A using convergent Figure 57: Isopach map for sandstone-lobe element 1 calculated from surfaces generated using convergent interpolation and polygon B at a range Figure 58: Isopach map for siltstone inter-lobe element A calculated from surfaces generated using convergent interpolation and polygon B at a range Figure 59: Zones 1 - 5 representing each of the elements subdivided into fixed Figure 60: Correlation panel of profiles R00A to R07 using convergent interpolation and polygon A showing the original DSL facies on the left and the model-generated facies on the right......99 Figure 61: Correlation panel of profiles R00A to R07 using sequential indicator simulation showing the original DSL facies on the left, grain size in the centre Figure 62: Locations of strike (green) and dip (blue) correlation panels. .... 101 Figure 64: Petrel correlation panel generated along strike, illustrating compensational stacking with thickening lobe elements indicated by a blue Figure 65: Facies-model attempt 1 using the Kriging algorithm and polygon A Figure 66: Close-up of an intersection (in darker blue) through the Kriging algorithm facies model confined to polygon A......105 Figure 67: Facies-model attempt 2 using sequential-indicator simulation and 

Figure 68: Close-up of an intersection (in darker blue) through the sequentialindicator simulation facies model confined to polygon A......107 Figure 69: Final facies model attempt using sequential-indicator simulation Figure 70: Close-up of a section through some of the study area showing upscaled well logs and the siltstone inter-lobe elements clearly defined as a Figure 71: Close-up of an intersection (in darker blue) through the sequential-Figure 72: Histogram showing the correlation between "MyFacies", "Upscaled cells" and "Well logs". The number 0 refers to massive sandstone, 1 to background deposition, 2 to siltstone and 3 to structured sandstone.......111 Figure 73: Isopach maps generated for sandstone-lobe elements 1, 2 and 3 and siltstone inter-lobe elements A and B. The thickness scale for the lobe elements is 0 – 10 metre. The thickness scale for the inter-lobe elements is 0 Figure 74: Depositional model superimposed on isopach map of lobe-element Figure 75: Depositional model superimposed on isopach map of lobe-element Figure 76: Depositional model superimposed on isopach map of lobe-element Figure 77: Diagram illustrating the internal stratigraphy of Middle Fan 2; photo location in the vicinity of vertical profile R00A (34H0399360/UTM6373789, on the farm Kleine Gemsbok Fontein 72). .....121 Figure 78: Profile R00A (34H0399360/UTM6373789) compiled in CorelDraw showing lithofacies and measured sedimentological features and a legend that includes all features that were used when creating the CorelDraw profiles. Figure 79: Image A shows the depositional model for Middle Fan 2 generated in this study......124 Figure 80: Image A shows the depositional model for Middle Fan 2 generated by this study......126 Figure 81: ArcView map of study area showing location of correlation panels 1 Figure 82: Correlation panel 1 of vertical profiles R06, R04, R03, R01A, R01B, R00A, R00B, R00C, R02, R05A, R05B and R07......130 Figure 83: Correlation panel 2 of vertical profiles R08, R09, R10, R11, R12, Figure 84: Correlation panel 3 of vertical profiles R81, R80, R79, R78, R76, R75, R74, R36, R35, R34, R33, R32, R31, R30, R29, R28, R27, R26, R25 Figure 85: Correlation panel 4 of vertical profiles R38, R39, R41, R42, R43, Figure 86: Correlation panel 5 of vertical profiles R55, R54, R53, R52, R51, R50, R49, R48, R47, R84, R83 and R82.....137 Figure 87: Correlation panel 6 of vertical profiles R56, R57, R58, R59, R60 and R61......139 Figure 88: Correlation panel 7 of vertical profiles R62, R63, R64, R65, R66, R67, R68, R69, R70, R71, R72, R73, R85, R86, R87 and R88......140 Figure 89: Lateral stacking of the Lower, Middle and Upper units of Fan 2, illustrating the eastward shift of depositional axes (after Rozman, 2000). ... 141 Figure 90: Stacking of sandstone-lobe elements 1, 2 and 3 in relation to each other......142 Figure 91: ArcView map showing the location of the up-dip (A) and down-dip (B) pinch out of lobe-element 1 (yellow), 2 (orange) and 3 (red) in relation to Figure 92: Panorama photomontage illustrating the pinch-out of lobe elements 1 (yellow), 2 (orange) and 3 (red) on the farms Los Kop 74 (Image A) in the north-east (down-dip) and the farm Drie Fontein 87 (Image B) in the southsouthwest (up-dip). Lobe-element 1 pinches out first in both locations, followed by lobe-element 2, and finally by lobe-element 3......144 Figure 93: Photomontage of profile R42 (34H0397661/UTM6374647) illustrating the position of Type 2 horizons (sequence boundaries, in red), Type 3 horizons (siltstone inter-lobe elements, in light blue), lobe elements 1, 2 and 3 (in yellow, separated by the Type 3 boundaries) and a prominent 

Figure 94: Groove casts at the base of a massive sandstone bed (R34, Figure 95: Ripple cross-lamination seen from above (arrow) (near vertical profile R01B, 34H0399413/UTM6373810, Klein Gemsbok Fontein)......151 Figure 96: Rose diagram of 142 palaeocurrent measurements representing Figure 97: Rose diagrams depicting palaeocurrent measurements of the lobe Figure 98: Depositional model for Middle Fan 2 generated using outcrop...156 Figure 99: Facies distributions in a lobe developed from observations in Fan 3 (Strat Group, 2008)......158 Figure 100: Depositional model illustrating axis and fringe zones of Middle Fan 2......159 Figure 101: Isopach maps for sandstone-lobe element 1 using Kriging interpolation (A) and convergent interpolation (B) with polygon A, convergent interpolation with polygon B at a range of 50 metres (C), and convergent Figure 102: Isopach maps for sandstone-lobe element 2 using Kriging interpolation (A) and convergent interpolation (B) with polygon A, convergent interpolation with polygon B at a range of 50 metres (C), and convergent Figure 103: Isopach maps for sandstone-lobe element 3 using Kriging interpolation (A) and convergent interpolation (B) with polygon A, convergent interpolation with polygon B at a range of 50 metres (C), and convergent Figure 104: Isopach maps for siltstone intra-lobe element A using Kriging interpolation (A) and convergent interpolation (B) with polygon A, and convergent interpolation with polygon B at a range of 50 metres (C), and Figure 105: Isopach maps for siltstone intra-lobe element B using Kriging interpolation (A) and convergent interpolation (B) with polygon A, convergent interpolation with polygon B at a range of 50 metres (C), and convergent  Chapter 1

Introduction

#### 1. Introduction

#### 1.1. General

This project forms part of the LOBE deep-water research project, an industry-supported project that is run in conjunction with Liverpool University, UK, and TU Delft, the Netherlands, and is sponsored by Chevron, Shell, Petrobras, StatoilHydro, Total, Maersk Oil and PetroSA. The LOBE project is a continuation of research investigations in Permian deep-water stratigraphy exposed in the south-western Karoo Basin that was initiated during the NOMAD project.

"Terminal submarine fan lobes are distributive systems at the most downdip depositional position of terrigenous sediment transported by gravity flows through basin margins" (Prélat *et al.*, in review, p. 3). Typically, the frontal and lateral pinch-out or fringe areas of these fan systems are below 2-D seismic resolution and poorly exposed at outcrop due to the fine-grained heterolithic facies in these settings. However, in the semi-arid Tanqua Karoo, South Africa, the study area provides an excellent opportunity to document the architecture and distribution of lithofacies in the frontal pinch-out of a terminal lobe complex, a poorly understood part of submarine-fan systems.

The research rationale behind this study is for possible use of the data as an outcrop analogue for fine-grained deep-water deposits, specifically as it targets the internal dynamics of distal turbidite deposits and how they terminate. Outcrop analogues supply a link between seismic, well log and core data as it provides the opportunity to interpret bed-scale architecture and internal heterogeneity at a 2-D sub-seismic level (Sullivan *et al.*, 2004; Luthi *et al.*, 2006). It also increases the spread of 3-D spatial data and can provide insight into regional changes in facies and net-to-gross values (Luthi *et al.*, 2006).

An accurate comparison of the reservoir characteristics of different analogues with the deep-water deposit being studied allows for the accurate confinement of three-dimensional (3-D) geological models. These models can be used to forecast well performance, recovery efficiencies and connected volumes for the object of study by populating the models with outcrop data, reducing the uncertainty involved in assessing the exploration, production and overall economic viability of deep-water deposits (Sullivan *et al.*, 2004).

This type of analogue application can be seen in the study by Sullivan *et al.* (2004) on the Diana field in the western Gulf of Mexico. They used the Permian Skoorsteenberg Formation in the Tanqua Karoo Basin, South Africa and the Upper Carboniferous Ross Formation in the Clare Basin, western Ireland, as outcrop analogues for the subsurface Diana sub-basin. Other outcrop-based studies include the Permian Brushy Canyon Formation, West Texas, USA (Gardner *et al.*, 2003) and the Eocene Hecho Group, Northern Spain (Remacha & Fernandez, 2003).

Fan 2 is one of five submarine fan systems of the Tanqua fan complex in the south-western Karoo Basin (Figure 1), and it has been mapped in two previous studies (Wickens, 1990; Rozman, 2000). It is subdivided into Lower, Middle and Upper units, of which Middle Fan 2 has the best-quality outcrop, making it the focus of this detailed follow-up study. A Google Earth satellite image shows the location of the study area (in yellow) (Figure 2).



Figure 1: Simplified geological map of South Africa (A), the Western Cape (B) and the Tanqua sub-basin (C) (Geological map of South Africa, Council for Geoscience, 2000; Tanqua sub-basin map after Van der Merwe, 2003).





#### 1.2. Previous work:

#### 1.2.1. The south-western Karoo Basin

Regional mapping of the Permian Ecca Group in the south-western Karoo has been conducted by Wickens as early as 1976 as part of regional mapping by the Geological Survey of South Africa (now the Council for Geosciences of South Africa) between 1978 and 1981. It culminated in a M.Sc. thesis in 1984 and a Ph.D. thesis in 1994 (Wickens, 1984; 1994).

The first full-scale study on the western Ecca turbidites was carried out by Wickens *et al.* (1990) for SOEKOR (Pty) Limited (now PetroSA), in conjunction with A.H. Bouma of Louisiana State University. This study addressed the stratigraphy, sedimentology, regional development and palaeogeographic reconstruction of the Tanqua submarine fan systems. Further studies include Wickens & Bouma (1991a, 1991b), Viljoen & Wickens (1992) and Scott (1997).

The NOMAD project was a European Union Framework 5 "Energie" project that ran from 2001 to 2004 as a partnership between Schlumberger Cambridge Research, Statoil, Technical University of Delft, University of Liverpool and the University of Stellenbosch. This integrated study incorporated outcrop and subsurface data to develop accurate geological and reservoir models in 3-D. It includes differential global positioning system mapping, drilling, full coring and wireline logging data of seven research wells drilled into the Tanqua fan complex (Hodgson *et al.*, 2006).

Luthi *et al.* (2006) used the wireline and core data to characterize the stratigraphic evolution of the Tanqua sub-basin fans. The findings of the core-logging of NOMAD wells NB2 and NB3 are summarised in Hodgson *et al.* (2006).

The SLOPE project (Strat Group, 2004) focuses on the basin floor, slope and siliciclastic shelf deposits that can be seen in the Tanqua and Laingsburg sub-basins. The study provides a structural geological analysis of the basin, the basin margins, the staging area and the sediment routeing system. Phase 1 of the SLOPE project focused on the Tanqua sub-basin and included studies by King *et al.* (2004), Wild *et al.* (2004), Van Lente (2004), Wild *et al.* (2005) and Van der Merwe (2005).

The LOBE project (Strat Group, 2004) continued the research on deepwater deposits in the south-western Karoo that was initiated by the NOMAD project. Paulissen (2007) conducted a study on Fan 4, and the most recent detailed study on certain aspects of Fan 3 was conducted by Prélat *et al.* (in review). This study defined a hierarchy of depositional elements that includes lobe elements, lobes and lobe complexes.

The relationship of Fans 1 to 5 to each other can be seen in Figure 3. A detailed study was conducted on Fan 3 by Van der Werff & Johnson (2003) to determine its architecture and growth history. They constructed a 3-D fan model using correlation panels and isopach maps.

#### 1.2.2. Fan 2

The initial study by Wickens *et al.* (1990) concluded that the predominant palaeocurrent direction of Fan 2 is to the north, with secondary trends suggesting a north-easterly direction. The thickness variation in Fan 2 from south to north is from 40 m to 1 m over a distance of 7 km. The study was also the first to divide Fan 2 into a Lower, Middle and Upper units and to generate a palaeogeographic reconstruction.

Research on Fan 2 by Rozman (2000) provided a regional overview of the facies associations in outcrop and a regional 3-D model for Fan 2. Twenty-six vertical sections were measured through the three internal sand-rich units in Fan 2 (Lower, Middle and Upper units) in the areas of the farms Kleine Riet Fontein 88, Kleine Gemsbok Fontein 72, Los Kop 74 and Drie Fontein 87. Each of the sand-rich units was interpreted as a depositional lobe, separated from each other by thin-bedded silt and claystone beds.



Figure 3: Geological map showing the outcrop distribution of Fans 1 to 5 in relation to each other. Fan 2 is indicated in red (after Wickens & Bouma, 2000).

The objectives of Rozman's study were to determine the external and internal geometry of the fan, to illustrate the lateral and vertical sedimentary characteristics, and to investigate the factors that may influence the efficiency of outer-fan deposits as a hydrocarbon reservoir. He concluded that Fan 2 is mostly progradational, and that the Lower, Middle and Upper units were deposited progressively further east in relation to each other, indicating a lateral-offset stacking pattern. Isopach and palaeocurrent data show that the units thin to the north and north-east (Figure 4) and that the sediment source area shifted from west to south.

Rozman interpreted the lenticular sandstone beds of Fan 2 as being deposited via "broad sediment pathways" that were shallow and only active for a short period of time. These pathways end in a lobe fringe that has finger-like pinch-out geometry (Prélat *et al.,* in review) and pinch out channels (Van der Werff & Johnson, 2003). This pinch-out geometry can also be found in Lobe 2 of Fan 3 (Prélat *et al.,* in review).



Figure 4: Isopach and palaeocurrent indicators for Lower, Middle and Upper Fan 2 (from Rozman, 2000).

Work on Fan 2 was also conducted by Johnson *et al.* (2001) as part of a larger study. They generated a basic depositional model by interpreting the architecture of Fan 2 (Figure 5). They also interpreted the sequence stratigraphy of Fan 2 and concluded that the remaining outcrop represents a mid- to outer-fan depositional environment. A palaeogeographic

reconstruction of Fan 2, showing the possible distribution of distal silty and mud-rich turbidites is suggested by Hodgson *et al.* (2006) (Figure 6).



Figure 5: Depositional model for Fan 2 (from Johnson et al., 2001).



Figure 6: A reconstruction of the outline of Fan 2 (from Hodgson et al., 2006).

## 1.3. Aims of the project

- To document the precise changes in stratigraphy and sedimentology towards a submarine-fan pinch-out within the Middle Fan 2 distal fan setting by accurately determining, defining and interpreting:
  - a. Lithofacies characteristics;
  - b. Architectural elements;
  - c. Internal stratigraphy;
  - d. Palaeocurrent patterns; and to
  - e. Apply sequence-stratigraphy concepts to Middle Fan 2.
- To determine the regional extent of co-genetic debrites (*sensu* Haughton *et. al.*, 2003) and the possible significance thereof when compiling a depositional model;
- 3. To generate a depositional model for Middle Fan 2;
- 4. To apply 1-, 2- and 3-dimensional manipulation of the vertical profile data to illustrate gradual changeover to pinch-out visually;
- 5. To generate surfaces, isopach maps, static-model grids and facies models using Petrel software to illustrate the sedimentological and stratigraphical changes towards the pinch-out visually, and to determine the efficacy of detailed measured vertical-profile data for use with Petrel software.

# 1.4. Methodology

Data acquisition for this study involved detailed measuring of 91 vertical profiles of Middle Fan 2 throughout the outcrop area. The latter includes the farms Kleine Gemsbok Fontein 72, Kleine Riet Fontein 88, Los Kop 74 and Drie Fontein 87 (Figure 7).

The locations of measured profiles were determined by the availability of good quality outcrop, which is mostly to be found in the back of gullies. The gullies can be anywhere from ten metres to 300 metres apart, commonly with little or no outcrop in between. More profiles were measured in areas with



Figure 7: 1:50 000 ArcView map shows the localities of the 91 vertical profiles in the study area (green dots), farm names and boundaries (grey) and 20 m interval contours (brown).

27

better outcrop, for example profiles R00A to R36 in the type area of Fan 2 on the farm Kleine Gemsbok Fontein 72.

The most important criteria when choosing profile locations was the presence of a dark-weathering sandstone bed found at the top of Middle Fan 2. It was used as the datum marker horizon for all outcrop data and the Petrel static model grids. The profiles were measured with the aid of a Jacob's staff (1.2 m length) and a measuring tape (5 m length). Bed-thickness measurements were noted in an A4 field book at a scale of 1:50 cm. Observations noted on the beds include grain size; type of base, for example loaded, amalgamated or eroded; the presence of plant fragments and rip-up clasts and sedimentary structures such as ripple-cross or parallel-lamination and sole structures.

GPS readings of latitude, longitude and altitude (x, y and z) were collected at the top and base of each vertical profile using a Garmin GPS 60 handheld device. Care was taken with readings at the base due to the steep sides of the gullies limiting the amount of sky available for satellite triangulation. The accuracy of the readings was within an error range of 0.5 m at the top and 33 m at the base of the vertical profiles.

A total of 142 palaeocurrent measurements were taken using a Krantz geological compass to measure flow direction exhibited by ripple crosslamination, flute casts and groove casts. Groove casts are bimodal, indicating the orientation of flow, but not the direction (Boggs, 2006). Ripple foreset beds (in plan view) and flute casts were used to measure unidirectional palaeoflow. Groove casts were also useful for indicating palaeoflow orientation. The palaeocurrent data are digitally represented in rose diagrams for each of the lobe and inter-lobe elements. No dip measurements were taken as the dip of the beds is negligibly small.

High-resolution digital photographs were taken with a 10 mega-pixel Canon XRF camera and a tripod. The photographs were used to compile panorama photomontages of all the outcrops to facilitate the lateral correlation of vertical profiles. Sandstone-lobe elements and siltstone inter-lobe elements can usually be clearly distinguished along well-exposed cliff sections. Closeup photos were also taken of all relevant sedimentary features to aid in their description and interpretation.

All the relevant outcrop data was then used to establish depositional models for Middle Fan 2.

All 91 measured vertical profiles were digitised using CorelDraw. This is in order to draw a computer-generated version of the outcrop data with all the sedimentary features noted on the profile for easy comparison with other profiles. CorelDraw was also used to generate correlation panels by placing digitised profiles next to each other in the order in which they occur in the actual outcrop. Examples of profiles and correlation panels can be seen in Chapter 4.2.

All profiles were also digitised using Virtual Reality Geological Studio, also referred to as DSL, an in-house programme provided by Liverpool University for use in the field. This programme allows the digitised lithofacies data of the vertical profiles to be imported into the Petrel seismic-to-simulation programme for the creation of static model grids. An example of a DSL profile can be seen in Chapter 4.3.

All bed-thickness measurements taken during the vertical profiling were recorded in Microsoft Excel spreadsheets. The bed-thickness datasets for each vertical profile were grouped in such a way as to calculate the thickness of each lobe and inter-lobe element across the entire study area. These thicknesses were imported into Petrel and used to generate surfaces, isopach maps and correlation panels. Facies modelling was also attempted.

#### 1.5. Geological setting

The Karoo Basin is one of the major Gondwanaide foreland basins, which also includes the Paranà, Beacon and Bowen basins (Figure 8). These basins

formed due to accretion tectonics in the late Palaeozoic along Gondwana's southern border (De Wit & Ransome, 1992; Veevers *et al.*, 1994).

The Karoo Basin developed as a retroarc foreland basin with subsidence being the result of loading by the orogenic Cape Fold Belt (CFB) (Johnson, 1991; Visser, 1993; Veevers *et al.*, 1994; Hodgson *et al.*, 2006).

The CFB lies along the southern and south-western border of the Karoo Basin, forming the western Cedarberg branch and the southern Swartberg branch with the syntaxis in the Ceres-Worcester area (De Beer, 1990, 1992; Wickens, 1994; Sixsmith, 2000).



Figure 8: Karoo, Paranà, Beacon and Bowen Basins in response to accretion tectonics along the southern margin of Gondwana (from De Wit & Ransome, 1992).

The presence of the CFB along the margin of the Karoo Basin suggests that the basin was formed in an active-margin depositional setting. Despite this, the basin has many characteristics of passive-margin deposition, including an almost negligible amount of tectonic disturbance resulting in a dip of 2 to 4 degrees to the east (Wickens, 1994; Wickens & Bouma, 2000). The CFB developed due to the northward subduction of the Panthalassan plate beneath the Gondwana plate. The result of this subduction was a magmatic arc that formed between the Karoo Basin and the margin of Gondwana (Johnson, 1991; Visser, 1993; Hodgson *et al.*, 2006). Further subduction eventually resulted in the formation of a fold-thrust belt on the continental side of the magmatic arc due to northward compression (Veevers *et al.*, 1994; Hodgson *et al.*, 2006).

The CFB underwent a regional-scale deformation event of late Carboniferous to Permian-Triassic age that resulted in the large-scale folding of the Cape Supergroup rocks (Booth *et al.,* 2004). The CFB forms part of a larger Gondwanide orogenic belt (Johnston, 2000) which stretches across South America, Australia, Antarctica and South Africa (Fouché *et al.,* 1992).

The south-western Karoo Basin is composed of Permian Ecca Group sediments, which lie between the Westphalian to Early Permian glaciogenic Dwyka Group and the fluvial Permo-Triassic Beaufort Group. These groups all form part of the larger Karoo Supergroup. The Tanqua sub-basin sediments are subdivided into four formations, namely the Tierberg, Skoorsteenberg, Kookfontein, and Waterford Formations. Their equivalent formations in the Laingsburg sub-basin (Figure 9), which formed along the southern margin of the Karoo Basin, are the Vischkuil, Laingsburg, Fort Brown and Waterford Formations (Wickens, 1994; Grecula *et al.*, 2003; Sixmith *et al.*, 2004; Fildani *et al.*, 2007).

The Tierberg Formation is composed of mudstones and has a thickness of approximately 600 metres (Hodgson *et al.*, 2006). The Skoorsteenberg Formation is composed of sand-rich submarine fans alternating with siltstone and mudstone and has a thickness of approximately 400 metres. The Kookfontein Formation is composed of interbedded upper-slope to shelf-margin to deltaic sandstone and mudstone and has a thickness of 250 metres. The Waterford Formation is composed of deltaic sediments and has a thickness of approximately 330 metres (Wickens, 1984, 1994; Fildani *et al.*, 2007).

The latest age constraint of the Permian Ecca Group sedimentary deposition in the south-western Karoo Basin was determined by analysing zircon grains from volcanic ash layers using U-Pb dating (Fildani *et al.*, 2007). The study concluded that the deep-water succession in the south-western Karoo Basin started forming at approximately 275 Ma. The deep-water sandstones in the Tanqua sub-basin were deposited at approximately 255 Ma (Fildani *et al.*, 2007). Each of the 20 - 60 m thick sand-rich fan systems were deposited in a progradational stacking pattern and are separated by mud- and silt-prone intervals of comparable thickness (Wickens, 1994; Wickens & Bouma, 2000).

## **1.6.** The Skoorsteenberg Formation

The Permian Skoorsteenberg Formation, which is also referred to as the Tanqua fan complex, is approximately 450 metres thick. The Skoorsteenberg Formation crops out over an area of approximately 640 km<sup>2</sup>. It is made up of five sand-rich submarine fans (designated as Fans 1 - 5) that are separated by fine-grained siltstone and mudstone interfan successions (Wickens, 1994; Hodgson *et al.*, 2006). Fans 1 to 4 are interpreted to be basin-floor fans (Johnson *et al.*, 2001) and Fan 5 a lower slope to base of slope unit (Bouma & Wickens, 1991; Wickens & Bouma, 2000; Van der Merwe, 2005; Hodgson *et al.*, 2006; Prélat *et al.*, in review).

The Skoorsteenberg Formation has a regional dip of maximum 5 degrees east and underwent some minor folding and faulting due to northward compression during the formation of the CFB (Wickens, 1994; Hodgson *et al.,* 2006).



Figure 9: Illustration of the Cape-Karoo succession (from Wickens, 1994).

The dominant palaeocurrent directions indicate that sediment transport was towards the north and north-east with an overall progradational stacking pattern (Wickens, 1994; Johnson *et al.*, 2001; Hodgson *et al.*, 2006). The intrafan stacking patterns for the individual fans are progradational for Fans 1, 2 and 3, aggradational for Fan 4 and retrogradational for Fan 5 (Johnson *et al.*, 2001). Fan 5 is referred to as "Fan System 5" by Van der Merwe (2005) and "Unit 5" by Hodgson *et al.* (2006).

## 1.7. Petrography

The sandstone of the Tanqua Fan Complex has a provenance of primarily granitic composition, most likely sourced from the North Patagonian Massif. They are classified as lithic arenites and greywackes.

The sandstone is well sorted and has a fine to lower-medium grain size. Cementing by authigenic quartz and mechanical compaction of the sandstone resulted in a decrease in the porosity of the sandstone. The Tanqua sandstones underwent high-grade diagenesis to low-grade regional burial metamorphism until it reached lower greenschist facies level. The alteration of biotite to chlorite and illite resulted in the sandstone having a very low permeability.

The shales and siltstones of the Tanqua Fan Complex are fine-grained and mainly consist of clay minerals, quartz and mica. They often show parallel lamination.

Due to the minimal amount of porosity and permeability in the sandstones, the Tanqua Fan Complex, and by extension Fan 2, is of very poor reservoir quality in the present day. Intra-lobe element siltstones A and B further decrease the movement of fluids between lobe elements 1, 2 and 3, as they act as permeability barriers or caprock. It is only in areas where the siltstones were eroded causing the overlying and underlying sandstones to amalgamate that permeability might be locally increased (Wickens, 1994; Van Lente, 2004, Nguema-Mve, 2005). Chapter 2

Brief overview of sediment gravity flow deposits and submarine fan models

# 2. Brief overview of sediment gravity flow deposits and submarine fan models

#### 2.1. Sediment gravity flow deposits

Sediment gravity flows are described as the movement of sediments or sediment-fluid mixtures under the influence of gravity (Middleton, 1993; Dasgupta, 2003). Four types of sediment gravity flow can be differentiated, namely fluidised sediment flows, grain flows, turbidity currents and debris flows.

In fluidised sediment flows, the sediment is supported by the fluid escaping upward through the grains as they settle. In grain flows, the sediment is supported by grain-to-grain interaction. In turbidity currents, the sediment is supported by turbulence. In debris flows, it is supported by a matrix (Dasgupta, 2003).

The type of mechanism that supports the sediment gravity flow is dependent on four variables. They are flow conditions, the concentrations and types of particles and the grain-size distribution of the particles in the flow (Mulder & Alexander, 2001).

This study focuses on turbidites and debrites, the deposits of turbidity currents and debris flows, respectively. The differences between transportation and depositional processes in turbidity currents and debris flows are illustrated in Figure 10.


Figure 10: Illustration to highlight the differences between transport and deposition of turbidity currents and debris flows (from Shanmugam, 2000).

# 2.1.1. Turbidity currents

# 2.1.1.1. Turbidity current formation

Turbidity currents are Newtonian flows that form when sediment is entrained and transported in suspension via turbulence in a current. This current flows downhill due to gravity and the density difference between the flow (e.g. a sediment-laden fluid) and the surrounding ambient fluid (e.g. sea water). When turbulence decreases, the flow is no longer able to support the sediment and the coarsest and densest grains settle out from suspension first (Middleton, 1993; Shanmugam, 1997; Boggs, 2006).

# 2.1.1.2. Turbidity current morphology

Turbidity currents are composed of a head, body and tail, in which the head is the thickest and most turbulent part. The body behind it is characterised by steadier flow, although it moves faster than the head. Its sediments are continuously replenishing those lost by the head as it moves down-slope (Middleton, 1993; Boggs, 2006). The concentration of sediment in the tail decreases rapidly as it is mixed with the surrounding water, causing dilution (Boggs, 2006).

# 2.1.1.3. Turbidity current deposits

The initiation of turbidity currents that result in deposition across large areas of submarine fan systems, require several factors to work together. When slumping occurs in submarine canyons or on continental margins, the sediment failure can be followed by liquefaction, which in turn may result in the formation of turbidity currents (Lowe, 1976). Turbidity currents can also form when catastrophic events such as earthquakes and floods cause sediment failures and/or during periods of relative fall in sea level due to tectonic basin uplift or glacio-eustatic cycles when there is less accommodation on shelves to store sediment. Low sea-level stands may also enhance the fluvial energy, as an increased gradient will allow for higher-velocity flows, increasing erosion, and escalating the sediment yield (Mutti, 2003).

Turbidites that originate as high-velocity flows generated by catastrophic floods transport sediments from a fluvio-deltaic to a marine setting. When these flows exit the river mouth and enter steep shelf- and slope-regions, they erode deep submarine channels, triggering sediment failures and bulking up the volume and concentration of the sediments in the flows. The acceleration of these currents along submarine channels enables the turbiditic flow to reach deep-water fans where they will eventually extend laterally into turbidite sheet deposits (Mutti *et al.*, 2003).

Catastrophic flooding in North America during the Pleistocene, resulting in a large volume of turbidites being deposited onto the Pacific Plate, was investigated by Normark & Reid (2003). They used flooding caused by an outburst of glacial Lake Missoula during the Late Pleistocene as an example. Hyperpychally-generated turbidity currents formed due to the flooding. These turbidity currents transported sediments through the Cascadia Channel and the Blanco Fracture Zone, and deposited large amounts of sediment (~1500 km<sup>3</sup>) onto the Tufts Abyssal Plain and into the Escanaba Trough as turbidity current overflows (Normark & Reid, 2003).

Turbidites are classed into two broad types based on their depositional facies. High-density flow deposits result from a turbidity current with a high sediment density and typically comprise thick-bedded, coarse-grained sandstones or gravels that generally display little internal lamination and are poorly graded. These turbidites are commonly deposited in the main submarine transport channels. The second type, low-density flow deposits, is deposited from turbidity currents with low sediment density. Low-density flows commonly result in thin-bedded, graded deposits that typically display laminations and cross-bedding. They may also have scour marks on the bases of the beds. These turbidites typically constitute overbank deposits adjacent to the submarine transport channels, or thin sheet deposits further away from the source (Lowe, 1976; Boggs, 2006).

### 2.1.1.4. Turbidite models

The Bouma Sequence (Bouma, 1962) describes an ideal turbidite deposit, with the divisions  $T_{abcde}$  stacked vertically on top of each other.  $T_a$  is the lowermost division that may be graded or structureless and ungraded.  $T_b$  is the parallel-laminated sandstone division, followed by  $T_c$ , which is the current-ripple laminated sandstone division. Next follows  $T_d$ , another parallel laminated finer-grained and silty division, which is finally topped by  $T_e$ , which is a pelitic division. The complete sequence is rarely observed at outcrop. It may be truncated on the top, weathered at the bottom, or both, resulting in various combinations of incomplete sequences (Bouma, 1962). These incomplete sequences may be the result of turbidity flows, with a concentrated sediment load having the ability to be very erosive (Mulder & Alexander, 2001).

Not all studies are in agreement with the Bouma Sequence. The  $T_e$  pelitic package may in fact be hemipelagic mudstone, which means it is not part of the turbidite sequence. Also the  $T_d$  parallel-laminated division may be absent in most turbidite sequences, so that the turbidite bed is only made up of a lower parallel-laminated package ( $T_b$ ) and an upper cross-laminated package ( $T_c$ ) (Boggs, 2006).

Shanmugam (1997; 2000; 2002) wrote many critical reviews of what he calls "the turbidite mind set". He states that the term "turbidity current" is too easily applied to deep-water deposits, without taking into account the differences in turbulence, matrix and fluid rheology. Debris flows and bottom contour currents may erroneously be described as high-density turbidites (Shanmugam, 1997). Shanmugam (2000) further suggests that a more accurate description of sediment-gravity flows can be made by discerning between Newtonian and plastic flows, based on the interpretation of their fluid rheology and flow state.

The Bouma Sequence has been extended to incorporate sections for finegrained and coarse-grained turbidites by Stow & Shanmugam (1980) and Lowe (1982) respectively. Stow & Shanmugam (1980) suggested that the fine-grained part of the classic Bouma turbidites be divided into nine subdivisions, from  $T_0$  to  $T_8$ .

Lowe suggested that the coarse-grained part of the classic Bouma turbidites be divided into six subdivisions, namely  $R_1$ ,  $R_2$ ,  $S_1$ ,  $S_2$  and  $S_3$  (Shanmugam, 2000). The possible relationship of additional divisions to the classic Bouma turbidite model by Lowe and Shanmugam can be seen in Figure 11.



Figure 11: Turbidite divisions as proposed by Lowe, Bouma and Shanmugam (from Shanmugam, 2000).

# 2.1.1.5. Laboratory-generated turbidity currents

Turbidity current events in the natural world are rare, and attempts to monitor them usually result in a loss of equipment (Middleton, 1993). Studies using laboratory experimental results are coming progressively closer to imitating the formation of turbidite fans on a small, reproducible scale. One such study was conducted by Parsons *et al.* (2002) in a 5 x 5 x 1.2 m basin that was created at the Massachusetts Institute of Technology (MIT) Experimental Sedimentology and Geomorphology Laboratory.

The laboratory experiment was conducted on the premise that deep-sea fans differ from subaerial flows, due to the driving force behind the flow. Subaerial flows are driven only by gravitational acceleration, whereas turbidity flows are driven by a reduced gravitational acceleration (due to the effect of the densities of the current and ambient fluid) that is boosted by ignition feedback. Ignition feedback refers to a turbidity flow having the ability to entrain sediment. This increases the density of the turbidity flow, which in turn can increase the gravitational acceleration to such an extent that large-scale sediment deposition occurs on the basin floor (Parsons *et al.,* 2002).

The turbidite fans deposited during the laboratory experiment were in the form of asymmetric lobes with the beginnings of channel formation after more than eight individual event-beds and showed indications of lobe switching after twenty event-beds (Parsons *et al.*, 2002).

# 2.1.2. Debris flows

Debris flows have a high viscosity and sediment concentration and are classified as plastic flows (Stow & Johansson, 2000) that are supported by a matrix of sand or mud (Middleton, 1993). Unlike turbidity currents, they are generally non-turbulent and entrain less fluid (Boggs, 2006).

Debris flows start moving down-slope when "the critical yield strength is exceeded and deformation (flow) begins in a basal zone of highest shear stress" (Stow & Johansson, 2000, p. 161). The first type of debris flow is a slow-moving laminate slurry that originates on steep slopes with an inclination of more than 10 degrees, but once initiated can continue flowing across large distances on gentle slopes of 5 degrees or less (Stow & Johansson, 2000; Boggs, 2006). The second type of debris flow is a fast-moving semi-rigid plug of material that aquaplanes over a basal shearing layer, due to a lack of friction.

A slow-moving debris flow can become a fast-moving debris flow when pore pressure builds up in the basal zone or by water entrapment under the plug of material (Stow & Johansson, 2000). Such flows result in a poorly sorted chaotic mixture of sand and mud intra-clasts deposited during *en masse* emplacement (Talling *et al.*, 2004), when water loss from the basal layer and a thickening of the plug causes the debris flow to freeze (Stow & Johansson, 2000).

# 2.1.3. Co-genetic debrites

# 2.1.3.1. Co-genetic debrite morphology

Co-genetic debrites are co-genetic beds that are composed of a lower mud-poor sandstone turbidite division and an upper mud- and organic-rich debrite division that are deposited as part of the original flow (Haughton *et al.,* 2003). Commonly, these bed types occur in distal fan settings, but not in channels (Talling *et al.,* 2004).

## 2.1.3.2. Co-genetic debrite deposits

Co-genetic flows that contain sand and mud for the deposition of cogenetic debrites can be formed when a debris flow is started on a slope due to slides and slumps. These flows then accelerate down the slope, causing the slope sediments to be eroded and water to be incorporated into the debris flow. This dilute debris flow changes partially to a turbidity current, allowing sand-rich and mud-rich components to be separated during the flow with resultant deposition as a co-genetic debrite.

There are two basic types of co-genetic debrite. The first type is defined as underlying mud-poor sandstone capped by an overlying mud-rich debrite (Haughton *et al.,* 2003). The second type consists of a mud-rich debrite enclosed within two related turbidites (Talling *et al.,* 2004).

Type one co-genetic flows can be formed when a debris flow is partially transformed into a turbidity flow during transport due to hydroplaning, thereby diluting the debris flow. Type two co-genetic flows can be formed when debris flows are set off by turbidity currents that encroach on distal slopes (Haughton *et al.*, 2003).

In the first type of co-genetic debrite, the sand is deposited first, and undergoes continuous dewatering. The resultant upward release of water and sand allows the debritic mixture to be carried along behind the turbidity current as a cohesive slurry. As the top of the underlying sand is partially liquefied, the debritic flow has an uneven and occasionally loaded basal boundary once it starts to settle, forming an irregular cap on the sand. The cogenetic debrite is often covered with a thin layer of fine silt or mud that was dragged behind the flow as a suspended load (Haughton *et al.*, 2003).

In the second type of co-genetic debrite, mud-poor sandy turbidites are deposited first, directly followed by a layer of mud-rich sandy debrites. This is capped by a thin layer of turbiditic sand or mud. The debrites are thus always enclosed in turbidites, and they are deposited in conjunction with each other during the same flow event (Talling *et al.*, 2004).

Several occurrences of co-genetic beds have been observed in Middle Fan 2 (Figure 12).



Figure 12: Panorama photomontage of the pinch out of the debritic part of a co-genetic bed (A) with two close-ups (B&C) of the same photographed at the Fan 2 type locality where it forms part of profile R00A (34H0399360/UTM6373789, on the farm Kleine Gemsbok Fontein 72). Image A further shows 4, the pinch-out of the debrite; 3, the underlying massive sandstone; 2, the debrite; and 1, the overlying sandstone. The outcrop is viewed towards the east.

# 2.2. Submarine fan depositional models

Many studies over the years have suggested various submarine fan depositional models, including Mutti & Ricci-Lucchi (1972) and Reading & Richards (1994). Four of the more recent depositional models will be briefly discussed in the following section.

Stow & Johansson (2000) suggested four main settings for the deposition of deep-water structureless sands. They are Type 1: fan delta – braid delta, Type 2: muddy slope apron, Type 3: fan channel – lobe complex and Type 4: restricted trough – basin fill complex (Figure 13). Type 3 (fan channel – lobe complex) is characterised by a wide range of turbidite facies (including levee, interchannel and lobe-fringe turbidites) that are found in the channel systems and stacked lobes of an established submarine fan such as the Tanqua fan complex (Stow & Johannson, 2000).



Figure 13: Four main depositional settings for deep-water sands (from Stow & Johannson, 2000).

Stow & Mayall (2000) used a model originally suggested by Reading & Richards (1994) to illustrate depositional models for sand-rich (Figure 14) and mud-rich (Figure 15) submarine fans with a single point source. The type of depositional environment depends on the volume, source, nature and grade of the sediment supply, and the type of sediment source, for example point

source, multiple sources or linear source. The mud-rich submarine fan is most representative of the Tanqua fan complex (Wickens & Bouma, 2000).



Figure 14: A sand-rich submarine fan system that originated from a point source (from Reading & Richards, 1994; Stow & Mayall, 2000).



Figure 15: A mud-rich submarine fan system that originated from a point source (from Reading & Richards, 1994; Stow & Mayall, 2000).

Bouma (2000) differentiated between coarse-grained and fine-grained turbidite systems. Coarse-grained fans are sand-rich and show a gradual decrease in thickness and grain size down-dip as they prograde into the basin. Fine-grained fans are bypassing systems and can be subdivided into three end-members, each with their own depositional features. These endmembers are a channel complex at the base of slope, a leveed channel at middle fan, and distributary channels and sheet sands at lower fan (Figure 16). Wickens & Bouma (2000, p. 153) classified the Tanqua fan complex as "a fine-grained, mud-rich bypass system within an unconfined basinal setting".



Figure 16: Fine-grained submarine fan subdivided into three end-members (from Bouma, 2000).

Johnson *et al.* (2001) generated a genetic fan model for a submarine fan (Figure 17) using Fans 1 - 4 in the Tanqua fan complex, South Africa. The fan model was subdivided into four zones. Zone 1 is predominantly characterised by erosive, non-depositional channel complexes. Zone 2 is characterised by channels and inter-channel sheets. Zone 3 is characterised by channels and tabular ripple-bedded interchannel sheets. Zone 4 is characterised by isolated channels and thin-bedded sheets. Johnson *et al.* (2001) also defined sequence boundaries and architectural elements for each of the four zones.

The outcrop of Fan 2 is predominantly interpreted to be found in Zone 3, where sequence boundaries are sharp below sheets, erosive below channels and gradational below thin-bedded turbidites. The architectural elements

display a transitional depositional style incorporating thin-bedded sheets (Johnson *et al.*, 2001).



Figure 17: Depositional model developed using Fans 1 – 4 of the Tanqua fan complex (from Johnson *et al.*, 2001).

# 2.2.1. Depositional elements

Deposition of deep-water sequences is commonly initiated by a relative fall in sea-level and ends with a relative rise in sea-level. Deep-water successions are commonly made up of mass-transport deposits at the base, followed by turbiditic frontal-splay deposits and leveed-channel deposits. This is followed by another mass-transport deposit, which is finally capped by a condensed section (Posamentier & Kolla, 2003).

Stow & Mayall (2000) compiled a synopsis of the most significant research in deep-water deposits that was available at the time. They concluded that structureless sand bodies can be divided into four geometries, namely chutes and flow slides, channel ribbons, lobes and lenses and basin-fill sheets. These can be found in fan deltas, slope channels, fan channels, lobes, and in restricted troughs and basins. Where they occur is dependent on tectonic activity and sediment supply. They also generated an overview of the most important depositional elements that can be components of deep water submarine fans (Figure 18 and Figure 19).



Figure 18: Illustration of architectural elements found in submarine fans, including mounds and lobes, contourite drifts and sheets, and drapes (from Stow & Mayall, 2000).



Figure 19: Illustration of architectural elements found in submarine fans, including surfaces, gradient changes, slides and slumps, canyons and channels, and levees (from Stow & Mayall, 2000).

# 2.2.1.1. Leveed channels

Leveed channels are commonly found in slope and basin-plain environments and are composed of amalgamated sands deposited by highdensity turbidity currents. They can either grow laterally and horizontally by channel-meander-loop migration and avulsion or vertically by aggradation. Channels often erode downwards into the underlying substrate, and can be found singly or in channel complexes. The width and depth of channels decrease down-system in the basin-ward direction in deep-water settings (Posamentier & Kolla, 2003).

# 2.2.1.2. Levee deposits

Levee deposits have channels as the source of their sediment supply. They are commonly composed of thin-bedded sandstones and shale beds.

Occasionally, sediment-waves can be found to the sides of levee channels. The sediment concentration of the turbidity currents decreases downstream, resulting in less sediment being available to construct levees. As a result the height of the levees decreases down-system in the direction of the basin. These waves form due to spillover and flowstripping of the upper-part of turbidity current overbank flows, with wave crests and troughs forming obliquely to the channel axis. The amplitude of the waves decreases with an increase in distance from the levee crests. The waves are better developed on the outsides of the outer bends of the channels than on the insides (Posamentier & Kolla, 2003).

### 2.2.1.3. Distributive channels

When leveed channels feed directly into lobes or lobe complexes (also called sheet-sand deposits or splay complexes), it is called a frontal-splay complex. When leveed channels feed into lobes or lobe complexes via distributive channels, it is called a distributary-channel complex.

The change, from a turbidity current confined to a leveed channel to an unconfined turbidity current in a splay complex, can be due to two main variables. These are the lowering of levees in a down-system direction, which leads to the turbidity current eventually not being contained in a channel, and a decrease in the gradient of the channel. The transition from confined to unconfined turbidity currents also depends on the characteristics of the turbidity current, including the flow volume, height and velocity and the sandto-mud ratio (Posamentier & Kolla, 2003).

### 2.2.1.4. Lobes

Lobes form in submarine fans as tabular sandy depositional bodies at the end of sediment-transport channels. They appear to be lenticular when viewed from the side and lobate when viewed from the top. Lobes can be subdivided into two types based on their location, architecture and type of feeder channel. "Proximal isolated lobes (PILs)" are small lobes found proximally on or near the slope and are fed by slope channels or gullies. "Composite mid-fan lobes (CMLs)" are larger, composite lobes, found distally and are fed by leveed fan valleys. Lobes deposited in an intermediate location are referred to as hybrids and may have features comparable to either of the types (Deptuck *et al.,* 2008).

Variation in the size, shape and architecture of lobes are due to various factors. These include the properties, frequency and amount of flows; the gradient and morphology of the sea floor at the mouth of the feeder channel; the geometry and stability of the feeder channel; and the time spent building the lobe before it is abandoned (Deptuck *et al.*, 2008).

# 2.2.2. Hierarchy

Architectural elements are structured according to a hierarchy in order to compare stacking patterns, scales, and processes from various datasets and to define them according to a spatial scale (Prélat *et al.*, in review). For this study, the hierarchic scheme was also used to represent internal architecture.

Mutti & Normark (1987) generated a hierarchy for turbidite deposits that subdivides them into a turbidite complex (1<sup>st</sup> order), system (2<sup>nd</sup> order), stage (3<sup>rd</sup> order), sub-stage (4<sup>th</sup> order) and beds (5<sup>th</sup> order).

Deptuck *et al.* (2008) used compensational stacking to describe a depositional hierarchy, which in turn allows for the better understanding of

lobe architecture. Lobes display compensational stacking at three scales: "Beds or bed-sets stack to form lobe-elements; lobe-elements stack to form composite lobes; and composite lobes stack to form lobe complexes" (Figure 20, Deptuck et al., 2008, p. 1).



Figure 20: Hierarchy of compensational stacking of composite lobes (from Deptuck *et al.,* 2008).

If the Mutti & Normark (1987) hierarchy is compared with the Deptuck *et al.* (2008) hierarchy, the 1<sup>st</sup> order turbidite complex remains the turbidite complex, the 2<sup>nd</sup> order system is equivalent to the lobe complex, the 3<sup>rd</sup> order stage is equivalent to composite lobes, the 4<sup>th</sup> order sub-stage is equivalent to the lobe elements and the 5<sup>th</sup> order beds are equivalent to the beds.

Prélat *et al.* (in review) suggests similar subdivisions to Deptuck *et al.* (2008) to interpret the depositional hierarchy of the Fan 3 lobe complex in the Tanqua fan complex. Beds (6<sup>th</sup> order) are the smallest architectural elements found in this hierarchy and each of them represents a sedimentary episode. If the beds are genetically related, they can be stacked to form bed sets (5<sup>th</sup> order) and lobe elements (4<sup>th</sup> order). Lobe elements stack to form lobes (3<sup>rd</sup>

order) and lobe complexes or fans (2<sup>nd</sup> order). Finally, fans stack to form fan complexes/turbidite complexes (1<sup>st</sup> order). Stacking patterns and element thickness are used in support of the suggested hierarchy.

Fan 2 is interpreted as a  $2^{nd}$  order lobe complex, with Middle Fan 2 classifying as a  $3^{rd}$  order lobe. Middle Fan 2 is subdivided into three  $4^{th}$  order lobe elements, each of which are further subdivided into  $5^{th}$  order bed sets and  $6^{th}$  order beds (Figure 21).



Figure 21: Hierarchical interpretation of Fan 2 illustrating the lobe complex, lobe, lobe-element and bed (outcrop viewed towards the west; located on the farm Drie Fontein 87, near vertical profile R88, 34H0396579/UTM6367977).

A comparison of the hierarchies used by Mutti & Normark (1987) and the LOBE project terminology as used by Prélat *et al.* (in review) can be seen in Figure 22.



Figure 22: Hierarchy for turbidite systems (modified after Mutti & Normark, 1987; Prélat *et al.*, in review).

Chapter 3

Lithofacies description

# 3. Lithofacies description

Five lithofacies have been described for the Tanqua-Karoo fan complex by previous studies, all of which are present in Fan 2. They are massive sandstone, ripple cross- and parallel-laminated sandstone, siltstone, carbonaceous and mica-rich siltstone and shale (Wickens, 1994; Rozman, 2000).

For the purposes of this study it was decided to work with six lithofacies subdivisions. They are:

- 1) Massive sandstone,
- 2) Ripple cross- and parallel-laminated sandstone,
- 3) Massive siltstone,
- 4) Ripple cross- and parallel-laminated siltstone,
- 5) Organic-rich co-genetic beds, and
- 6) Claystone

# 3.1. Lithofacies 1: Massive sandstone

### Description

Massive sandstone makes up the bulk of the Middle Fan 2 deposits. The sandstone is relatively clean and is fine-grained sandstone that can grade upwards to very fine-grained sandstone. The very fine-grained sandstones have a darker weathering colouration than the fine-grained sandstones, resulting in a darker section of sandstone overlying a lighter section of sandstone in fining-upwards sandstones.

Weathering of the sandstone causes it to be friable, resulting in pieces flaking off, especially towards the top of a sandstone layer. Most of the sandstone units, constituting the lobe elements, show amalgamation. On average, the amalgamated sandstone units of the lobe elements are 4.11 metres thick, with a minimum of 1.03 and a maximum of 6.2 metres, classifying the sandstone units as very thick beds (Boggs, 2006).

Sole marks such as load- (Figure 23) and groove casts (Figure 24) can be found at the bases of several sandstone beds.

Fossilised plant-fragment imprints commonly occur on the top of sandstone beds (Figure 25). Calcareous concretions in the study area are red to dark brown and vary in size from 10 to 70 centimetres in diameter. They are found distributed in massive fine-grained sandstones (Figure 26).

Rip-up clasts (Figure 27) commonly occur in at the base of sandstone beds. They are also scattered in smaller groups or singly throughout the body of some sandstone beds. They vary in size from less than a centimetre in diameter to a maximum of 15 centimetres. Their shapes vary from rounded to angular.



Biogenic structures such as trace fossils are found as sole markings at the base of some of the massive sandstone beds (Figure 28).

Figure 23: Load casts (arrow) at the base of a massive sandstone bed (1.2 m Jacob's staff for scale, vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72).



Figure 24: Groove casts at the base of a massive sandstone bed (head of Jacob's staff for scale, vertical profile R42, 34H0397661/UTM6374647, on the farm Kleine Gemsbok Fontein 72).



Figure 25: A plant fragment imprint (arrow) encased in a massive sandstone bed (vertical profile R39, 34H0398211/UTM6374607, on the farm Kleine Gemsbok Fontein 72).



Figure 26: Secondary calcareous concretion (arrow) in a massive sandstone bed (vertical profile R01B, 34H0399413/UTM6373810, on the farm Klein Gemsbok Fontein 72).



Figure 27: A claystone rip-up clast (arrow) in a massive sandstone bed (1.2 m Jacob's staff for scale; vertical profile R00C, 34H0399356/UTM6373839, on the farm Klein Gemsbok Fontein 72).

# Interpretation

Massive sandstone (Bouma-T<sub>a</sub> division) forms by rapid fallout from suspension of grains from high-density turbidity currents (Wickens, 1994; Baas, 2004). Amalgamation occurs when the upper fine-grained part of sandy turbidites or thin siltstone layers are eroded away during deposition of the overlying layer (Stephen *et al.*, 2001).



Figure 28: Casts of feeding burrows (arrows) in the pelitic top of the underlying turbidite (vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72).

This results in sand-on-sand contacts and seemingly continuous sandstone units of more than 6 metres thick. This facies is predominantly deposited in the upper flow regime and originates when high-density turbidity currents flow rapidly down a slope (Johnson *et al.*, 2001).

Flute casts are formed by current eddies, and groove casts by objects dragged in the hemipelagic mud prior to being filled in by sand (Boggs, 2006). Load casts are common at the bases of sandy turbidites and form when sand is deposited rapidly on top of a water-saturated mud layer. Differences in density cause loading of the higher-density sandstone, into the underlying lower-density, watery mud, forming irregularly-shaped protuberances (Boggs, 2006).

Plant fragments were possibly transported into the Tanqua sub-basin from deltas and coal swamps that surrounded the inland sea. The flora that most closely resembles the plant fragment imprints seen in outcrop include *Glossopteris* and *Noeggerathiopsis hislopii* leaves and charophyte stems; possibly *Octachara gracilis* (MacRae, 1999).

Calcareous concretions are secondary sedimentary structures that can consist of various minerals, such as calcite, siderite, haematite or dolomite. They are diagenetic in origin and their shape is dependent on the permeability of the host sediment, such as sandstone or shale, in which it was formed. Calcareous concretions grow concentrically around a nucleus by precipitation of carbonate that is drained from the surrounding sandstone (Boggs, 2006; Seilacher, 2001).

Most trace fossils are feeding burrows, such as *Cosmorhaphe* (Johnson *et al.,* 2001), which is classified under the abyssal plain *Nerites* ichnofacies. Ichnofacies are used to group trace fossils together that are indicative of the same palaeo-environment, in this case a deepwater basin-floor environment. The *Nerites* ichnofacies have ichnogenera that include *Nerites, Paleodictyon* and *Spirorhaphe*. They are found in abyssal-zone deep-water depositional environments and are associated exclusively with turbiditic sandstones and associated hemipelagic deposits that overlie the turbidites (Boggs, 2006).

# 3.2. Lithofacies 2: Parallel- and ripple crosslaminated sandstone

### Description

Fine-grained or very fine-grained sandstone beds often display paralleland ripple cross-laminations. The laminations are between 1 and 10 millimetres in thickness, thus thinly to thickly laminated. The ripples are small, asymmetrical and linguoid (Allen, 1966; Boggs, 2006) with an amplitude of less than 5 centimetres. Rip-up clasts and plant fragments may be present. The very fine-grained sandstones often display a darker weathering pattern, due to a higher organic or rip-up clast content. An example of a sandstone displaying parallel-lamination can be seen in Figure 29, and a sandstone bed with ripple cross lamination along the top half of the sandstone can be seen in Figure 30.

Occasionally, sandstone beds show some indication of ripple cross- or parallel-lamination, but the laminations are not clearly defined in an individual bed. In this study, these beds are defined as structured sandstones to differentiate between it and massive sandstone. Gently deformed parallellaminated layers that formed due to loading are visible in some of the structured sandstone layers (Figure 31).



Figure 29: Parallel-laminated sandstone bed (arrow) (vertical profile R05B, 34H0399263/UTM6374071, Kleine Gemsbok Fontein 72).

#### Interpretation

Parallel- (Bouma- $T_b$  division) and ripple cross-lamination (Bouma- $T_c$  division) are the result of grains transported by traction and deposited grainby-grain during fall-out from suspension from weakening turbidity currents (Wickens, 1994; Saito & Ito., 2002). Parallel-laminations are formed by "upper-flow regime transport during turbidity current flow" (Boggs, 2001, p. 95). The initiation of parallel-laminations can be due to changes in the conditions of sedimentation. These changes include variations in grain size; organic, microfossil and clay content; and mineral composition (Boggs, 2006).

Ripple cross-laminations form due to traction as part of the planar bed phase of the lower-flow regime (Johnson *et al.*, 2001). Climbing ripples are produced when migrating ripples are superimposed on top of each other during very rapid deposition.



Figure 30: Ripple cross-lamination (arrow) found in the upper half of a sandstone bed (vertical profile R13, 34H0398427/UTM6373891, on the farm Kleine Gemsbok Fontein 72).



Figure 31: Soft-sediment deformation due to loading in an area of parallel lamination (vertical profile R85, 34H0398427/UTM6373891, on the farm Kleine Riet Fontein 88).

# 3.3. Lithofacies 3: Massive siltstone

### Description

The siltstone varies between coarse- and fine-grained, and it weathers to a darker brown colour than do the sandstone beds. The siltstones are much thinner than the sandstone beds; on average, the siltstones of the inter-lobe elements are of medium thickness (0.12 metres thick), with a minimum of 0.03 metres (very thin to thin) and a maximum of 0.3 metres (medium to thick). They are occasionally absent due to loading or erosion by the overlying sandstone, giving the sandstone an amalgamated appearance. Plant fragments and rip-up clasts are abundant in the siltstones, and mica flakes can be seen from time to time.

### Interpretation

Massive siltstones are often found interspersed between and within sandstone beds as inter-lobe and intra-lobe elements. This is due to the siltstones being deposited by suspension from the silt-rich tail-end of low-velocity dilute turbidity currents after the deposition of the sand in the head and body of the current (Wickens, 1994; Boggs, 2006). It represents the Bouma-T<sub>d</sub> division (Figure 32).

# 3.4. Lithofacies 4: Parallel- and ripple crosslaminated siltstone

### Description

Ripple cross- and parallel-laminated siltstones often alternate with siltstone and sandstone layers (Figure 32). The ripples have a shape similar to the ripples found in Lithofacies 2, but the amplitude is much smaller, usually on a millimetre scale. A close-up of a coarse-grained parallel-laminated siltstone bed can be seen in Figure 33.

# Interpretation

Parallel- and ripple cross-lamination in siltstones form in a similar manner as those found in sandstones. Low-energy turbidity currents form traction structures as fine-silt grains fall out of suspension (Wickens, 1994; Saito & Ito, 2002). Changes in the flow regime (Boggs, 2006; Johnson *et al.*, 2001) and a decline in the fall-out rate translate into a change from parallel-lamination to ripple cross-lamination and can also affect the type of ripple that forms (Wickens, 1994).



Figure 32: Alternating layers of 1) coarse-grained siltstone, 2) very fine-grained sandstone, 3) sand injection into underlying siltstone, and 4) massive fine-grained siltstone (vertical profile R00C, 34H0399356/UTM6373839, located on the farm Kleine Gemsbok Fontein 72).



Figure 33: Parallel-laminated coarse-grained siltstone (vertical profile R05B, 34H0399263/UTM6374071, located on the farm Kleine Gemsbok Fontein 72).

# 3.5. Litofacies 5: Organic-rich co-genetic beds

# Description

Co-genetic beds are composed of dark weathering, coarse "siltstones" with rip-up clasts and plant fragments chaotically distributed in the matrix, and an underlying massive sandstone. Black carbonaceous material and mica flakes are common. They occasionally display internal parallel-lamination (Figure 34). Carbonaceous material and mica flakes are commonly present. The beds are approximately 10 - 15 metres in length and commonly limited in extent, due to lateral pinching.

### Interpretation

Debrites are the non-turbulent deposits from slow-moving laminar debris flows, and the flow is supported by a matrix. The debrites may be linked to underlying massive sandstone beds and are co-genetically deposited as cohesive slurry associated with the top part of the turbidite sandstone bed. This is then termed a co-genetic bed (see Chapter 2.1.3 on co-genetic debrites) (Johnson *et al.*, 2001; Haughton *et al.*, 2003; Talling *et al.*, 2004).



Figure 34: Co-genetic bed composed of underlying massive sandstone and an overlying dark-weathering organic-rich siltstone (arrow, 1.2 m Jacob's staff for scale; vertical profile R00A, 34H0399360/UTM6373789, located on the farm Kleine Gemsbok Fontein 72).

# 3.6. Lithofacies 6: Massive claystone

### Description

Blue-weathering silt-rich claystone can be seen at the base and top of Middle Fan 2 in areas where it has not yet been weathered. The layers often display parallel-lamination and are very fine-grained (Figure 35).

### Interpretation

Claystone is classified as shale that has a composition of more than two thirds clay particles that are smaller than 0.06 mm (Boggs, 2006). The claystone can be deposited in three ways. Pelagic settling involves "vertical settling under the influence of gravity" (Stow *et al.*, 2001, p. 491). Hemipelagic

deposition involves "vertical settling and slow lateral advection through the water column" (Stow *et al.*, 2001, p. 491). Hemiturbiditic sedimentation involves "upward dispersion from a dilute turbidity current ... mixes with any background pelagic or hemipelagic material and deposits slowly by vertical settling" (Stow *et al.*, 2001, p. 491). Each of these depositional processes occurs in a water depth of greater than 200 metres (Stow *et al.*, 2001). This facies makes up the interfan successions of the Skoorsteenberg Formation and represents periods of slow but continuous background deposition (Wickens, 1994; Johnson *et al.*, 2001).



Figure 35: Blue-weathering silt-rich claystone (1.2 m Jacob's staff marked in 10 cm increments for scale; vertical profile R13, 34H0398427/UTM6373891, located on the farm Kleine Gemsbok Fontein 72).

Chapter 4

Data manipulation and presentation

# 4. Data manipulation and presentation

This chapter provides an overview of the step-by-step manipulation of the vertical profile data from 1-dimensional (1-D) line-drawing images to 2-dimensional (2-D) CorelDraw images to 3-dimensional (3-D) DSL images. It also discusses the methodology in using the Petrel seismic-to-simulation software for the generation of surfaces, isopach maps and static-model grids. The creation of facies models was also attempted.

# 4.1. 1-D

Detailed vertical profiles were measured at 91 locations in the field to generate a one-dimensional representation of the outcrop. The profiles were measured with the aid of a Jacob's staff (1.2 centimetre length) and a measuring tape (5 m length) and the bed-thickness measurements were noted in an A4 field book at a scale of 1:50 cm.

Observations include grain size; types of base, for example loaded, amalgamated or eroded; the presence of plant fragments and rip-up clasts; ripple-cross or parallel lamination; sedimentary structures including sole structures. An example of vertical profile R00A as measured in the field can be seen in Figure 36.

## 4.2. 2-D

CorelDraw Graphics Suite X3, version 13.0.0.739, developed by the Corel Corporation, is a software package that was used for the detailed drawing of the 91 vertical profiles and the manipulation and stitching of photopanels and correlation panels in 2-D.

Figure 37 shows a typical vertical profile completed in CorelDraw superimposed on its associated photopanel. Figure 38 shows a segment of a correlation panel, in which the lobe elements across the study area were linked up to display their internal variation and lateral and vertical connectivity. As the correlation panels can only be seen in 2-D, the profiles were connected


irrespective of their orientation in space, but taking into account the order in which they are found in the outcrop.

Figure 36: Hand-drawn representation of vertical profile R00A

(34H0399360/UTM6373789) at a scale of 1:50 cm. The notations "R00-A-B" and "R00-A-T" refer to the base and top of the vertical profile, respectively.



Figure 37: Vertical profile R00A (34H0399360/UTM6373789) compiled in CorelDraw format superimposed on its associated photopanel.



Figure 38: Vertical profiles R01A, R01B, R00A, R00B, R00C and R02 represented as a correlation panel in CorelDraw.

# 4.3. 3-D

# 4.3.1. Introduction

All 91 vertical profiles that were compiled for this project were digitised using Virtual Reality Geological Studio version 03.11.05, also known as DSL, which was developed by David Hodgetts from the Department of Earth Sciences at the University of Manchester. Figure 39 shows a typical vertical profile compiled in DSL.

The facies that were differentiated between in the DSL programme for this project are:

- 1) Massive sandstone,
- 2) Structured sandstone,
- 3) Sandstone ripple-cross and planar lamination,
- 4) Siltstone/sandstone (>50% silt),
- 5) Sandstone/siltstone (>50% sand),
- 6) Laminated/rippled siltstone,
- 7) Debrite (dominant sandstone with organics),
- 8) Mudstone, and
- 9) Mudstone/siltstone (>50% mud).

Although only six lithofacies descriptions were used during the measuring of the vertical profiles in the field, the DSL programme differentiates between nine different facies. These facies were then reduced to five for the facies upscaling of the final static model grid that was run in Petrel. The decision to reduce the DSL facies for the purposes of the final static model grid was made in an attempt to get a more accurate representation of the lobe and inter-lobe elements.



Figure 39: Vertical profile R00A (34H0399360/UTM6373789) compiled in DSL format showing the representation of facies used in the legend on the right.

A tabular representation of the different facies as used for the lithofacies descriptions in Chapter 3, and the DSL and Petrel facies in Chapter 0 can be seen in Figure 40. DSL colour codes the different facies and it is possible to choose the type of base (amalgamated, erosive, transitional, sharp, loaded and faulted) and grain size (very fine sand, fine sand, coarse silt, fine silt, clay and no exposure). The facies data were imported from DSL into Petrel,

Lithofacies description	DSL facies	Petrel facies
1) Massive sandstone	1) Structureless sandstone	1) Massive sandstone
2) Ripple cross- and paral-	2) Structured sandstone	2) Structure-bearing
lel-laminated sandstone	3) Sandstone - ripples/planar lamination	sandstone
3) Siltstone	4) Siltstone/sandstone (>50% silt)	3) Siltstone
4) Ripple cross- and paral-	5) Sandstone/siltstone (>50% sand)	
lel-laminated siltstone	6) Laminated/rippled siltstone	
5) Organic-rich	7) Debrite (dominant sandstone	4) Other
co-genetic beds	with organics)	
6) Claystone	8) Mudstone	5) Background
	9) Mudstone/siltstone (>50% mud)	

allowing for the facies to be incorporated into correlation panels and modelled in 3-D.

Figure 40: Tabular representation of Virtual Reality Geological Studio (DSL) facies.

Petrel seismic-to-simulation software, Version 2007.1.2, is a 3-D modelling software package developed by Schlumberger. It was used to create surfaces, to construct isopach maps, to develop correlation panels, to build simple 3-D static model grids and to generate facies models using the digitised profile outcrop data. The Petrel help file was used extensively to describe the various algorithms and methods used for the modelling. Figure 41 shows wells that were generated using Petrel with the DSL input data on the left (a), the reduced Petrel facies in the middle (b), and the model-generated facies up-scaled into the grid on the right (c). DSL differentiates between 17 facies (d), of which 9 were used for this study. The facies were reduced to 4 for the purposes of up-scaling in Petrel (e). This is done in Petrel using the "calculator" and simple word equations.

## 4.3.2. Aims

The primary concern, when considering the use of Petrel, was whether the detailed scale used during the measuring of the vertical profiles in outcrop could be effectively imported and modelled in Petrel. This is directly influenced by the processing power of the available computers used to run the Petrel program. Thus, a key aim of this work was to obtain insight into the using of Petrel. Once the efficacy of the data was determined, the primary aim for using Petrel was to build a 3-D model of lobe-element distribution. It was used to represent the outcrop in an attempt to illustrate the internal variation in the



Middle Fan 2 lobe, including variation in facies. It was also useful in visualising the depositional model (Chapter 7).

Figure 41: Petrel-generated image of profile R00A (34H0399360/UTM6373789) showing the DSL input data (a), Petrel facies (b), the model-generated facies up-scaled into the grid (c), the DSL facies legend (d) and the Petrel facies legend (e).

## 4.3.3. Model size

Analogue data collected in the field for the 12000 x 7000 x 25 metre study area were imported into Petrel in the form of 91 DSL profiles, GPS coordinates, and thickness-calculations of the various lobes and lobe elements to give as accurate a depiction of the internal structure of Middle Fan 2 as possible. Each of the profiles are seen as "wells" in Petrel and they are oriented according to their top X, Y and Z GPS coordinates to allow for some indication of the topography of the study area. As most of the profiles were measured in the backs of gullies the base GPS coordinates (Z) were commonly too inaccurate to be useful, thus the base GPS was calculated using the top GPS and the measured thickness of the profiles. The margin of error of the Z-readings varied from 0.5 m at the top to 33 m at the base of vertical profiles. The study area was constrained to the region surrounding the measured profiles using a broader polygon (A, ~1000 metres from data points) for the first two static model grids and a narrower polygon (B, ~400 metres from data points) for the third static model grid. The polygon size was reduced in order to minimise the amount of extrapolation by Petrel where no data points are available. Despite this, there were still some anomalous results in areas more than 100 metres from the nearest profile. The location of the vertical profile data points and the two polygons can be seen in Figure 42.



Figure 42: Location of data points (pink dots) and polygons A (yellow) and B (green).

## 4.3.4. Petrel workflow

The workflow diagram (Figure 43) shows the seven steps (in green) involved in generating a Petrel facies model, starting with data input (1), the creation of surfaces (2) and isopach maps (3), generating static-model grids (4), the upscaling of wells (5), and the creation of correlation (6) panels and finally the attempted generation of facies models (7).

Some of these steps required several attempts before obtaining the required results. The failed attempts were termed "vintage" attempts, and the successful attempts were termed "final" attempts. The workflow diagram also shows some of the iterative steps (A – E, in red) that had to be undertaken in an effort to generate the most accurate facies models given the available outcrop data.

Iterative step A corresponds to a change from the Kriging algorithm to the convergent interpolation algorithm after the first attempts at creating a surface and an isopach map.

Iterative step B corresponds to a change from polygon A to polygon B in order to better constrain the boundaries after the first two attempts at surfaces and isopach maps.

Iterative step C corresponds to a change from a facies model generated using the Kriging algorithm to a facies model generated using sequential indicator simulation.

Iterative step D indicates a change from the subdivision of zones using "follow top" layering with a thickness of 20 centimetres each to a proportional subdivision assigning 60 layers to each of the sandstone-lobe elements and one layer to each of the siltstone inter-lobe elements.

Iterative step E corresponds to a reduction of facies from the 19 DSL facies to the five Petrel facies.



Figure 43: Petrel workflow diagram.

## 4.3.4.1. Data input

The DSL data for all the measured and digitised vertical profiles was imported into Petrel as iRap RMS well logs. The imported data include bed thickness, grain size, facies, and UTM GPS readings in the form of X, Y and Z coordinates. Petrel imports the top GPS coordinate as the Kelly Bushing (KB) height, which ensures that each well honours the true outcrop topography as measured in the field using hand-held GPS devices. The Z data confirmed the low dips in the area.

The imported DSL data do not include the well-tops of lobe- and inter-lobe elements. These data were determined by calculating the top and bottom UTM GPS coordinates of each successive lobe- and inter-lobe element in Microsoft Excel 2003 spreadsheets, before the data were imported into Petrel. Once all the data were imported, the well-tops could be directly linked to their corresponding wells.

The lobe- and inter-lobe element well-tops were named Top 3, Base 3/Top B, Base B/Top 2, Base 2/Top A, Base A/Top 1 and Base 1 respectively from top to bottom. The thickness data for the measured profiles in Excel format can be seen in Figure 44.

The topmost measured GPS coordinate was used as a starting point and the measured thickness of each consecutive lobe and inter-lobe element was subtracted from it. An extract of the Excel data can be seen in Figure 45. The colourless columns are the names and X and Y GPS coordinates, the purple column the Z GPS coordinates, and the yellow, blue and orange columns represent the data for the well tops Base 3/Top B, Base B/Top 2 and Base 2/Top A, respectively.

	ROOA				
Surfaces	X	Y	Z	Pochelle Stevn:	
Тор З	-32.7692	19.92548	649	Top measured GPS	
	0.7			coordinates	
	0.1				
	0.02				
	0.6				
	0.17				
	0.28				
	0.53				
	0.5			Rochelle Steyn:	
	0.34			of sandstone lobe	
	0.76	4	645	element	
Base 3/Top B	0.15	0.15	644.85		
Base B/Top 2	0.38				
2400 2.100 2	0.25				
	0.1			Rochelle Steyn:	
	0.4			of siltstope inter-lobe	
	1.85			element	
	1.00				
	0.65				
	0.00				
	0.48				
	0.05				
	1.85				
	0.24				
	0.24				
	0.25				
	0.20				
	0.05			Rochelle Steyn:	
	0.00			//Calculated GP5 Z	
	0.11				
	0.20				
	0.04				
Base 2/Ton A	0.04	9.42	635.43	Rochelle Steyn:	
Base A/Top 1	0.34	0.42	635.40	Bottom calculated GPS	
	0.27	0.27	000.10		
	0.04	0.51	634.65	*	
Base 1	0.41	0.01	004.00		
Base 3/Top B Base B/Top 2	0.17 0.28 0.53 0.5 0.34 0.76 0.15 0.38 0.25 0.1 0.4 1.85 1.22 0.65 0.11 0.48 0.05 1.85 0.24 0.23 0.25 0.17 0.25 0.17 0.05 0.11 0.25 0.11 0.25 0.14 0.25 0.14 0.25 0.14 0.25	9.42 0.27 0.51	645 644.85 644.85 635.43 635.16 634.65	Rochelle Steyn: Measured thickness (m) of sandstone lobe element   Rochelle Steyn: Measured thickness (m) of siltstone inter-lobe element   Measured thickness (m) of siltstone inter-lobe element   Rochelle Steyn: Calculated GPS Z coordinate for surface Base 2/Top A   Rochelle Steyn: Dotom calculated GPS coordinate	

Figure 44: Thickness and GPS coordinate data (m) for measured vertical profile R00A (34H0399360/UTM6373789).

	Х	Y	Z	Z - Thickness	Base	3/Top B	Thickness	Z - Thickness	Base	B/Top 2	Thickness	Z - Thickness	Base	2/Top A	Thickness
R00A-T	399360	6373789	649	645	Base	3/Top B	4	644.85	Base	B/Top 2	0.15	635.43	Base	2/Top A	9.42
R00B-T	399319	6373788	646	641.38	Base	3/Top B	4.62	641.31	Base	<b>B/Top 2</b>	0.07	633.19	Base	2/Top A	8.12
R00C-T	399356	6373839	663	658.42	Base	3/Top B	4.58	658.04	Base	<b>B/Top 2</b>	0.38	649.62	Base	2/Top A	8.42
R01A-T	399461	6373834	641	637.26	Base	3/Top B	3.74	636.55	Base	<b>B/Top 2</b>	0.71	629.59	Base	2/Top A	6.96
R01B-T	399413	6373810	643	637.95	Base	3/Top B	5.05	637.63	Base	<b>B/Top 2</b>	0.32	629.81	Base	2/Top A	7.82
R02-T	399363	6373957	645	640.62	Base	3/Top B	4.38	639.97	Base	<b>B/Top 2</b>	0.65	632.26	Base	2/Top A	7.71
R03-T	399485	6373960	645	639.68	Base	3/Top B	5.32	639.21	Base	B/Top 2	0.47	636.11	Base	2/Top A	3.1
R04-T	399406	6374250	665	659.16	Base	3/Top B	5.84	658.56	Base	B/Top 2	0.6	655.23	Base	2/Top A	3.33
R05A-T	399305	6374070	656	651.69	Base	3/Top B	4.31	651.16	Base	B/Top 2	0.53	643.33	Base	2/Top A	7.83
R05B-T	399263	6374071	649	643.78	Base	3/Top B	5.22	643.7	Base	B/Top 2	0.08	637.98	Base	2/Top A	5.72
R06-T	399398	6374267	671	665.18	Base	3/Top B	5.82	665.16	Base	<b>B/Top 2</b>	0.02	661.01	Base	2/Top A	4.15
R07-T	399120	6374219	656	649.38	Base	3/Top B	6.62	649.2	Base	B/Top 2	0.18	644.24	Base	2/Top A	4.96
R08-T	399071	6374194	668	661.56	Base	3/Top B	6.44	661.52	Base	B/Top 2	0.04	657.07	Base	2/Top A	4.45
R09-T	398945	6374123	660	653.4	Base	3/Top B	6.6	653.34	Base	B/Top 2	0.06	650.24	Base	2/Top A	3.1
R10-T	398799	6374055	663	656.84	Base	3/Top B	6.16	656.77	Base	B/Top 2	0.07	653.88	Base	2/Top A	2.89
R11-T	398687	6373980	665	658.66	Base	3/Top B	6.34	658.58	Base	B/Top 2	0.08	655.79	Base	2/Top A	2.79
R12-T	398577	6373981	667	661.53	Base	3/Top B	5.47	661.49	Base	B/Top 2	0.04	658.51	Base	2/Top A	2.98
R13-T	398427	6373891	675	669.51	Base	3/Top B	5.49	669.47	Base	B/Top 2	0.04	665.68	Base	2/Top A	3.79
R14-T	398468	6373977	673	667.695	Base	3/Top B	5.305	667.675	Base	B/Top 2	0.02	662.395	Base	2/Top A	5.28
R15-T	398587	6374072	666	660.26	Base	3/Top B	5.74	660.22	Base	B/Top 2	0.04	657.04	Base	2/Top A	3.18
R16-T	398670	6374131	658	651.32	Base	3/Top B	6.68	651.28	Base	B/Top 2	0.04	648.43	Base	2/Top A	2.85
R17-T	398755	6374221	667	662.53	Base	3/Top B	4.47	662.49	Base	B/Top 2	0.04	660	Base	2/Top A	2.49
R18-T	398692	6374249	662	658.48	Base	3/Top B	3.52	658.36	Base	B/Top 2	0.12	655.79	Base	2/Top A	2.57
R19-T	398497	6374265	666	660.74	Base	3/Top B	5.26	660.69	Base	B/Top 2	0.05	656.82	Base	2/Top A	3.87
R20-T	398521	6374348	669	664.6	Base	3/Top B	4.4	664.56	Base	B/Top 2	0.04	659.79	Base	2/Top A	4.77
R21-T	398500	6374440	670	665.28	Base	3/Top B	4.72	665.21	Base	B/Top 2	0.07	661.24	Base	2/Top A	3.97
R22-T	398780	6374535	680	675.26	Base	3/Top B	4.74	675.16	Base	B/Top 2	0.1	671.23	Base	2/Top A	3.93
R23-T	398846	6374635	669	664.49	Base	3/Top B	4.51	664.43	Base	B/Top 2	0.06	660.34	Base	2/Top A	4.09
R24-T	399472	6374454	660	654.61	Base	3/Top B	5.39	654.49	Base	B/Top 2	0.12	650.15	Base	2/Top A	4.34
R25-T	399547	6374507	657	652.28	Base	3/Top B	4.72	651.99	Base	B/Top 2	0.29	647.54	Base	2/Top A	4.45
R26-T	399593	6374607	653	647.87	Base	3/Top B	5.13	647.79	Base	B/Top 2	0.08	643.99	Base	2/Top A	3.8
R27-T	399666	6374653	653	648.8	Base	3/Top B	4.2	648.52	Base	B/Top 2	0.28	644.45	Base	2/Top A	4.07

Figure 45: An Excel spreadsheet containing GPS and thickness data for profiles R00A to R27 and surfaces Base 3/Top B, Base B/Top 2 and Base 2/Top A.

Each of the Excel datasets had to be saved as text documents and then imported separately into Petrel as well tops, containing the colourless columns and the Z coordinates and names of the surfaces from either the yellow, blue or orange columns. An example of the imported data can be seen in Figure 46. The "well" names, X, Y and Z coordinates and the names of the well tops are listed in the first 5 columns. The last column of data is the calculated thickness of the lobe-element, but it is not needed to generate a well top in Petrel.

🗢 Imp	ort p	etrel well	tops: b	ase2topa	g£tt.txt						×
	¥ [	2									
Colum	n #		1	2	3		4	5			
Attrib	ute		Well	X	Y		Z	Surface	•		
Attrib	ute na	ame Wel		X	Y	Z		Surface			
Hoit	uce cy	pe	rext	meter	Lontinuo		inuou eter	Text			
One				motor				J			
Con	unaat k	trace:	A BOOM	ът	6		I	- (		1	
O LUI	medi ((		- Di	-011.1			vumber	or neader	lines:		
O We	ll name		aseztopaj	gatitixt			Jndehn	ed value:		-999	
Depth -											
🗌 Ne	gate Z	values									
Time —											
Ne Ne	gate ti	me values									
	_										
Date —											
	e curre	nt window's	settinas								_
C Custom date format:											
Header info (first 30 lines):											
Line	1:		x	Y							~
Line	2:	ROOA-T	39936	0 6373'	789 635	.43 1	Base	2/Top	A	9.42	
Line	3:	ROOB-T	39931	9 6373'	788 633	.19 1	Base	2/Top	A	8.12	
Line	4:	ROOC-T	39935	6 63738 1 63738	339 649 334 629	.62 J	Base Rece	2/Top 2/Top	A d	8.42 6 96	
Line	6:	RO1B-T	39941	3 63738	310 629	.81 1	Base	2/Top	A	7.82	
Line	7:	RO2-T	39936	3 63739	957 632	.26 1	Base	2/Top	A	7.71	
Line	8:	RO3-T	39948	5 63739	960 636	.11	Base	2/Top	A	3.1	≣
Line	9:	RO4-T	39940	6 63742 5 62744	250 655	.23 1	Base	2/Top	A	3.33	
Line	11:	ROSA-T	39930	5 63740 3 63740	סיט סי∉ט 171 637	.33 J .98 ]	Base	2/Top	A A	7.03	
Line	12:	RO6-T	39939	8 63742	267 661	.01 1	Base	2/Top	A	4.15	
Line	13:	R07-T	39912	0 63742	219 644	.24 1	Base	2/Top	A	4.96	
Line	14:	R08-T	39907	1 6374:	194 657	.07 1	Base	2/Top	A	4.45	
Line	15:	RU9-T R10-T	39894	5 6374) 9 6374)	123 650 155 653	.24 J .88 J	Base	2/10p 2/Top	A d	3.1 2.89	
Line	17:	R11-T	39868	7 63739	980 655	.79 I	Base	2/Top	Â	2.79	
Line	18:	R12-T	39857	7 63739	981 658	.51 1	Base	2/Top	A	2.98	
Line	19:	R13-T	39842	7 63738	391 665	.68 1	Base	2/Top	A	3.79	
Line	20:	R14-T	39846	8 63739 7 63740	977 662 172 657	.395 1	Bage	2/Top	A	5.28	
LINE	21:	K15-1	39030	. 03740	572 057	.01 1	Jase	2,100	^	5.10	~
<										2	
						1 OK 4		04		Com.	
						V UKI	orall	V UK			

Figure 46: Data for surface Base 2/Top A imported from a text file into Petrel.

# 4.3.4.2. Surfaces

Two different arithmetic equations were used to generate the surfaces in Petrel, namely the Kriging and convergent interpolation algorithms. These two algorithms were chosen as their descriptions in the Petrel help file indicated that they would be the most effective for use with this kind of outcrop data.

Middle Fan 2 is interpreted as a lobe, subdivided into three sandstone-lobe elements and two siltstone inter-lobe elements. Each of these five elements can be classified as a zone in Petrel, with bounding surfaces at top and bottom (Figure 47). Surfaces were generated for each of the elements, thought only the lobe-element 2 surfaces are shown in the following section.

B 3 A 2	Legend: Sandstor Siltstone Siltstone Claystone	ne lobe element inter-lobe element intra-lobe element e background
Elements	Zones	Surfaces
		Тор 3
Lobe element 3	Zone 5	
		Base 3/Top B
Inter-lobe element B	Zone 4	
		Base B/Top 2
Lobe element 2	Zone 3	
		Base 2/Top A
Inter-lobe element A	Zone 2	
		Base A/ Top 1
Lobe element 1	Zone 1	
		Base 1

Figure 47: Line diagram illustrating elements, zones and surfaces used in Petrel.

### Vintage attempt 1:

The Kriging algorithm only uses the X, Y and Z data that are within its equation's variogram range, resulting in anomalous extrapolation beyond the variogram range, and the algorithm will not exceed the minimum or maximum values of the data. All default settings were retained. The range was adjusted to 2000 for both the major and minor direction to honour the well data as closely as possible. The default grid size of 50 x 50 metres was used, and polygon A was used as a boundary constraint. The resultant surface (Figure 48) is highly contoured, but does not honour the vertical well data, generating artificial highs and lows, but not with enough variation to honour the actual outcrop topography.



Figure 48: Surface of lobe-element 2 done using the Kriging algorithm.

### Iterative step A:

As the Kriging algorithm did not honour the topographic outcrop data sufficiently, it was decided to attempt to create a surface using the convergent interpolation algorithm. It is important to honour the topography as closely as possible to give an accurate representation of the size and shape of the reservoir, in this case Middle Fan 2.

### Vintage attempt 2:

The convergent interpolation algorithm works by preserving the general trends in areas where there are little or no data and honouring the data in areas where there are enough data available. Outside of the available data points, the convergent interpolation algorithm tends to cause anomalous extrapolation. However, it does honour the topographic data in this project more accurately than the Kriging algorithm, especially after the well tops were added as a constraint, forcing the surface to honour all the data points. The default grid size of 50 x 50 metres was retained, as well as the original boundary polygon A. The generated surface shows a more varied topography, but appears bulleted (small circular areas of very steep dip) in some areas, where extreme differences in topographic height can be observed (Figure 49). These anomalous heights are interpreted to be a result of the range of influence overlapping for vertical profiles that were measured in close proximity to each other.

### Iterative step B:

The boundary polygon was reduced from polygon A to polygon B in an attempt to constrain the anomalous extrapolation of data better where no outcrop data are available. Polygon A allows extrapolation up to approximately 1000 metres from the nearest data point. Polygon B restricts the extrapolation to approximately 400 metres from the nearest data point.

#### Final attempt 3:

The convergent interpolation algorithm and polygon B were used to generate the final surface. The grid size was reduced to 5 x 5 metres. This surface (Figure 50) shows the closest resemblance to the outcrop topography. In areas where the data distribution was limited, due to poor outcrop exposure or the weathering of lobe- and inter-lobe elements, overlying surfaces can be forced to cross each other. These surfaces were adjusted to ensure that they

<figure>

Figure 49: Surface of lobe-element 2 done using convergent interpolation and polygon A.



Figure 50: Surface of lobe-element 2 done using convergent interpolation and polygon B.

followed on top of each other in the correct horizontal sequence without crossing in order to create accurate isopach maps.

# 4.3.4.3. Isopach (thickness) maps

Petrel isopach maps were generated by subtracting the Z-values of one surface from another to illustrate the variation in thickness between two surfaces, for each of the lobe and inter-lobe elements, using both polygons A and B (Appendix C). Only the isopachs generated for sandstone-lobe element 1 and siltstone inter-lobe element A are shown in the following section. The scale was set at 0 - 10 metres for the sandstone maps, and at 0 - 1 metres for the siltstone maps. Rose diagrams illustrating the palaeocurrent orientations are superimposed on each of the isopach maps. Amalgamation between sandstone-lobe elements means siltstone inter-lobe elements are often absent, resulting in anomalous maps. Warm colours indicate a minimum thickness and cold colours a maximum thickness, with the scale on each of the isopach maps indicated in depth (thickness).

### Vintage attempt 1:

The first isopach maps of sandstone-lobe element 1 (Figure 51) and siltstone inter-lobe element A (Figure 52) were generated using the Kriging algorithm and polygon A with the default grid size of 50 x 50 metres.



Figure 51: Isopach map for sandstone-lobe element 1 calculated from surfaces generated using Kriging interpolation and polygon A.



Figure 52: Isopach map for siltstone inter-lobe element A calculated from surfaces generated using Kriging interpolation and polygon A.

### Iterative step A:

The isopach maps calculated from surfaces generated using the using the Kriging algorithm shows anomalous thickening (indicated in purple) and thinning (indicated in red) of the lobe and inter-lobe elements, which does not honour the outcrop data. The isopach maps also appear artificially smoothed with no local highs or lows. The convergent interpolation algorithm was used in an attempt to honour the outcrop thicknesses more accurately.

### Vintage attempt 2:

A second isopach map of sandstone-lobe element 1 (Figure 53) was calculated from surfaces generated using the convergent interpolation algorithm and polygon A with the default grid size of 50 x 50 metres. An isopach map of siltstone inter-lobe element A (Figure 54) was also generated.





Figure 53: Isopach map for sandstone-lobe element 1 calculated from surfaces generated using convergent interpolation and polygon A.

Figure 54: Isopach map for siltstone inter-lobe element A calculated from surfaces generated using convergent interpolation and polygon A.

### **Iterative step B:**

The isopachs calculated from surfaces generated using the convergent interpolation algorithm show a closer approximation to the outcrop data than those generated using the Kriging algorithm, but there are still areas outside of the data points that show some anomalous extrapolation. In an attempt to decrease the amount of extrapolation in areas where there are little or no data, isopachs were calculated again from surfaces generated using convergent interpolation and polygon B.

### Vintage attempt 3:

Isopach maps were calculated using surfaces generated for sandstonelobe element 1 (Figure 55) and siltstone inter-lobe element A (Figure 56) using convergent interpolation and polygon B at the default Petrel range of 50 x 50 metres. Much less anomalous extrapolation in the form of red and purple are visible in the thickness maps.



Figure 55: Isopach map for sandstone-lobe element 1 using convergent interpolation and polygon B at a range of 50 metres.



Figure 56: Isopach map for siltstone inter-lobe element A using convergent interpolation and polygon B at a range of 50 metres.

### Final attempt 4:

The final isopach maps for sandstone-lobe element 1 (Figure 57) and siltstone inter-lobe element A (Figure 58) were calculated using the convergent interpolation-generated surfaces constrained by polygon B. The grid size was reduced to 5 x 5 metres and proved to be the most accurately generated isopach map for the sandstone-lobe element.

The only anomalously generated thickness data (in red) can be seen in areas where there is no outcrop available. The siltstone isopach map still indicates large areas of anomalous thickness data (in red and purple). This may be accurate as a large area of the outcrop does not contain siltstone inter-lobe element A as it is often amalgamated, eroded or weathered.







Figure 58: Isopach map for siltstone inter-lobe element A calculated from surfaces generated using convergent interpolation and polygon B at a range of 5 metres.

95

# 4.3.4.4. Static model grids

A grid with cell-dimensions of 20 x 20 x 0.2 m was defined using the created surfaces. The algorithms used include the Kriging algorithm and the sequential indicator simulation. The facies data imported from DSL and the thickness data of the lobe elements and inter-lobe elements were imported into the model to allow the programme to build up the elements in Middle Fan 2 layer by layer. Grids produced using surfaces generated by vintage attempts resulted in anomalous truncations and pinch-outs. The grid produced using the final surfaces resulted in a more accurate representation of the elements in Middle Fan 2.

# 4.3.4.5. Upscaling of facies

Layering defines the vertical scale of the cells as it subdivides each of the five zones generated in the static model grid into discrete layers. The zones correspond to the sandstone-lobe elements and siltstone inter-lobe elements.

## Vintage attempts 1 and 2:

Layers with a thickness of 20 cm were assigned to each of the five zones using the "follow top" command (Figure 59). This causes each of the underlying layers to follow parallel to the layer created above and shows a top-lap truncation. The "follow top" command was chosen as each of the vertical profiles or "wells" used the top GPS coordinates as a datum. The layering was then used for the upscaling of the facies using the Kriging algorithm in the first attempt and sequential indicator simulation in the second attempt.



Figure 59: Zones 1 - 5 representing each of the elements subdivided into fixed layers.

### Iterative step D:

The subdivision of the zones was changed from fixed layering to proportional layering in an attempt to constrain the facies better and to limit the amount of anomalous thickening of some of the zones. Anomalous thickening of zone 4 (orange) may be due to the lack of data for zone 5 where parts of lobe-element 1 and inter-lobe element A were weathered.

### Final attempt 3:

Each of the zones was assigned proportional layering of 60 layers for each of the sandstone-lobe elements and one layer for each of the siltstone interlobe elements. The facies were then upscaled using sequential indicator simulation.

# 4.3.4.6. Correlation panels

All 91 DSL profiles containing facies descriptions were imported into Petrel to allow an accurate display of correlation panels. The profiles are oriented according to their X, Y and Z GPS coordinates so they can be seen in their actual spatial configuration in a 3-D window and exported in their correct order into a 2-D correlation panel. The tops and bases of the lobe and intra-lobe elements are indicated on the 2-D correlation panel as coloured, dashed lines to indicate some of the internal structure.

#### Vintage attempt 1:

The Petrel correlation panel in Figure 60 was compiled after the data were run through a 3-D static model grid. The original DSL facies were used at a grid size of 20 metres and a layer thickness of 20 centimetres with the area confined to polygon A. The measured facies and grain size from the DSL profiles can still be seen in the two columns on the left. The column on the right depicts the facies generated by the 3-D static model grid. The vertical profiles were measured along the sides of a roughly U-shaped valley and were imported into the correlation panel in the order in which they occur in the outcrop from south to north, namely R07, R02, R00C, R00B, R00A, R01B, R01A, R03, R04 and R06. As the 3-D static model grid extrapolates some of the data, especially where there are outlying data points, the generated and measured facies can occasionally differ substantially. An example of this can be seen in vertical profile R00C. Profile R00C lies topographically higher than the surrounding profiles. As a result, the 3-D Petrel static model grid cuts out the facies data at the base of the profile and only the top six metres of the generated facies of profile R00C can be seen. This is due to the static-model grid not honouring the well data, clearly showing where surfaces had crossed over, and resulting in incorrect correlations. Most of the generated facies columns in this correlation panel are missing either the facies at the top or base. Any data that fall outside of the average data, as decreed by the algorithm used for the modelling, is discarded, resulting in an incomplete picture of the study area.

### Iterative steps B, D and E:

The three zones corresponding to sandstone-lobe elements were subdivided into 60 layers and each of the two siltstone inter-lobe elements were assigned one layer. The area was confined to polygon B and the original nine DSL facies were reduced to five.

### Final attempt 2:

The Petrel correlation panel in Figure 61 was compiled after iterative steps B, D and E. This methodology proved more successful than that of the previous correlation panels, as the facies generated by the 3-D static model grid (column on the right) more closely resembles the original DSL facies and the data were honoured for every well.

Both correlation panels (Figure 60 and Figure 61) are of the same type locality area of Fan 2 on the farm Kleine Gemsbok Fontein.



Figure 60: Correlation panel of profiles R00A to R07 using convergent interpolation and polygon A showing the original DSL facies on the left and the model-generated facies on the right.



Figure 61: Correlation panel of profiles R00A to R07 using sequential indicator simulation showing the original DSL facies on the left, grain size in the centre and model-generated facies on the right.

Petrel correlation panels were also generated to illustrate the strike and dip sections of the study area. The locations of the strike and dip panels are illustrated in Figure 62, with strike in green and dip in blue. The correlation panel, generated along dip, can be seen in Figure 63 and the panel generated along strike can be seen in Figure 64.

The dip section covers vertical profiles R01A, R05B, R10, R18, R20, R41, R42, R43, R45, R46, R52, R53, R54 and R55 from left to right on the correlation panel, and from north-east to south-west across the outcrop study area. The typical facies type changes from more structured (parallel- and ripple-cross laminated sandstone) to more massive sandstone and then back to structured sandstone from left to right across the strike section. There is some compensational thickening visible between the three sandstone-lobe elements to the left side of the correlation panel (R01A – R46). In comparison, there is a rapid thinning of lobe elements 1 and 3 and a thickening of lobe-element 2 in profiles R52 – R55.

The strike section covers vertical profiles R88, R87, R86, R85, R73, R01B, R01A, R03, R28, R31, R32, R74, R75, R76, R78, R77 and R80 from left to right across the correlation panel and from north to south across the study area. The correlation panel shows a change from massive to structured to massive sandstone from left to right across the panel. There is also an abrupt thinning in lobe-element 3 from vertical profile R31 to R32. Some indications of compensational stacking are visible in profiles R74 R75, R76, R78 and R77.

A compensational increase in thickness of a lobe-element is indicated by a blue arrow. A decrease in thickness of a lobe-element is indicated by a red arrow. The pattern of compensational stacking for the profiles in question shows a decrease in thickness of lobe-element 3 when there is a corresponding increase in thickness of lobe-element 2, and *vice versa*.



Figure 62: Locations of strike (green) and dip (blue) correlation panels.



Figure 64: Petrel correlation panel generated along strike, illustrating compensational stacking with thickening lobe elements indicated by a blue arrow and thinning lobe elements indicated by a red arrow.

# 4.3.4.7. Facies modelling attempts

The process involved when creating models starts with a structural model commonly based on seismic survey data. For the purposes of this study, this data are represented by the vertical profiles measured in outcrop.

This is followed by a conceptual sedimentary model, similar to the depositional model created in Chapter 7. Ideally, the conceptual sedimentary model will be incorporated into Petrel for the generation of a static facies model. Due to the time constraints of this study, the depositional model was not used in the attempts at generating facies models.

In order to create an accurate facies model of the Middle Fan 2 study area, the core data of the relevant NOMAD wells must preferably be incorporated into Petrel along with the 91 measured vertical profile "wells". Dummy wells should also be created to populate the areas on the outskirts of the available outcrop data so that it matches the outlines of the depositional model.

The final step is to create a dynamic model which incorporates the porosity and permeability data of the sandstone reservoir rocks and siltstone baffles and barriers to simulate possible hydrocarbon flow characteristics. This final step was not undertaken in this study, but would make an interesting addition to future studies on Middle Fan 2.

### Vintage attempt 1:

The first facies model was created using the Kriging algorithm confined to polygon A, and can be seen at a vertical exaggeration (VE) of 10 x in Figure 65. Only a small amount of colour other than light blue (massive sandstone) is present, and there is no indication of the internal inter-lobe siltstone elements.

This indicates that the variogram used by the Kriging algorithm does not extrapolate far enough away from the wells, so the radius of influence was increased from 1000 metres to 2000 metres, when using the sequential indicator simulation in an attempt to rectify this problem.



Figure 65: Facies-model attempt 1 using the Kriging algorithm and polygon A shown at 10 x VE.

A horizontal intersection was made through the Kriging algorithm facies model to illustrate the internal structure of the demarcated zones. No discrete internal layering can be seen for the first facies model. The location of the horizontal intersection and its close-up for the Kriging algorithm facies model illustrates the lack of visible facies (Figure 66).

### Iterative step C:

The Kriging algorithm was replaced by the sequential indicator simulation in an attempt to generate zones with more discrete internal layering indicating extrapolated facies to capture the internal heterogeneity of Middle Fan 2.



Figure 66: Close-up of an intersection (in darker blue) through the Kriging algorithm facies model confined to polygon A.

## Vintage attempt 2:

The sequential indicator simulation applies stochastic modelling using the input upscaled well log data, distributions, variograms and trends. The algorithm generates a more accurate model than the Kriging algorithm when the shapes of any of the facies bodies are unknown or uncertain. The result is a closer representation of the facies found in the study area.

The second facies model was generated using the sequential indicator simulation confined to polygon A (Figure 67). As the layering of the zones is



extrapolated by the Petrel program, pinch-outs are not uncommon, where there are in actuality no pinch-outs in the measured outcrop.

Figure 67: Facies-model attempt 2 using sequential-indicator simulation and polygon A at 10 x VE.

A horizontal intersection through the sequential indicator simulation facies model (Figure 68) shows that some connectivity is visible between the facies. The facies can however not be effectively subdivided into discrete sandstone and siltstone units as there is not enough detail available. This indicates that the area of influence is still not large enough, resulting in the facies appearing patchy rather than layered as they are not extrapolated far enough laterally.

### Iterative step D:

Another grid was created with a size of 20 x 20 metres, but instead of assigning a thickness of 20 cm to each layer as was previously done, proportional layering was used. Sixty layers were assigned to each of the zones that represent sandstone-lobe elements 1, 2 and 3, and one layer was assigned to each of the two siltstone inter-lobe elements. The area was constrained to polygon B (also used in iterative step B) in an attempt to limit

the extrapolation of data outside of the constraints of the polygon and the study area.



Figure 68: Close-up of an intersection (in darker blue) through the sequential-indicator simulation facies model confined to polygon A.

## Iterative step E:

The number of facies was decreased from the 19 original DSL facies to the five facies generated for Petrel to create a less cluttered facies model and to simulate the conditions found in outcrop.

## Final attempt 3: "Success case"

The final and most successful facies model attempt was generated with the following characteristics:

- 1. Sequential indicator simulation algorithm;
- 2. Study area confined to polygon B;
- 3. Static model grid size of 20 x 20 m;
- 4. Proportional layering assigning 60 layers to each sandstone zone and 1 layer to each siltstone zone;
- 5. Facies reduced from 19 to 5.

In the final facies model (Figure 69) the different facies can be more clearly defined across the study area. The internal layering of the sandstone-lobe elements and siltstone inter-lobe elements can also be more clearly defined (Figure 70).



Figure 69: Final facies model attempt using sequential-indicator simulation and polygon B at 10 x VE.


Figure 70: Close-up of a section through some of the study area showing up-scaled well logs and the siltstone inter-lobe elements clearly defined as a discrete layer (arrow).

Also shown is an intersection through an area with a good indication of layering, although there is still an abnormally thickened siltstone towards the right of the intersection (Figure 71).

This abnormality is attributed to the siltstone thickness being anomalously extrapolated due to a lack of well data in that specific area. The input of dummy wells into sections of the study area, where there are little or no outcrop data available, will limit the amount of extrapolation. This will in turn result in a more accurate facies model.



Figure 71: Close-up of an intersection (in darker blue) through the sequential-indicator simulation facies model confined to polygon B.

## 4.3.5. Results and discussion

After the sequential indicator simulation was used to generate the final attempt at a facies model, a histogram was created (Figure 72). This histogram shows the correlation between the facies associations created for the 3-D Petrel grid ("MyFacies", in blue), the upscaled or ("Upscaled cells", in green), and the input facies created by DSL ("Well logs", in pink). The

numbers 0, 1, 2 and 3 correspond to the dominant facies associations that were used in the final facies model, namely massive sandstone, background deposition, siltstone and structured sandstone.



Figure 72: Histogram showing the correlation between "MyFacies", "Upscaled cells" and "Well logs". The number 0 refers to massive sandstone, 1 to background deposition, 2 to siltstone and 3 to structured sandstone.

The histogram indicates that the input facies ("Well logs"), upscaled wells ("Upscaled cells") and the Petrel facies associations ("MyFacies") retain approximately the same percentage throughout, proving that a minimal amount of data was lost during each of the processes. This indicates that the 3-D percentage of the facies is equivalent to the input well data.

This is a function of the good 3-D control provided by the outcrop data, resulting in the high-quality input facies generating high-quality output facies. This also reiterates the importance of the iterative process and doing careful quality control of the field data. This ensures that surfaces and well tops generated using the field data are as accurate as possible.

The model can be improved by adding core-well data and dummy wells to the dataset to populate regions of the study area that lack sufficient outcrop data. This ensures a good 3-D spread of data throughout the area of interest, allowing for the construction of a more accurate facies model. The more exact the facies model, the more precise the depiction of the heterogeneity within the lobe. The inclusion of a conceptual depositional model in the facies modelling process can further increase the accuracy of the final facies model.

The proximity of the wells to each other, in some cases less than ten metres apart, results in a radius of influence where the data are not honoured. This can be remedied by decreasing the radius of influence or by forcing the grid to honour the well tops to ensure that all the data are included, when upscaling or modelling facies.

The facies models were more effective in defining sandstone-lobe elements than siltstone inter-lobe elements. This is due to much of the interlobe elements being amalgamated or weathered. This results in a gap in the data that is imported into Petrel, which in turn results in anomalous extrapolation of data, especially in an area that is farther away from the nearest available data points.

This can be remedied by decreasing the constraining polygon size. It can also be remedied by assigning a proportional layer with a set thickness to represent the siltstone layer during facies modelling. This ensures that the sandstone-lobe elements always honour their vertical limits, resulting in fewer anomalous lateral facies being generated.

Small-scale variation within the sandstone-lobe elements, and especially within the siltstone inter-lobe elements, often fell below the resolution of the 3-D models that were used. This is due to the deficient processing power of the computers used to run the Petrel program, necessitating the reduction of the resolution of the 3-D model.

The computer used to run the Petrel program at the University of Stellenbosch had a 2.4 Gigahertz dual-core processor, a 3-D gaming graphics card with 256 Megabytes of dedicated memory and 2 Gigabytes of RAM. The vintage attempts at defining grids, assigning layering to zones and creating facies models were often run at the limits of the processing power required by the algorithm to render results in 3-D. This resulted in frequent programme crashes.

The computer made available for our use at PetroSA had two 3.2 Gigahertz quad-core CPU's, a workstation graphics card with 512 Megabytes of dedicated memory and 2 Gigabytes of RAM. Despite this significant increase in processing power, attempts at rendering grids and zone layering, at higher resolution than defined in the final attempts defined in this chapter, still resulted in the programme slowing down or crashing. Careful quality control of the data, inserting dummy wells to better constrain the dataset, and using a more powerful processor may decrease the amount of programme crashes.

The final isopach maps generated for the sandstone-lobe elements can be used to reiterate the findings of the depositional model. The general trend for the thickened sandstones, illustrated by the isopach maps, lies in a north north-easterly direction. This is in line with the palaeocurrent measurements and the interpretation of the architectural elements found in outcrop.

Figure 73 illustrates all the isopach maps generated for the sandstone-lobe elements and siltstone inter-lobe elements of Middle Fan 2 for comparison. The red areas on the isopach maps represent elements that have been weathered or amalgamated away or outcrop with no exposure. The purple areas represent elements of maximum thickness, which are often anomalously extrapolated when there is no vertical profiles in the immediate vicinity.



scale for the lobe elements is 0 – 10 metre. The thickness scale for the inter-lobe elements is 0 – 1 metre.

114

The isopach maps, generated for the sandstone-lobe elements, show more accurately definable thickness trends across the study area defined by polygon B than the siltstone inter-lobe elements. This is due to the inter-lobe elements commonly being weathered or amalgamated away, thus representing incomplete outcrop.

As a result, only the three isopach maps generated for the sandstone-lobe elements were compared with the depositional model (Figure 98) depicted in Chapter 7. The images below (Figure 74, Figure 75 and Figure 76) were created by superimposing the isopach maps on top of the contour maps of the study area. The outlines of the depositional model were then overlain over both.

Lobe-element 1 (Figure 74) at the base of Middle Fan 2 is found throughout the study area, but is on occasion partially weathered or covered by scree. These include the areas indicated in red surrounding  $\star 1$  and  $\star 3$ . Despite the steps undertaken to decrease the amount of extrapolation by Petrel, especially when there are limited outcrop data available, there are still some areas of anomalous thinning. These areas are indicated by the red colouring surrounding  $\star 2$  and  $\star 4$ .

The areas with the thickest sandstones are delineated by ellipses A and B. These areas generally correspond with the channelised areas suggested by the depositional model. These areas of thickening can also be followed throughout most of the amalgamated sheet areas.

Arrows I, II and III indicate a general thinning trend, ending in sheeted areas. Arrow I represents an area of rapidly thinning sandstone beds. Middle Fan 2 in this area only comprises approximately half of the thickness of Middle Fan 2 found in the type locality. Arrows II and III represent thinning of the lobe elements, culminating in pinch-outs in the north-east and south-west of the study area.



Figure 74: Depositional model superimposed on isopach map of lobe-element 1.

The same general description can also be used for Figure 75, representing lobe-element 2, and Figure 76, representing lobe-element 3.

Lobe-element 2 shows anomalous pinch-out in the areas of  $\pm 1$  and  $\pm 2$  due to a lack of available outcrop data.

Ellipses A and B delineate thickened sandstone trends along the channelised areas similar to lobe-element 1.

Arrows I, II and III are oriented in the same direction as for lobe-element 1, but there is less thinning across the isopach in all three directions. Lobeelement 2 has the most complete outcrop record of the three lobe elements, and is represented across the study area.

Lobe-element 3 shows large areas of anomalous pinch-out in the areas surrounding  $\star 1$  and  $\star 2$ . This is due to lobe-element 3 being unrecorded in these areas due to weathering and obscuring by scree.

Ellipses A and B are in the same general area as for lobe elements 1 and 2, but there is a distinct thickening (indicated in purple squares) in the areas surrounding the channels measured in outcrop. These areas of thickening corresponds to areas of thinning in lobe-element 3 (indicated in red squares), offering a good example of compensational stacking. The thickened channelised sandstones are limited to lobe-element 3. Arrows I and II indicate the same thinning trends as lobe-element 1.

Suggestion for future studies: to further increase the accuracy of the 3-D facies model (Figure 69), the co-genetic debrites measured in outcrop must be added to the model as constrained data points. This will allow the co-genetic debrites to be modelled independently to the other facies associations, enabling them to be compared to the second depositional model (Figure 100) as separate entities. The thickness and spatial distribution of the debrites can then be represented in a similar way as the isopach maps as compared to the first depositional model (Figure 74, Figure 75 and Figure 76).



Figure 75: Depositional model superimposed on isopach map of lobe-element 2.



Figure 76: Depositional model superimposed on isopach map of lobe-element 3.