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CHARACTERIZATION OF THIN-BEDDED TURBIDITES FROM THE PERMIAN TANQUA KAROO SUBMARINE FAN DEPOSITS, SOUTH AFRICA

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Geology and Geophysics

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ABSTRACT

Thin-bedded turbidites (TBTs, 5-60 cm) constitute a common facies in fine-grained deep-water clastic environments. Proper characterization of these deposits are lacking due to the scarcity of well preserved outcrops exposing TBTs and the difficulty in resolving them by conventional subsurface logging methods. The objective of this study is to characterize TBTs developed in a variety of laterally contiguous depositional environments in a submarine fan. These deposits are well exposed in the Permian Tanqua Karoo subbasin, South Africa. The subenvironments studied include upper mid-fan channel levee-overbank, mid-fan passive channel fill, lower mid-fan channel-sheet transition, and lower-fan distal sheet deposits. Field and laboratory approaches reveal systematic variations in grain-size, sedimentary structures, grain-orientation, bed-thicknesses and vertical gamma-ray patterns between different subenvironments that indicate variable depositional styles. Coarsest grain-size (very-fine sand) is present in distal sheet sandstones and the finest (medium silt) in passive channel fills. Levee overbanks and passive channel fills are dominated by base truncated Bouma Sequences (Tc, Tcd, Tcde), while channel sheet transition and distal sheet deposits are characterized by top-truncated Bouma Sequences (Ta, Tab, Tabc). Grain-orientations based on ferromagnetic grains using anisotropy of isothermal remanent magnetization (IRMA) are primarily flow perpendicular (active channel fill, channel-sheet transition, and distal sheet deposits) or flow parallel (levee-overbank, passive channel fill) reflecting active tractional reworking or lack thereof. Active channel fills and channel-sheet transition deposits have the highest percent anisotropies that indicate flow confinement.
Unconfined flows in levee-overbank and distal sheet deposits have lower percent anisotropies. Bed-thickness distributions are monotonously skewed towards lower values with minor variations between different subenvironments.

Associated with the study of TBTs, a conceptual temporal correlation has been proposed between spatially separated depositional elements (e.g., upfan channel-levee overbank complexes, downfan depositional lobes etc.). A primarily retrogressive or backstepping mode of deposition is observed within a depositional sequence. A higher resolution temporal correlation is proposed based on field observations than previously reported. The Tanqua subbasin by virtue of its high latitude paleo-position also represents an analog to deposition controlled by asymmetric levees as a result of Coriolis forcing.
CHAPTER 1

GENERAL GEOLOGY OF THE TANQUA KAROO AND INTRODUCTION TO THIS DISSERTATION

1.1 Introduction

Thin-bedded turbidites (TBTs) are one of the most commonly occurring facies in a variety of subenvironments in deep water clastic sediments deposited from density currents. Thin-bedded turbidites have been neglected in terms of detailed scientific analyses, primarily due to their undistinguished physical characters and partly due to the common belief regarding their lack of economic potential. Recently with the advent of high-resolution logging techniques, thin-bedded turbidites have proven to be economically important in a variety of deep-water basins around the world. The present study is aimed at characterization of TBTs developed in various subenvironments of a submarine fan.

The Permian Tanqua Karoo submarine fan deposits were selected for the present study, where the rocks are very well exposed and tectonically undeformed. The depositional attributes of the Skoorsteenberg Formation, in the Tanqua Karoo subbasin, mimic a typical fine-grained submarine fan complex (Wickens, 1992). This subbasin has well developed thin-bedded turbidites from a suite of depositional elements which permits detailed facies analysis (Bouma and Wickens, 1994).

1.2 Problem Statement

TBTs develop in a variety of depositional settings but are very similar in their gross physical attributes. This study was undertaken to document and analyze
variations in physical features from various TBT deposits in an ancient submarine fan. Thin-bedded turbidites are problematic to evaluate because conventional petrophysical and geophysical data cannot resolve their internal architecture from the subsurface and extensive outcrops for analog studies are rare. Proper characterization and delineation of these types of deposits require high resolution log and seismic interpretations as well as detailed core analyses and analog studies. The present work is directed at detailed description and documentation of these deposits from the outcrop with the purpose of differentiating between TBTs developed in various subenvironments. Presentation of a suite of criteria to distinguish between numerous TBT sedimentary facies was deemed necessary from a purely scientific perspective as well as to contribute to technical resources for the economic utilization of these deposits. This is the first comprehensive study that looks at TBTs developed in a variety of depositional facies in a submarine fan.

A multi-pronged approach was used to compare and contrast thin-bedded turbidites from various subenvironments in the Tanqua Karoo submarine fans. Fieldwork involved documenting variations and relationships between different depositional facies, detailed measurement of sedimentary profiles, measurement of gamma-ray intensities to generate gamma-ray profiles, and collection of samples for laboratory analyses. Laboratory analyses entailed petrographic studies aimed at grain-size and provenance determination, grain-orientation studies using anisotropy of isothermal remanent magnetization (IRM), and X-ray diffraction analyses on extracted clay fraction in the rocks. Field and laboratory results were integrated to generate criteria to distinguish between thin-bedded turbidites from various localities.
in the submarine fans. The thin-bedded turbidites from the various settings are characterized by varying physical attributes, namely, grain-size, grain-orientation, sedimentary structures, bed-thickness distributions and relationship with associated facies, which can be related to their respective depositional styles.

1.3 General Geology of the Tanqua Karoo

The study area is located in the southwestern part of South Africa, approximately 200 km northeast of Cape Town. It is bounded on the south and west by the Cape Fold Belt (CFB), as shown in Figure 1.1. This area was part of the Gondwana supercontinent in the late Paleozoic (Fig. 1.2) and was located at a very high southern
Figure 1.2 Schematic diagram showing the location of the Karoo Basin as part of the Gondwana Supercontinent in the late Paleozoic. The tectonic setting with the position of the paleo-Pacific subduction zone is also depicted (From de Wit et al., 1992).

latitude (~ 65° S; Smith, 1973). The general stratigraphy of the study area is shown in Figure 1.3. The submarine fan deposits of the 250 m thick Skoorsteenberg Formation, on which the present study is based, belongs to the Permian Ecca Group. The Ecca Group is the middle unit of the Karoo Supergroup (Fig. 1.3). The Ecca Group is underlain by the glaciogenic Dwyka Group of Permo-Carboniferous age. Glacial sedimentation predominated in southwestern Africa from late Carboniferous (Stephanian) until early Permian (Sakmarian-Artinskian) time (Visser, 1989). The first phase of folding in the Cape Fold Belt, south and west of the study area, occurred around 278 ± 2 Ma (Hälßich et al., 1983), syn-tectonic with Dwyka sedimentation. Dwyka ice sheets retreated around early Permian, resulting in marine transgression (McLachlan and Anderson, 1973). The initiation of the Karoo basin is attributed to a combination of isostatic depression due to loading by ice sheets and post glacial
I.

BEAUFORT GROUP

ECCA GROUP

Dwyka GROUP

WITTEBERG GROUP

BOKEVELD GROUP

CAPE SUPERGROUP

RAIL MOUNTAIN GROUP

CAPE GRANITE SUITE

Shale

Prominent shale markers

Sandstone

Sandstone and shale

Conglomerate

Tillite

Tuff abundant

Granite

NB. Not to scale

Figure 1.3 Stratigraphy of the Cape and Karoo Supergroups in the southwestern Karoo Basin. The present study is based on the Skoorsteenberg Formation of the Ecca Group (After Wickens et al., 1992).
flooding. Another significant component in initial basin formation is attributed to the depression in the weak crust associated with the Southern Cape Conductive Belt (SCCB, De Beer et al., 1982) tied to compression due to subduction of the paleo-Pacific plate under the Gondwana plate (Visser, 1992). This makes the Tanqua Karoo a foreland basin in the early Permian. Post-Dwyka sedimentation was initiated by suspension settling of mud as part of the lower Ecca Group, in a marine to brackish water setting (Visser, 1992). At the end of early Permian, the distinctive Whitehill Formation (lower Ecca Group) was deposited which is characterized by a mesosaurid reptilian fauna and is correlatable with the Irati Formation in the Parana Basin of South America (Oelofsen and Araùjo, 1987; Visser, 1990; Cole and McLachlan, 1991). The first phase of folding in the Cape Fold Belt (~ 278 ± 2 Ma) did not have significant effect on deposition as suggested by continuous deposition of the Whitehill Formation over the Cape Fold Belt (Wickens, 1992). However, the observed thinning of the Whitehill Formation over the Cape Fold Belt reflects the generation of incipient relief due to folding (Wickens, 1992). The first folding event set the stage for later tectonism which had a profound effect on sedimentation. The second paroxysmal folding event of the Cape Fold belt affected the southern and western rim of the Karoo Basin. This is also known as the Outeniqua Folding which occurred around 258 ± 2 Ma (Hälbich et al., 1983). This tectonic event presumably affected basin development and sedimentation significantly (Wickens, 1992).

Water depths probably reached 500 m or deeper in the foredeep immediately to the north of the southern branch of the Cape Fold Belt (Visser and Loock, 1978). The second paroxysmal folding event led to the enhancement of the northeast trending Hex
River and Baviaanshoek (HRB) mega-anticlinal syntaxial folds (Fig. 1.4). The syntaxis played a vital role in the development of the Tanqua and the Laingsburg subbasins, in the southwestern part of the Karoo Basin as shown in Figure 1.4. The HRB anticlinoria had sufficient basin floor relief to partition sediments into the Tanqua and Laingsburg subbasins. The northeast-trending zone between the two subbasins, occupied by the syntaxial fold-axis, remained an area of non-deposition (Wickens, 1992). The Skoorsteenberg and the Laingsburg Formations (Fig. 1.3), comprised of submarine fan deposits in the Tanqua and the Laingsburg subbasins, respectively, were initiated.

Figure 1.4 Influence of the Cape Fold Belt on Ecca subbasin development in the Tanqua and Laingsburg areas. The Tanqua and Laingsburg submarine fan complexes are separated by the syntaxial anticlinoria trending northeast-southwest (After Wickens, 1992).

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around the same geological time as the second paroxysmal event of the Cape fold belt (~258 Ma, Visser, 1991; DeBeer, 1992; for more details see Scott, 1997). The Tanqua submarine fan complex is 250 m thick and covers an area of 650 km². It is composed of five submarine fan units (Fig. 1.5). The fans are silty to sandy in composition and are stratigraphically separated by basinal shales and silty shales (Wickens et al., 1992; Bouma and Wickens, 1994). The Tanqua submarine fans are part of the late Permian Skoorsteenberg Formation. The preserved succession of the five fans reflects characteristics of a middle to lower fan setting. The lowermost two fans (Fans 1 and 2) display extensive sheet-like geometry in the form of stacked outer fan depositional lobes. Two of the three upper fans (Fans 3 and 5) are characterized by both middle fan channelized and outer fan sheet-like elements, with well developed thin beds. Fan 4 primarily has outer fan characteristics with some middle fan channelized deposits. Fans 1, 2, 3, and 5 are sourced from the south or southwest while Fan 4 had a westerly source (Wickens, 1992; Fig. 1.6). This variation in direction is assumed to be due to a shifting deltaic point source, which migrated from the south to the west and then back to the south again. According to Reading and Richard's (1994) classification scheme, these fans represent mud-rich point-sourced submarine fans. A sixth fan (Fan 6), exposed near the southern edge of the study area, is supposed to represent a slope fan but detailed work needs to be done to constrain its depositional character. The submarine fan deposits of the Skoorsteenberg Formation in the Tanqua subbasin are stratigraphically overlain by the deltaic facies of the Kookfontein and Koedoesberg Formations (Fig. 1.3). They represent the uppermost formations of the Ecca Group. The Ecca Group is overlain by the fluviatile deposits of the Beaufort Group. On a larger
Figure 1.5 The outcrop map of the Tanqua submarine fans. The fans are numbered 1 to 5 and are separated by basinal shales in-between. Fan 6 is located in the extreme southern part and is not represented in this figure.

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timescale (~ Permo-Triassic) the Ecca and the Beaufort Groups represent a shoaling upward mega sequence, starting with basinal sediments and culminating in continental deposits.

The Laingsburg Formation developed in the Laingsburg subbasin, are likely to be time correlatives of the submarine fan deposits of the Skoorsteenberg Formation from the Tanqua Subbasin (see Scott, 1997; Fig. 1.5). They are more tectonically deformed and are physically separated from the Tanqua submarine fan complex by the syndepositional tectonic barrier of the northeast trending Hex River mega anticlinoria. The Laingsburg Formation submarine fan deposits are also overlain by shallow water deltaic facies of the Fort Brown and Waterford Formations (Fig. 1.3).

The present research is aimed at characterization of thin-bedded turbidites from the submarine fan units of the Skoorsteenberg Formation. They are very well exposed
along with the intervening basinal shales and silty-shales (Fig. 1.7). Upfan to downfan exposures are correlatable over several kilometers with relative ease due to the excellent quality of outcrops. The outcrop quality is primarily due to arid climate and lack of vegetation.

Figure 1.7 An overview of the Tanqua submarine fan complex around Skoorsteenberg Peak. The lack of vegetation enhances the outcrop quality. On the slope Fan 3 (~15 m thick) outcrops in the lower part followed upward by Fans 4 and 5, which forms the prominent cliff. The peak itself is composed by deltaic deposits of the Kookfontein and Koedoesberg Formations culminating in the fluvial deposits of the Beaufort Group at the top.

1.4 General Understanding of Thin-Bedded Turbidites

Thin-bedded turbidites comprise a common facies in submarine fan deposits, both in the Recent and in the geological record. They are integral parts of submarine
fan deposits of both active and passive margins, but are more extensively developed in
the latter. Outcrop studies on thin-bedded turbidites include the Ordovician Cloridorm
and Tourelle Formations (Quebec; Hiscott, 1980), Cambrian St. Roch Formation,
Gaspe Peninsula (Quebec; Strong and Walker, 1981), Precambrian Kongsfjord
Formation (Norway; Pickering, 1982a), and the Pennsylvanian Jackfork Formation
Arkansas (Jordan et al., 1991). Similar thin-bedded analogs from the Recent and
Tertiary submarine fans are commonly encountered from deep-water reservoirs in the
Gulf of Mexico, North Sea, Indonesia, Alaska and West Africa. These thin-bedded
deposits are commonly referred to as low-resistivity, low-contrast (LRLC) pay sands in
the Gulf of Mexico (Darling and Sneider, 1992). Well documented thin-bedded
turbidites from the Gulf of Mexico include the Ram Powell, Spirit and Tahoe
prospects (Viosca Knoll; Shew et al., 1994), Einstein prospect (DeSoto Canyon;
Hackbarth et al., 1994), and Auger prospect (Garden Banks; McGee, 1994), to mention
a few. DSDP Leg 96 reported well developed thin-bedded turbidites from the flank of
fan lobes and overbank complexes from the Mississippi Fan (Bouma et al., 1985).
Thin-bedded turbidites are extensively developed in the outer Bengal Fan as reported
from ODP Leg 116 (Stow et al., 1989). These studies from the recent and the rock
record addressed issues as general as reporting the occurrence of TBTs as part of a
regional study to as applied as focusing on lateral continuity and reservoir
characterization. The present work is aimed at resolving the characteristics of thin-
bedded turbidites from the numerous subenvironments that display TBTs, a problem
that has not been addressed in any detail in the previously mentioned works.
Thin-beds range in thickness from 1-10 cm (Ingram, 1954; Campbell, 1967). Beds less than 1 cm thick are referred to as very thin bedded, between 10-30 cm are medium-bedded and those between 30-100 cm are thick-bedded. In this dissertation, however, the classification scheme of McKee and Weir (1953) is followed. According to them, 1-5 cm thick strata are very thin-bedded, 5-60 cm thick strata are thin-bedded, and 60-120 cm thick strata are thick-bedded. In the Tanqua submarine fans, the very thin-beds (1-5 cm) and thin-beds (5-60 cm) are commonly associated with each other. Among the three thickness intervals the thin-bedded strata are most abundant in the specific sites selected for profile descriptions. Terms describing thin-bedded strata deposited from the full spectrum of sediment gravity flows range from the more generic name, thin-bedded sandstones to the more specific, thin-bedded turbidites. In this dissertation thin-bedded turbidite is used because siltstones are more abundant than sandstones in this bed-thickness range (5-60 cm) and the deposits have been recognized as turbidites. Moreover, the term thin-bedded turbidites (TBTs) is more commonly used in the literature related to deep-water clastics (Shew et al., 1994).

Several models of deep-water deposition from sediment gravity flows have been introduced over the last few decades. The models are based on observations from both Recent and ancient fans. The initial tripartite spatial division of facies into upper, middle and lower fans was introduced by Normark, based on seismic lines from the Cape Lucas and La Jolla Fans (1970). Mutti and Ricci Lucchi (1972), independently elaborated on the three-fold morphological model from the deep-water Tertiary deposits in the Apennines. Their model is based on deposits from an active tectonic setting where conglomerate and sand deposition is prevalent. Although the Mutti and
Ricci Lucchi model has been deeply entrenched in the literature it has limited application in passive margin settings dominated by deposits with a low sand/shale ratio. Bouma et al. (1995) introduced a submarine fan depositional model which is more applicable to systems with a low sand/shale ratio (Fig. 1.8). It is geared towards depositional settings that develop under relative tectonic quiescence representing or mimicking a passive margin. This model is based on observations from the Gulf of Mexico (Mississippi Fan: DSDP Leg 96, Bouma et al., 1985; salt withdrawal basins; Bryant Canyon cutting through Sigsbee Escarpment: Lee et al., 1996) and outcrops in the Tanqua Karoo subbasin in South Africa, the Pennsylvanian Jackfork Group in Arkansas, and the Delaware Basin in West Texas. The Tanqua Karoo submarine fans were deposited in a foreland basin setting but the sedimentary characteristics are similar to submarine fans that develop in a passive margin like the Gulf of Mexico. The primary attribute that is similar to a passive margin fan is the low sand/shale ratio throughout the entire turbidite/deltaic basin-fill as well as the ensuing fluvial facies of the lower Beaufort Group (Wickens, 1992).
Figure 1.8 Model of a fine-grained submarine fan based on studies on modern and ancient deposits (After Bouma et al., 1995).
CHAPTER 2

DESCRIPTION AND INTERPRETATION OF MEASURED SECTIONS

2.1 Introduction

Specific localities in the Tanqua Karoo deposits were selected where thin-bedded intervals are well developed. The thin-bedded intervals exhibit clear relationships with associated facies at these locations. This scheme resulted in selection of five sites (Fig. 2.1) from which a total of nine sections are presented in this dissertation that comprise of the following subenvironments:

1. Levee-overbank in an upper mid-fan setting (Fan 3, Kanaalkop),
2. Distal sheet sandstones (depositional lobes) in a lower-fan setting (Fan 3, Skoorsteenberg),
3. Channel-sheet transition deposits in a mid- to lower-fan setting (Fan 3, Rondawel West)
4. Levee-overbank deposits in a lower mid-fan setting (Fan 5, Blaukop),
5. Passive channel fill in a mid-fan setting (Fan 4, Bizansgat)

Detailed measured sections from the aforementioned sites are presented in Appendix A. Summary diagrams with discussions based on the measured profiles are presented on each of these outcrops in the following sections. Interpretations are based on observations made on grain-size variations, sedimentary structures, paleocurrent patterns, bed-geometry, relationship with over-, underlying and adjacent deposits,
Figure 2.1 Map showing the five submarine fans in the Tanqua Subbasin. Locations of measured profiles are indicated. Kanaalkop (KP, Fan 3 mid-fan), Skoorsteenberg (SK. Fan 3 lower fan), Rondawel West (RW. Fan 3 lower mid-fan), Blaukop (BK. Fan 5 mid-fan), and Bizansgat (BZ. Fan 4 mid-fan).
gamma-ray profiles, and grain-orientations. These observations enabled division of the sections into genetic intervals.

2.2 Kanaalkop (Fan 3)

2.2.1 Description

Profiles KP 1, KP 2 and KP 3 are measured sections of Fan 3 at Kanaalkop (Fig. 2.1). They are 48, 37 and 39 m thick, respectively. An overview of the outcrop is presented in Figure 2.2. These profiles exhibit a wide array of bed-thicknesses and sedimentary structures but are fairly restricted in grain-size variations. Description of the profiles are presented below and a graphical summary diagram is presented in

Figure 2.2 An overview of the central part of the north-face of the Kanaalkop outcrop with the locations of measured sections KP 1 and KP 2 marked. The "Kanaalkop Channel" is exposed at the top which has a maximum thickness of 20 m between KP 1 and KP 2. The photo has been taken from the top of the mesa formed by Fan 2 sandstones, the recessional slope in the foreground is the shaley interval between Fans 2 and 3. Thin-bedded turbidites are well developed in the interval below the base of the channel with occasional interbedded thicker sandstones.
Figure 2.3. The actual measured profiles are presented in Appendix A, where the datums used in the summary diagram (Fig. 2.3) are also depicted.

Interval from base to level A-A''-A''': The siltstones and silty-shales from the base up to level A-A''-A''' in profiles KP 1, 2, and 3, respectively, are characterized by thin beds (~3-8 cm) which contain parallel and ripple cross-laminations (Fig. 2.3). The ripples indicate a paleocurrent direction towards the east. They represent thin, base-truncated Bouma sequences in the form of Tc or Td beds (Bouma, 1962).

Figure 2.3 Summary diagram demonstrating the depositional interpretations from Fan 3 at Kanaalkop. See text for details. The vertical profiles are approximately 35-40 m thick. Also see location map in Fig. 2.1.
Interval A-A''-A''' to B-B''-B''': From datum A (level A-A''-A'''') to datum B (level B-B''-B''') in profiles KP 1, 2 and 3, respectively, the sections are composed of 10-40 cm thin beds and 50-130 cm thick beds (Fig. 2.3), often with very thin beds (1-5 cm) in between (nomenclature of bed-thickness after McKee and Weir, 1953). The 10-40 cm thin beds are characterized by very fine-grained sandstones fining upward to siltstones. They have Type A and B (abundance of Type B over Type A) climbing ripple-laminations gradational to sinusoidal ripple-laminations as defined by Jopling and Walker (1968), representing Tc beds (Fig. 2.4). The measured paleocurrent direction observed from the ripples, is directed towards E-ESE. The 50-130 cm thick beds are very fine-grained sandstones that are Ta,c beds (thickness of Ta >> Tc). Groove marks indicate a NE-SW azimuth of flow. These thicker beds (50-130 cm) do not show any evidence of erosion at their base and are conformable with the interbedded thinner (10-40 cm) units. The thick (50-130 cm), predominantly massive beds, often

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Fig 2.4 The classification of climbing ripples by Jopling and Walker (1968).
pinch out within the extent of the outcrop (e.g., Bed 8 in KP 3 between sections KP 2 and 3, Bed 23, approximately 100 m east of KP 1, shown in Appendix A).

Interval B-B’-B” to C-C’-C”: The interval from datum B (level B-B’-B”) to datum C (level C-C’-C”), in profiles KP 1, 2, and 3 (Fig. 2.3), respectively, is characterized in the lower part by thicker beds (20-40 cm) on the western side (at KP 3, see Fig. 2.1) and progressively thinner beds (10-20 cm) on the eastern sections (at KP 1, KP 2 in the north-face, Fig. 2.3). Going upsection the trend reverses the eastern beds become thicker (30-45 cm, in profiles KP 1 and 2) and the western beds become thinner (10-25 cm). Presence of Type B ripple-drift cross-laminations and sinusoidal ripples indicate an eastward sediment transport.

Interval C-C’-C” to D-D’-D”: The next interval up to datum D (level D-D’-D”) in the three sections KP 1, 2, and 3, respectively, is composed of very thin (1-5 cm) siltstone beds characterized by ripples and occasional parallel lamination (Fig. 2.3). The ripples indicate a paleocurrent direction toward the east.

Interval D-D’-D” to E-E’-E”: The next interval is up to datum E (Level E-E’-E”, Fig. 2.3). This datum corresponds to the base of the top “Kanaalkop Channel”. The Kanaalkop Channel is thicker in KP 1 than in KP 2 and KP 3 because of erosional relief at its base. This interval is characterized by poorly developed bedding and is composed of very-fine to fine-grained sandstones that have well-developed ripples, with rare climbing ripples (both Type A, B and sinusoidal ripples). Paleocurrent directions within this interval are to the NE (N30°-45°E) in KP 1 and NW (N25°-65°W) in KP 2 and KP 3 suggesting an approximately symmetrical and radially diverging flow with respect to the overlying Kanaalkop channel trend (Fig. 2.8).
2.2.2 Interpretation

Base to level A-A''-A''': The thin, base-truncated Bouma Sequences in the form of Tc or Td from base to level A suggest that they were deposited in an overbank setting as spillovers from minor flows in a channel that existed to the west of Kanaalkop which is not present in outcrop (West Channel, Figs. 2.5 and 2.6). The easterly directed paleocurrent flow in this interval, considered within the regionally established north to north-northeastwards (N-NE) directed downfan direction, supports this interpretation. This is part of a levee-overbank complex referred in its entirety as LOC 1 in Figures 2.3 and 2.8.

Level A-A''-A''' to B-B''-B'''': The variations in sedimentary structures and bed thicknesses indicate that the two bed thickness groups, (10-40 cm) and (50-130 cm) had considerably different depositional styles. A head spill versus a body spill mechanism from channelized turbidity currents is invoked to explain the massive thicker (50-130 cm) beds interbedded with the climbing ripple laminated thinner (10-40 cm) beds (Figs. 2.5 and 2.6). The appearance of head spill and body spill deposits is shown in Figure 2.7. The relatively thinner beds (10-40 cm), with the Type A and B ripple-drift cross-laminations and sinusoidal (aggradational) ripple-laminations, were deposited from spill over flows that were charged with a very high suspended- to bed-load ratio. It is suggested that these 10-40 cm beds are lateral spillovers from the turbulent suspended sediment cloud that rides as part of the body, above and behind the coarse-grained head of a turbidity current flowing downfan along a channel (possibly located to the west of Kanaalkop, here called the "West Channel", Fig. 2.8, also Fig. 2.5a). Deposition sets in due to flow expansion once the body spills.
Figure 2.5 The Kanaalkop area demonstrating its position on the right levee-overbank (LOC 1, in text and Fig. 2.3) with respect to the West Channel. (a) Map and (b) cross-sectional view of H-head, B-body of turbidity currents, HS-headspill, BS-bodyspill.
across the levee-crest. In contrast the thicker (50-130 cm) T_{ac} beds (T_{ac} thickness greater than T_{c} and T_{b} is lacking or not observable), are probable spillovers from larger flows when the confines of the channel fail to restrict the upper reaches of the head of turbidity currents at bank-full stages (Fig. 2.5b). Once across the levee crest, deposition occurs from these head/body spill flows by a flow-freezing mechanism resulting in the T_{a} division (Lowe, 1982). The thin T_{c} divisions at the top are the result of deposition from the lagging tail of the same spillover current, as well as possible reworking of the newly deposited bed. This interpretation is supported by the angular divergence in the direction of paleoflow, eastward from the thinner beds (10-40 cm)
Figure 2.7 Body spill and head spill deposits (a) Massive thick-bedded head spill deposit underlying thin-bedded body spill deposits. (b) Typical body spill deposits showing Type B climbing ripple-laminations (both stoss and lee sides preserved), indicating paleocurrent flow towards the left.
Figure 2.8 The inferred spatial relationship between the older levee-overbank complex (LOC 1) and the younger channel system (CS 1).

with climbing ripples and northeastward from the thicker massive beds (50-130 cm) with sole marks (Fig. 2.5a). The head spills, due to their higher inertial state, flow out into the overbank area at a shallower angle (30°-45°, headed NE) with respect to the sourcing channel (headed N-NE) than do the body-spill deposits (90°-100°, headed E; Fig. 2.5a). This interval is part of the same levee-overbank complex (LOC 1, Fig. 2.3 and 2.8) as the first interval.

Interval B-B”-B”’ to C-C”-C”’: This interval also suggests a predominantly body spill mode of deposition from the suspended sediment cloud in channelized flows from the inferred channel located to the west (West Channel, Figs. 2.5a and 2.8). The high suspended-load to bed-load ratio of the flows form the Type B climbing ripples grading towards sinusoidal (aggradational) climbing ripple-
laminations (Fig. 2.4). The reversal in thickness pattern from west to east is possibly due to depositional topography leading to compensation in a levee-overbank setting. This interval is also part of the same levee-overbank complex (LOC 1, Figs. 2.3 and 2.8).

Interval C-C"-C"" to D-D"-D"": This interval most likely represents the abandonment of the levee-overbank complex (LOC 1, Figs. 2.3 and 2.8) which is also composed of the intervals previously described. The transition from the active levee-overbank to a passive overbank fill probably records an avulsion in the sourcing West Channel further upfan (southward) rendering a shift in the local depocenter (Fig. 2.8).

Interval D-D""-D"""" to E-E""-E""": The presence of current ripples (suggesting a lower suspended-load to bed-load ratio, contrasting with deposits stratigraphically below) and poorly developed bedding indicate that these deposits have developed in a more active depositional site than the underlying units. The Kanaalkop channel axis is located in between the measured profiles KP 1 and 2 (see Figs. 2.1 and 2.2). A genetic link is suggested between this interval (D-D""-D"""" to E-E""-E"""") and the overlying Kanaalkop Channel on the basis of these observations. These deposits are inferred to represent a channel terminus depositional-lobe into which the Kanaalkop Channel incisively prograded at a later time (Fig. 2.8). This interval, including the overlying Kanaalkop Channel, comprises a channel system (CS 1 in Figs. 2.3 and 2.8) that represents a younger and separate genetic entity from the underlying levee-overbank complex (LOC 1 in Figs. 2.3 and 2.8) that was fed by the West Channel. The Kanaalkop Channel is located farther to the east of the inferred older/lower channel (the West Channel, Fig. 2.8) that had sourced the levee-overbank complex sediments.
LOC 1 (Fig. 2.3) from the west up to level D. The location of the top Kanaalkop channel was most likely prompted by an avulsion process in the inferred lower channel (the West Channel), further upfan than the Kanaalkop location (Fig. 2.2). The avulsion could have initially deposited the channel terminus depositional-lobe (interval from level D to level E, lower part of CS 1 in Fig. 2.3) to the east of the pre-existing West Channel. The younger Kanaalkop Channel subsequently entrenched itself into its own depositional-lobe and later filled up the erosional vacuity with a compound fill (Figs. 2.2 and Fig. 2.8). The spatial offset of the Kanaalkop Channel course with respect to the West Channel is most likely guided by post depositional differential compaction in the older channel/levee-overbank complex (LOC 1). The pre-existing course of the West Channel effectively became a sandy submarine ridge due to differential compaction and the younger Kanaalkop Channel levee-overbank lens (CS 1 in Figs. 2.3 and 2.8) onlapped onto the flanks of the older levee-overbank wedge (LOC 1, Fig. 2.8).

2.2.3 Gamma Ray Pattern and Bed-thickness Distribution

The gamma-ray profile measured from KP 1 is shown in Figure 2.9. The profile upto ~ 27 m (level D in KP 1, top of LOC 1, see Fig. 2.3) shows the typical serrate pattern for a levee-overbank complex (Stelting et al., 1985). The base of the section starts with relatively high gamma-counts (> 440 cps), representing the gradual transition from the basinal shales below. Within the overall serrate log-motif up to 27 m, are blocky patterns represented by the inferred head spill deposits (e.g., interval 7-11 m in Fig. 2.9). The erosional base of the Kanaalkop Channel is marked by higher gamma values (kick to the right, ~ 30 m in Fig. 2.9). The complex nature of the
Figure 2.9 Serrated gamma-ray character from profile KP 1. The measured section is heavily reduced in size. Refer to section KP 1 in Appendix A for a detailed representation of measured section KP 1.
Kanaalkop Channel fill is represented by the non uniform gamma-ray pattern above 30 m. The lack of a more significant variation in the gamma-ray counts is attributed to the relative abundance of feldspars and volcanic rock-fragments in the rocks.

The bed-thickness distribution from a representative section (KP 3) at Kanaalkop is represented in Figure 2.10. It has a heavy skewed bimodal distribution. Beds < 25 cm thick comprising more than 90% of the beds and beds 25-70 cm thick comprises 10%. The thinner beds are inferred to represent body spill deposits and the thicker beds supposedly represents head spill deposits.

![Figure 2.10](image)

Figure 2.10 Bed thickness distribution from profile KP 3. Data from 250 beds.

2.2.4 The Paleo-Position of South Africa and the Kanaalkop Deposits

As discussed in the previous section the position of the lower part of the Kanaalkop outcrop from the base to level D (Fig. 2.3) is in a levee-overbank setting (LOC 1, Fig. 2.8) with respect to a channel flowing northwards. This is referred to as the West Channel (Figs. 2.5a and 2.8) that is assumed to have existed to the west of Kanaalkop and is not present in outcrop. A model should be invoked to explain
the relatively common occurrence of the 50-130 cm thick massive beds interbedded with the 10-40 cm climbing ripple-laminated thinner beds (especially in the interval between levels A to B in Fig. 2.3) in a levee-overbank setting (LOC 1 in Figs. 2.3 and 2.8). It has been suggested earlier that the thicker $T_{ac}$ beds are head spill deposits as opposed to the more frequent thinner $T_c$ beds being body spill deposits from turbidity currents flowing northwards or downfan along the West Channel (Fig. 2.5a). But the high frequency of occurrence of the 50-130 cm thick head-spill beds in a levee-overbank setting needs justification because it is an exception to a common notion developed from well documented modern fans.

The paleo position of South Africa in the Permian was in very high latitudes, ~ $65^\circ$ S (Smith, 1973; Figure 2.11). It has been observed that late Tertiary to Recent submarine fan channels in high latitudes ($> 45^\circ$ N or S) have a profound difference in levee-heights at any transverse channel profile. This levee asymmetry at any given transect is attributed to the Coriolis Effect. Right-hand levees are higher in the

![Figure 2.11 The paleo-position of South Africa located at approximately 65°S in the Permian (After Smith, 1973).](image)
northern hemisphere due to a pull in sediment gravity flows to the right. In the northern hemisphere this results in preferential aggradation of right levees with fine-grained sediments from the body of channelized flows. The North Atlantic Mid-Ocean Channel (NAMOC) in the Laurentian Fan, offshore Labrador, has levee asymmetries up to 90 m (Hesse and Rakofsky, 1992; Fig. 2.12a). It is the reverse in the southern hemisphere. In the channels in the Otago Fan Complex, offshore New Zealand, the left levees are higher than their right-hand counterparts (Carter and Carter, 1988; Fig. 2.12b).

![Figure 2.12 Levee asymmetries in high-latitude submarine fan channel systems. (a) The NAMOC Channel in the Laurentian Fan (After Hesse et al., 1996) and (b) The Bounty Channel in the Otago Fan Complex (After Carter and Carter, 1988).](image)
Coriolis Force = $2\Omega u \sin \Phi$, where $\Omega$ is the angular velocity of the earth's rotation, $u$ the velocity of flow, and $\Phi$ is latitude. Here $\Omega$ is a constant and $u$ has a restricted range of values in submarine channels. Hence the high latitudinal position ($\sim 65^\circ$ S) of the submarine fan complex of the Tanqua Karoo is likely to have been impacted by Coriolis Effect. The position of the Kanaalkop outcrop was to the right-hand (east) side with respect to the north-directed sourcing channel (West Channel, Figs. 2.5 and 2.8). This supports the previous discussion on the deposition in the Kanaalkop area (up to level D in Fig. 2.3) being characterized by frequent body spill and occasional head spills across the lower levee (right-hand levee being lower in the southern hemisphere). This happened when the body and head of flows were higher than the levee relief at bankfull stages (Fig. 2.5b). The higher left-handed levee would have acted as a barrier to spillover, especially from the heads of turbidity currents. The lower, right-handed levee (eastern levee of LOC 1, Figs. 2.5b and 2.8) is the likely reason not only for the relatively easy spillover of sediment clouds from the body of the flows but also the occasional head spills. Sand beds of similar thicknesses (100 cm plus) have been reported from overbank sites across the lower left levee in the NAMOC channel setting (being in the northern hemisphere) but similar sand bodies have not been found in the right overbank across the higher levee (Hesse et al., 1987; 1996).

A detailed analysis of medium to thick bedded sandstones in a levee-overbank setting is necessary to evaluate their depositional affinities. Conventional interpretation of these massive sandstones is channeling in some form, but the variability
in processes revealed through the study of modern fans (Bouma et al., 1985; Piper and Stow et al., 1991) warrant more than such casual interpretation.

2.3 Skoorsteenberg (Fan 3)

2.3.1 Description

The two sections measured from Fan 3 at Skoorsteenberg, SK 1 and SK 2, are separated by 200 m. Profile SK 1 is located on the depositional strike section and SK 2 on the depositional dip section of Fan 3. The locations of the two profiles are shown in Figure 2.1. An overview of the outcrop is presented in Figure 2.13. Both the sections are approximately 19 m thick. A summary diagram with tie-lines delineating genetic

Figure 2.13 Overview of Fan 3 at Skoorsteenberg along profile SK 1. The uppermost bed is 6 m thick.
Intervals is shown in Figure 2.14. The detailed measured profiles are presented in Appendix A. The description of each genetic unit is represented below.

Interval from base to A-A': The interval from datum A to datum A' in SK 1 and SK 2 (up to ~ 6.5 m), respectively, is composed of very thin siltstone and silty-shale beds that are 0.5-5 cm thick (Fig. 2.14). The beds are characterized by parallel lamination and ripple cross-lamination. They represent Bouma Tc,d,e and Tc,d divisions.

Interval A-A' to B-B': The interval from datum A (level A-A', ~ 6.5 m) to datum B (level B-B', ~ 13 m) is characterized by thin-bedded very fine sandstones (8-30 cm, average 20 cm) that are flat-based and tabular in geometry (Figs. 2.13, and 2.14). They represent T_{ab} or T_{abc} Bouma divisions for the most part with the T_{a} division dominating (Fig 2.15). The base of these beds are characteristically groove-marked with the mean azimuth directed SSW-NNE. Interbedded with the turbidite beds are rare thin-bedded (4-10 cm) siltstone units characterized by small rip-up clasts, fine degraded plant debris and convolute laminations.

Interval B-B' to the top: This uppermost interval from datum B (level B-B') to the top of Fan 3 at Skoorsteenberberg is characterized by a single, very thick, amalgamated, fine-grained sandstone bed (Fig. 2.13 and Fig. 2.14). This bed is 6 m thick and is devoid of any observable sedimentary structures. The base of this bed is sharp and slightly undulatory but does not show any evidence of erosion.

### 2.3.2 Interpretation

Base to A-A': It is inferred that these thin beds were deposited from dilute turbidity currents at the distal end of the fan system. They could also be marginal deposits of shifting depositional lobes. They were deposited by minor flows which
were the local precursors of major ensuing flows that comprises the bulk of Fan 3 in this locality.

Interval A-A' to B-B': The grain-size, sedimentary structures and bed-thickness characteristics of these beds are similar to the attributes of the distal edges of depositional lobes described by Twichell et al. (1992 and 1995) from the Mississippi Fan Complex. This interval (datum A to B, Fig. 2.14) is probably a sublobe within the entire depositional lobe of Fan 3 at Skoorsteenberg. These sublobes are larger in scale than the available outcrops, hence the lateral terminations of these beds were not observed, neither in strike nor in dip sections. The beds were deposited mostly as top-truncated Bouma Sequences from relatively large turbidity currents. The currents finally deposited their load at the termination of channelized conduits and beyond. The channels effectively behaved as sediment bypass features that were finally filled at a

![Figure 2.14 Summary diagram from Skoorsteenberg representing depositional features.](image)

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Fig. 2.15 Typical top-truncated Bouma Sequences from the Skoorsteenberg sections, composed of \( T_a \) and \( T_b \) beds. Scale is 40 cm thick.

later time. Deposition at channel mouths occurred due to gradual decay of turbulence and some flow expansion related to unconfinement. In the \( T_{a,b,c} \) or \( T_{a,b} \) beds (\( T_a \) thickness \( >> \) \( T_{b,c} \) thickness, Fig. 2.15) the \( T_a \) subdivisions were deposited by a frictional freezing mechanism resulting in the formation of a "quick-bed" (Middleton, 1966a). The topmost part, including the \( T_b \) and \( T_c \) subdivisions, was deposited by the same flows that degenerated due to bulk deposition in the form of the \( T_a \) division. The dampened flow is only able to add a thin interval on top with a succession of sedimentary structures, as upper plane-bed parallel laminations (\( T_b \)) followed with or without by ripples (\( T_c \)). The \( T_{b,c} \) subdivisions indicate rapid sedimentation during the tractive stage of deposition (Middleton, 1966b). The interbedded thin siltstone beds
with small rip-up clasts, fine degraded plant debris and convolute laminations represent debris-flow deposits or slurry beds (Morris, 1973) that could have originated upfan or even farther updip indicated by the common presence of plant matter. Alternatively, the debris flows could have a more immediate source, e.g., resedimentation of fine-grained material derived from levee instabilities in the mid fan. The turbidite origin for fine-grained sandstones and debris-flow origin for the convoluted siltstones may be very similar to observed facies in depositional lobes of the outer Mississippi Fan (Schwab et al., 1996).

The sudden increase in bed-thickness and grain-size from datum A (~ 6.5 m, Fig. 2.14) to datum B is most likely in response to a variety of reasons. A progradational shift in deposition farther to this downfan depocenter is likely. This possibly resulted from a further fall in relative sea-level or major sediment influx related to renewed slope instabilities. Upfan channel avulsion, favoring the onset of active deposition by transporting sediments to this locality, is also a possibility. That this thin-bedded interval may be the marginal or lateral equivalent of thicker beds developed at the axis of depositional lobes, represents another possible scenario. The apparent thickening upward could also have been due to depositional topography resulting in compensation style lateral switching of lobes (Mutti and Sonnino, 1981; Bouma et al., 1995).

Interval B-B' to the top: A sudden increase in bed-thickness is in response to continued downfan or lateral shift of deposition due to progradation of Fan 3. The progradation is indicative of a sudden spike in sediment influx and could reflect either an autocyclic or an allocyclic forcing mechanism. It is difficult to extract either an
autocyclic or an allocyclic signature as the driving mechanism for the deposition of this very thick bed. The discussion presented in Section 2.4, however, is suggestive of an autocyclic causal mechanism.

2.3.3 Gamma Ray Pattern and Bed-Thickness Distribution

The gamma-ray profile measured along section SK 1 is presented in Figure 2.16. It represents higher values (~ 370 cps) towards the base to lower values (~ 260 cps) in the middle and top, indicative of a coarsening upward package. The upward coarsening is abrupt and not gradual, present at the base of the meter thick bed at ~ 6.5 m (level A, in Fig. 2.14). The sudden influx of sediments at this site is possibly related to upfan channel avulsions that directed sediments to this new locality or in response to a progradational shift in deposition to this downfan depocenter. The interval from ~ 6.4 to 12.5 m represents the log-motif typical of layered sheet sandstones encountered in the Gulf of Mexico (Mahaffie, 1994; Chapin et al., 1994), i.e. they are blocky but punctuated by breaks with higher gamma counts.

Bed thickness distribution from profile SK 1 is shown in Figure 2.17. Excluding the uppermost 6 m thick bed, the bed-thickness distribution is roughly trimodal (< 9 cm, 10-28 cm, and 35-45 cm).

2.3.4 The Skoorsteenberg Outcrop in a Regional Perspective

Determination of depositional settings and a conceptual interpretation of the growth of a turbidite system (Fan 3) has been attempted in this section. This approach has been recognized by Mutti and Normark (1991) as ideal to the development of a sufficiently precise chronostratigraphic scale to ensure that time-equivalent elements are compared within a proper lateral stratigraphic framework. The characteristic of the
Figure 2.16 Gamma-ray profile corresponding to measured section SK 1. It represents an abruptly coarsening upward profile.

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uppermost part of Fan 3 at Kanaalkop (in the upper/mid fan, see Figs. 2.2 and 2.3) and at Skoorsteenberg (downdip location, in the lower fan, Figs. 2.13 and 2.14) points to an interesting possibility. The top of Fan 3 at Kanaalkop is marked by the erosional Kanaalkop Channel and its compound fill. At Skoorsteenberg the top of Fan 3 is characterized by a 6 m thick amalgamated sandstone (datum B-B' to the top, Figs. 2.13 and 2.14). It appears that the erosional scour leading to the development of the Kanaalkop Channel could have transported sediments that built the uppermost 6 m thick massive bed at Skoorsteenberg (Figs. 2.13 and 2.14). The mid fan erosional surface at Kanaalkop could then be the time-correlative channel cut that effectively remained as a sediment bypass horizon in an upfan location for an extended period of time while the 6 m thick bed was deposited at Skoorsteenberg in a distal setting (see
Fig. 2.1). This temporal and spatial relationship is depicted in Figure 2.18. The majority of the sediments passing down the Kanaalkop Channel conduit (erosional vacuity) were very likely deposited in the upper reaches of Fan 3 in the Skoorsteenberg area as the compound 6 m thick amalgamated bed (correlative deposit). Most of the well documented modern fans represent this style of deposition, sequestering coarser sediments in the distal depositional lobes. The sediments get progressively finer upfan with consequent back-stepping of the system. Presence of 35-50 % sand in the lower fan depositional lobes of the Mississippi Fan as compared to 4-12 % in the middle and lower fan channel and channel-levees (Stow et al., 1985) is a typical example.

Figure 2.18 The inferred synchronicity between the channel scour at Kanaalkop and the very thick bed at the top of Fan 3 in Skoorsteenberg is depicted. A-A’ and B-B’ are datums in profiles SK 1 and SK 2 (see Fig. 2.14). The location of the Rondawel West outcrop is also indicated. Thicknesses are not to scale.
After the deposition of the 6 m thick bed in the downfan location at Skoorsteenberenberg, Fan 3 was characterized by upfan retrogression. The retrogressive, or backstepping mode of deposition, was most likely in response to a rise in relative sea-level resulting in consequent decrease in the volume of the density currents or upfan channel avulsion. Rise in relative sea-level shifted the main depocenter farther upfan and filled the channelized conduit in the updip location at Kanaalkop. The latter was already partially filled by deposition from turbidity currents that traveled past this locality during active deposition downfan. However, the 6m thick bed could have been deposited by another channel in the mid-fan setting other than the Kanaalkop Channel. But the extrapolated trend of the Kanaalkop Channel axis and the location of both the intervals (at Kanaalkop and Skoorsteenberenberg, Fig. 2.1) at the very top of Fan 3 suggests the Kanaalkop Channel to be the most likely candidate for depositing the 6 m thick interval at Skoorsteenberenberg.

2.4 Rondawel West (Fan 3)

2.4.1 Description

Two profiles were measured in Fan 3 at Rondawel West that are separated by 50 m. The base of Fan 3 is not exposed in this locality. The measured thickness of profiles RW 1 and RW 2 is ~ 9 m. The detailed sections are presented in Appendix A. The location of the profiles are shown in Figure 2.1. An overview of the outcrop (Fig. 2.19) is presented. The measured sections are described in two intervals as indicated in the summary diagram (Fig. 2.20).

Base to A-A': This interval from the base to datum A (Level A-A'; Fig. 2.20), is characterized by thin siltstone/silty-shale beds that are interbedded with very fine
Fig. 2.19 An outcrop photograph of the Rondawel West section. The bush is 2 m high.

grained thin-bedded sandstones. The siltstones (2-5 cm thick) are commonly ripple laminated on a very fine scale and occasionally parallel laminated. The very fine sandstones (very fine lower, vfL) are 5-25 cm thick and are mostly massive Ta beds with or without Tb and Tc intervals. These thicker beds are predominantly tabular but have considerable variation in thicknesses within the length of the outcrop, which is ~100 m in extent. As a result they appear somewhat lens-shaped. Amalgamation surfaces commonly divide beds internally into subunits. The subunit thickness and lengths vary due to the wavy and or discontinuous nature of the amalgamation contacts. Rip-up clasts are commonly associated with the upper surfaces of the beds and are distributed on certain bedding planes. The meter plus interval just below level
A-A’ (Figs. 2.19 and 2.20), is characterized by thin-bedded siltstones. A minor proportion of siltstone beds are characterized by the presence of disrupted/convolute bedding and outsized clay-clasts.

Interval A-A’ to B-B’: This interval from datum A (level A-A’) to datum B (level B-B’) is characterized by thick beds with common thin interbeds (Fig. 2.20). The beds are 30-300 cm thick and are highly variable in thickness. The thicknesses are commonly seen to change drastically within the length of the outcrop indicative of the lobate shape of the individual beds. They are primarily massive Tₐ beds without any observable laminations. Amalgamation surfaces are common, separating a single bed
into two or more subunits when traced laterally along the outcrop. Large flutes are commonly present.

2.4.2 Interpretation

Base to A-A': This interval appears to be under the effect of active deposition resulting in beds with minor but observable variations in thickness, scours in the form of wavy bases, amalgamated contacts and residual lags as rip-up clasts. The effects are most likely due to increased flow turbulence possibly related to transitional flows in a channel-sheet transition area (Mutti and Normark, 1991; Chapin et al., 1994). The meter plus thick siltstone bed just below A-A’, probably represents the waning activity of the feature that deposited most of this interval (probably a sourcing channel farther updip, likely to be the West Channel in the Kanaalkop area, see Figs. 2.5 and 2.8). The siltstone beds with disrupted/convolute bedding can be interpreted as being deposited by minor debris flows.

Interval A-A' to B-B': Large flutes at the bases of certain beds are indicative of scouring in this locality. The presence of relatively large scours (mega flutes, 1.5-2 m wide) acting as short term sediment bypass features, common rip-up clasts occurring as residual lag deposits, lobate geometry of the medium to thick beds, and the location between known channel-fill and distal sheet deposits support the interpretation that Rondawel West represents a channel-sheet transition facies.

2.4.3 Gamma Ray Pattern and Bed-Thickness Distribution

The gamma-ray profile measured along RW 1 is devoid of any significant trend (Fig. 2.21). The thinner-bedded intervals are, however, characterized by higher gamma-counts than the medium and thick beds. The difference in gamma-counts
Figure 2.21 Gamma-ray profile measured from section RW 1. Refer to measured section in Appendix A for details.
between beds of varying thickness is not pronounced due to masking by the high abundance of feldspars and volcanic-rock fragments in the rocks. Towards the very top (6-8 m), the profile progressively coarsens upward corresponding to the amalgamated massive sandstones (Figs. 2.19 and 2.20).

The bed thickness distribution from section RW 1 is presented in Figure 2.22. The distribution is roughly bimodal, 2-25 cm thick and 30-40 cm thick. The distribution is heavily skewed towards lower bed-thickness values.

2.4.4 The Rondawel West Outcrop in a Regional Perspective

The thicker beds at the top of the Rondawel West outcrop (interval AA'- BB', in Figs. 2.19 and 2.20) are inferred to be related to the upfan and downfan expressions of the upper reaches of Fan 3 in the Kanaalkop and Skoorsteenberg areas, respectively. As discussed before, the Kanaalkop area is the site of mid-fan channel levee-overbank deposits and the Skoorsteenberg area is the site of deposition of distal sheet deposits. The Kanaalkop Channel at the top of Fan 3 at Kanaalkop, is an erosional feature through which much of the sediment bypassed resulting in active deposition in distal settings at Skoorsteenberg and Rondawel West (graphically shown in Fig. 2.18). The thicker beds at the top of Fan 3 at Skoorsteenberg and at Rondawel West can be considered as time-equivalents of the interval through which the Kanaalkop Channel acted as a sediment bypass feature (see Fig. 2.18).

The underlying deposits of Fan 3 at Rondawel West (interval from base to datum A in Fig. 2.20) and Skoorsteenberg (base to B, see Fig. 2.14) however, can be related to the older West Channel in the Kanaalkop area (not preserved in outcrop, see section on the Kanaalkop outcrop and Figs. 2.5 and 2.8). The lower part of Fan 3 at
these two downfan sites (Skoorsteenberg and Rondawel West) are possible time equivalents of the levee-overbank wedge exposed in the lower part of Fan 3 at Kanaalkop (LOC 1 in Figs. 2.3 and 2.8) which was sourced from the West Channel (Fig. 2.5 and 2.8). The depositional break seen at Kanaalkop (thin-bedded interval from datum C to D, top of LOC 1 in Fig. 2.3) representing the waning activity of the older West Channel may also be represented at Rondawel West by a meter thick thin-bedded, sediment starved interval just below datum A (Fig. 2.20).

2.5 Blaukop (Fan 5)

2.5.1 Description

The relationship between thin-bedded siltstones and a massive channel fill is well exposed in Fan 5 at Blaukop (Fig. 2.23). The genetic link between a channel fill and its laterally equivalent thin-bedded levee-overbank deposits are inferred from the
relationship exposed at this location. A few thin-beds are seen as continuations from within the confines of the channel going into the levee-overbank area (Fig. 2.24). A similar relationship between channel and levee-overbank deposits is exposed in the Permian Brushy Canyon Formation, West Texas (Basu, 1995). One representative profile from this site, BK 1 (see Fig. 2.1 and Appendix A), is going to be discussed in detail.

Base to ~ 2.75 m: The base of Fan 5 is not exposed at this locality. The very thin to thin-bedded interval from the base to ~ 2.75 m in profile BK 1 (Fig. 2.25) is characterized by medium to coarse siltstones. The bed thickness distribution has three modes, < 9 cm, 10-15 cm, and 20-45 cm (Fig. 2.26). The two thinner bedded
Figure 2.24 The spatial relationship between the levee-overbank and channel fill deposits at Blaukop. The location of profile BK 1 and Bk 92.1 are shown.

Fig. 2.25 Summary diagram showing the inferred depositional environments of the 6m thick section of Fan 5 at Blaukop.
Figure 2.26 Bed-thickness distributions, based on profile BK 1, show three modes, < 9 cm comprising 83 %, 10-15 cm comprising 9 %, and 35-34 cm comprising 8 % of the measured beds. A total of 43 beds were measured.

populations are characterized by parallel laminations and ripple-cross laminations, the latter being abundant in the 10-15 cm group. The 35-45 cm thick group is characteristically climbing ripple laminated (Type A climbing ripples of Jopling and Walker, see Fig. 2.4). These three bed thickness groups are interbedded with each other. The < 9 cm and 10-15 cm bed-thickness populations have wavy lower and upper bedding contacts. The ripple-cross laminations in the thin-bedded intervals (<10 cm and 10-15 cm groups) are directed NNE while the climbing ripples in the medium bedded units (35-45) cm) are directed NE. The associated channel fill has its margin exposed and the paleocurrent direction observed from flute and prod marks is ENE. This relationship is depicted in Fig. 2.27. There is a conspicuous deviation in flow direction between the interpreted levee-overbank deposits and the sourcing channel.
2.75 m to the top: From ~ 2.75 m onwards to the top of the profile (see Fig. 2.25) the layers are thin-bedded very-fine sandstones (vfL). These are massive beds with few parallel laminations seen towards the tops. Very thin interbeds are rare in this interval. The sandstone beds are commonly amalgamated and have occasional rip-up clasts. The bases are mostly flat to slightly undulatory with the exception of a 1.5 m thick bed (at ~ 3.5 m level, see profile BK 1 in Appendix A), the base of which is erosional.

2.5.2 Interpretation

Base to 2.75 m: The two thinner bedded populations (< 9 cm and 10-15 cm) exhibit parallel and ripple cross laminations but is devoid of any climbing ripples. This suggests deposition from minor spillover flows in a levee-overbank setting. The greater deviation (~ 60°; Fig. 2.27) between the channel trend and the paleoflow direction from these thin-beds is also suggestive of spillover of suspended sediment clouds from relatively smaller flows passing down the channel. The wavy bedding contacts in these thin-beds are attributed to deposition over a ripple-field in a levee-overbank setting.

Figure 2.27 Sketch showing the variations in paleocurrent directions from the various facies at Blaukop.
overbank setting. The bedding contacts mimic the depositional topography of the ripple field.

The presence of climbing ripples (Type A, Jopling and Walker, 1968) in the 20-45 cm bed thickness group is suggestive of these beds being deposited from larger flows that are charged with a high suspended sediment load. The lesser deviation in respective paleocurrent directions (~ 40°, Fig. 2.27) between the channel fill and these thin-bedded (20-40 cm) siltstones with climbing ripples (Fig. 2.27) is due to spillover into the levee area from relatively larger flows. The angular deviation is lesser in this case due to greater inertia of the spillover plumes having originated from larger and faster flows passing down the channel.

2.75 m to the top: This interval is inferred to be channel margin deposits related to renewed flow along the older channel as seen along profile BK 92.1 (Fig. 2.24). This channel fill is probably the result of an offshoot, following a period of dormancy represented by a minor diastem, of the underlying channel and is an integral part of the same system.

2.6 Bizansgat (Fan 4)

2.6.1 Description and Interpretation

Bizansgat is located in the southern portion of the field area as shown in Fig. 2.1. Profile BZ 1 is measured from a short but well exposed section of Fan 4. This section represents a passive fill of the upper part of a channel in Fan 4 (Bouma, 1994; Fig. 2.28).

The profile is 3.5 meters thick and is characterized by thin-bedded siltstone and silty shale units with base-truncated Bouma Sequences (see BZ 1 in Appendix A).
Beds are on an average 3 cm thick (range ~ 0.5-10 cm, Fig. 2.29). Beds having ≤ 1cm thickness are common. The most commonly occurring sedimentary structure is parallel lamination which is often difficult to observe due to lack of variation in grain-size. Structureless siltstones and silty shales are also common. Incipiently developed ripple cross-laminations are present but are not common. The structural sequence (Bouma divisions; Bouma, 1962) in individual beds form base-truncated Bouma Sequences, namely Tc,d,e, or more commonly Td,e. Each of these beds are fining upward. Siltstones are capped by silty shale to shale partings, < 1 cm thick, which are rich in organics. Degraded plant fragments are very common in the millimeter scale partings. These partings represent deposition of the very fine grain-size fraction from suspension. They are most likely deposited from the tail of turbidity currents that have passed through a particular location. Organics are fairly well dispersed in the siltstone beds but the
density is lower when compared to the top of each bed. Toward the top of the section are a few thin to medium bedded units that are composed of very fine grained sandstones. They are mostly massive with or without convolute bedding and rip-up clasts. They are interpreted to represent renewed activity in the channel that ensued after a period of relative dormancy.

2.6.2 Gamma Ray Pattern and Bed-Thickness Distribution

The gamma-ray profile from this locality (Fig. 2.30) is characterized by the highest gamma-counts (~ 425 cps or more) of all the thin-bedded turbidite localities. There are less variations in gamma intensities within the interval representing the passive channel fill (0-2.7m, in Fig. 2.30). The intensities become lower (250-300 cps)
Figure 2.30 Gamma-ray profile from section BZ 1. It is characterized by very high gamma-ray intensities towards the base that represent a passive channel fill. Progressively higher values towards the top reflects renewed activity in the channel.
towards the top which most likely represents renewed activity in the channel. The bed thickness distribution from section BZ 1 is presented in Figure 2.31. The beds are thin-bedded and are less than 10 cm thick within the interval, 0-2.7 m, representing the passive channel fill.

![Bed thickness distribution](image)

**Figure 2.31** Bed-thickness distribution from measured section BZ 1. A total of 75 beds were measured.
CHAPTER 3

GRAIN-ORIENTATION RELATED TO PALEOFLOW CONDITIONS IN VARIOUS SUBENVIRONMENTS OF A FINE-GRAINED SUBMARINE FAN

3.1 Introduction

Grain orientation developed due to primary depositional processes in clastic rocks has been intensively studied over the last decades. Apart from direct field measurements of pebbles in unconsolidated sediments, all other methods, especially when sandstones and finer-grained sediments are concerned, are laboratory based. The more commonly used techniques have employed photometric (microscopic), electric, and magnetic methods of sedimentary fabric determination. In the photometric method oriented thin-sections are made and the dominant quartz c-axis orientation is determined (Martinez, 1958). This technique measures the variation in intensity of monochromatic light passing through a thin-section under crossed nicols with an inserted gypsum plate during a 360° rotation of the stage (Martinez, 1958). In the dielectric anisotropy method, anisotropy is a function of the variation in dielectric constant of grains under different orientations (Winkelmolen, 1972). In the magnetic method of grain-fabric determination the carriers of anisotropy are ferro-magnetic grains and the method is a fast way of obtaining quantified information on grain-orientation (Hamilton and Rees, 1970a; Jackson and Tauxe, 1991). In the specific technique used in this study, anisotropy of isothermal remanent magnetization (IRMA), measurements are made after all preexisting magnetization are erased and a laboratory induced magnetization is imposed. The controlled magnetization is imposed
along specified sample axes and the bulk anisotropy residing in the magnetic grains is brought out. The magnetic methods, in general, have focused mainly on recent sediments from deep-sea cores, but sedimentary rocks as old as the Precambrian and early Paleozoic have also been analyzed with success (Tarling and Hrouda, 1993; Lu and McCabe, 1993). There have been successful attempts at inferring paleocurrent direction from sedimentary (Ellwood and Ledbetter, 1979; Schieber and Ellwood, 1988) and volcanic rocks (Ellwood, 1980; Knight and Walker, 1988) with or without traditional current markers, using rock-magnetic techniques. Several studies have been conducted that show that grain-lineations determined by more conventional optical methods, like photometry and petrography, yield concordant results with the rock-magnetically determined grain alignment (Taira and Lienert, 1979).

3.2 Comparison Between Different Methods of Anisotropy Measurements

1. Lithologic control: Photometric and dielectric methods work best for quartz arenites. This is because both these methods are based on the variation of interference color and the dielectric constants, respectively, of quartz varying in phase with the c-axis. Quartz is an uniaxial mineral while feldspar is biaxial. Presence of significant amount of feldspars and rock-fragments, as in arkoses and lithic sandstones, tend to make assessment and interpretation of the results difficult (Martinez, 1958). The magnetic methods are solely based on the ferro-magnetic minerals in a rock. All common clastic rocks and carbonates carry sufficient quantities of ferro-magnetic minerals for the sensitive magnetic methods to be applied.

2. Bulk versus two-dimensional anisotropy: The photometric method is thin-section based and as such the orientation of the thin-section controls whether the
maximum anisotropy is revealed. The dielectric and magnetic methods are bulk techniques based on small cores that represent the anisotropy as a vector unlike the photoelectric method where only the apparent azimuth of anisotropy is obtained. The dielectric and magnetic methods determine bulk anisotropies in a true three-dimensional sense.

3. Basic assumptions: In the photometric and dielectric method it is assumed that the long-axis of quartz grains are parallel to their c-axis direction. One is based on the interference color varying with the projected orientation of the quartz c-axis and the other is based on the dielectric constant varying with the orientation of the same. Conflicting reports are present in the literature regarding the orientation of the quartz c-axis and the long axis of detrital quartz grains. Wayland (1939), Krynine (1940), and Martinez (1958) state that the long-axes of eroded quartz grains tend to coincide with the c-axis directions. Ingerson and Ramisch (1942) however, concluded that quartz has no pronounced tendency to fracture parallel to the c-axis and elongation resulting from differential abrasion is not likely to develop parallel to the c-axis. Rowland (1946) demonstrated that more than 70% of the quartz grains formed angles in excess of 50° to the quartz c-axes in his study. The magnetic methods assume that the bulk anisotropy can be represented as a triaxial ellipsoid and statistical tests reveal that it is correct.

4. Usage and accessibility: The photometric method is by far the best suited for determination of anisotropy in terms of equipment needed and the expense involved in the procedure. The dielectric and magnetic methods require drilling of small cores either in the field or from hand samples in the laboratory. The basic equipment
necessary for these two methods are fairly simple but are not commonly available. The magnetic method in particular requires a magnetically shielded rock-magnetic laboratory which is relatively expensive to maintain.

3.3. Conceptual Background

Magnetic data for any sample may be expressed as a triaxial ellipsoid whose major, intermediate and minor axes represent the relative susceptibility magnitudes and azimuths (Wolff, 1989). The total ellipsoid shape and orientation reflects the overall directional fabric of the sample, as expressed by magnetic mineral grains (Khan, 1962). Rock-fabric determination by anisotropy of isothermal remanent magnetization (IRMA) has this underlying assumption that is substantiated by repeated studies (McCabe et al., 1985). The IRMA technique uses a strong field to magnetize a sample along different sample axes. The field used is strong enough to saturate magnetic particles. Any preexisting magnetization residing in the magnetic grains is completely destroyed by this laboratory treatment. The magnetization that is induced will be strongest parallel to the predominant long-axis of the magnetic grains in the sample (C. McCabe, personal communication, 1997). The presence of anisotropic grains is a basic requirement for this method to work but the directional coherence of long-axes in the samples are also important for a sample to have good bulk anisotropy.

In the absence of currents on a horizontal depositional surface, deposition is controlled only by gravitational settling of grains. Platy (oblate) grains lie on the depositional surface or the bedding plane. The more rod-like (prolate) grains will also lie on the bedding plane but with their long axes randomly dispersed. The resultant fabric will be strongly oblate and confined to the bedding plane with the minimum
axes of grains being perpendicular to bedding (Tarling and Hrouda, 1993). In the presence of slope and a lack of currents the more rod-like grains tend to roll down the gradient. The grains that actually roll down are dependent on their prolateness and the dip and roughness of the depositional surface. The resultant fabric is strongly oblate but with a superimposed lineation perpendicular to the maximum slope. With increase in slope the superimposed lineation increases until the angle of repose for the grains is reached and slumping sets in. In such a case the fabric mimics one affected by currents.

In the presence of currents there are two main effects on the oblate and prolate grains (Tarling and Hrouda, 1993). Firstly, the oblate grains are lifted at their leading edges which results in imbrication. The minimum shape axes are tilted by increasing amounts (up to 20°) from the vertical, as the velocity increases. Secondly, the more prolate grains impose a lineation on the primarily oblate fabric, the lineation direction being dependent on the current velocity and the slope of the depositional surface. The long axis of the anisotropy ellipsoid will lie on the bedding plane and the short axis will be perpendicular to it (Fig. 3.1). The grain long-axis orientation is either parallel or perpendicular to paleoflow directions. The present study describes the relationship between grain long-axis orientation/percent anisotropy and flow characteristics from thin-bedded turbidites.

3.4. Methodology

Oriented samples were collected from six locations in the Tanqua Karoo subbasin. These locations were based on well-developed thin-bedded deposits spanning a variety of subenvironments in the submarine fans. The next step was to
drill 2.2 x 2.5 cm cores from the oriented samples for the rock magnetic study. For the anisotropy study, isothermal remanent magnetization (IRM) was imparted, using a pulse magnetizer set at a saturation value of 450 milli Teslas (mT). IRM was given along nine specified axes for calculation of the anisotropy ellipsoids using the method of McCabe et al. (1985). The best fit anisotropy tensor was determined using a least squares method. Percent anisotropy = 100(K_{\text{max}}-K_{\text{min}})/K_{\text{int}}$, where $K_{\text{max}}$, $K_{\text{int}}$ and $K_{\text{min}}$ are maximum, intermediate and minimum anisotropy axes (McCabe et al., 1985). The determination of the carrier phase of magnetism was done by stepwise IRM acquisition, starting at 50 mT and going up to 1100 mT.

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3.5. Results

Subenvironments from which samples were collected, from an upfan to a downfan location (see Fig. 2.1), are upper mid-fan levee-overbank (Fan 3, Kanaalkop), mid-fan passive channel fill (Fan 4, Bizansgat), mid-fan channel-fills (Fan 5, Blaukop), mid-fan channel and levee-overbank (Fan 5, Blaukop), lower-fan channel-sheet transition (Fan 3, Rondawel West), and lower-fan distal-sheet sandstones (Fan 3, Skoorsteenberg). The $K_{\text{max}}$, $K_{\text{int}}$, $K_{\text{min}}$, lineation ($L$), foliation ($F$), and % anisotropy, for each specimen from the various subenvironments are presented in Appendix B. $K_{\text{max}}$, $K_{\text{int}}$, $K_{\text{min}}$, $L$ and $F$ are the maximum, intermediate and minimum axes, lineation and foliation of anisotropy ellipsoids, respectively. Figures 3.2a to f represent equal area stereonet plots for $K_{\text{max}}$ and $K_{\text{min}}$ for each subenvironment. It is observed that in all the subenvironments the $K_{\text{max}}$ plunges at shallow angles (~$0^\circ$-$25^\circ$) and $K_{\text{min}}$ has very steep plunges (~$65^\circ$-$90^\circ$). Most of the lineation represented by the $K_{\text{max}}$ vectors from the various subenvironments has azimuths in the acute arcs bounded by NNW-SSE to WNW-ESE. The percent anisotropies from the various environments are presented in Figure 3.3. The primary magnetic carrier was found to be primarily magnetite as revealed by saturation of IRM experiments (Fig. 3.4). In the plot of field versus magnetization in Figure 3.4, the samples are seen to saturate at approximately 250 mT demonstrating magnetite to be the predominant magnetic mineral present.

Scanning electron microscope images revealed that the magnetite grains are predominantly scattered within the fine-grained matrix which suggests their detrital origin. They are approximately 2-4 μm long and have aspect ratios of roughly 3:1 (Fig. 3.5). This demonstrates an intrinsic anisotropy associated with the magnetite grains.
Figure 3.2 Equal area stereonet plots of sample maximum ($K_{\text{max}}$, squares) and sample minimum ($K_{\text{min}}$, circles) axes of anisotropy ellipsoid. Open and solid symbols represent upper and lower hemisphere projections, respectively. (a) upper mid-fan levee overbank (Fan 3, Kanaalkop); (b) mid-fan passive channel fill (Fan 4, Bizansgat); (c) mid-fan channel-fill (Fan 5, Blaukop); (d) mid fan channel and levee-overbank (Fan 5, Blaukop); (e) lower fan channel-sheet transition (Fan 3, Rondawel West); and (f) lower fan distal-sheet sandstones (Fan 3, Skoorsteenberg). (Fig. 3.2 Con’d)
Figure 3.3. Percent anisotropies from the six depositional settings: upper mid-fan levee-overbank (Kanaalkop), passive channel fill (Bizansgat), mid-fan channel-fill (Blaukop), lower mid fan levee-overbank (Blaukop), channel-sheet transition deposits (Rondawel West), and distal sheet sandstones (Skoorsteenberg). The number of samples, mean anisotropies and standard deviations are represented.

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Figure 3.4. IRM acquisition curves. Saturation magnetization at 200-300 mT indicates that the predominant remanence carrier is magnetite.

3.6. Discussion

The dataset shows that the grain fabric in the samples has a depositional signature that has not been altered by later tectonics. This is demonstrated by the unique combination of the short axes ($K_{\text{min}}$) of anisotropy ellipsoids being oriented perpendicular to bedding planes and the long axes ($K_{\text{max}}$) lying in bedding planes. This is contrary to a tectonic fabric where $K_{\text{min}}$ is parallel to bedding and is directed parallel to the layer-parallel shortening direction. The directions of the $K_{\text{max}}$ axes of anisotropy ellipsoids of the Tanqua samples are hence interpreted to be related to paleoflow conditions i.e. the orientation of $K_{\text{max}}$ is a signature of primary deposition. It should however be borne in mind that the magnetic particles are much smaller (clay-sized) compared to the framework grains which are coarse silt to very fine sand sized. The shielding effect could have implications that are not being considered for lack of methods to evaluate its significance. The results are being discussed in two parts,
Figure 3.5 The fine-grained magnetites occur in the matrix of the Tanqua Karoo siltstones and sandstones. A typical magnetite grain is marked with an arrow in the figure. They are 2-4 μm long and demonstrate aspect ratios of ~ 3:1. Bar is 10 μm long.
1) interpretation of the $K_{\text{max}}$ directions, and 2) interpretation of the variation in % anisotropy in samples from different subenvironments. An attempt is made to explain the $K_{\text{max}}$ directions and percent anisotropy in the light of flow velocities and depositional style (traction or suspension, flow confinement etc.) which varies from one subenvironment to the other.

3.6.1 $K_{\text{max}}$ Orientations and Depositional Environment

$K_{\text{max}}$ orientations with respect to current flow are difficult to evaluate due to the multiple factors that govern it such as current velocity, depositional slope angle, depositional slope roughness, and grain-shape and -size. The $K_{\text{max}}$ orientations in most of the samples are aligned with an approximately northwestern azimuth irrespective of the depositional environment sampled (azimuths restricted to the acute arcs bounded by NNW-SSE and WNW-ESE). This relative uniformity of $K_{\text{max}}$ directions between subenvironments was unexpected because a variation was anticipated. From earlier works in other areas, most sedimentary fabric measurements determined by magnetic methods have a common parallelism between $K_{\text{max}}$ directions and paleocurrent flow (Hamilton, 1963; Ellwood, 1980; Flood et al., 1985). This is primarily the case for sediments that are deposited by weak currents. It has been observed that currents with higher velocities, greater than a few centimeters per second, can align the more prolate grains roughly perpendicular to flow direction (Granar, 1958; Ellwood and Ledbetter, 1977; Ledbetter and Ellwood, 1980). Therefore, it seems justified that the suite of samples from the Tanqua Karoo be divided into two populations. The first group having $K_{\text{max}}$ orientations roughly parallel to observed flow direction (those environments that have lower flow velocities, e.g., levee-overbank at Kanaalkop, and
top-fill of channel at Bizansgat), and the second group with $K_{\text{max}}$ orientations that are roughly perpendicular to flow direction (those environments with relatively higher flow velocities, e.g., channel-fill and levee-overbank deposits at Blaukop, channel-sheet transition deposits at Rondawel West, and distal sheet-sandstones at Skoorsteenberg). Table 3.1 summarizes the flow-parallel versus flow-normal $K_{\text{max}}$ orientations from the various subenvironments and their relation to traction or suspension modes of deposition as discussed in the following discussion. Amongst the group of rocks that supposedly have flow-parallel $K_{\text{max}}$ direction are the levee-overbank deposits from the Kanaalkop area (Fig. 3.2a). They were deposited by lateral spillover of sediment clouds that ride above and behind the bottom-hugging head of turbidity currents advancing downfan along channelized courses. The sedimentary structures observed in these deposits are climbing ripples (Types B and sinusoidal laminations of Jopling and Walker, 1968) which are indicative of a variable but consistently high suspended-load/traction-load ratio. It is inferred that the higher tractive velocities needed to align the grains normal to flow are lacking and the flow is only able to align grains parallel to paleocurrent direction (Granar, 1958). The other group that has parallelism of $K_{\text{max}}$ lineations and paleocurrent flow are passive channel-fills at Bizansgat (Fig. 3.2b). In this subenvironment the traction flow velocities are low due to the lack of activity in the channel. Hence the flows are only able to align the grains approximately parallel to flow. The general lack of agreement in directions of the $K_{\text{max}}$ vectors in the passive channel-fills as opposed to the uniformity of $K_{\text{max}}$ directions in levee-overbanks (Figs. 3.2a and 3.2b) is most likely related to their mode of deposition. Top-fills of channels are deposited from decaying...
Table 3.1 Summary table showing how $K_{\text{max}}$ direction, anisotropy % and depositional mechanism are related to depositional environments. Traction versus suspension mode of sedimentation is suggested as the key to observed variations.

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>$K_{\text{max}}$ direction</th>
<th>Anisotropy</th>
<th>Depositional mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levee-overbank (Kanaalkop)</td>
<td>flow parallel</td>
<td>Low, 5.48 %</td>
<td>dominantly suspension, high suspension load/bed-load ratio</td>
</tr>
<tr>
<td>Passive channel-fill (Bizansgat)</td>
<td>flow parallel</td>
<td>Low, 4.38 %</td>
<td>suspension deposition from decaying flows</td>
</tr>
<tr>
<td>Active channel-fill (Blaukop)</td>
<td>flow normal</td>
<td>High, 13.26 %</td>
<td>traction, high flow velocity, confined flow</td>
</tr>
<tr>
<td>Levee-overbank (Blaukop)</td>
<td>low normal</td>
<td>Intermediate, 6.06 %</td>
<td>dominantly traction, lower suspension load: bed-load ratio</td>
</tr>
<tr>
<td>Channel-sheet transition (Rondawel West)</td>
<td>flow normal</td>
<td>High, 6.62 %</td>
<td>traction, scouring and subtle channeling common, relatively confined flow</td>
</tr>
<tr>
<td>Distal sheet-sandstones (Skoorsteenberg)</td>
<td>flow normal</td>
<td>Low, 3.85 %</td>
<td>traction/suspension, sudden flow-freezing</td>
</tr>
</tbody>
</table>

flows lacking in a dominant direction that passively fills up the channel whereas levee-overbank sediments are deposited from consistently directed spillover plumes.

The $K_{\text{max}}$ directions observed in mid-fan channel-fills (Blaukop, Fig. 3.2c), mid-fan levee-overbank deposits (Blaukop, Fig. 3.2d), channel-sheet transition deposits (Rondawel West, Fig. 3.2e), and lower fan distal-sheet sandstones (Skoorsteenberg, Fig. 3.2f) are flow perpendicular. The flow directions from sole-marks and current ripple laminations indicate a NE to NNE paleoflow, whereas the $K_{\text{max}}$ directions have an azimuth ranging from NW-SE to WNW-ESE. This flow normal $K_{\text{max}}$ lineation is attributed to higher traction flow velocities in this
subenvironment. Observations from Wheeler Gorge, California (Rees, 1965), and the Vema Channel, South Atlantic (Ellwood and Ledbetter, 1979) have demonstrated the flow-normal orientation of magnetic grains under high current velocities.

The two levee-overbank settings studied, Kanaalkop (Fig. 3.2a) and Blaukop (Fig. 3.2d), supposedly have different responses to grain alignments. The levee deposits at Kanaalkop in the upper mid-fan setting are characterized by Type B (stoss-side preserved) and sinusoidal climbing ripple laminations (Jopling and Walker, 1968) which imply a high suspended-load to bed-load ratio. This suggests that tractive forces were minimal and hence flows were only able to align the grains parallel to themselves (Fig. 3.2a). On the other hand the levee-overbank deposits at Blaukop in the lower mid-fan setting are characterized by Type A climbing ripples (stoss-side eroded) and current ripple-laminations that suggest greater influence of traction. This has resulted in current normal K\textsubscript{max} orientations at Blaukop (Fig. 3.2d).

### 3.6.2 Percent Anisotropy and Depositional Environment

The mean anisotropy values for the various subenvironments are presented in Table 3.1. The upper/mid-fan levee overbank at Kanaalkop has a mean of ~ 5.48 % (σ = 1.29), mid-fan top-fill of channel at Bizansgat ~ 4.38 % (σ = 1.29), mid-fan channel fill at Blaukop ~ 13.26 % (σ = 6.04), lower-fan channel-sheet transition at Rondawel West ~ 6.62 % (σ = 2.46), mid-fan levee-overbank at Blaukop ~ 6.06 % (σ = 1.79), lower-fan distal sheet sandstones at Skoorsteenberg ~ 3.85 % (σ = 0.72) presented in Fig. 3.3. A fair amount of scatter is present in the values which makes interpretations based solely on % anisotropy difficult. The following interpretations are based primarily on % anisotropy but are substantiated by systematic variations in the K\textsubscript{max}.
directions. The relationship between paleoflow condition and direction to $K_{\text{max}}$ orientation and $\%$ anisotropy is summarized in Table 3.1. It is evident that channel-fill deposits and those that have a channelized component (e.g., channel-sheet transition) have higher percent anisotropies. On the other hand, those units that were deposited from unconfined flows (levee-overbank and distal-sheet sandstones) have relatively low values of percent anisotropy. The channel-fill deposits at Blaukop are supposed to have been deposited by fast flowing traction currents that developed the highest mean anisotropy of 13.26 $\%$ in the amalgamated fine-grained sandstones. It has been suggested that the ‘traction carpet’ mode of sediment transport at the base of turbidity currents lead to flow normal lineation in grains (Ledbetter and Ellwood, 1980). The $K_{\text{min}}$ orientations in the channel-fill deposits are most aberrant from their expected bedding-normal orientations (Fig. 3.2c). This is also suggestive of higher flow velocities in an active channel setting (Tarling and Hrouda, 1993). The flows from which the channel-sheet transition facies at Rondawel West were deposited were relatively unconfined. The effect of subtle channeling and possible hydraulic jumps could be attributed to the relatively high mean anisotropy of ~ 6.62 $\%$. A dominantly traction carpet mode of deposition is envisaged in this setting also. The distal-sheet deposits from Skoorsteenberg have a low mean anisotropy of 3.85 $\%$, due to deposition by a flow-freezing type of mechanism which hinders tractional reworking (Lowe, 1982). This is due to unconfined flows at channel mouths where flow expansion promotes deposition. The upper mid-fan levee-overbank deposits at Kanaalkop are characterized by a moderate mean anisotropy of ~ 5.48 $\%$, probably owing to the possible lack of strong traction currents. Observed sedimentary structures
(Type B, stoss side preserved, and sinusoidal climbing ripple-laminations), indicate deposition from lateral spill-over sediment clouds that are characterized by high suspended-load to bed-load ratio. The lower mid-fan levee-overbank deposits at Blaukop have an average anisotropy of 6.06%. This slightly higher value than the Kanaalkop levee-overbank deposits most likely reflects the greater effect of traction as evidenced by current ripples and Type A (stoss side eroded, see Fig. 2.6) climbing ripples. The passive channel-fills at Bizansgat have an average anisotropy of 4.38%. This low anisotropy is a signature of a good foliated fabric with lack of superimposed lineation due to the absence of strong and uniform tractive flows.

3.7 Conclusions

The conclusions based on the IRMA study are:

1. The IRMA method is a sensitive technique compared to other methods of grain-fabric determination that reveals information on grain orientation based on observations on magnetic minerals. It has multiple advantages over more traditional methods of sedimentary fabric determination.

2. The information on grain-fabric in the present study is revealed by magnetite grains which are the predominant carrier of magnetization in the Tanqua Karoo deposits.

3. In the Tanqua Karoo thin-bedded turbidites, the magnetite grain long axes are flow-parallel in depositional environments characterized by low flow velocities e.g., passive channel-fills and certain levee-overbanks. Flow-normal lineations are predominant in depositional environments with high flow velocities like active
channel-fills, channel-sheet transition deposits, distal sheet sandstones, and certain levee-overbanks sediments.

4. Percent anisotropies are directly correlated with flow confinement. It is highest in depositional environments with a channelized (confined flow) component, e.g., active channel-fills and channel-sheet transition deposits. Percent anisotropies are consistently lower in depositional environments characterized by unconfined flows e.g., distal-sheet sandstones, levee overbanks deposits, and passive channel-fills.

5. Studies like the present have the potential to elucidate the relationship between magnetic grain-orientation and flow characteristics in subenvironments of a particular depositional system (e.g., submarine fans). The approach has far reaching applications because depositional signatures can be extracted without ambiguity, especially when used in conjunction with traditional facies analysis tools. The predictable variations in percent anisotropies can be used to answer questions presently raging in the field of sediment gravity flows relating to the precise nature of deposition, specifically, turbidity currents versus debris-flows.

6. The IRMA technique can be used as a predictive tool to locate reservoir quality clastic deposits, by comparing the nature of grain-orientation and magnitudes of percent anisotropies. These parameters being related to depositional style, could be specifically used as proxies for depositional flow velocities. The shielding effect due to discrepancy in size between framework grains and the magnetite grains however, should be kept in mind.
CHAPTER 4

PETROGRAPHIC AND XRD ANALYSES OF SEDIMENTS FROM VARIOUS DEPOSITIONAL SETTINGS IN THE SKOORSTEENBERG FORMATION

4.1 Analysis of Clay Minerals to Extract Depositional Signatures

4.1.1 Introduction

It is critical to evaluate the clay mineral paragenesis of sediments in the light of early or late diagenesis that is environmentally controlled because they might identify different realms of post depositional evolution in rocks. Early diagenesis is essentially controlled by original pore-water chemistry, sediment texture, detrital composition, and organic content (Stonecipher and May, 1990). These aspects of clastic sediments are primarily related to depositional environment. Late diagenetic patterns are less facies dependent but are instead related to changing pore-fluid chemistry (Kantorowicz, 1985), burial pressures and temperatures (Hutcheon et al., 1980). In this study an attempt was made to extract the early diagenetic signature from the various depositional settings within the Tanqua Karoo submarine fan depositional system. The various subenvironments analyzed are levee-overbank, passive channel fill, channel-sheet transition deposits, and distal sheet sandstones, all of which contain thin-bedded turbidites. Channel fill sandstones were also analyzed to document the variations in clay mineral assemblages with respect to other subenvironments.

4.1.2 Methodology

Hand specimen sized samples were collected in the field from various subenvironments. They were broken into small pieces, then ground to approximately
coarse sand size using a mortar and pestle. Two splits were made at this stage. One was put in the micronizer to be powdered for bulk analyses and the other was suspended in a sodium phosphate solution for peptizing and extraction of the < 2 μm clay fraction. The data concerning the < 2 μm fraction are presented here. The extracted clay was centrifuged for preparation of smear slides and X-ray analysis. The slides were analyzed using a Siemens D5000 X-ray diffractometer. Four treatments were carried out, air dried, glycolated, and heated to 300°C and 550°C. The XRD patterns were then matched against NEWMOD mineral reference files generated with a computer program called Multicalc 1.0 for Windows. With Multicalc a wide spectrum of patterns were generated by varying selected physical and chemical parameters of the mixed-layer clays such as layer type, proportion of the layers, ordering, Fe and K content, etc., to get the best visual fit with the observed XRD patterns.

4.1.3 Results

The samples were selected to fully represent a submarine fan from an upfan to a downfan direction (see Fig. 2.1). From the upper mid fan, samples were collected from a levee-overbank setting (Kanaalkop, Fan 3). In the mid fan setting samples were collected from an active channel-fill (Blaukop, Fan 5), passive channel fill (Bizansgat, Fan 4), and a levee-overbank (Blaukop, Fan 5) setting. In the lower fan thin-bedded turbidites were sampled from distal sheet sandstones in the Skoorsteenberg area (Fan 5). The depositional environment for the samples and their respective abundances of clay mineral species are presented in Table 4.1. All the samples monotonously have the same clay species illite (dimica) and an iron-rich tri-trichlorite. Smectite and
Table 4.1 The abundance of clay minerals from various thin-bedded turbidite settings in the Tanqua Karoo submarine Fan deposits. See text for details.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Subenvironment</th>
<th>Illite %</th>
<th>Fe-Chlorite %</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBKK94.1E</td>
<td>upper midfan levee-overbank</td>
<td>90.06</td>
<td>9.03</td>
</tr>
<tr>
<td>DBKK94.3E</td>
<td>upper midfan levee-overbank</td>
<td>78.74</td>
<td>21.25</td>
</tr>
<tr>
<td>DBKK94.5E</td>
<td>upper midfan levee-overbank</td>
<td>93.31</td>
<td>6.68</td>
</tr>
<tr>
<td>DBZB94.1E</td>
<td>passive channel-fill</td>
<td>89.28</td>
<td>9.8</td>
</tr>
<tr>
<td>DBZB94.4E</td>
<td>passive channel-fill</td>
<td>97.08</td>
<td>2.91</td>
</tr>
<tr>
<td>DBSK94.1E</td>
<td>distal sheet sandstones</td>
<td>81.56</td>
<td>18.44</td>
</tr>
<tr>
<td>DBSK94.2E</td>
<td>distal sheet sandstones</td>
<td>85.22</td>
<td>14.77</td>
</tr>
<tr>
<td>DBBK94.1E</td>
<td>midfan channel-fill</td>
<td>90.32</td>
<td>9.03</td>
</tr>
<tr>
<td>DBBK94.2E</td>
<td>midfan channel-fill</td>
<td>84.41</td>
<td>15.59</td>
</tr>
<tr>
<td>DBBK94.23E</td>
<td>midfan levee-overbank</td>
<td>79.16</td>
<td>20.83</td>
</tr>
<tr>
<td>DBBK94.32E</td>
<td>midfan levee-overbank</td>
<td>88.60</td>
<td>11.40</td>
</tr>
</tbody>
</table>

Kaolinite are absent. Illite is the most common clay species present, the abundance ranging from 78 wt. % to 97 wt. %. The abundance of chlorite ranged from 3 wt. % to 21 wt. %. The XRD patterns are presented in Figure 4.1 and Appendix C.

No first order variations (presence of different clay species from various facies) were observed in the study that would suggest a facies control on the clay mineral assemblages. Irrespective of their facies and location in the submarine fan, the samples were characterized by the presence of illite (an Fe and K bearing dimica) and chlorite.
(an iron rich tri-trichlorite). The types of chlorite and illite and the ratio of illite/chlorite from the various depositional settings were determined to see if there is a systematic second order variation (possible difference in types and abundance of respective clay species). The ratio of illite to chlorite varied from 4 to 33, but the variation was not systematic and it crossed facies boundaries. A facies control is lacking in the clay assemblage in the suite of samples analyzed both in the first order (i.e. it has same species in different facies), and also in the second order (i.e. abundance of clay species in different facies lack any trend). Observed and simulated XRD patterns are presented in sequence in Figures 4.1 and Appendix C, from the five depositional settings studied. Simulated XRD patterns were matched with observed (ethylene glycolated) patterns. The illite (001), (002), and (003) peaks are listed in the simulation diagrams, in order of their relative abundance, the quartz effect being deducted from the illite (003) peak. The characteristic relative intensity pattern of the illite (00l) sequence of peaks is best matched by a NEWMOD reference file of illite that has a low N of 10 and a high N of 20 (N is the number of unit cells stacked in the z-direction that make up the largest and smallest crystallites). The iron content is 0.2 (Fe atoms per 2 octahedral sites), and the K content is 0.6 (K atoms per 12-fold site), and a Reichweite (R, ordering in mixed-layer clays) = 1. The chlorite in the samples has intense even-ordered peaks and a set of odd-ordered peaks with weak intensities. This pattern is suggestive of an iron-rich chlorite (Moore and Reynolds, 1989) and is simulated by a NEWMOD reference file of tri-trichlorite with a Si(Fe) = 3 (Fe in octahedral sheets), Hydroxide (Fe) = 3 (in the hydroxide interlayer), Hydroxide Layer = 1 and R = 0.
Figure 4.1 XRD patterns of clay fraction from sample DBKK94.1 from a mid-fan levee-overbank setting (Kanaalkop, Fan 3). 
(a) Pattern represents various treatments, A - air dried; B- ethylene glycol saturated; C- heated to 300°C; and D-heated to 550°C. Numbers on the diffractograms indicate d-spacings (Å). The 14 Å and 10 Å series of peaks represent the chlorite and illite (00l) series, respectively; (b) The observed (solid line) and simulated XRD patterns (dashed line) for sample DBKK94.1; and (c) sample DBKK94.5, are representatives of a mid-fan levee-overbank setting (Kanaalkop, Fan 3).  
(Fig. 4.1 con’d)
4.1.4 Discussion

The lack of any facies control in the analyzed samples may be due to several reasons. A good explanation is offered by the following two alternatives to justify the same clay species and their similar abundances in samples from different depositional settings. These hypotheses hinge upon the primary mineralogy of the clays and/or their derivation from burial diagenesis.

(1) The primary detrital composition of the clay fraction, or the breakdown of frameworking grains into the observed clay species, could explain the monotonous presence of illite and chlorite in all the samples. The sandstones and siltstones are rich in feldspars and volcanic rock fragments which could be the source from which illite and chlorite were derived. Although the source rocks for the sediments of the Skoorsteenberg Formation are not preserved anymore, it has been suggested that they were derived from foreland thrust sheets and a distant southern magmatic arc some 1500 km away (Cole, 1992).

(2) The exclusive presence of illite and chlorite in the submarine fan deposits fits well with the proposed burial diagenetic model from the Tertiary of the Gulf of Mexico by Boles and Franks (1979). Illite is likely to be derived from the transformation of smectite through burial diagenesis. The K and Al, released from the dissolution of feldspars, could have driven the smectite to illite transformation. Fe and Mg, liberated during this transformation from smectite to illite, could in turn be incorporated into the authigenic Fe-rich chlorite. The Mg and Fe liberated from the smectite to illite transformation could also have replaced any primary kaolinite into
chlorite. The effect of partial dissolution of feldspars can be observed from petrographic analysis of the siltstones and sandstones.

Facies control on diagenesis is lacking in these deposits because early diagenetic signatures, if any, were most likely overprinted by burial diagenesis. This is all the more likely due to the Permian age of the deposits unlike the well developed facies control on diagenesis that has been documented from younger deposits like the Eocene Wilcox Group (Stonecipher et al., 1990). The deposits that were analyzed as part of the research, are deep marine sediments that were under the influence of the same hydrologic system. This is unlike the Wilcox Group where the delta plain and subaqueous deltaic deposits were affected by variable pore-water chemistries and had systematic variations in clay mineral paragenesis.

4.2 Mineralogy of Framework Grains in Sandstones and Siltstones From the Skoorsteenberg Formation

4.2.1 Introduction

Petrographic analysis of sandstones and siltstones from the submarine fans of the Skoorsteenberg Formation were done to shed light on provenance and tectonic setting of the Tanqua Basin during the deposition of the Ecca Group. Published work suggests ongoing active tectonics in the hinterland area to the south and southwest which served as the source terrain for the sediments (Visser, 1992; Scott, 1997).

4.2.2 Methodology

Traditional point counting technique was employed for classifying sandstones using Folk’s diagram (1974). Four thin-sections were analyzed (BK.94.2, Blaukop A4, Blaukop A and Blaukop B23), from a channel-fill from Blaukop in Fan 5.
Approximately four hundred grains were identified from each thin section. The data is presented in Table 4.2. Gazzi and Dickinson technique was employed to point count thin-sections for interpretation of the tectono-sedimentary conditions during deposition. Q-F-L and Qm-F-Lt diagrams as described by Dickinson and Suzcek (1979) were used to characterize the syn-depositional tectono-sedimentary conditions.

4.2.3 Results

The framework grains are dominated by quartz (~59%) and subequal proportions of feldspars (~19%) and rock fragments (~22%). Cements in the form of chlorite, calcite and quartz overgrowths are present in insignificant quantities (<4%). Matrix is less than 5% and porosity nonexistent. The sandstone units that were studied are feldspathic litharenites according to Folk's classification (1974) as shown in Figure 4.2. The tectonic setting of the basin was inferred from fine grained sandstones using a Dickinsonian approach (Dickinson & Suzcek, 1979). The data from traditional and Dickinsonian point-counts are presented in Table 4.2 and 4.3, respectively. In both the Q-F-L and Qm-F-Lt diagrams the samples plotted in the recycled orogen domain (Figs. 4.2a and b).

4.2.4 Discussion

In the Early Permian southwestern Karoo was characterized by rapidly disintegrating Dwyka ice sheets which was accompanied by marine transgression (Visser, 1989; McLachlan and Anderson, 1973). At this time, 278 ± 2 Ma ago (Hälbich et al., 1983), the southwestern Karoo Basin was a foreland basin initiated by the first folding episode of the Cape Fold Belt. The 2nd. “paroxysm” or the Outeniqua Folding at 258 ± 2 Ma (Hälbich et al., 1983) significantly affected basin evolution.
Table 4.2 Minerals and other components from four Tanqua Karoo sandstones measured from thin-sections using standard point-counting technique.

<table>
<thead>
<tr>
<th>Slide</th>
<th>BK.94.2</th>
<th>Blaukop A4</th>
<th>Blaukop A1</th>
<th>Blaukop B23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono quartz</td>
<td>180</td>
<td>182</td>
<td>171</td>
<td>183</td>
</tr>
<tr>
<td>Poly Quartz</td>
<td>29</td>
<td>16</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Chert</td>
<td>11</td>
<td>14</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Potash feldspar</td>
<td>51</td>
<td>49</td>
<td>43</td>
<td>30</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>22</td>
<td>18</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Volcanic rock fragment</td>
<td>22</td>
<td>21</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Sedimentary rock fragment</td>
<td>15</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Metamorphic rock fragment</td>
<td>34</td>
<td>33</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td>Mica</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Zircon</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Opaque</td>
<td>13</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Chlorite</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Calcite</td>
<td>22</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Quartz overgrowth</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Matrix</td>
<td>15</td>
<td>22</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>Porosity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Count</td>
<td>453</td>
<td>389</td>
<td>380</td>
<td>368</td>
</tr>
</tbody>
</table>

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Figure 4.2 Classification of very fine-grained sandstones from Fan 5 of the Tanqua Karoo, using Folk (1974). The plots lie within the feldspathic litharenite field.

Table 4.3 Tabulated data from Fan 5 of the Tanqua Karoo based on point counting according to Dickinson and Suzcek (1979).

<table>
<thead>
<tr>
<th>Slide</th>
<th>BK.94.2</th>
<th>Blaukop A4</th>
<th>Blaukop A1</th>
<th>Blaukop B23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total quartz ($Q_t$)</td>
<td>60.43 %</td>
<td>63.28 %</td>
<td>62.42 %</td>
<td>62.38 %</td>
</tr>
<tr>
<td>Feldspar ($F$)</td>
<td>20.05 %</td>
<td>20 %</td>
<td>20 %</td>
<td>16.81 %</td>
</tr>
<tr>
<td>Lithics ($L$)</td>
<td>19.5 %</td>
<td>16.71 %</td>
<td>17.57 %</td>
<td>20.79 %</td>
</tr>
<tr>
<td>Mono quartz ($Q_m$)</td>
<td>49.45 %</td>
<td>54.32 %</td>
<td>51.81 %</td>
<td>55.96 %</td>
</tr>
<tr>
<td>Feldspar ($F$)</td>
<td>20.05 %</td>
<td>20 %</td>
<td>20 %</td>
<td>16.81 %</td>
</tr>
<tr>
<td>Lithic ($L_t$)</td>
<td>30.49 %</td>
<td>25.67 %</td>
<td>28.18 %</td>
<td>27.21 %</td>
</tr>
</tbody>
</table>
Figure 4.3 Gazzi-Dickinson plots of Fan 5 sandstones at Blaukop. (a) Q-F-L diagram and (b) Qm-F-Lt diagram. In both the ternary diagrams the sandstones plot on the recycled orogen domain.
This resulted in rapid downwarping of the basin as a consequence of loading by thrust sheets in the adjacent Cape Fold Belt, a process typical of retroarc foreland basin development (Jordan, 1981). Both the southern and the western branches of the Cape Fold Belt were probably uplifted above sea-level and were likely to have acted as sediment sources for the basinal clastics. Concomitant with this second event of folding vigorous volcanic activity was associated with plate convergence and subduction along the paleo-Pacific margin, an estimated 1,500 km to the south of the basin (Cole, 1992; Fig 4.4). The plots from the present study in Figure 4.7a and 4.7b, in the recycled orogen domain lends support to the foreland basin origin of the Tanqua subbasin during the deposition of the Ecca Group.

The abundance of chemically and mechanically unstable grains like feldspars and volcanic/metamorphic rock fragments suggest active tectonics in the source area. The relative abundance of feldspar is also suggestive of a cold and possibly a dry climate in South Africa during the Permian. The high southern latitude of South Africa (~ 65°S; Smith, 1973) during the Permian supports the interpretation regarding a prevailing cold climate. The probable relief and climate were both favorable for the preservation of the mechanically and chemically unstable grains in the rocks. Volcanic rock fragments are common in these deposits but are relatively finer and more altered than both the feldspars and the metamorphic rock fragments. This is suggestive of feldspars and metamorphic rock-fragments being derived from a more immediate or proximal source and the volcanic rock fragments from a relatively distant source. The feldspars and metamorphics were most likely sourced from the Cape Fold and Thrust Belt immediately to the south and west of the basin (see, Fig. 1.5). This interpretation
is slightly different from the conclusions of Johnson (1991). The discrepancy in interpretations could be due to Johnson's study being from the southeastern Karoo while the present study is based on southwestern Karoo. The present discussion is not directed at refuting Johnson's interpretations since this work involves much fewer analyses and should only be considered as results from a pilot study. Johnson's QFL plots indicate a lack of contribution from the Cape Fold Belt and the primary source rocks were supposed to have been the paleo-Pacific volcanic arc. As part of the conclusions based on the present study a greater contribution from the Cape Fold Belt is suggested contrary to what is envisaged by Johnson (1991). In his argument the Cape Fold Belt probably did not have significant relief to shed substantial sediments.

In the present study it is believed that significant relief is not necessary for contributing
sediments to basins especially during sea-level lowstands. The correlative fluvial systems feeding the deep sea fans would incise into the incipient relief of the Cape Fold Belt, by means of incised valley systems because of base-level lowering during lowstands. In my interpretation sediment scavenging by base-level lowering of the correlative fluvial system would have been the overwhelming factor controlling sediment contribution than the acquired relief of the hinterland.

The petrographic analyses suggest contributions from metamorphic and intrusives rocks in the sandstones from Fan 5 indicated by the presence of metamorphic rock-fragments and feldspars from petrographic analyses (Fig. 4.5a). The sediments from the Fold Thrust Belt were fairly rich in metamorphic rock fragments in addition to contributing rock-fragments and feldspars from associated synorogenic intrusives (Visser, 1992). The volcanic rock-fragments were derived from the paleo-Pacific volcanic arc which is in agreement with the paleogeographic reconstructions of Cole (1992) as presented in Figure 4.4. Most of the volcanic rock fragments are beyond recognition as to their type. Although very altered, a few of the volcanic rock-fragments exhibit andesitic affinities with feldspar laths and elongated hornblende crystals visible in a glassy groundmass, suggesting a subduction related volcanic derivation (Fig. 4.5b). Volcanic rocks dated between 290 and 210 Ma presently crop out in Patagonia and Central Andes (Breitkreuz et al., 1989). These rocks are within the age range through which the Cape Fold Belt orogeny and formation of the Tanqua fans took place. Alternatively the presence of volcanic rock-fragments could also be due to reworking (by incised fluvial channel systems) of tillites of the older Dwyka
Figure 4.5 Photomicrographs showing composition of the feldspathic litharenites from the Tanqua subbasin. (a) Feldspars and metamorphic rock-fragments along with quartz, from slide BK.94.2 (center of photo) and (b) Volcanic rock-fragment at the center showing feldspar laths, from slide A2 (center of photo). Field of view 2 mm.

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Group which are fairly rich in volcanics being related to active subduction in the south during Early Permian (Artinskian) times (Johnson, 1991; Cole, 1992).

4.3 Grain-Size Characteristics of Submarine Fan Deposits of the Skoorsteenberg Formation

4.3.1 Introduction

Grain-size of the sandstones and siltstones from the various depositional settings in the Skoorsteenberg Formation were analyzed to determine any systematic variations that may exist. The specific problem addressed was to test for variations in grain-size between different thin-bedded turbidite facies that would shed light on their different depositional styles. Grain-size fractionation, due to sediment bypassing mechanisms related to shifting depocenters and available accommodation space, developed the observed variations. The grain-size variations in the arenaceous submarine fan deposits of the Tanqa subbasin are fairly limited. The coarsest grain-size is very fine sand and the finest is fine silt. Pure clay sized sediments are rare, constituting the argillaceous facies which are stratigraphically restricted in occurrence in between the five arenaceous fans. The restricted grain-size distribution is possibly inherited from the source terrain.

4.3.2 Methodology

Grain-size analysis from the submarine fans in the Tanqua subbasin posed a challenge due to the extreme fine grained sediments in most of the depositional subenvironments. The lack of any significant dissolvable calcitic cement meant that the rocks could not be disaggregated and sieved. Standard petrographic determination of grain-size was done on a few of the coarsest grain-sizes available in the Tanqua, i.e.,
channel-fill sandstones from the Blaukop area. Grain-size from other samples were determined by importing digitized images of portions of thin-sections using NIH Image developed by the National Institute of Health. NIH Image is a public domain Macintosh-based program which is routinely used in optical rock and materials laboratories equipped with scanning electron microscope and electron microprobes. All the grain-size analyses were performed on thin-sections made from representative samples from the respective depositional settings.

4.3.3 Results

The thin-bedded turbidite settings analyzed for grain-size are upper mid-fan levee-overbank (Kanaalkop, Fan 3), mid-fan passive channel-fill (Bizansgat, Fan 5), mid-fan levee-overbank (Blaukop, Fan 5), lower fan channel-sheet transition (Rondawel West, Fan 3), and lower fan distal sheet sandstones (Skoorsteenberg, Fan 3). The channel-fill deposits at Blaukop (Fan 5) and Kanaalkop (Fan 3) were also analyzed to compare the variations with the rest of the settings. The mean grain-size varies from medium silt to very-fine sand as presented in Table 4.4.

4.3.4 Discussion

Although the grain-size range available from the Tanqua subbasin is not large there is a systematic variation from one depositional subenvironment to the other.

The finest grain-size analyzed is 32 \( \mu \text{m} \) (medium silt) which is present in the passive channel fill in a mid-fan setting at Bizansgat (Fan 4). They were likely to have been deposited from decaying turbidity currents as evidenced by the stacked thin T.d.e beds (base truncated Bouma Sequences, Bouma, 1962).
Table 4.4 Grain-size from various depositional settings and their fan designations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Fan #</th>
<th>Mean grain-size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bizansgat (passive channel-fill)</td>
<td>5</td>
<td>32 μm</td>
</tr>
<tr>
<td>Blaukop (levee-overbank)</td>
<td>5</td>
<td>41 μm, 37 μm</td>
</tr>
<tr>
<td>Blaukop (channel-fill)</td>
<td>5</td>
<td>75 μm, 72 μm</td>
</tr>
<tr>
<td>Kanaalkop (levee-overbank)</td>
<td>3</td>
<td>47 μm, 40 μm</td>
</tr>
<tr>
<td>Kanaalkop (channel-fill)</td>
<td>3</td>
<td>77 μm, 72 μm</td>
</tr>
<tr>
<td>Skoorsteenberg (distal sheet-sandstone)</td>
<td>3</td>
<td>70 μm, 56 μm</td>
</tr>
<tr>
<td>Rondawel West (channel-sheet transition)</td>
<td>3</td>
<td>56 μm</td>
</tr>
</tbody>
</table>

The levee-overbank deposits at Blaukop (mid-fan, Fan 5) have mean grain-sizes of 41 μm (coarse silt) and 37 μm (medium silt), measured from two thin-sections. The thin bedded units at Blaukop comprise levee-overbank sediments which were deposited from spill over flows from channelized turbidity currents. The genetically related channelized deposit is also present in the same outcrop where the channel-margin is exposed (see Figs. 2.23 and 2.24). The associated massive channel fill has a coarser mean grain-size of 75 μm and 72 μm (vfl sand), measured from two thin-sections. This variation in mean size is a result of grain-size fractionation between the head and body of a channelized turbidity current. The head of a turbidity current sequesters the coarser size fraction and the suspended sediment cloud riding as part of the body at the upper reaches of the flow concentrates the finer grain size (Middleton, 1966a; see Fig. 2.5b). The suspended cloud of sediments is loaded with finer grains.
and spills over into the interchannel area across the levee. The topographic relief of the levee promotes the grain-size fractionation further and allows only the finest sediments to leave the confines of the channel. This model is supported by the Type A climbing (Jopling and Walker, 1968) ripple lamination present in the thin-bedded deposits which requires a high suspended-load to bed-load ratio.

The levee-overbank deposits at Kanaalkop (upper mid-fan, Fan 3) has a mean grain-size of 47 μm and 40 μm (coarse silt) and are spillover deposits from a channel located to the west of Kanaalkop (West Channel, see Figs. 2.5a and 2.8). The West Channel is not present in outcrop. These units are inferred to have easily overcome the lower right hand levee (due to the Coriolis effect in the southern hemisphere) of the West Channel (Fig. 2.5b, see Section 2.2.4 in Chapter 2) and deposited as part a levee-overbank wedge. The high suspended-load to bed-load ratio is supported by the sedimentary structures in the form of Type B climbing ripples (Jopling and Walker, 1968) grading into sinusoidal ripple laminations (Fig. 2.7b).

The Kanaalkop Channel (Fan 3) is a compound fill that develops from residual deposition in a channelized conduit which effectively acted as a sediment bypass system. The bypassed sediments were deposited in the Skoorsteenberg area as depositional lobes which are now represented as distal sheet sandstones (Fig. 2.18). The mean-size from the base of the Kanaalkop channel fill is the coarsest size fraction delivered to the system and is 77 μm and 72 μm (vfL sands) as measured from two thin-sections. A similar mean grain size of 70 μm (vfL sand) is measured from a representative bed in the distal sheet sandstone setting at Skoorsteenberg (see Fig. 2.1). This supports the model that the Skoorsteenberg area is characterized by sediments
that bypassed the inner reaches of the fan while flowing downfan through channelized conduits like the West Channel and Kanaalkop Channel and were deposited in distal settings (Fig. 2.18). The bulk of the Kanaalkop channel fill however, was deposited when the locus of deposition shifted upfan as a result of backstepping due to generation of accommodation space in that direction. The representative bed that was analyzed for grain size at Skoorsteenberg (Fan 3) yielded a mean size of 70 µm at the base and 56 µm at the very top, suggesting normal grading as expected in a turbidite bed. The base with the coarser grain size is devoid of sedimentary structures (Tₛ) and the top with the finer grain-size has upper plane bed parallel laminations (Tᵤ).

The mean grain-size from the outer fan channel-sheet transition deposits at Rondawel West (Fan 3) is 55 µm (coarse silt). This site is characterized by erosional scours of limited extent also referred to as mega-flutes and is probably related to flow unconfinement associated with hydraulic jumps (Chapin et al., 1994). This site is essentially an area of sediment bypass enabling active deposition in a distal setting in the form of depositional lobes (sheet sandstones at Skoorsteenberg). This becomes the site of active deposition only after the locus of sedimentation starts shifting upfan primarily in response to a relative rise in sea-level.
CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

The principal results of this research are important to the field of facies analysis of turbidites. Fine-grained, thin-bedded turbidite subenvironments have not been thoroughly studied before from both a field and laboratory perspective. The major findings of this study are summarized below.

5.1.1 Petrographic Characteristics of Thin-Bedded Turbidites

The XRD analysis of the < 2 \( \mu \text{m} \) clay fraction from a variety of thin-bedded localities yielded the same clay species, illite and an iron-rich chlorite. There was no variations in diagenetic clay mineral assemblages that are consistently different from one thin-bedded environment to the other. Facies control on diagenesis, for which the study was conducted, does not exist in the thin-bedded turbidites of the Tanqua Karoo.

The mineralogic analysis from thin-sections is suggestive of a predominant sediment source from the syndepositional orogen comprising the Cape Fold and Thrust Belt with a minor but consistent contribution from a distant volcanic arc. However, more thin-sections should be analyzed to prove this conclusion. The mineral compositions consistently plots on the recycled orogen field in Q-F-L and \( Q_m-F-L_t \) Dickinsonian diagrams. The sandstones are classified as feldspathic litharenite.

Petrographic grain-size determinations yielded a restricted grain-size range. The coarsest grain-size is fine sand and the finest is fine silt. The coarsest grains are
present in basal channel-fills and distal sheet sandstones in thin and thick beds. The finest grain-sizes are present in passive channel-fills and levee-overbank thin-beds.

### 5.1.2 Possible Effect of Coriolis Forcing on Overbanking in a Mid-Fan Channelized Setting

The lower part of the Kanaalkop measured profiles is identified as a levee-overbank complex. It is composed primarily of body spill deposits from turbidity currents transporting sediments downfan along a channelized course. The body spill deposits are characterized by thin-bedded siltstones and very-fine grained sandstones. They are climbing ripple laminated (Type B; Jopling and Walker, 1968), comprising stacked Tc beds. Interbedded with the body spill deposits are groove-marked, thick-bedded, very fine-grained, massive sandstones. They are interpreted to be head spill deposits from bankfull-channelized turbidity currents that spilled over and across the levee. Overbanking of head spills is achieved with relative ease in this setting because of the inferred levee-asymmetry due to the Coriolis Effect. The high latitudinal position of South Africa (~ 65° S) in the Permian favored levee-asymmetry, because Coriolis Effect is proportional to the degree of latitude. The location of the Kanaalkop outcrop is on the right-hand side with respect to a channel (the West Channel) flowing downfan. Due to the Coriolis Effect the right-handed levee in the southern hemisphere is the lower levee. This interpretation explains the common occurrence of head spill deposits interbedded with the more common body spill beds in the right-handed levee-overbank setting of the West Channel. This scenario is analogous to the Laurentian Fan (offshore of Labrador, ~ 55° N) where the left-handed levee is lower, being in the northern hemisphere.
5.1.3 Variations in Grain-Anisotropy from Thin-Bedded Turbidites using IRMA

Anisotropy of isothermal remanent magnetization (IRMA) results reveal excellent primary depositional fabrics from the various subenvironments. The anisotropy ellipsoids have their long-axes on the bedding plane (roughly horizontal) and the short-axes perpendicular or at high angles to the bedding. The results reveal that the direction of the long-axis ($K_{max}$) of anisotropy ellipsoids and % anisotropy are related to the style of deposition.

The depositional environments that are characterized by weak tractional reworking have flow-parallel $K_{max}$ alignment, e.g. levee-overbank setting at Kanaalkop and passive channel-fill at Bizansgat. The % anisotropy is also relatively lower in these settings (< 5 %). Interpretations based on sedimentary structures, supports the inference of depositional style as being primarily from suspension. The levee-overbank deposits at Kanaalkop have Type B climbing ripples which are indicative of a very high suspended-load to bed-load ratio, hence suppressing traction. The stacked $T_{d,e}$ beds (bottom-truncated Bouma Sequences) in the passive channel-fill at Bizansgat are also indicative of minor traction.

The depositional environments where sedimentation is traction dominated are characterized by flow normal $K_{max}$ orientations, namely channel-fill (Blaukop), channel-sheet transition setting (Rondawel West), levee-overbank (Blaukop), and distal sheet environment (Skoorsteenberg).

Percent anisotropies are highest in depositional settings with a channelized component and lower in unconfined depositional systems. Active channel fills have
the highest mean anisotropy of 13.26 % and channel-sheet transition deposits have a relatively high mean anisotropy of 6.62 %. Unconfined flows of the distal sheet sandstones have the lowest anisotropy of 3.85 %. The levee-overbank deposits have intermediate values.

5.1.4 Sedimentary Characteristics of Thin-Bedded Turbidites From the Tanqua Fans

Thin-bedded turbidites studied from various settings in the Tanqua fans reveal sufficient differences to enable a clear distinction between them. The thin-bedded deposits are from upper mid-fan levee-overbank (Kanaalkop), mid-fan passive channel fill (Bizansgat), mid-fan levee-overbank (Blaukop), channel-sheet transition deposits (Rondawel West), and distal sheet-sandstones (Skoorsteenberg). A summary chart is presented that highlights the differences between the thin-bedded intervals developed in the various settings. Bed-thickness, grain-size, grain-orientation, sedimentary structures and possible depositional mechanisms are compared (Table 5.1).

5.1.5 Conceptual Framework of Time Equivalence of Depositional Elements in a Fine-Grained Submarine Fan

This section presents the style of deposition of submarine fan elements within a chronostratigraphic framework with specific reference to the thin-bedded turbidite subenvironments. The well known “slug diagram” and its chronostratigraphic counterpart depicts the spatial relationship of lowstand deposits as part of a depositional sequence (Vail et al., 1991; Fig. 5.1). This section goes one step further to focus on details of the lowstand fan and attempts a high resolution correlation of time equivalent depositional elements based on observations from Fan 3 in the Tanqua Karoo. Fan 3 is completely exposed in the Tanqua Subbasin and enables proper
Table 5.1 Table represents the characteristics of thin-bedded turbidites of the Tanqua Karoo submarine fan deposits. Characteristic bed-thickness, grain-size, grain-orientation/anisotropy, sedimentary structures and inferred depositional mechanisms from the various settings are summarized.

<table>
<thead>
<tr>
<th>Depositional Environments</th>
<th>Bed-Thickness</th>
<th>Grain-size</th>
<th>Grain orientation/Grain anisotropy</th>
<th>Sedimentary Structures</th>
<th>Depositional Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanaalkop (upper/mid-fan levee-overbank)</td>
<td>Bimodal ~ &lt; 40 cm</td>
<td>Coarse siltstone ~ 43 μm mean</td>
<td>Flow parallel/ 5.48 %</td>
<td>~ &lt; 40 cm: ripple-drift cross-laminations (Type B), Tc beds; ~ 50-130 cm: massive (Tb), very thin Tc tops.</td>
<td>~&lt; 40 cm: Bodyspill from channelized turbidity currents. ~&lt; 50-130 cm: Headspill from channelized turbidity currents.</td>
</tr>
<tr>
<td>Bizansgat (mid-fan passive channel-fill)</td>
<td>1-12 cm</td>
<td>Medium siltstone ~ 31.5 μm</td>
<td>Flow parallel/ 4.38 %</td>
<td>Lower plane bed parallel- and rare current ripple-laminations with non-laminated silty-shale tops.</td>
<td>Base truncated Bouma Sequence ~ weak turbidity currents.</td>
</tr>
<tr>
<td>Blaukop (mid-fan levee-overbank)</td>
<td>Trimodal ~ &lt; 9 cm, 10-15 cm, 35-45 cm</td>
<td>Medium siltstone ~ 40 μm</td>
<td>Flow perpendicular/ 6.06 %</td>
<td>~&lt; 9 cm &amp; 10-15 cm: ripple cross-laminations; 10-45 cm: climbing ripple-laminations (Type C).</td>
<td>Suspended sediment spill-over from channelized flows.</td>
</tr>
<tr>
<td>Rondawel West (lower-mid-fan channel-sheet transition)</td>
<td>Trimodal ~&lt; 15 cm, 2-25 cm, 30-40 cm</td>
<td>Coarse siltstone, vfl. sandstone, ~ 56 μm</td>
<td>Flow perpendicular/ 6.62 %</td>
<td>~&lt; 25 cm: T ab, Tb, Tc; ~ 30-40 cm: T a, T ab, large flutes, rip-up clasts, large scours.</td>
<td>Top truncated Bouma Sequences, deposition from flow unconfinement.</td>
</tr>
<tr>
<td>Skoorsteenberg (lower-fan-distal sheet sandstones)</td>
<td>Trimodal ~&lt; 9 cm, 10-15 cm, 35-45 cm.</td>
<td>Coarse siltstone, vfl. sandstone ~ 70 μm</td>
<td>Flow perpendicular/ 3.85 %</td>
<td>~&lt; 9 cm: T c, ~ 10-45 cm: T ab, T c.</td>
<td>Deposition from unconfined flows.</td>
</tr>
</tbody>
</table>
identification of depositional facies from an updip to a downdip direction. Based on field observations in Fan 3, from the upper mid-fan channel/levee-complex (at Kanaalkop), channel-sheet transition (at Rondawel West), and distal-sheet sandstones (at Skoorsteenberb), a time-stratigraphic framework is generated (Wheeler Diagram; Fig. 5.2). This diagram relates temporally equivalent depositional elements along a dip line. This approach has been recognized to be ideal for developing a precise chronostratigraphic model to ensure that time-equivalent elements are compared within a proper stratigraphic framework (Mutti and Normark, 1991; Posamentier et al., 1991).

The initial shift of the locus of deposition from shallow water to deep water across the shelf edge may be due to a suite of reasons (Normark and Piper, 1991). The triggering mechanism may be directly related to the lowering of relative sea level.
Figure 5.2 A schematic diagram showing the general disposition of channelized and non-channelized (distal sheet) depositional systems. (a) Map-view and (b) The time stratigraphic (Wheeler Diagram) based on line X-X' in the map view. The Wheeler Diagram is generated from observations in Fan 3. See text for details.
which eliminates accommodation space on the shelf and funnels sediment farther downdip. Initially, when deposition begins on the basin floor the depocenter is skewed towards the distal end, where sheet sands develop in the form of depositional lobes (e.g. Skoorsteenberg area, Fig 5.2). For sediments to be delivered to the distal end of a submarine fan, the upper and middle fans (Kanaalkop and Rondawel West areas, respectively; see Fig. 2.1 for locations) essentially act as bypass systems. Submarine fan channels are produced and maintained by turbidity currents in the upper and the middle fans and act mainly as long term pathways for sediment transport (Flood et al., 1991; Mutti and Normark, 1991). The line ABC in Figure 5.2b, is a time line which develops during early lowstand and has a variable nature. Proximally it represents the initial entrenchment into basinal sediments by the first major flow emanating from shallow waters (sequence boundary, AB in Fig. 5.2). Distally it (line AB) represents a surface on which depositional lobes downlap (correlative conformity, BC in Fig. 5.2). Initial deposition results essentially from updip failures and includes a minor component of sediments eroded from the basin floor (the wedge ABD). The bulk of the sediments passing down the newly entrenched channel (e.g., the West Channel, the Kanaalkop Channel), are laid down in the downfan setting, initiating the depositional lobe. While the depositional lobe builds vertically and laterally with time (BCHG in Fig. 5.2), the feeder channel primarily acts as a bypass system (the wedge DBE). At this time the flows have the largest volumes (A in Fig. 5.3) in response to maximum base-level lowering in the correlative fluvial system. The wedge of time ABE, is hence composed of two components, an erosional vacuity (wedge ABD) and a hiatus (wedge DBE), together representing the lacuna, as shown in Figure 5.2. Simultaneous to the
building of depositional lobes, there are lags and sediment blankets that form in the channel, from larger and smaller flows respectively (L, L’ in Fig. 5.2). Smaller turbidity currents are generally poorly efficient and drop part of their load within the channel because they cease to flow before the site of depositional lobes is reached. The larger flows (bankfull stages), are usually highly efficient and contribute to the levee-overbank wedge by spillover of turbidity currents simultaneously delivering sediments to the distal sheets. A complex stacking results in the channel fills from depositional and erosional events by successive flows. As a result of the subsequent turnaround of relative sea level the volume of flows progressively diminishes and the depocenter shifts upfan. This response is related to base-level elevation in the correlative fluvial

Figure 5.3 The variations in volumes of sediment deposited in submarine fans during early (A) and late (B and C) sea level lowstand are depicted. The model is based on observations from the Fan 3 depositional system in the Tanqua Karoo. See text for details.
system. At this time of relative sea-level turnaround (late lowstand) sediment gravity flows are generally characterized by lower volumes and reduced frequency (B and C in Fig. 5.3). This backstepping or retrogressive mode of deposition results in active sedimentation in the middle and upper-fan (channel-sheet transition and channelized levee-overbank settings, depicted by EBGF, Fig. 5.2). The bulk of the channel levee-overbank wedges are formed at this time. With an upfan shift in depocenter, a surface of non-deposition develops over the depositional lobes in the distal setting which is aptly termed the “top lowstand surface” (i.e. initiation of a condensed section, Vail et al., 1991; GH in Fig. 5.2). The top-lowstand surface (FGH, Fig. 5.2) is a diachronous surface that starts to form in the distal end earlier than in the proximal end. The time-transgressive nature of the surface FGH results in a wedge of time that tends to pinchout upfan (GHIFJ, Fig. 5.2). The time-line U likely represents the base of another fan or a sublobe within the same fan from where the same essential motif is repeated.

5.2 Conclusions

On the basis of field observations and laboratory results on thin-bedded turbidites from the Tanqua Karoo the following conclusions are drawn.

1. Grain-size variations between different subenvironments are limited but a systematic trend is observed. The passive channel-fills and mid-fan levee overbank deposits have the finest grain-size (medium silt). The distal sheet sandstones and channel sheet transition deposits characteristically have the coarsest grain-size (very fine sand).
2. Bed-thickness distributions from the different subenvironments are primarily bimodal or trimodal and are heavily skewed towards thin-beds that are < 15 cm in thickness.

3. Anisotropy of isothermal remanent magnetization (IRMA), a rock magnetic technique, was employed successfully to extract grain-fabric information to shed light on depositional processes. A predictable relationship between grain-orientation/percent anisotropy and depositional styles in the various thin-bedded turbidite deposits was observed for the first time. The magnetite long-axes are flow-parallel in depositional environments characterized by low flow velocities e.g., passive channel fills and certain levee-overbanks. Flow normal alignments are characteristics of depositional environments with higher flow velocities e.g., channel-sheet transition and distal sheet sandstones. Percent anisotropies are correlated with flow velocity and flow confinement. Channels and channel-sheet transition deposits have consistently higher percent anisotropies. Distal sheet sandstones, levee-overbanks and passive channel-fills have predictably lower percent anisotropies.

4. Sedimentary structures in the thin-bedded turbidites are numerous. Base truncated Bouma sequences are observed from passive channel fills and levee-overbank settings, the latter often present as monotonously stacked climbing ripple laminated beds. The passive channel-fills and levee-overbanks represent deposition from weak turbidity currents and body spill from channelized turbidity currents, respectively. Distal sheet sandstones and channel-sheet transition deposits are characterized by top truncated Bouma sequences. They have well developed T_4 capped
by thin $T_b$ and $T_{bc}$ subdivisions. They represent deposition from relatively unconfined flows.

5. The Tanqua Karoo subbasin represents an ancient analog of submarine fan deposition in high latitudes (~65°S for the Permian Tanqua subbasin). A model is presented that incorporates the idea of pronounced levee asymmetries as a result of enhanced Coriolis Force in high latitudes to explain interbedded lenticular sandstone bodies within a levee-overbank sequence. The sandstones represent head spills from channelized turbidity currents in overbanks located on the side of the lower (right, in the southern hemisphere) levee. The thin-bedded siltstones represent the more common levee-overbank body spill deposits.

6. A conceptual chronostratigraphic model for the deposition of lowstand submarine fans correlating time-equivalent depositional elements is introduced based on observations from Fan 3. This model incorporates the thin-bedded depositional sites within the framework of time-equivalence presented and in the form of a chronostratigraphic Wheeler diagram.

7. Inferences based on both field and laboratory observations and approaches have been successfully employed to distinguish between thin-bedded turbidites developed in a variety of depositional sites. The results of this study are significant in the area of thin-bedded turbidites (TBTs) and will facilitate detailed facies analysis. Assignment of precise depositional facies names to thin-bedded turbidites recovered from the subsurface requires approaches similar to the presently concluded study.
REFERENCES


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APPENDIX A

PRESENTATION OF MEASURED PROFILES

The measured sedimentary profiles from the various subenvironments are presented here. The profiles are presented in Figures A.2 through A.10. There are three profiles from Kanaalkop (KP 1, KP 2, and KP 3), two from Skoorsteenberg (SK 1 and SK 2) and Rondawel West (RW 1 and RW 2). One profile each from Blaukop (BK 1) and Bizansgat (BZ 1) are also represented. For locations refer to Figure 2.1. For detailed discussions on the profiles see Chapter 2. The legend used in the sections are presented in Figure A.1. The sections were plotted using Applecore version 6.0.1.
Figure A.1 Legend used in the measured profiles presented in the following pages.
Kanaalkop (KP 1)

Figure A.2 Measured profile at Kanaalkop (KP 1, Fan 3). The section is represented in segments (a) 0-10.5 m; (b) 10.5-21.2 m, (c) 21.2-31 m, (d) 31-39.8 m, and (e) 39.8-48 m. (Fig. A.2 con’d.)
Kanaalkop (KP 1)

b.

Bed #36. Overall poorly exposed (scree).
- Lowermost unit of Bed #36
  - Bed #35
    - N105-110E ripples
    - Topmost unit of Bed #34

Numerous beds within Bed #34, with distinct wavy bases and indistinct wavy tops. Average thickness 25 cm.
- Lowermost unit of Bed #34, Tc.
  - Bed #33, Tc.

Uppermost 7-8 cm heavily rippled.
  Has the appearance of a bedform. Good Ta-Tc bed.
  Bed #32
- Lower part massive, with ripup clasts.
  Apparently Beds #32-33-34 are parts of the same genetic package.
  Gamma reading #56, at base of Bed #32.
  Topmost unit of Bed #31.

(15.0-22.50 m): INTERBEDDED VERY-FINE GRAINED SANDSTONES WITH MINOR SILTSTONES. LATTER COMMON OVER SOME INTERVALS. COUPLE OF BEDS WITH GOOD

Average 8 cm beds fining upward. Bed #31 is an aggregate of several units. Upper 1/3rd goes up to 30 cm. Individual units with wavy distinct bases and wavy indistinct tops. (Similar to overbanks at Blaukop, by the road.
  N110E, ripples.
  Basal unit Bed #31
  Foliated top, due to wavy laminations. Bed #30.
  Partings in between Beds #26-29.
  N105-130E.
- Beds 24 to 29 are fining upward beds, with sharp bases and indistinct tops, finer-grained at the top. Graded beds. Bed #26

(Fig. A.2 con’d.)
Kanaalkop (KP 1)

(Fig. A.2 con’d.)

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Kanaalkop (KP 1)

Heavily erosional at the base. Scouring not visible within short distances. Over 25-30m considerable scour relief visible. From E to W, steplike cuts (at least 3 major ones) on each side of the axis of the channel.

Occasional ripup clasts along single wavy surfaces.

Amalgamation surfaces common.

Parallel to slightly wavy laminations common (traction carpet/incipient freezing).

Bed #32

(Fig. A.2 con’d.)
Kanaalkop (KP 1)

e.

Topmost unit of Bed#38
N40E ripples.

Heavily ripple laminated and wavy laminated (aggradational climbing ripples).

N35E ripples
N60E ripples

Lowermost unit of Bed#33
Heavily ripple laminated and climbing ripple laminated.

Bed#32
Channel
Figure A.3 Measured profile at Kanaalkop (KP 2, Fan 3). The section is represented in segments (a) 0-10.5 m; (b) 10.5-19.7 m; (c) 19.7-28.6 m; and (d) 28.6-37.5 m.

(Fig. A.3 con’d.)
b. Kanaalkop (KP 2)

(Fig. A.3 con'd.)
Kanaalkop (KP 2)

Better directional features, no partings. But not well beded either.

Lowermost Bed 41
Topmost B40
Not as well bedded as below. N40-60W. Better directional features than below. Not much in terms of aggradational climbing ripples.

Lowermost Bed 40

Scree cover

Topmost Bed#36
Lowermost Bed#36

(Fig. A.3 con’d.)
d.

Kanaalkop (KP 2)

- Mostly massive, occasional festoon and trough cross beddings, with rip up clasts.
- Rare parallel beddings present.
- Top channel, few amalgamations & parallel laminations (upper flow regime flat beds?)
- Topmost Bed 41

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Kanaalkop (KP 3)

Figure A.4 Measured profile at Kanaalkop (KP 3, Fan 3). The section is represented in segments (a) 0-10.5 m; (b) 10.5-20.7 m; (c) 20.7-31.2 m; and (d) 31.2-39.6 m.

(Fig. A.4 con'd.)
Kanaalkop (KP 3)

(Fig. A.4 con’d.)
Kanaalkop (KP 3)

B 74. Ta,b,c. Tc~50 cm. Ta~40cm.(3D) N6W (multiple readings). Loadings (small) at the base. Subtle erosion at the base. B74 is 160 cm at the NW corner (180m from KP#3) of the outcrop but pinches out below the top of channel close to the NW corner but on the front north-face, below the top channel, ~250m from KP#3.

B 73. Top loaded into by B 74. Jopling type ripples. Compensational stacking-ripple field-fill.

B 71. 1 wavy amalgamation at the center. Climbing ripples and wavy laminations.

B 70. Wavy to climbing ripples.

B 67. Also a ripple field fill-compensational stacking.

B 64. N 40W.


Top B 59.

B 58. Wavy lams. grading towards climbing ripples.

Wavy laminations grading towards climbing ripples.

B5S. N20W, ripples.

Top B 54.

Base B54. This interval B 54 is equivalent to LV2/CB2 (KP#2).

B 52. (3D)N40W. Base B 54.

Top B 51. Ripple laminated: N35W. Subunits show compensational stacking.

Interbedded vFl and siltstones with silty shales. Ave. thickness 10cm.

B50 = B36-37in P1.

Scree above B36 in P2 = B50 in P3.

(Fig. A.4 con’d.)
Kanaalkop (KP 3)

d. Top channel-fill.

Few clusters of organics at places. Ta-b. Ta>>Tb

B 81. Avg. 4-6cm. vFI-siltstones interbedded, with silty shale. No wavy-laminations or climbing ripples.

B 80.

B 76.

Top B 75. Thin partings. Wavy to ripple laminated.
Figure A.5 Measured profile at Skoorsteenberg (SK 1, Fan 3). The section is represented in segments (a) 0-11 m and (b) 11-19 m. (Fig. A.5 con'd.)
Skoorsteenberg (SK 1)

b.

**GRAIN SIZE**

- cobble
- pebble
- granule
- sand
- silt
- clay

---

B 33. Ta=25cm, Tb=3cm. N 75E. Rills and fluted.

B 32. Ta=23cm. Tb=5cm.

B 29. Ta=15cm. Tb=6cm.

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Figure A.6 Measured profile at Skoorsteenberg (SK 2, Fan 3). The section is represented in segments (a) 0-10.5 m and (b) 10.5-19 m. (Fig. A.6 con’d.)
b.

Skoorsteenberg (SK 2)

---

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Figure A.7 Measured profile at Rondawel West (RW 1, Fan 3). The section is represented in segments (a) 0-4.6 m and (b) 4.6-9 m. (Fig. A.7 con’d.)

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b.

Rondawel West (RW 1)

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Figure A.8 Measured profile at Rondawel West (RW 2, Fan 3). The section is represented in segments (a) 0-4.6 m and (b) 4.6-9 m.

(Fig. A.8 con’d.)
b.

Rondawel West (RW 2)

- vfU sandstones. Uppermost 18cm wavy laminated, rest massive, Ta.
- Some ripups standing vertically; sandy debris flow?
- B 29 as in P1. Isolated ripup clasts, upper 25cm, paralllely laminated. Ta,b bed.
- B 27+828 in RW P1 amalgamated into one here. Ta,b. Upper 10% tb.
Blaukop (BK 1)

Figure A.9 Measured profile at Blaukop (BK 1, Fan 5).
Biansgat (BZ 1)

Figure A.10 Measured profile at Bizansgat (BZ 1, Fan 4).
APPENDIX B

PRESENTATION OF ANISOTROPY OF ISOTHERMAL REMANENT MAGNETIZATION DATA

The data from the IRMA study is presented here. The sample number, $K_{\text{max}}$, $K_{\text{int}}$, $K_{\text{min}}$ magnitudes, $(D/I)_{\text{max}}$, $(D/I)_{\text{min}}$, % anisotropy, L, and F are provided. $K_{\text{max}}$, $K_{\text{int}}$ and $K_{\text{min}}$ represent sample maximum, intermediate and minimum axes, respectively. D and I represent the declination and inclination in degrees, respectively. L is lineation ($K_{\text{max}}/K_{\text{int}}$) and F is foliation ($K_{\text{int}}/K_{\text{min}}$).
Table B.1 IRMA anisotropy data presented from the various depositional environments in the submarine fans. $K_{\text{max}}$, $K_{\text{int}}$, and $K_{\text{min}}$ represent the maximum, intermediate and minimum axes of anisotropy ellipsoids respectively. D and I are declinations and inclinations in degrees. \% anisotropy = 100 x ($K_{\text{max}}$-$K_{\text{min}}$)/$K_{\text{int}}$. L is lineation ($K_{\text{max}}$/K_{\text{int}}), F is foliation ($K_{\text{int}}$/K_{\text{min}}).

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**Rondawel West (Lower mid-fan levee-overbank, Fan 3)**

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**Skoorsteenberg (Lower fan distal sheet deposits)**

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APPENDIX C

X-RAY DIFFRACTION DATA

The X-ray diffractograms and Newmod reference file matches with sample diffraction patterns are presented in this appendix. Newmod reference file matches represent overlays of observed and simulated XRD patterns.
Figure C.1 XRD patterns of clay fraction from sample DBBZ94.4, representative of a mid-fan passive channel-fill (Bizansgat, Fan 4). (a) Pattern represents various treatments, A - air dried; B- ethylene glycol saturated; C- heated to 300°C; and D-heated to 550°C. Numbers on the diffractograms indicate d-spacings (Å). The 14 Å and 10 Å series of peaks represent the chlorite and illite (00l) series, respectively. (b) The observed (solid line) and simulated XRD patterns (dashed line) for sample DBBZ94.1, (Bizansgat, Fan 4) and (c) sample DBKBZ94.4, are representatives of a mid-passive channel-fill (Bizansgat, Fan 4). (Fig. C.1 con'd)
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Figure C.2 XRD patterns of clay fraction from sample DBSK94.2, representative of a lower-fan distal-sheet sandstone setting (Skoorsteenberg, Fan 3). (a) Pattern represents various treatments, A - air dried; B- ethylene glycol saturated; C- heated to 300°C; and D- heated to 550°C. Numbers on the diffractograms indicate d-spacings (Å). The ~ 14 Å and ~ 10 Å series of peaks represent the chlorite and illite (001) series, respectively. (b). The observed (solid line) and simulated XRD patterns (dashed line) for sample DBSK94.1, and (c) for sample DBSK94.2, are representatives of a lower-fan distal-sheet sandstone setting (Skoorsteenberg, Fan 3). (Fig. C.2 con’d)
Figure C.3 XRD patterns of clay fraction from sample DBBK94.2, representative of a mid-fan channel fill setting (Blaukop, Fan 5). (a) Pattern represents various treatments, A - air dried; B- ethylene glycol saturated; C- heated to 300°C; and D-heated to 550°C. Numbers on the diffractograms indicate d-spacings (Å). The ~ 14 Å and ~ 10 Å series of peaks represent the chlorite and illite (00l) series, respectively. (b) The observed (solid line) and simulated XRD patterns (dashed line) for sample DBBK94.1, and (c) for sample DBBK94.2, are representatives of a mid-fan channel fill (Blaukop, Fan 3). (Fig. C.3 con’d)
Figure C.4 XRD patterns of clay fraction from sample DBBK94.32, representative of a mid-fan levee-overbank setting (Blaukop, Fan 5). Pattern represents various treatments, A - air dried; B- ethylene glycol saturated; C- heated to 300°C; and D-heated to 550°C. Numbers on the diffractograms indicate d-spacings (Å). The ~ 14 Å and ~ 10 Å series of peaks represent the chlorite and illite (00l) series, respectively. (b) The observed (solid line) and simulated XRD patterns (dashed line) for sample DBBK94.32, and (c) for sample DBBK94.23, are representatives of a mid-fan levee-overbank setting (Blaukop, Fan 3)
b.

![Graph b](image)

- Dotted line: New Mix
- Solid line: DBB943E

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c.

![Graph c](image)

- Dotted line: New Mix
- Solid line: DBB942E

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Debnath Basu was born October 30, 1966 to Indrani Basu and Shakti Kumar Basu. He completed his elementary and secondary schooling from St. Thomas Boy's School and high school education at Vidyasagar College, Calcutta. Mr. Basu earned a Bachelor of Science degree with honors in Geology from Presidency College under the University of Calcutta in 1988. He completed a Master of Science degree in Geology from the Ballygunj Science College Campus of the University of Calcutta, in 1991. His masters thesis involved petrology of the Precambrian terrain of eastern India under the supervision of Dr. Aniruddha Dey at the University of Calcutta.

Mr. Basu embarked on his doctoral studies in August, 1991 at the Louisiana State University, Baton Rouge, USA. During his stay in Baton Rouge he learned much about geology in general and sedimentary geology in particular from his advisor, Dr. Arnold H. Bouma and other faculty members. Mr. Basu, being an international student, has learned much about other cultures and societies in the cosmopolitan environment at Louisiana State University. He expects to receive the Doctor of Philosophy degree from Lousiana State University in May 1997. Mr. Basu married Tanwi Gangopadhyay in May, 1992.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Debnath Basu

Major Field: Geology

Title of Dissertation: Characterization of Thin-Bedded Turbidites from the Permian Tanqua Karoo Submarine Fan Deposits, South Africa

Approved:

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Major Professor and Chairman
Dean of the Graduate School

EXAMINING COMMITTEE:

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Date of Examination:

January 9, 1997