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Vol I

IMPROVED RECOVERY FROM GULF OF MEXICO RESERVOIRS

Volume I (of 4)
Task 1, Conduct Research on Mud-Rich Submarine Fans
(subtask 1.1, subtask 1.2)

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Task 1, Conduct Research on Mud-Rich Submarine Fans
(subtask 1.1, subtask 1.2)
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ABSTRACT

The objective for this portion of the research involved conducting field studies and laboratory investigations to develop and refine models for mud-rich submarine fan architectures used by seismic analysis and reservoir engineers. These research aspects have been presented in two papers as follows:

- Bouma,A.H., "Review of Fine-Grained Submarine Fans and Turbidite Systems"
- Kirkova, J.T. and Lorenzo, J.M., "Synthetic Seismic Modeling of Measured Submarine Fan Sections, Case Study of the Tanqua Complex, Karoo, South Africa"

The "Review of Fine-Grained Submarine Fans and Turbidite Systems" by Arnold Bouma discusses research targeted toward stimulating an increase in oil and gas recovery by developing new and improved geological understanding.

The "Synthetic Seismic Modeling of Measured Submarine Fan Sections, Case Study of the Tanqua Complex, Karoo, South Africa" by J.T. Kirkova and J.M. Lorenzo discusses the limitations of vertical resolution and how this affects the interpretation and characterization of submarine fan complexes.

EXECUTIVE SUMMARY

Review of Fine-Grained Submarine Fans and Turbidite Systems

The field of deep-water clastic deposits has expanded tremendously with contributions about sedimentary characteristics, models, processes, geophysical characteristics, sequence stratigraphy, examples and descriptions of modern and ancient deposits, etc. Most deep-water sands belong to the category of submarine fans. The main influencing factors that control the development and characteristics of submarine fan deposits are:

1. the tectonic setting and activity on both the sediment generation and the sediment receiving areas,
2. sedimentary factors, especially sand/shale ratio, volume of the sediment involved, and climatic conditions, and,
3. relative sea level fluctuations.

The Mississippi Fan and the Amazon Fan are the only submarine fans that have been drilled systematically and reported on in the open literature by late 1995. Significant findings have changed opinions about these types of sediment bodies. These are:

1. a submarine fan is a non-vertical stacking assembly of individual depositional units (fanlobes or time slices),
2. fanlobes may display variability between them, but in general each fanlobe can be described as a channel-levee-overbank-sheet sand complex,
3. each fanlobe starts at the upper slope or outer shelf with a canyon that merges downslope into an erosional upper fan channel (conduit)
4. near the base of the slope the erosional characteristics change into depositional ones
5. the middle fan is aggradational with a rather straight or slightly sinuous channel (meandering characteristics)., probably underlain by debris flow deposits and
6. a lower fan with a "distributary" channel system and sheet deposits.

Only two areas are known that have good and accessible examples of "passive" margin submarine fans in outcrop (northern Norway, and southern South Africa).

No model can be applied universally to similar types of deposits in different areas, but general characteristics may well be applicable. Basin size and gradients, climatological and tectonic activites in the area where rocks are eroded into sedimentary particles, the length and time involved to bring that sediment to the coast line, the sand/mud ratio of the sediment passing through the deltaic distributary mouth, current and tidal influences at the delta shore line, width of the shelf and the slope toward the receiving basin, and the relative sea level fluctuations present at that time, will influence the construction and the characteristics of a submarine fan. In spite of all of these variations a model is proposed for a fine-grained, single entry point, basin floor fan that is part of a mud-rich submarine fan complex.

At the entry to the basin floor, in the base-of-slope zone, a very sand-rich channel complex is constructed comprised of channel fills that cut into each other (erosional events) and are often separated by thin sand-rich, laminated zones. This complex changes into channel-levee-overbank deposition. A main channel progrades rapidly onto the basin floor, after which total accumaulation is the result of local vertical accumulation and the frequent lateral switching as the sediment pile reduces the local gradient too much.

The channel gradually shoals and finally loses its constraining influence on the head of the density current. The turbidity curent will fan out and an elongate sheet sand will be deposited. Succeeding sheet sands may stack vertically, form a shingling set of layers or a compensational arrangement.

As a general rule, the basin-floor fan increases in thickness in the updip area of the basin and then gradually thins downdip and laterally. The base-of-slope channel complex migrates upwards into the lower part of the upper fan channel in order to maintain a downdip gradientwhen the submarine fan aggrades. The sand/shale ratio is very high in the base-of-slope area, lower and variable in the channelized area (mid-fan) and high again on the lower fan with its sheet sand deposition.

Seismically, the channelized area is the easiest to recognize. The base-of-slope area might be an important reservoir target but it is more difficult to distinquish on seismic records.

Synthetic Seismic Modeling of Measured Submarine Fan Sections, Case Study of the Tanqua Complex, Karoo, South Africa

One of the limitations of seismic studies is vertical resolution. Terrigenous clastic sequences less than 15 m thick could be laterally extensive for many kilometers but undetectable on seismic profiles. A submarine fan complex off the Skoorsteenberg Formation in the southwestern Karoo is used to examine the consequences of underestimating the extent of submarine fans separated by basin shales.

It was found that the practical vertical resolution of the turbidite sequences studied, by using 40 Hz wavelet and 1 ms sampling rate, is 5-7 m. Below this limit the base of any fan unit cannot be resolved. Thus, the study proves the limitation of the seismic modeling when detecting the lateral extent of turbidite sequences on seismic sections.

Review

of

Fine-Grained

Submarine Fans and Turbidite Systems

by

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February, 1996

INTRODUCTION

The DOE (1993) report indicates that for the onshore and nearby offshore areas a quantity of 60 billion barrels of original oil-in-place (OOIP) should be present in Slope-Basin and Basin clastic reservoirs. Nearly 26% of that amount was produced by December 1991. An estimated 14.7 billion barrels was assigned to the unrecovered mobil oil (UMO) category. Unfavorable fluid characteristics and macroscopic heterogeneities prevent standard production. In order to recover that advanced secondary recovery (ASR) techniques, including horizontal drilling, infill drilling, polymer flooding, permeability profile modification, and other approaches, have to be applied. A total of 28 billion barrels are trapped with reservoirs by surface tension and capillary forces. That immobile oil is the target for enhanced (tertiary) oil recovery (EOR) processes (DOE, 1993, p. II-I).

In order to stimulate an increase in oil and gas recovery it is not only necessary to develop new and improved engineering techniques, but also geological understanding. Examples of improved geological, geophysical and petrophysical knowledge include the collection of hard data on the architecture (internal build-up and sand-body geometry) of these deposits, the effect of interbedded shales on connectivity, improved geophysical and petrophysical recognition of the various depositional units present in subenvironments of submarine fans, integration of outcrop studies with synthetic sonic logs, seismics and several engineering parameters, and modeling.

A significant amount of literature on submarine fans, (deep-water sands or turbidite systems) exists. A complete review will not be provided; a rather complete overview with major reference lists can be obtained from the few books compiled on this topic (Bouma et al., 1985a; Weimer and Link, 1991; Mutti, 1992; Weimer et al., 1994; Pickering et al., 1995).

The field of deep-water clastic deposits has expanded tremendously with contributions about sedimentary characteristics, models, processes, geophysical characteristics, sequence stratigraphy, examples and descriptions of modern and ancient deposits, etc. As a consequence the studies on submarine fans vary tremendously in approach making certain comparisons impossible. Modern fans are primarily studied using seismic techniques (multifold, high-resolution, side-scan sonar) and short cores, while ancient outcrops of submarine fans are good for stratigraphic studies, detailed investigations of the sediments, and sometimes lend themselves to carry out lateral studies. Subsurface occurrences are primarily investigated by industry using seismics and well logs with occasionally a core. Because of the different approaches and difference of scale and resolution, a straight forward comparison between these different

approaches is impossible.

Flume studies and other experiments conducted on transport and deposition have improved our understanding tremendously. However, the results can not be applied directly to the field using visual observations only. Nevertheless a general understanding of processes makes it easier to understand some of the internal characteristics of the sandstones, such as porosity and permeability trends, connectivity, geometry of sandstone bodies, etc.

Most deep-water sands belong to the category of submarine fans. The majority of those depositional bodies have accumulated in the marine realm on continental margins and adjacent basins. The shape and size of submarine fans, as well as the sand/shale ratio of their sediments and the thickness and distribution of the sands, are more variable and complex than has been encountered in many other depositional environments. The main influencing factors that control the development and characteristics of submarine fan deposits are: 1) the tectonic setting and activity on both the sediment generation and the sediment receiving areas, including the width of the shelf, seafloor gradients, and the size and shape of the receiving basin, 2) sedimentary factors, especially sand/shale ratio, volume of the sediment involved, and climatic conditions, and 3) relative sea level fluctuations.

Non-compatibility in approaches and scale of resolution has introduced major confusion between published models and the results from outcropping formations, subsurface occurrences, and seismic analyses of submarine fans. Because of post-depositional tectonic activity, the active margin settings have a good chance to become exposed subaerially. Only, in a few cases will passive margin setting deep-water sands be exposed. The majority of the published models, therefore, have been derived from outcrops and from modern fans located in active margin settings. This has led to serious misunderstandings by earth scientists dealing with "passive" margins. In addition, most models are based on criteria that are too small to be recognized or even detected seismically. Therefore, it is necessary to work with geological concepts to fill the gap within the seismic framework, or with some inconsistencies inherent to lithological variations when working with conventional well logs.

The Mississippi Fan and the Amazon Fan are the only submarine fans that have been drilled systematically and reported on in the open literature by late 1995 (Bouma et al., 1986; Flood et al., 1995). Significant findings have certainly changed our opinions about these types of sediment bodies. These can be summarized as follows: 1) a submarine fan is a non-vertical stacking assembly of individual depositional units (fanlobes or time slices), 2) fanlobes may

display variability between them, but in general each fanlobe can be described as a channel-levee-overbank-sheet sand complex, 3) each fanlobe starts at the upper slope or outer shelf with a canyon that merges downslope into an erosional upper fan channel (conduit), 4) near the base of the slope the erosional characteristics change into depositional ones, 5) the middle fan is aggradational with a rather straight or slightly sinuous channel (meandering characteristics), probably underlain by debris flow deposits, and, 6) a lower fan with a "distributary" channel system and sheet deposits.

Channel axis gravels, sands, and fine-grained sediments form ideal hydrocarbon migration paths and reservoirs, while "pointbar"-type deposits and "levees" (proximal overbank) have excellent reservoir qualities. Acoustic high-amplitude zones often indicate the location of these channel fills, where erosional channel shapes may not be apparent on seismic records. On the lower fan, the channel(s) gradually become smaller and terminate, changing the depositional style from channel-overbank to very significant sheet deposits that often have high sand/shale ratios.

Although the large-volume Mississippi Fan has a rather low sand/shale ratio in overall sense, the total amount of sand in the channel fill and in the outer fan sheet sands is very attractive (high N/G ratio). A major exploration/production question is how far can industry utilize the findings and interpretations from the Mississippi Fan when working in the salt-withdrawal intraslope basins of the northern Gulf of Mexico, as well as in basins internationally.

Only two areas are known that have good and accessible examples of "passive" margin submarine fans in outcrop (northern Norway, and southern South Africa). In order to obtain a more balanced idea about the internal architecture of channels, levee-overbank areas, and distal sheet sands it is recommended to study more than one area. A larger data base provides a more balanced insight into the variations that may occur in the architecture of similar depositional subenvironments and into variations of connectivity.

SEDIMENT GRAVITY FLOWS

The transport and depositional processes of sediment gravity flows have a primary effect on initial porosity and permeability. The original packing of the sedimentary grains, together with petrographical characteristics, chemistry of the fluids, and overburden pressures, largely dictates the early and later diagenetic effects that may take place.

The classification of sediment gravity flows is somewhat confusing and often deals with ideal circumstances rather than with natural complexity. Insight into this matter will become more and more important in the future, specifically for the understanding of petroleum reservoir quality and the selection of enhanced recovery problems.

Experiments are very essential to better understand the processes responsible for the transport and deposition of terrestrial sediments to deeper water. However, to transfer experimental variations into characteristics that can be identified in outcrop or in a core is not a straight forward procedure and consequently gives rise to disagreement between researchers. It also has to be understood that many more experiments have to be conducted before an acceptable coverage of possibilities has been obtained. Kneller and Branney (1995) present one of the latest examples of progress in that field (their findings are briefly discussed in the chapter on models).

The entire spectrum of sediment flows driven by gravity, including turbidity currents, has been labeled "sediment gravity flows" by Middleton and Hampton (1973, 1976). Those authors noted that in a fluid gravity flow the fluid is moved by gravity and consequently drives the sediment along, and that in a sediment gravity flow it is the sediment that is moved by gravity and that the sediment moves the interstitial fluid. Mechanisms such as suspension (by turbulence), saltation (by hydraulic lift forces and drag), and traction (by dragging or rolling of particles over the bottom) may all operate in some types of sediment gravity flows, as they do in some types of fluid gravity flows.

Middleton and Hampton (1973, 1976) outlined a number of end members in the continuum of sediment gravity flow processes (Fig. 1) that become active from the time sediment movement is initiated until it ceases at some depositional site (Fig. 2). In all the processes, as long as there is support in the flow to keep particles from settling out, sediment particles move downslope parallel to the dip of the bed in response to gravity.

The four end members are defined on the basis of their grain support mechanism as

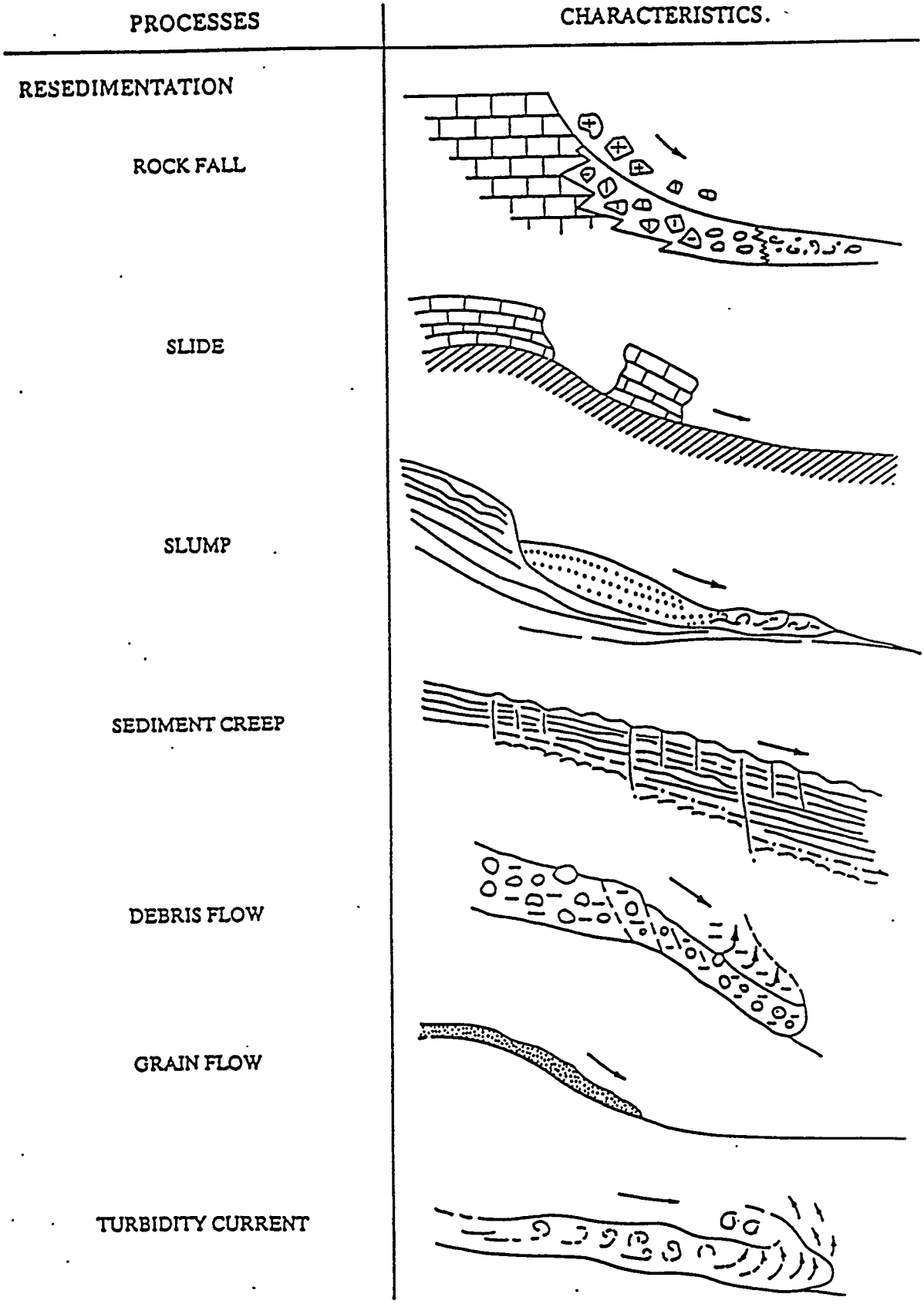


Figure 4. Schematic presentations of the major resedimentation processes. Most are known from aquatic environments, some also occur subaerially. The various processes shown are end products of a continuum of processes. Several processes can operate simultaneously which results in a deposit that may show vertical or lateral successions of end member deposits or mixtures of them (Redrawn after Stow, 1985).

structures and/or fluid-escape pipes) can be observed (Fig. 4). The lack of noticing those structures can be the direction of light falling onto the outcrop or of textural characteristics of the rock like a fine grain size, and thus should not be considered deterministic.

It has to be kept in mind that all these different sediment gravity processes, discussed briefly, are end members of a continuum and that the boundaries are poorly defined. In Nature the rocks typically display combinations of processes making strict genetical interpretations illogical. Good descriptions, therefore, are preferred over genetic terms, especially when doing visual observations on mixtures of end members.

Other sediment transport agents are internal waves, tidally-induced currents in submarine canyons, contour currents, eolian transport, and pelagic/hemipelagic transport. Internal waves can "clean" a sand-containing deposit when they encounter the seafloor, like waves running onshore. Tidal currents can transport sand in updip direction in a submarine canyon. The amount, however, is very small compared to downslope transport during active submarine fan construction.

Contour currents are global thermo-haline phenomena based on stratification of major water bodies in the oceans. Where a major water body (thick layer) moves away from its source and touches the seafloor with sufficient force, sediment sorting and transport can take place. The Antarctic Bottom Current is the best known example. These currents are depth contour-following currents and the fine-grained sediments that result are known as contourites. Some investigators regard these contourites as important aspects of some submarine fans (Mutti et al., 1980; Carminatti and Scarton, 1991).

It has to be realized that small and large depressions are very common in major ocean basins, including subbasins. Local currents, not related to contour-following currents, can affect the basin floor sediments and short-distance transport can result. These should not be called contourites because literature suggests that contourite deposits can be very thick and extensive. Such would give a wrong signal to explorationists.

Hemipelagic and pelagic transport/deposition agents are very important because they produce the massive basin shale and the condensed sections, respectively. Fine-grained sediment leaving the deltaic area will be transported in suspension to the delta front and prodelta areas, as well as to the deeper basins and ridges between them. The muds in the deltaic areas may partly become incorporated in a slide or slump when a segment of a delta or basin slope fails. They will become a significant part of any of the sediment gravity flows. The resulting

shales can be recognized by their layering.

Clays and fine silts that move over a significant distance through the water column before becoming deposited, result in more homogeneous shale series. If those fine-grained sediments become deposited on the flanks of a basin occasional instability can result. This causes resedimentation via sediment gravity flows to the deeper part of that basin.

Pelagic sedimentation is a slow accumulation process that can be the major process during relative high sea-level when the other processes do not operate or are insignificant. The resulting pelagic deposit can become a marl or a marly carbonate of several cm thickness. Its density differs from the other deposits and when its thickness is sufficient it will form a condensed section that may be detectable on a seismic record.

FACTORS CONTROLLING SUBMARINE FAN GROWTH AND THE SELECTION OF A MODEL

The distribution of sand-sized and finer grained materials in submarine fans and turbidite systems seems to be as variable as has been noticed in deltaic settings. Several factors, including size and shape of a fan, do have a significant influence on the sediments and their distribution, because the different factors that control the development of a submarine fan are interactive. Their relative importance for any specific fan cannot be provided at this time until more details are known about these sediment bodies.

Present models are typically based on one or a few field examples, representing either a modern submarine fan or an outcropping ancient turbidite system. Application of a specific model is commonly made without appreciation of the parameters that were used to construct that example. To work with only one geologic model or exploration concept is insufficient, especially if one realizes that several factors can influence the construction of a fan and the deposition of its reservoir-quality material. The four most important sets of influencing factors are;

Tectonic setting
Climate
Sedimentation
Sea-level variations

TECTONIC SETTING

The importance of realizing the interrelationship of these factors can be best illustrated by denoting the difference in the two most common tectonic settings. Active-margin submarine fans normally are small and sand rich; passive-margin fans typically are medium to large and have a "low" sand/shale ratio. The terms active and passive relate to the degree of tectonic activity during deposition of the fan. The terms sand-rich and mud-rich fans can also be used although they are not the equivalent of the tectonic terms (Reading and Richards, 1994).

Comparison between modern and ancient submarine fans is in effect a comparison between apples and oranges. Modern submarine fans are often divided into two major end groups: those located in active margin settings and those located in passive margin settings. Practically all ancient submarine fan deposits that can be studied in outcrop typically were built in active margin settings, allowing later plate motions to expose them. Exposed sections of

submarine fan systems, deposited in "passive" margin settings, are rare (Kongsfjord System in northern Norway, Ecca Group in South Africa).

Realization of large differences in both the size and shape of submarine fans makes it easier to understand that it will be difficult to gather all fans into one model, because such a model would contain so little information that it would be worthless. In addition, there are significant differences in study approaches toward modern and ancient fans (Fig. 5; Normark et al., 1979; Bouma et al., 1985b). In studies of modern fans, most acoustical systems that scan the seafloor at a water depth of 1000 m or more cannot adequately resolve a relief that is less than 2 m or more, or horizontal dimensions that are smaller than several tens to hundreds of meters. Deep-towed equipment provides a much higher resolution, but coverage is minimum. Seismic resolution will not come close to the actual size of a reasonable outcrop when using multichannel CDP equipment. An increase in resolution causes a decrease in acoustic penetration, with the result that only the upper part of a fan system is analyzed.

A number of modern and ancient submarine fan systems at the same scale are presented in Figure 6 (Barnes and Normark, 1985). This figure shows the wide variety in size and shape of submarine fans and turbidite systems. Very few fans have a fanlike shape, the Magdalena Fan being the most ideal. When a submarine fan is large, such as the Bengal Fan, the overall shape of the receiving basin will directly influence its shape. Smaller fans, deposited in a passive margin setting, can approach a fan shape (Mississippi and Amazon Fans).

Fans located in active margin settings often are small and have an elongated shape, typical of the basins in such areas (Astoria, Delgada, and Navy Fans). The ancient equivalents generally also show an elongated shape, although it must be kept in mind that the outlines of these bodies are based on interpretations of what is, after erosion, still present in the field because most of the shaly areas are weathered away (e.g., Marnoso Arenacea, Gottero, Hecho, Blanca, and Chugach Turbidite Systems) (Fig. 6).

Consequently, a direct comparison between ancient and modern systems is very difficult. Nevertheless, investigators propose models using the same terminology which may be based on different definitions. It should be understood that models developed from modern submarine fans will emphasize morphology, major seismic characteristics, and sediment information from the surficial part of a fan. Models based on ancient systems emphasize lithologies, layer or sandstone package thickness, vertical sediment sequences, and sedimentary structures.

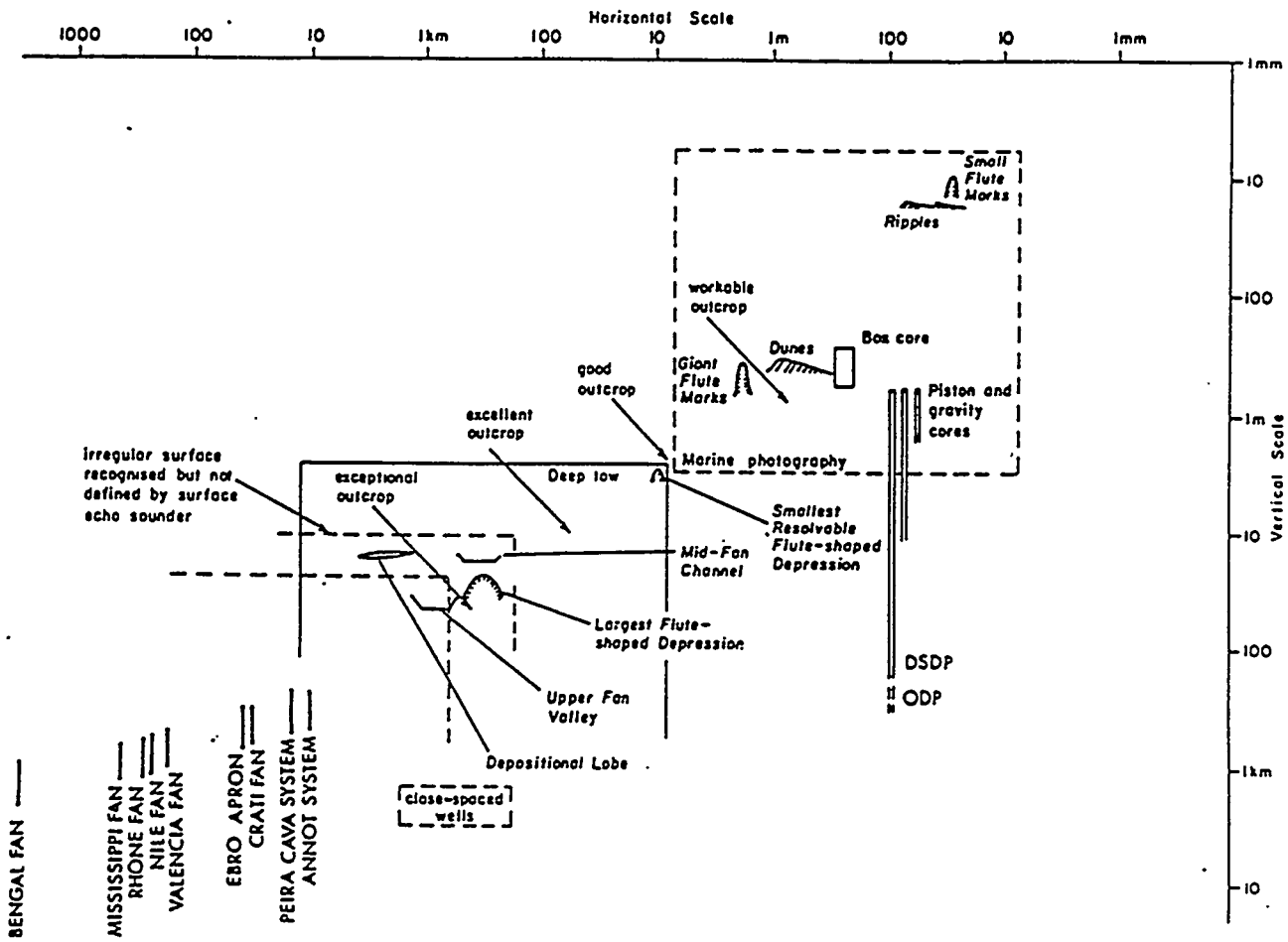


Figure 5. Double logarithmic plot of horizontal and vertical scales of several phenomena to compare modern fan data sets with sedimentologic observations based on outcrop studies in ancient turbidites (Modified from Bouma et al., 1985b). Note that most of the excellent outcrops normally are smaller than most mid-fan channels and outer fan depositional lobes. That can be a reason for errors in lateral correlation using several outcrops of tectonically tilted deposits.

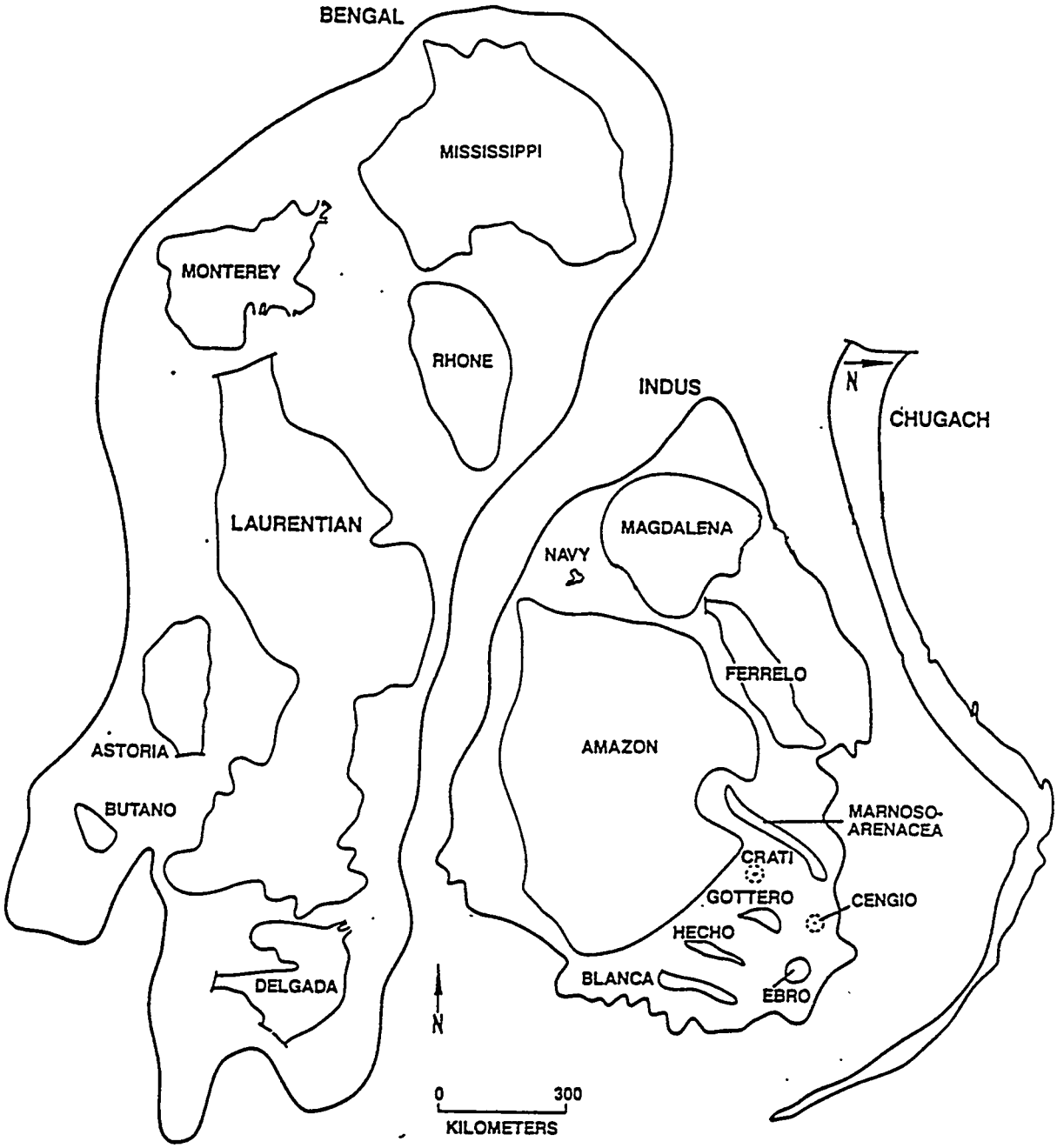


Figure 6. Comparison of sizes and shapes of some modern submarine fans and ancient turbidite systems at the same scale. The outlines of modern fans are normally based on reflection seismics and possibly side-scan sonar and cores. The outlines of ancient turbidite series are based on non-weathered parts of outcrops with most of the shales removed, or in the subsurface making use of drilling with or without seismics (Redrawn from Barnes and Normark, 1985).

Note: north is to the top of the figure, except for the Chugach Turbidite System.

CLIMATE

Climate and sedimentary characteristics commonly are closely linked, except for the petrographical characteristics that represent the rock types of the sediment source area. Physical weathering is the strongest activity in the higher mountains while biological and chemical processes commonly prevail in the lower altitudes. The longer these processes can operate, and thus the longer the time frame is that relates to the transport of particles, the finer the sediment size is.

Sediment that is released from coastal mountains, therefore, has the best chance to be coarse grained and low in fine-grained silt and clay. When the transport route is long, as is the case with the larger rivers, the fluvial gradient becomes extremely low before the flow reaches the outer coastal plain and the delta. Coarse material normally can not be transported anymore and the relative clay content increased tremendously, often to a degree that the transported sediment can be classified as sand poor.

SEDIMENTATION

Low sand/clay sediment can be deposited in a deltaic complex. When relative sea level drops the most active distributary will become the major transport route for the discharge. Lateral switching to other distributaries becomes less frequent. Rapid accumulation will take place in front of that distributary. The clays will not be able to release water fast enough to keep up with the weight of the overlying accumulation. An increase in pore pressure results, causing instability, making the sediment pile prone to failure. Sliding and slumping will follow, initiating transport to a basin (Coleman et al., 1983).

The sand/shale ratio directly affects the transport capabilities of the sediment gravity flow, especially those of a turbidity current. When the sand/clay ratio is high the distance over which the sand can be transported is short (low-efficiency transport). A low sand/clay ratio sediment results in a high efficient transport (Mutti, 1985; Mutti and Normark, 1987). For those reasons the high sand/clay ratio fans are small while the low sand/clay ratio ones can be very large and more elongate in shape.

The above-mentioned rules are not always applicable. The Pennsylvanian Jackfork Formation in Arkansas-Oklahoma is a typical trough (foredeep) deposition. Theoretically that means an active margin setting. However, such a tectonic setting has active and passive periods. The sediment source was sufficiently far away that fine-grained sediment dominates the deposits.

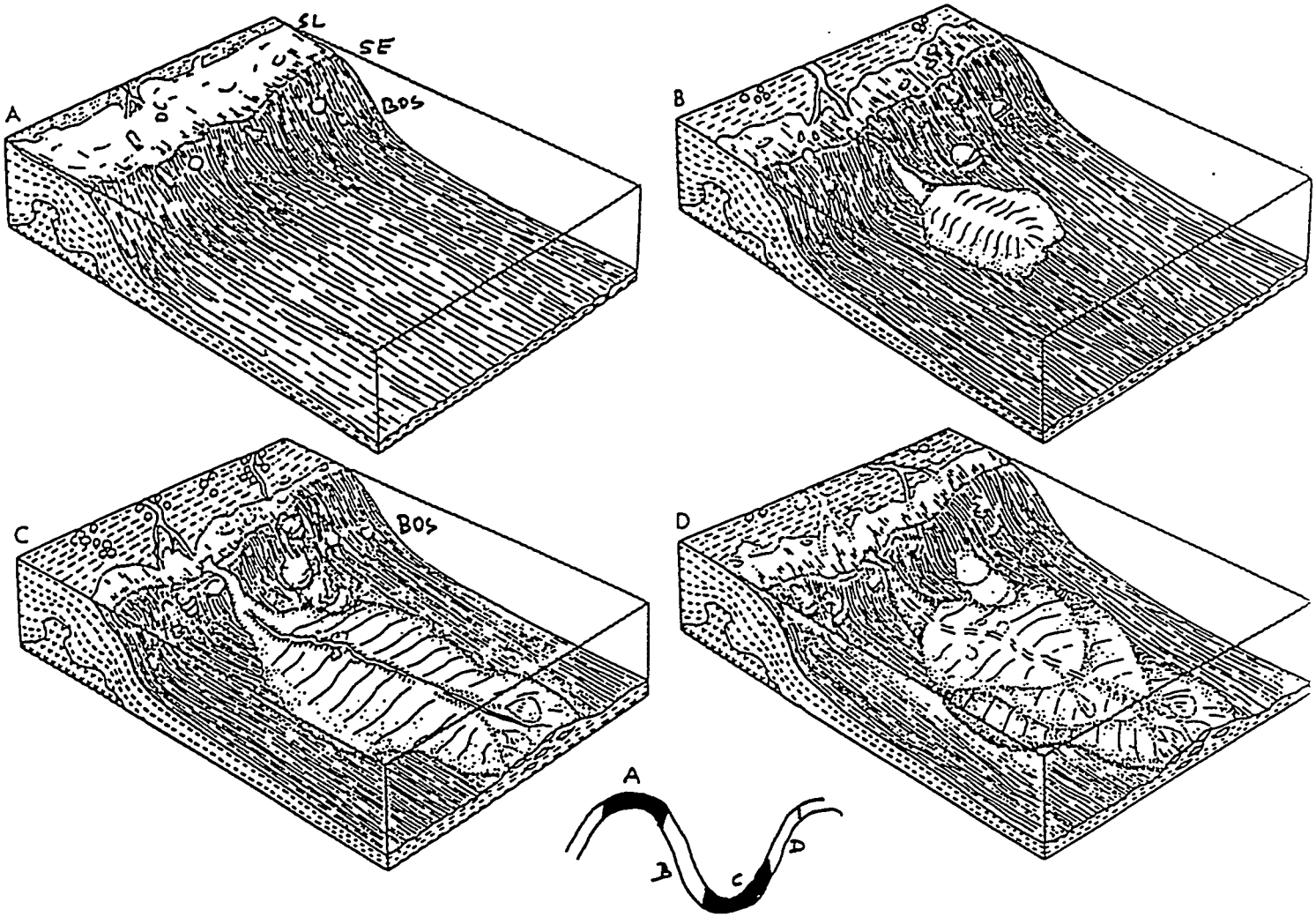


Figure 7. Schematic presentations showing the construction of the youngest submarine fan unit (fanlobe) of the Mississippi Fan during four stages of a relative sea-level cycle.

A: high stand with the deposition of a condensed section: a thin, blanketing deposit of draping pelagic and hemi-pelagic deposits.

B: initial lowering of sea level with the progradation of the coastline towards the shelf break, rapid accumulation of deltaic deposits resulting in high pore pressures creating instability that results in slumping. The slump carves a major cut in the basin slope deposits. The carved material is deposited on the basin floor.

C: continued lowering and initial rise of sea level: major construction of the fan. The scar on the basin slope acts as a conduit for density flows. Deposition starts at the base-of-slope.

D: continued sea level rise: gradual decrease in density currents as well as sand/mud ratio. Thinning of deposits and gradual covering of the depositional lobes and filling of the channel tops. The slope conduit is the last feature to be filled; in this situation with mud.

Not to scale. SL: strand line; SB: shelf break; BOS: base-of-slope (Redrawn after Bouma et al., 1989).

The South African Permian deposits fit that same pattern.

SEA LEVEL

Relative sea level fluctuations, either the result of glacial growth or melting, tectonic movements or subsidence, have a major timing and construction influence, especially on wide-shelved passive margin settings. Not all investigators share the same opinions but a general trend is accepted. Figure 7 presents a schematic portrayal of four stages of fan growth through a sea level cycle. One of the major arguments is when active supply of sediment stops. The figure caption suggests that as soon as sea level starts to rise the supply of bottom transported sand stops. However, in most glacially-controlled instances the initial tremendously high fluvial discharge of the melt water contains so much sediment that it becomes denser than the ocean water. In that case the fluvial outflow would be hyperpycnal and will move as a turbidity current through the deltaic distributary channel and across the shelf into a basin. Another possibility is that the delta keeps on prograding because of an increase of sediment supply and a decrease of accommodation space, provided that no major channel/distributary or entire delta switching takes place. That brings the sediment source closer to the basin slope.

The major factor groups that can control the growth of a submarine fan can each be divided into a number of subordinate factors. The block diagram in Figure 8 helps the reader to relate the interactions that can occur, each different combination resulting in differences in the architecture and sand distribution of the resulting fans.

The following subdivisions can be visualized:

I. Tectonic setting and activity

1. Type of margin or tectonic style; active vs inactive tectonics before and during filling of the basin.
2. Rates and frequency of uplift and subsidence.
3. Drainage patterns, rate of denudation, size of the sediment delivery area.
4. Coastal plain and shelf gradients, width and morphology.
5. Seafloor gradients.
6. Size and shape of the receiving basin.

II Sedimentary and climate characteristics

1. Sediment type and sand/shale ratio.
2. Volume of sediment involved.

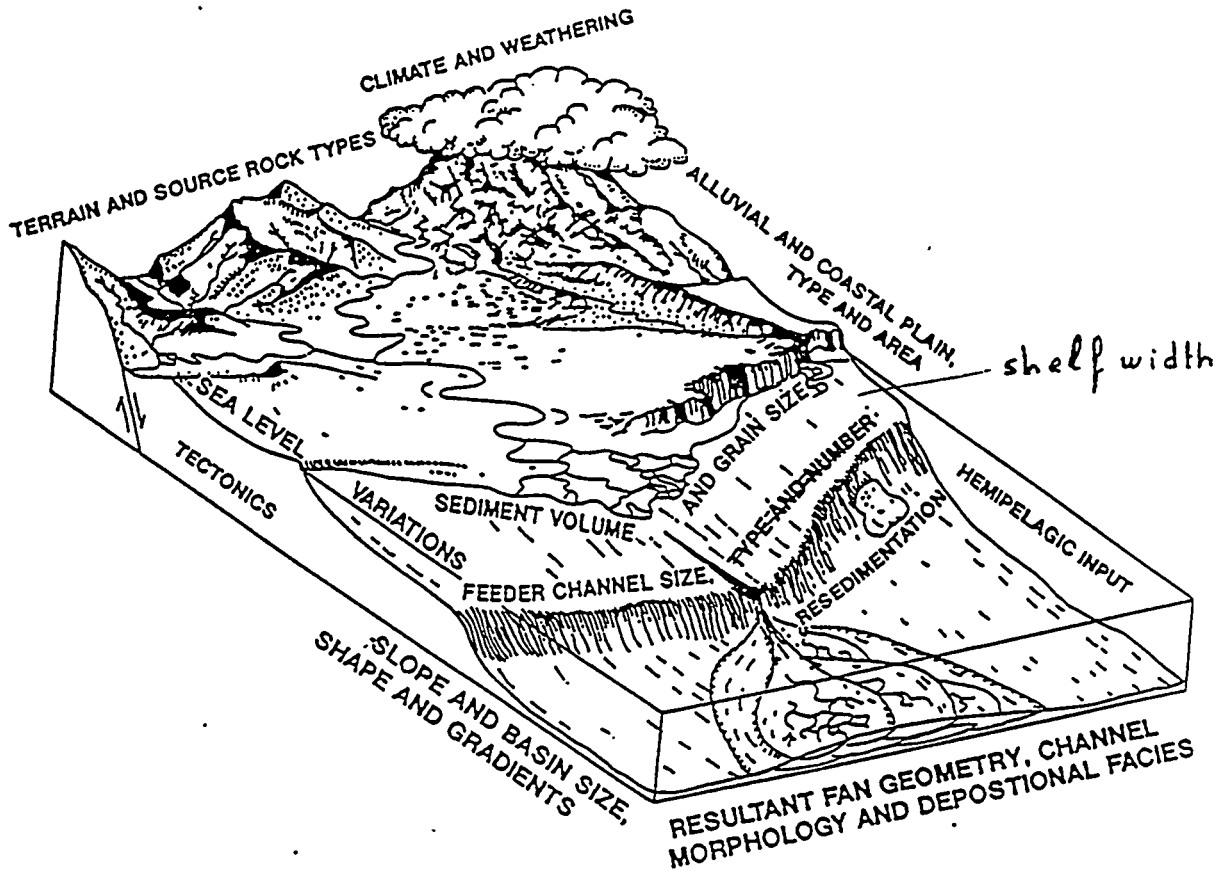


Figure 8. Block diagram showing the major factors that influence sediment supply, subaerial and submarine transport, and deposition of a submarine fan. See text for additional details (Redrawn after Stow et al., 1985).

3. Supply rate.

III Sea-level variations

1. Rate of sea-level variation.
2. Amplitude.
3. Complexity of the sea-level curve.

IV Minor controls

1. Water column (currents, waves, tides, etc.).
2. Biological factors (bioturbations).
3. Coriolis force.

An active margin setting normally means a mountainous coast, narrow shelf, and rather steep basin sides. Its offshore basins commonly are small and elongate, and parallel to shore. The grain size can be coarse, the sand/shale ratio normally high; excellent sorting of sediment can result from longshore transport. Sediment volumes may be relatively small. The canyons and upper fan channel have a high possibility to become sand filled. The middle fan, containing a distributary pattern, is called the suprafan (Normark, 1970). The suprafan is a region of high sand content that is typical for the area inside the channels, in the levee deposits, and often outside the levees in the overbank areas. Canyons are typically formed by the scouring action of upper shelf sands moving down via minor depressions in the shelf.

Passive margins are characterized by wide shelves with gentle basin sides. The receiving basins commonly are large and the overall transport directions are away from the coastal sediment source, rather than turning parallel to the shore. Sediment commonly was generated far inland and the long transport route to the coast resulted in a low sand/clay ratio, often in large volumes. Much of the sand is concentrated in channel fills of the submarine fan and in the distal sheet deposits. Likely all submarine canyons are shale filled and so are the upper and middle sections of the large upper fan channel (conduit).

INPUT TO MODELS OF SAND-RICH SUBMARINE FAN SYSTEMS

The fact that Nature seldom recognizes end members but normally deals with a combination of a few or several, and that so many types of influences will act in no set order and strength on the deposition of a submarine fan, makes one wonder if a model can have any validity. It is, therefore, not amazing that a large number of models exist in the literature, many of them relating to only one example. Most of the examples presented in the literature are based on sand-rich, often coarse-grained turbidite systems found in outcrop. Over the last years an increase of models published comes from seismic and sequence stratigraphic studies. There is little need to discuss as many models as can be found. Only a few well-known and often used examples will be discussed and emphasis will be placed later on fine-grained fans.

BOUMA MODEL (BOUMA SEQUENCE).

The first model published was by Bouma in 1962. It presents an idealized presentation of the deposit of a turbidity current (Fig. 1). However, most turbidites are incomplete, missing lower divisions or occasionally upper ones. It is a field description terminology and some intervals may not be recognized due to thinness, weathering, or absence (Bouma, 1972). This has resulted in a number of modifications of the original turbidite model. Much controversy exists about the (a) division (graded or massive division). The lack of grain size variations in the coarsest sediment in a turbidity current makes it impossible to end up with graded bedding; hence the term massive bedding. Some investigators want to use the absence of graded bedding as an indication that the deposit is the result of a debris flow. It is impossible to recognize in the field the difference between the deposits from a "high-density" turbidity current and a "low-density" debris flow. An other point of discussion is the naming of typical submarine fan channel fills that normally are massive. Are they massive T_a divisions of the Bouma Sequence and miss the upper four divisions, or are they deposits from low-turbulent or non-turbulent density flows?

The Bouma Sequence was initiated as a field descriptive model for deposits of turbidity currents. At that time there was no direct knowledge that submarine fans existed and that true turbidites are typical for only part of a fan.

NORMARK MODEL.

The first model published that incorporated the entire depositional body (submarine fan)

was by Normark (1970). The model was based on deep-tow observations and some cores from offshore Southern California and Baja California. The Normark model portrays the morphology and upper sediments of sand-rich fans in active margin settings. Follow-up research elaborated on active vs abandoned fan parts, terminology, channel and lobe characteristics (Normark and Piper, 1969; Normark, 1978; Normark et al., 1979; Normark and Hess, 1980).

Figure 9 presents the schematic model that shows a canyon across the basin (continental) slope. This canyon and its downdip continuation (Fan Valley) form the conduit through which sediment is transported from the shelf and upper slope to the basin. Deposition starts at the base of the continental slope or basin slope in the area called base-of-slope (BOS in Fig. 7). The submarine fan is divided into three major segments (upper fan, mid fan, lower fan) based on surficial characteristics. The upper fan contains a major leveed channel, the mid fan a set of distributary channels, and the lower fan no visible channels. The area of active deposition (the distributary channel system) is called the suprafan, characterized as a very sand-rich bulge. Cross sections in Figure 9 emphasize the major morphological shapes. Normark (1978) suggested that the suprafan model would only apply to fans that have a relatively high sand/mud ratio of the incoming sediment.

Normark and Hess (1980) indicated that large submarine fans are not simple scaled-up versions of small fans but a composite of many fan-shaped lobes. The area in between the channels (interchannel or overbank areas) are very sand-rich, making a distinction between a channel fill and interchannel areas sometimes impossible, when dealing with a core or a normal-sized outcrop. The bifurcation of channels causes the channels to become shallower and a little narrower, increasing the frictional surface between density current and channel floor. The resulting slowing down raises the height of the current and overflowing results followed by a lack of containment by the levees. The density currents start to flow out, forming depositional lobes (sheet sands). Normark et al. (1979) clearly showed that accumulation of a submarine fan is not vertical, even not on the small Navy Fan. Channel avulsion and related switching of the area of depositional lobe construction are the important processes.

In 1980 Normark et al. reported on the presence of sediment waves in the updip area of a basin. Those waves may be specifically related to the levees of submarine fan channels. Till that time sediment waves had only been reported from broad ocean bottom swales (e.g., Damuth, 1975; Bouma and Treadwell, 1975; Hess and Normark, 1976). The orientation of the sediment waves on channel levees showed to be oblique to the channel direction. Since that time several

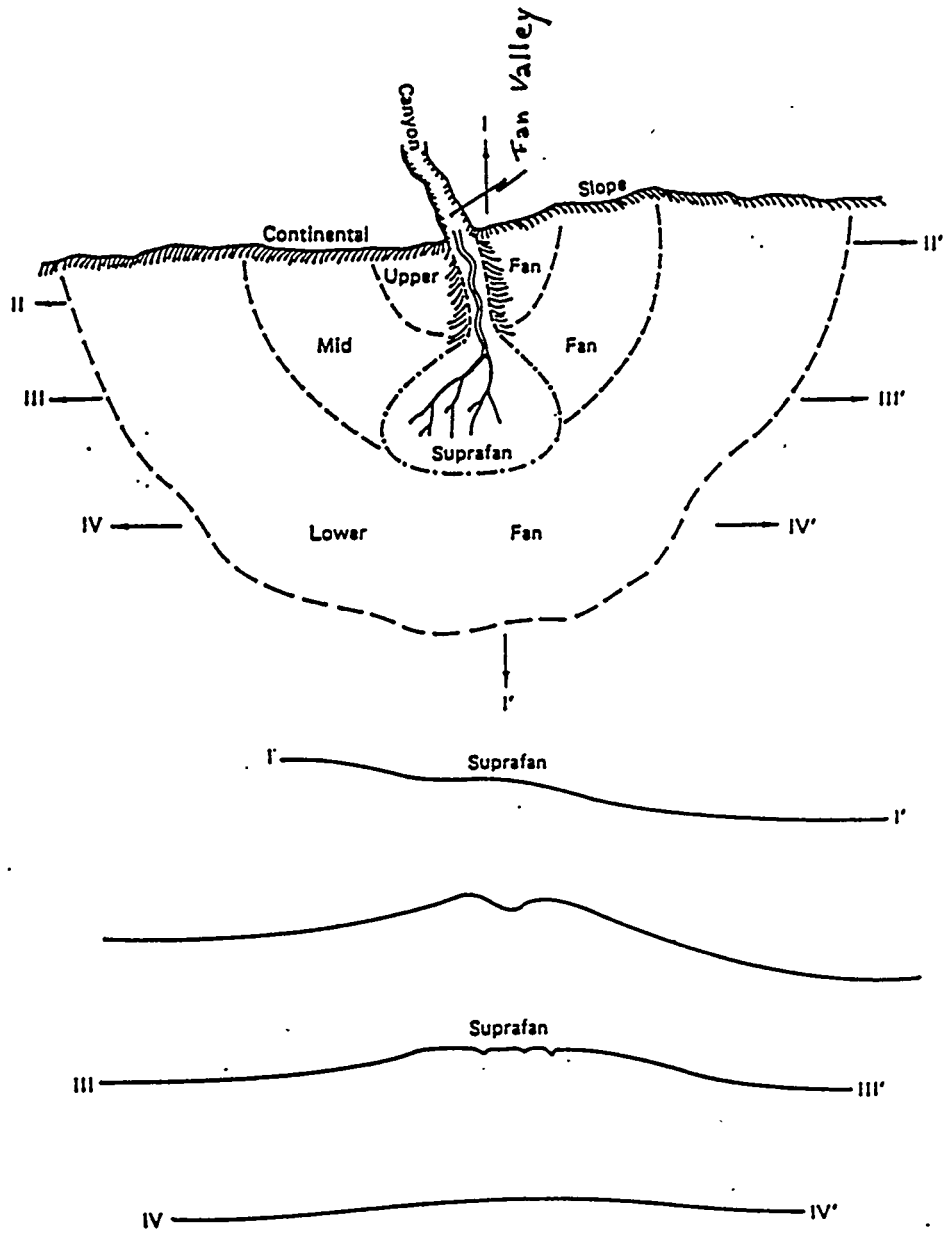


Figure 9. Schematic presentation of a model for the growth of a sand-rich submarine fan, emphasizing fan zonation, the most active depositional area (suprafan) and morphological shapes in cross sections (Modified from Normark, 1970; After Normark, 1978).

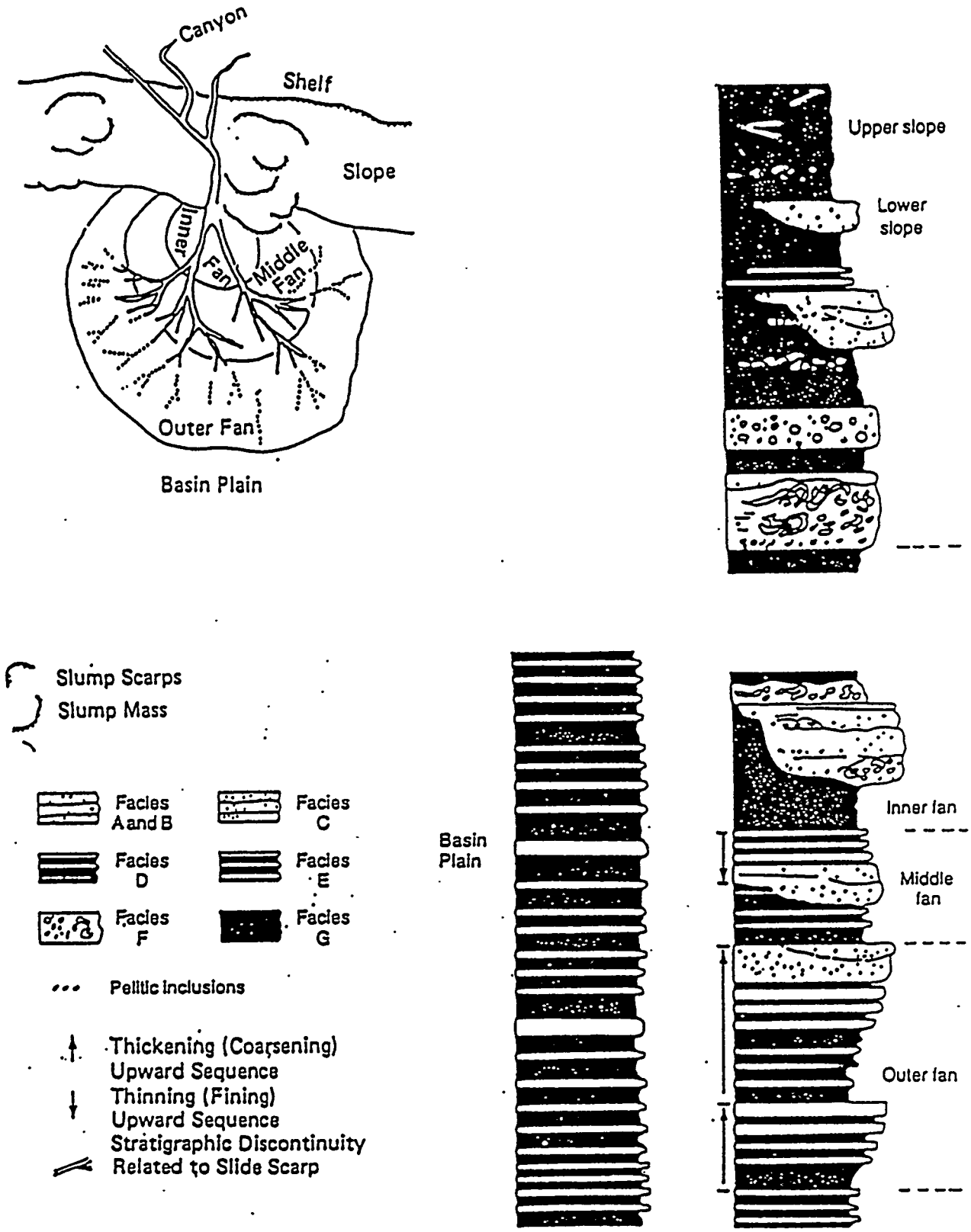


Figure 10. Schematic presentation of the Mutti-Ricci Lucchi model, showing lithofacies A through G, vertical sequences, vertical columns with facies associations and a map projection (Redrawn after Mutti and Ricci Lucchi, 1972).

shows secondary structures such as dish structures and water-escape pipes. Subfacies B2 is well organized with large-sized current-ripple lamination, and sometimes with small-scale current ripple lamination and climbing ripples.

Facies B is considered to be the product of fluidized and grain flows as well as of high-velocity turbidity currents (upper flow regime).

Facies C: Sandstones with Shale Interbeds. This facies is comprised of medium to fine-grained sandstones with minor amounts of homogeneous shales. Occasionally coarse-grained material can be found at the base of some layers. The sandstone beds are bound by even, parallel surfaces and show good lateral continuity. The complete Bouma Sequence can be present. Small shale clasts can occur either in distinct lenses, at certain levels, or in a scattered mode. Broad, low relief channels are frequently observed in this type of facies.

Facies C can be divided into two subfacies. Subfacies C1 is an incomplete turbidite with division T_d and T_e and sometimes division T_b missing. Subfacies C2 refers to the more complete turbidites.

The deposits belonging to Facies C are inferred to be the product of "classical" turbidity currents.

Facies D: Shale with Sandstone Interbeds I. This facies is comprised of fine and very fine-grained sandstones, siltstones and shales, having good lateral continuity. Internal structures in the sandstones include normal current-ripple lamination, undulating lamination, convolute lamination and climbing ripples. One or more of the lower divisions of the Bouma Sequence are typically missing.

Three subfacies are recognized. The division depends on the degree of completeness of the Bouma Sequence. Subfacies D1 lacks division T_a, Subfacies D2 misses divisions T_a, T_b and T_c. Subfacies D3 lacks primary sedimentary structures and may be extensively burrowed.

Facies D deposits are interpreted as the products of low density turbidity currents which transported their load primarily in the lower flow regime.

Facies E: Shale with Sandstone Interbeds II. This facies differs from Facies D by the following characteristics: 1) higher sandstone/shale ratio, 2) thinner irregular layers, and 3) more

discontinuous beds showing wedging and lenticularity. Commonly the tops of the sandstones have sharp contacts with their overlying shales.

No subfacies are recognized. This facies is interpreted to be the product of local processes related to levee-overbank deposition.

Facies F: Chaotic Deposits. This facies includes the various types of sediment deformation, such as slumps, mudflow, intraformational folding, some pebbly mudstones, etc.

This facies can be found within any of the submarine fan subenvironments, either as a small or a large phenomenon.

Facies G: Hemipelagic and Pelagic Shales and Marls. These fine-grained deposits are often silty and calcareous. The carbonate contact is typical for most of the pelagic deposits. Indistinct parallel bedding and lamination are common, while graded bedding may be observed under the microscope in the hemipelagic deposits.

No subfacies have been described. The sediments belonging to Facies G are inferred to be the product of diluted flows, such as very low density turbidity currents, nepheloid layers, sediment concentrations falling out of the contact between two water masses with different densities, etc. The deposits commonly blanket large areas. The hemipelagic deposits include many of the basin shales deposited during the latter part of a rise in relative sea level or during the initial fall. The pelagic marls often stand out in outcrop by their yellowish color. They represent condensed sections.

The lithofacies shown in Figure 10 are used by many investigators when describing outcrops or cores. It is a well-workable system when dealing with sand-rich systems with or without gravels. The lack of sharp boundaries between the facies and subfacies does not present a major difference between various observers.

Mutti and Ricci Lucchi (1972) discuss three different types of Facies (Fig. 10):

Slope Association. The characteristic component is Facies G, principally the hemipelagic sediments. Chaotic deposits of Facies F, and sandstones that often represent Facies A, are frequently incorporated.

Submarine Fan Association. The inner submarine fan is characterized by sediments of Facies G which enclose thick and broad bodies of sandstone that represent the filling of large submarine fan valleys (Fig. 10). These sandstone bodies, typically are comprised of Facies A, B and F. Facies E may be present.

The middle submarine fan is characterized by sediments belonging to Facies D and E. Facies C sediments are present in subordinate amounts. The deposits often reveal a fining and thinning-upward sequence.

The outer submarine fan is characterized by Facies D sediments that include more or less lenticular bodies of Facies C sandstones. The lack of major erosional features at the base of the sandstone bodies suggests that deposition is not controlled by channel filling processes but more by a gradual waning of the transport processes. The role of containing the density currents within the channel levees is gradually diminishing and fanning out takes place. That is supported by the dispersion of paleocurrent directions. The grain size and layer thickness of the included sandstones increase upward, forming an upward coarsening/thickening sequence.

NOTE OF CAUTION: several investigators discovered that thinning and thickening upward sequences are seldom distinct. Opposite interpretations are not uncommon. Personal experience has shown that one observer interpret a major outcrop to be comprised of upward fining and/or thinning sequences while an other observer, present at the same time and location, interpreted the series to show upward coarsening and/or thickening sequences. Discussions revealed that each observer had locked in his eyes on a different level to be used as the base of a sequence. It is strongly suggested to use the sequence idea as a descriptor only when it is distinct, and never as a primary interpretation tool.

Often one observes an irregular layer thickness distribution compared to the mentioned sequences. One may see one or a few thick layers overlain by a set of thinner bedded ones without really noticing a gradual thinning upward. Nevertheless several authors use the term thinning upward for such a series of layers. Therefore one should only use the descriptor if the phenomenon is more or less ideal.

Basin Plain Association. The deposits belonging to this association consist almost entirely of Facies D sediments. Facies G may be present, although it may be difficult to detect due to the thinness of the shale or marl layers.

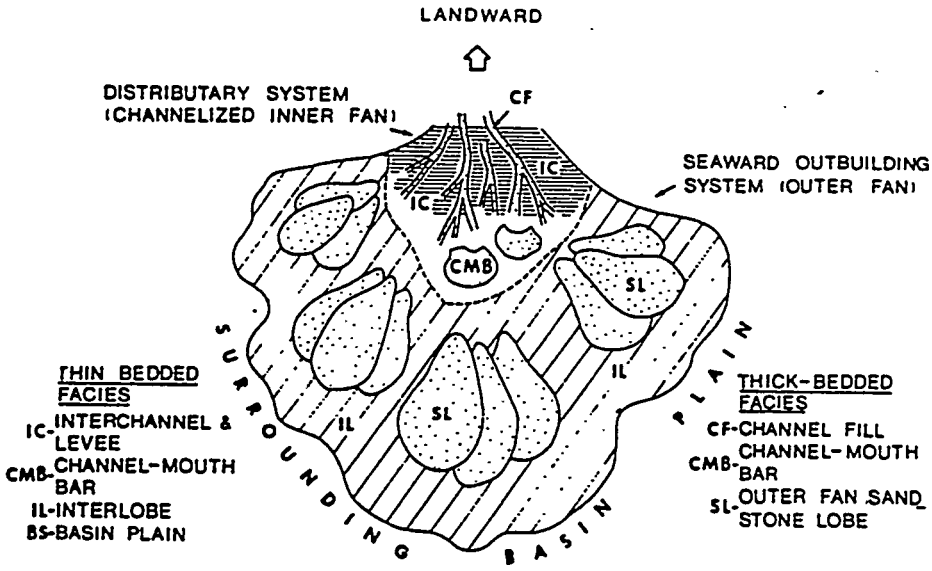


Figure 11. Areal distribution of facies associations and sub-associations in a deep-sea fan/basin plain setting. See notes in text (After Mutti and Ricci Lucchi, 1975).

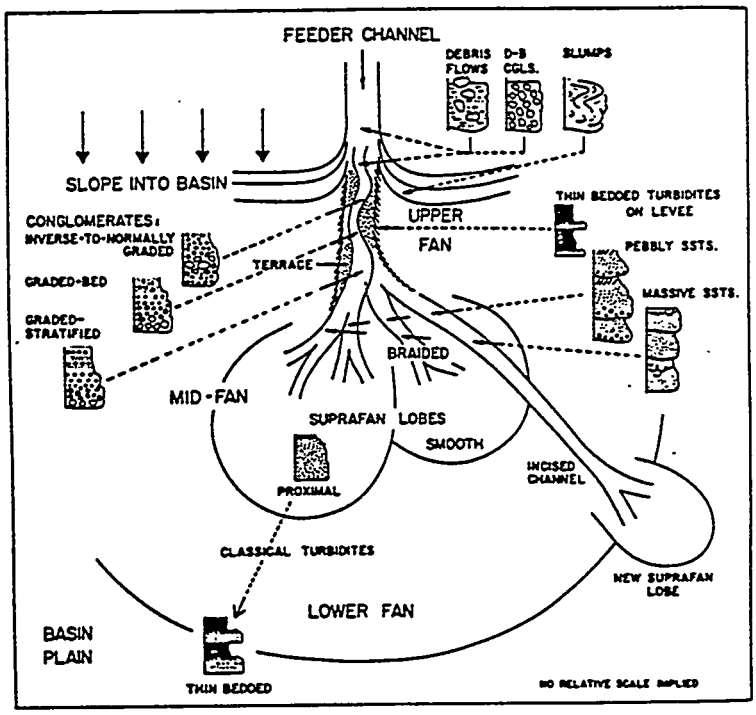


Figure 12. Schematic presentation of the Walker model. Details of the model and a comparison with the Mutti-Ricci Lucchi is provided in the text. The Walker model also relates lithofacies, fan morphology and depositional environment. On the top right: D-B CGLS = disorganized-bed conglomerates (After Walker, 1978).

Mutti and Ricci Lucchi (1975) presented a somewhat modified model in which they disconnected the channel fill from the depositional lobes and placed in that gap a sand body (channel mouth bar) surrounded by shale (Fig. 11). The channel mouth bar consists mainly of Facies B2 and E deposits that originated as tractional lag deposits left behind by overloaded density currents in an area of sediment bypassing. According to Mutti and Ricci Lucchi (1975) channel mouth bars are characterized by an upcurrent imbrication of sandstone beds and by more or less well developed thickening-upward sequences.

NOTE OF CAUTION: the idea of the presence of channel mouth bars in a submarine fan has greatly lost its validity and practically all workers have abandoned that concept.

WALKER MODEL

Walker (1978) indicated that five main lithofacies of deep-water clastic rocks can be defined: classic turbidites, massive sandstones, pebbly sandstones, conglomerates, and debris flow deposits (debrites) with slumps and slides. These lithofacies nicely fit into a model of a submarine fan that shows similarities to the Mutti and Ricci Lucchi (1972) model with the addition of the presence of suprafan lobes and a preponderance of coarse-grained material (Fig. 12). Walker (1978) also indicated that irregularities in the flow conditions of the waning turbidity current are reason that divisions within the Bouma Sequence can be very thin or missing. Other important remarks by Walker (1978) are: 1) the order of divisions within a complete or incomplete Bouma Sequence has never been seen to be reversed indicating that acceleration of a turbidity current does not occur, and 2) that a complete Bouma Sequence (T_{a-e}) can only be found in the proximal (updip) area of a submarine fan lobe, but that incomplete ones (T_{c-e} and T_{d-e}) are not only present in the distal area but also in the proximal region as levee deposits. Those general remarks are still valid although later studies may place it in a slightly different light.

Walker's (1978) model reveals an increase in organization in downdip direction of pebble-rich sediment, as well as a gradual decrease in pebble/sand ratio and total grain size (Fig. 12). The feeder channel, crossing the basin slope, contains debris flow deposits and disorganized conglomerates with slumps off the sides. Once in the basin, the channel deposits of the upper fan reveal a downdip change from 1) inverse-to-normal grading of conglomerates to 2) normally graded conglomerates to 3) graded conglomerates overlain by stratified sandy conglomerates. The adjacent levees are mud-rich with thin cross-bedded sandstones. Moving downdip onto the suprafan the channel fill changes to pebbly sandstones to massive sandstones

with dewatering structures to graded sandstones. The outer parts of the suprafan and the adjacent lower fan are characterized by thin-bedded sandstones with a medium to low sandstone/shale ratio.

Walker (1978) also shows in Figure 12 that lateral switching of suprafan lobes takes place when the sediment accumulation becomes too high and the downdip gradient too low. In addition to lateral switching a major density current may break out the upper fan channel, crosses an older suprafan lobe and constructs a new suprafan lobe at a more basinward location. In vertical succession one can thus find outer fan deposits overlain by upper fan deposits, or any other order.

NOTE OF CAUTION: comparing the Mutti-Ricci Lucchi model (Fig. 10) with the Walker model (Fig. 12) one observes a difference in terminology: inner fan vs upper fan, middle fan vs mid-fan, and outer fan vs lower fan. The first terms are the better ones when dealing with ancient deposits. A major difference between the two models is the zone in which channel bifurcation and channel termination occurs.

BASIN APPLICATIONS OF TURBIDITE SYSTEMS

The models by Mutti and Ricci Lucchi for sand-rich turbidite systems and by Walker for conglomeratic sandstone-rich systems are well applicable to many other areas that contain similar lithofacies.

A change took place in the late 1980's when seismic and sequence stratigraphic concepts became introduced to understand the stage (order) of development of a basin fill with submarine fan deposits. The result is the construction of generalized fan models that are very helpful when dealing with a total basin. They are too general, and therefore can be easily misused, when dealing with an individual submarine fan, its architecture and especially the geometries and connectivities of sand bodies and individual layers. Global sea-level changes (Vail et al., 1977) became introduced much stronger than was realized during the first COMFAN (COMmittee on FANs) meeting in 1982 (Bouma et al., 1985a; Normark et al., 1985; Mutti, 1985). Mutti and Normark (1987) indicated a number of limitations many of the existing fan models have not dealt with adequately:

1. Not all turbidite systems have formed submarine fan sequences. The well-known turbidite facies can be deposited in a variety of restricted basins and in tectonically active areas that do not permit the development of complete fan systems.

2. The major factors that control the development of submarine fan systems have to be recognized, such as: (a) the type of crust on which the system is formed; (b) the longevity of the sediment source; (c) the rate of sediment supply, and (d) the global sea-level controls and local tectonics that control the supply of sediment.

3. The scale of observations has to be similar when comparing ancient with ancient fans, modern with modern fans, or modern with ancient fans. Those scale factors refer to temporal as well as spatial dimensions (Fig. 13).

4. Complications that result from different definitions in the technology.

Mutti (1985) suggested three main types of turbidite systems (Fig. 14), called type I, II and III (see also Mutti and Normark, 1987; Mutti 1992).

Type I systems are those where the bulk of the sandstones occurs in non-channelized, elongated bodies in the outer region of the system. These bodies are known as depositional lobes or sand sheets. These systems are also known as the "highly efficient" fans of Mutti (1979), meaning transport systems that are efficient in transporting sand over significant distances, typical for mud-rich submarine fan complexes. Updip from the depositional lobes one observes large-scale submarine canyons that erode into the shelf deposits and the basin slope shales. These erosional depressions are filled with an abundance of chaotic sediments that change downdip into thin-bedded mudstones and sandstones, as well as lenticular bodies of sandstone and conglomerate.

The Type I system is actually a sand-bypass system that results in detached lobes and a non-time equivalency with the channel-fill sequences observed in the inner parts of the same system.

Type II systems refer to those depositional systems in which the sandstone facies are predominantly deposited in the lower reaches of channels and just beyond the channel mouths. The result is extensively channelized bodies that grade downcurrent into sheet sands. The channel and depositional lobes are physically connected (attached), both vertically and laterally.

Very coarse-grained Type II systems are nearly completely composed of channelized deposits. A decrease of grain size tends to promote the development of associated lobes.

The Type II system fits the model of the "poorly efficient" submarine fans of Mutti (1979). An other term is sand-rich fans.

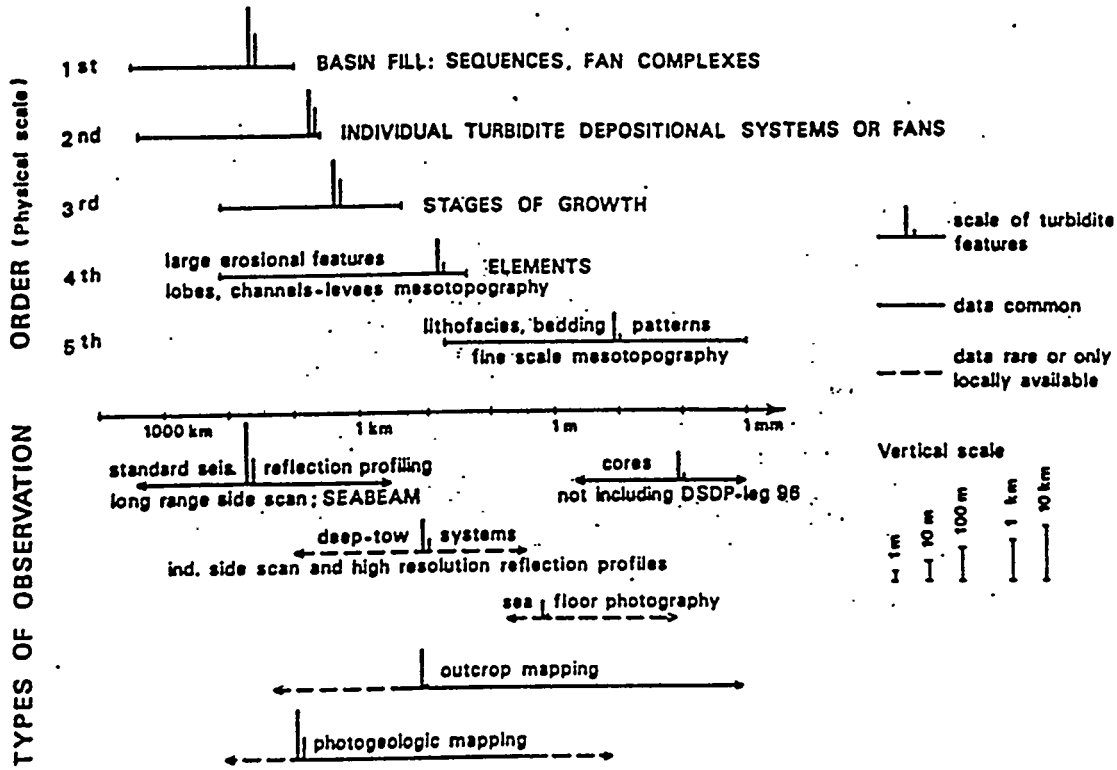


Figure 13. Scale comparisons for horizontal and vertical dimensions of submarine fan (turbidite system) basin fill and depositional features (top), and of typical observations: outcrops, cores, acoustical records (bottom). SEABEAM: all multibeam echo-sounding systems. DSDP Leg 96 (Mississippi Fan: Bouma et al., 1985c, cores are not included (After Mutti and Normark, 1987).

Type III systems are characterized by small sandstone-filled channels that are enclosed by and grade downcurrent into predominantly muddy shales. The channelized facies do not extend basinward, consequently they are restricted to the inner portions of the turbidite system.

The Type III systems are likely the ancient expression of modern channel-levee complexes. However, the size of ancient systems studied is much smaller than that of modern systems found off major deltas.

Figure 15 shows the suggested relationship between the three types as observed in elongate flysch basins (Mutti, 1985, 1992; Mutti and Normark, 1987). Tectonic confinement and ponding are important in the development of elongate, unusually thick sandstone bodies. The high percentage of fine-grained sediments, related to deltaic sedimentation and adjacent shelves enhances the long-distance transport by turbidity currents.

Combining the three previous figures a conceptional classification framework for turbidites was developed (Mutti and Normark, 1987, 1991; Mutti, 1992). Figure 16 shows it in a schematic drawing as well as in a table format, emphasizing the hierarchial classification as a physical scale and the time classification in words, respectively.

The recognition of the order of magnitude (turbidite complex, turbidite system, turbidite stage, turbidite sub-stage, turbidite beds) is not always easy. Especially the recognition of stages and substages requires a knowledge of the time relations among the various parts of a turbidite system. The rapid deposition of the sandstones makes it very difficult to impossible to obtain a biostratigraphical time scale that has the refinement that fits the sub-stage unit. Mutti and Normark, (1987, 1991) suggest that mapping of any of the systems (Fig. 16) should be based on characteristic elements (Fig. 13), which can be defined to allow recognition in both modern and ancient deposits using varied types of data.

NOTE OF CAUTION. The above makes sense if the various important elements can be recognized in seismic profiles (high, medium or low resolution depending on depth below the mud line), in outcrop or in both. For all practical purposes those schemas are useful in a general sense but lack applicability to the detailed exploration/development scale. To compare scales of erosional and depositional elements, primarily channels, only major features can be identified on seismic. No depositional channel fill is without erosion, the depth of which often is below resolution in many instances. Consequently those schemes are dependent on the instrumentation

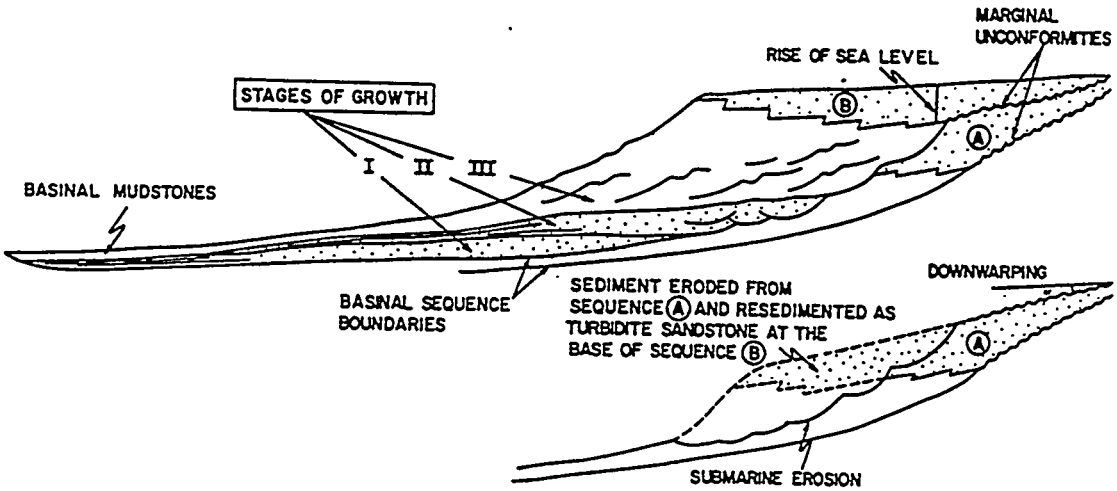


Figure 15. Conceptual diagram that relates the position of the three turbidite system types in elongate flysch basins to relative changes in sea level (Redrawn after Mutti, 1985 and Mutti and Normark, 1987).

Compared to coarser-grained sand-rich fans, the fine-grained systems are less known when referring to reservoir-scale architecture. Submarine fans that form in passive margin basins have much less chance to be uplifted and become exposed than those in active margins. Fine-grained fans in active margin settings are typically deformed by tectonism, greatly reduced in size by weathering, and the remainder folded and faulted, preventing extensive observations on lateral continuity. Although the fine grain size of the sands is commonly used as an indication that the sediment source area was far removed from the coast, this rule can not be handled blindly. However, it can be said in general that a long, low dip continental transport is required to lose coarser material from the fluvial transport load.

Much literature on subsurface located fine-grained fans comes from the oil industry (see in Weimer et al., 1994) but only limited information from outcrops and modern fans (in Bouma et al., 1985a; Bouma and Wickens, 1991, 1994; De Vries and Bouma, 1991; Chapin et al., 1994; Cook et al., 1994; Wickens and Bouma, 1995; and a few examples in Pickering et al., 1995).

Examples that will be briefly discussed here come from the Gulf of Mexico, the Jackfork Formation in Arkansas, and the Tanqua Karoo subbasin in southwestern South Africa. Background can be found in the publications mentioned in the text. The present text concentrates on findings that became part of a model.

MISSISSIPPI FAN

The Mississippi Fan is a good example where long distance transport of low sand/mud ratio input material was possible. The medium size of this fan is still too large to have sufficient data density as was observed during DSDP Leg 96 (e.g., Bouma et al., 1985a, 1986; Stelting et al., 1985) and follow-up studies (e.g., Weimer, 1989, 1991; contributions in Weimer and Link, 1991 and Weimer et al., 1994). Following the approach used by Mutti and Ricci Lucchi (1972) and Walker (1978) a model of the Mississippi Fan was constructed that demonstrates the partial bypassing of sand to the lower fan resulting in a general increase of the sand/shale ratio from middle to outer fan.

Authors differ on definitions about specific parts of a submarine fan, as well as the location of the boundaries of the upper/inner fan, middle/midfan, and lower/outer fan (see contributions in Bouma et al., 1985a). We use the physiographic boundaries established for the Mississippi Fan as discussed in Bouma et al. (1985a) because those have been accepted by other workers in the Gulf of Mexico and because those coincide with morphological and seismic changes (Fig.

19). Important physiographic terms for mud-rich fans are: shelf, shelf-break (or shelf-edge area), slope (basin slope or continental slope), base-of-slope (the area where the slope changes into the basin floor), and basin floor.

A submarine canyon is an erosional feature formed initially during lowering of sea level near the shelfbreak as the result of rapid deposition of clay-rich sediment. That type of deposited sediment results in high pore pressures which often leads to mass failure (Coleman et al., 1983). The failed mass carves out a major depression across the slope, known as a "fan valley" by Shepard and Dill (1966) or as the upper fan channel. Its upper part and the updip submarine canyon continue to extend themselves towards the sediment source (deltaic distributary channel) by retrogressive slumping; they act partly as a source and mainly as a conduit for sediment transported to the basin by sediment gravity flows. The lower part of the conduit becomes more depositional toward the base-of-slope (Bouma et al., 1995b). The widening of the lowermost part of the upper fan channel provides a configuration that is too wide for most of the individual currents. This area is where most of the initial sand deposition starts due to a decrease in bottom gradient. The accumulation is characterized by many flat channels that cut into each other, leaving massive amalgamated sandstones preserved with erosional remnants of shaly levee deposits.

The middle fan starts where the density currents form leveed channels and overbank deposits (often called interchannel). The levees are sufficiently high to direct the head of most density currents, but cannot prevent overflowing of the upper part of the body of a current. Although most sediment moves through a channel, part of the sediment load will be deposited on the channel floor, the channel levees, and in the overbank areas. Gradual aggradation results. In a downdip direction the dimensions of the channel gradually decrease and bifurcation commonly takes place. The coarser-grained or massive sand channel fills can be seen on reflection seismics as a zone of high acoustical amplitudes (Stelting et al., 1985). This zone decreases in width and thickness downdip, the lower fan starts where the zone of high acoustical amplitudes disappears.

The updip part of the lower fan also has channel characteristics but soon the levees become too low to be effective (constraints for the head of a density current). Gradual overflowing commences and deposition of high sand/shale ratio sediment occurs in elongated sheets (depositional lobes or sheet sands). Once most of the deposition has taken place, rapid thinning of the layers occurs in the outer fringes of the submarine fan.

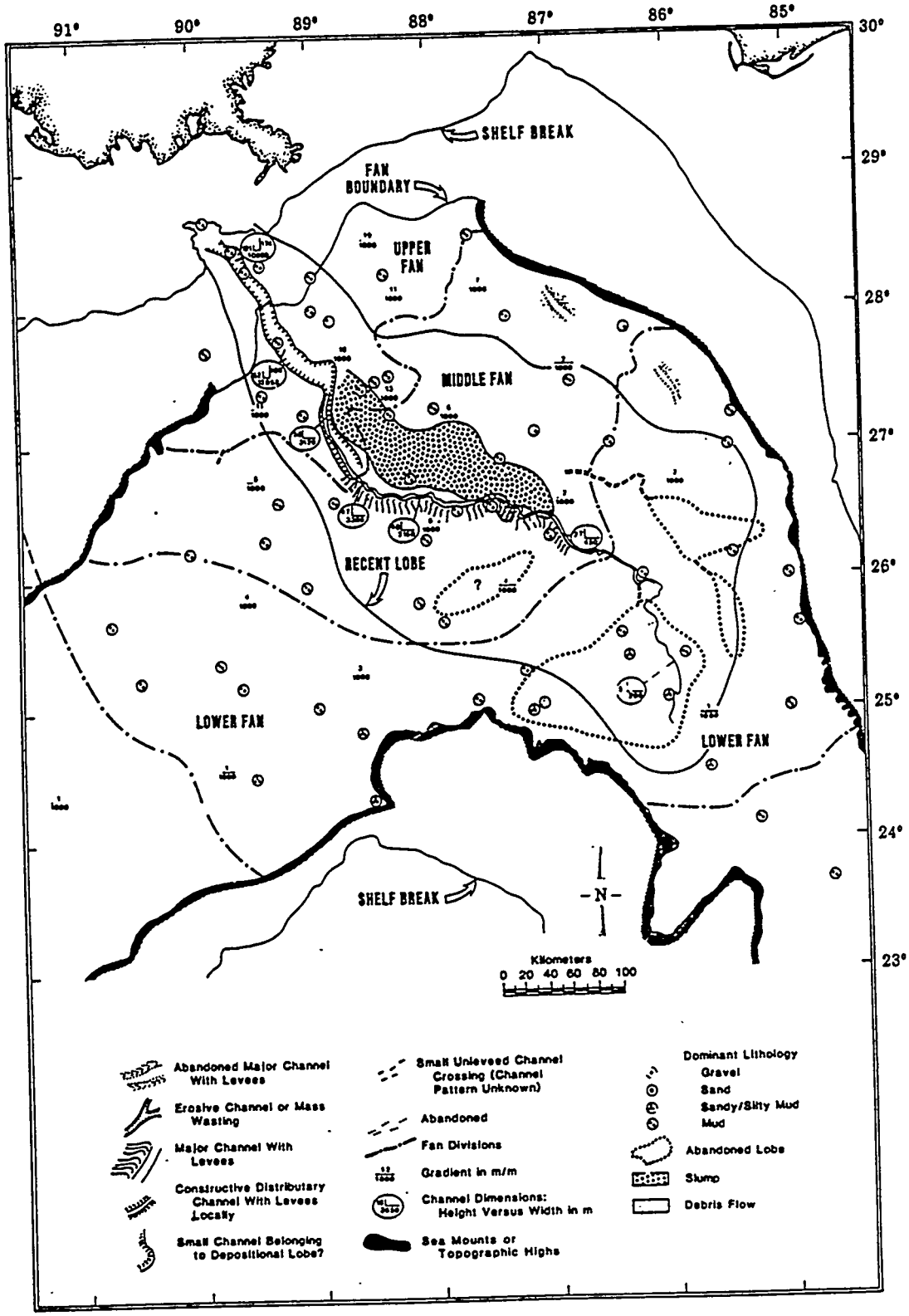


Figure 19. Morphometric map of the Mississippi Fan, showing fan divisions, local gradients, channel pattern and dimensions, and the general lithology of the upper meters. Note the abundance of mud about everywhere, resulting from deposition during the last stage of relative sea-level rise. The solid line denotes the schematic outline of the youngest fanlobe (individual submarine fan). (After Bouma et al., 1985c).

A simplistic model, based on general lithologies, was developed in the 1980's (Fig. 20). It was not published till it could be used to construct a general model of fine-grained submarine fans (Bouma et al., 1995a).

Stelting et al. (1985) demonstrated that the leveed-channel on the middle fan was rather straight and wide during active periods of transport and sand deposition in the channel. However, when the sediment supply started to decrease the density currents became too small for the original channel width and sinuosity commenced. The degree of sinuosity increases with time (Fig. 21).

NOTE: we do not know if this is common. It seems that the Amazon Fan has highly sinuous channels throughout the thickness of an individual fan. A vertical change may occur, however.

The Mississippi Fan has one major channel across the upper and middle fan (Bouma et al., 1985c). Seismic studies, using similar differences in acoustical amplitude strength and reflection patterns, revealed that more than one major channel can have operated (Weimer, 1989, 1991). However, careful analyses of the seismic records demonstrated that only one channel was active at a given time. Channel avulsion may not occur, takes place in a modest way or can be very intensive (Fig. 22). This figure clearly demonstrates the complexity that can occur for which we do not have an explanation yet.

BRYANT CANYON

The presence of small channels in the subsurface just downdip from Bryant Canyon, where the canyon cuts through the Sigsbee Escarpment, is shown by Lee et al. (1996). Those authors indicate a widening of the upper fan area directly south of the escarpment (Fig. 23). A few channel depressions can be seen in the bathymetry. The lateral switching becomes apparent when studying the upper 3/4 second (TWT) of the seismic records presented in Figure 23. Several channel cuts can be found in that record (Bouma et al., 1995b). The zone directly south of the escarpment can be called a base-of-slope zone. This is one of the examples used to develop a model for fine-grained submarine fans (see Fig. 31).

JACKFORK FORMATION, DEGRAY SPILLWAY, ARKANSAS

Several good outcrops can be found in the Pennsylvanian Jackfork Formation (see Jordan et al., 1991) that represent different aspects of fine-grained submarine fans. DeGray Spillway is

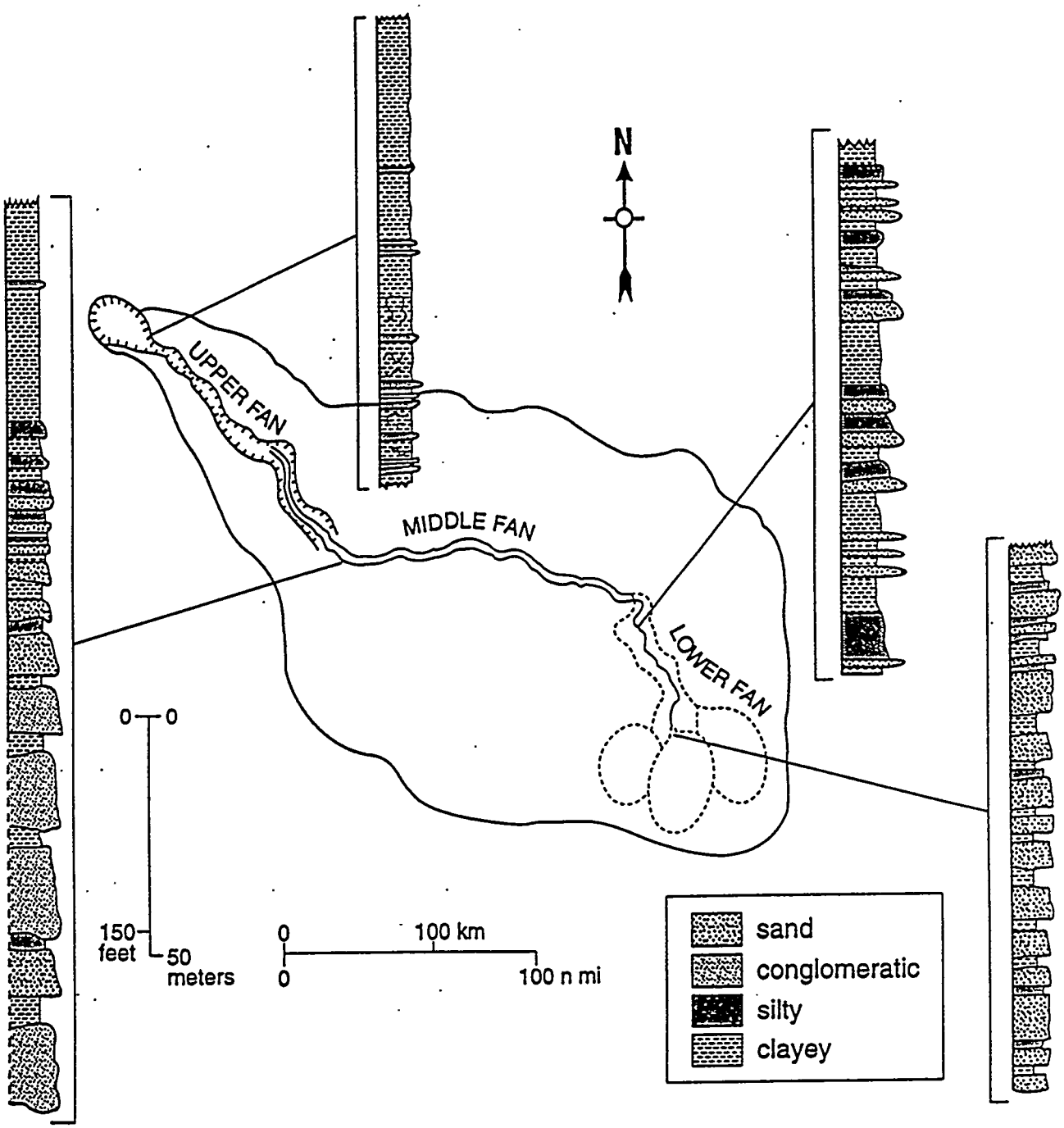


Figure 20. Lithological model of the Mississippi Fan, based on core descriptions from DSDP Leg 96 (see in Bouma et al., 1985a, 1986). The fill of the canyon comes from industrial sources (Coleman et al., 1983). The lower part of the lithological column of the middle fan channel fill is projected from seismic data. The mud-rich outer levee and overbank deposits are not shown. The updip part of the lower fan area with bifurcating channels show several fills. The core from the downdip sheet sands (depositional lobes) has the highest sand/shale ratio (After Bouma et al., 1995a).

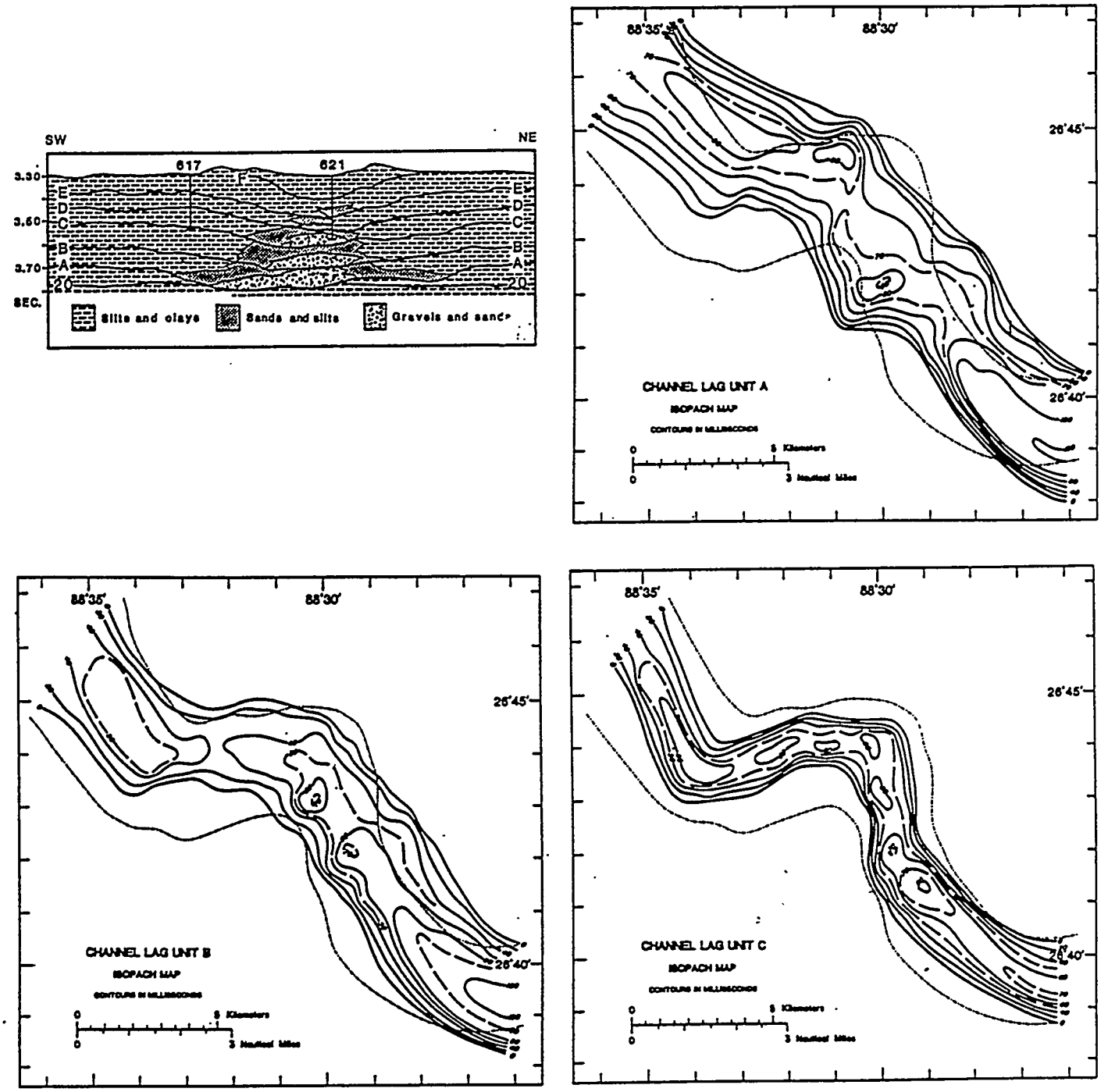


Figure 21. Interpretation of a seismic line across the channel through drill sites 617 and 621. The three lenses with coarse-grained sediments are the high-amplitude zones. Vertical scale in TWT. The three maps show the isopachs from the lower, middle, and upper high-amplitude lenses. The dash-dot line depicts the levee crests for reference (Modified after Stelting et al., 1985).

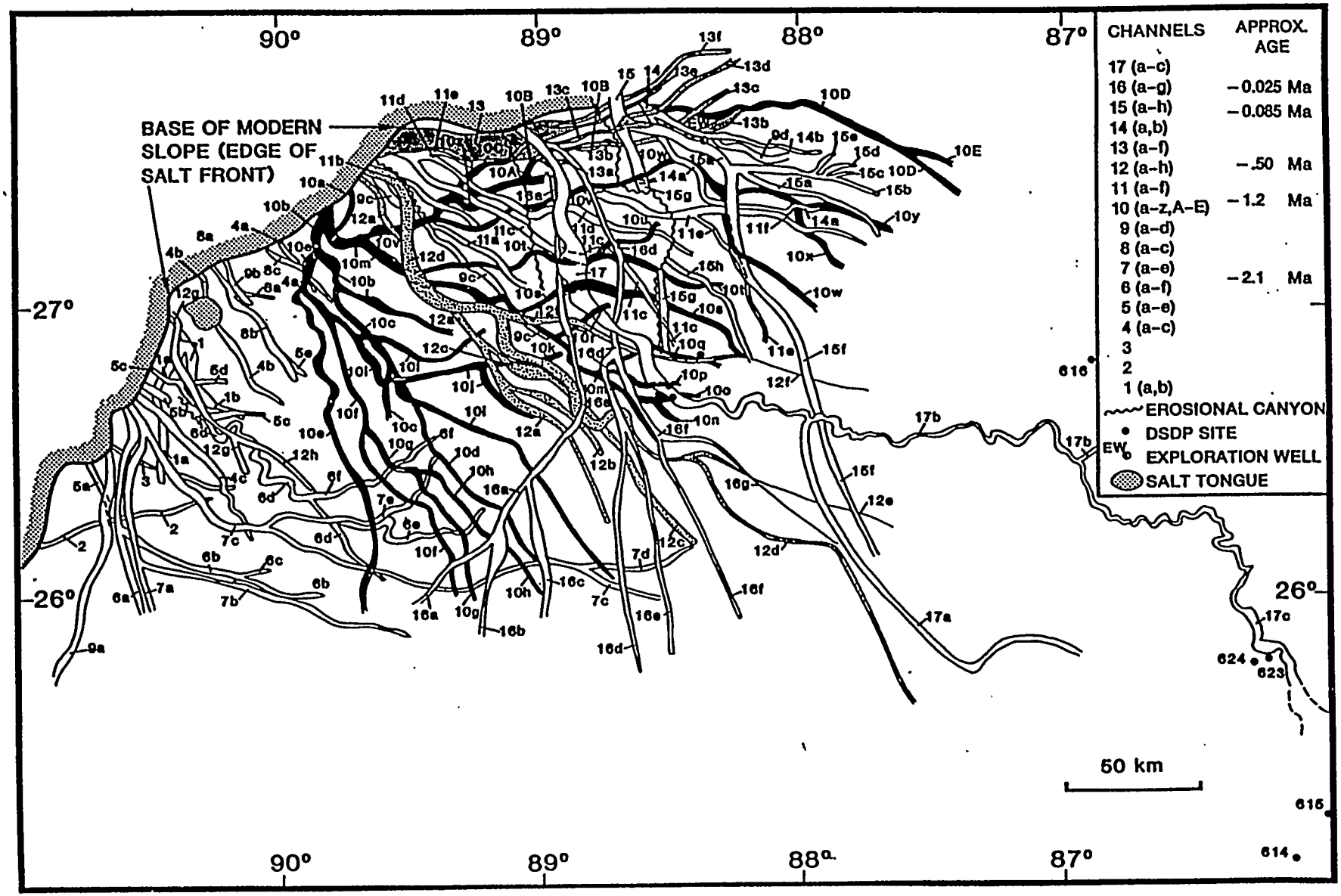


Figure 22. Location of channel axes of 17 channel-levee systems identified in the Mississippi Fan complex. Channels are numbered from 1 to 17 (oldest to youngest). Within any channel-levee system the relative ages of its channels are identified by letters from oldest to youngest (a, b, c, ...). Youngest channel (#17) is from EEZ Scan 85 (1987) (After Weimer, 1991).

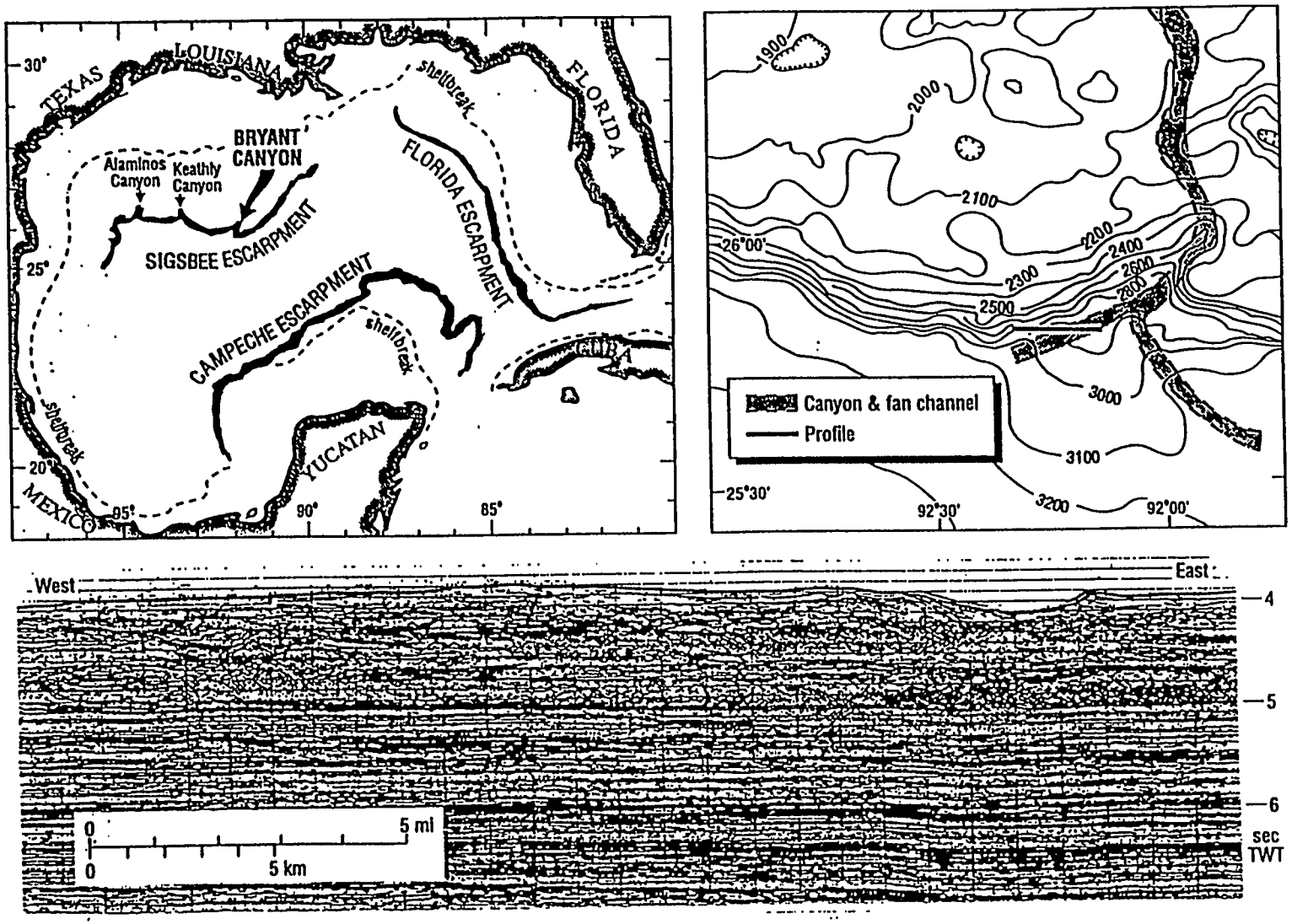


Figure 23. Location and general shape of Bryant Canyon in the Sigsbee Escarpment region. Bathymetric details in the local map show the widening of the upper fan with two channels. The seismic line reveals a number of channel shaped reflection configurations, with and without potential levees. The salt canopies on both sides of the canyon are just beyond the sides of the seismic segment shown (After Bouma et al., 1995b).

one of the most visited outcrops on field trips by industry and universities. The two sides of the spillway are about 65m apart which allows for a rather detailed correlation. Lithological profiles and hand-held gamma-ray profiles have been made by many investigators. However, layer by layer correlation is not always possible (De Vries and Bouma, 1991). Vertical trends in layer packages, separated by well-correlatable thick shales, make excellent correlations, similar to what can be done between wells (Fig. 24). The number of layers and their individual thicknesses correlate well for the very thin beds. Correlatability and individual thicknesses decrease with the increase in layer thickness.

The above has been interpreted as follows: the thick layers, often amalgamated or separated by thin shales, are channel fills. The very thin layers are overbank deposits that cover a large area and therefore can be correlated well. The 10-50cm thick layers are either channel margin or levee deposits, many of them thinning and thickening over hundreds of meters or more, resulting even in thickness differences over the distances between both walls of the spillway.

The switching back and forth of the thickest correlatable package, supports the concept of sea-floor compensation, a phenomenon that seems to be very sensitive.

JACKFORK FORMATION, BIG ROCK QUARRY, ARKANSAS

An abandoned quarry, known as Big Rock Quarry, exposes a vertical section that is 60 m high and 900 m long. The quarry is located in the western outskirts of North Little Rock along the Arkansas River.

The deposits represent deepwater sedimentation, characterized in this case by laterally imbricated and cross-cutting channel fills (Stone and Haley, 1986; Link and Stone, 1986; Jordan et al., 1991; Cook et al., 1994; Bouma et al., 1995b). The intensive tectonics makes it difficult to place its depositional position accurately but the most likely position is the base-of-slope (C.G. Stone, pers.comm., 1993; Bouma et al., 1995b).

A combination of field observations, three well logs, a core obtained just behind the outcrop wall, and photo-mosaics resulted in measuring 24 vertical sections from those mosaics, after which a reservoir simulation study could be conducted (Cook et al., 1994). Figure 25 shows the complexity of the deposits with laterally and vertically some significant changes in lithology. The figure shows that the lower half of the quarry wall is comprised of sandstone and debris flow deposits, all in channel-shaped configurations. A zone in the middle of the wall and near the top on the southern side is characterized by thin beds. The northern upper half is comprised of

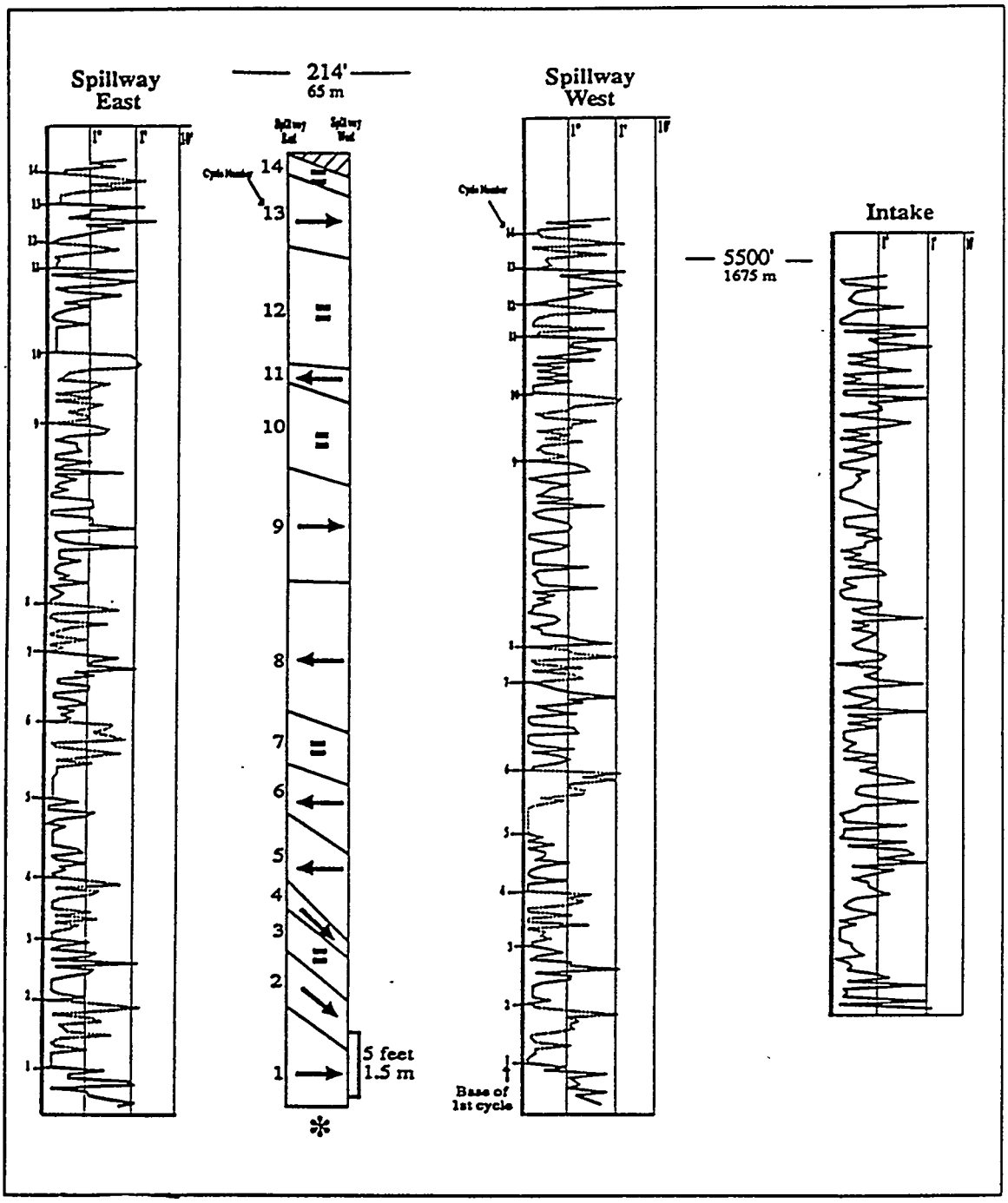


Figure 24. Sandstone bed thickness plot which can be divided into cycles. Solid and dashed lines are used for successive cycles to ease correlation between east and west sides of the Spillway. Individual bed correlation is good between the east and west Spillway sections, but poor between the Spillway and Intake sections except in overall thickness trend. Individual beds are weighted the same on the vertical scale with the horizontal scale representing bed thickness. Notice that this scale is not linear, but is close to logarithmic. Cycle thicknesses are plotted on the vertical scale in the graphic which is between the East and West Spillway bed thickness plot (asterisk *). Arrows show direction of thinning which switches back and forth; equal signs are assigned to cycles which show negligible lateral thinning (From De Vries and Bouma, 1991).

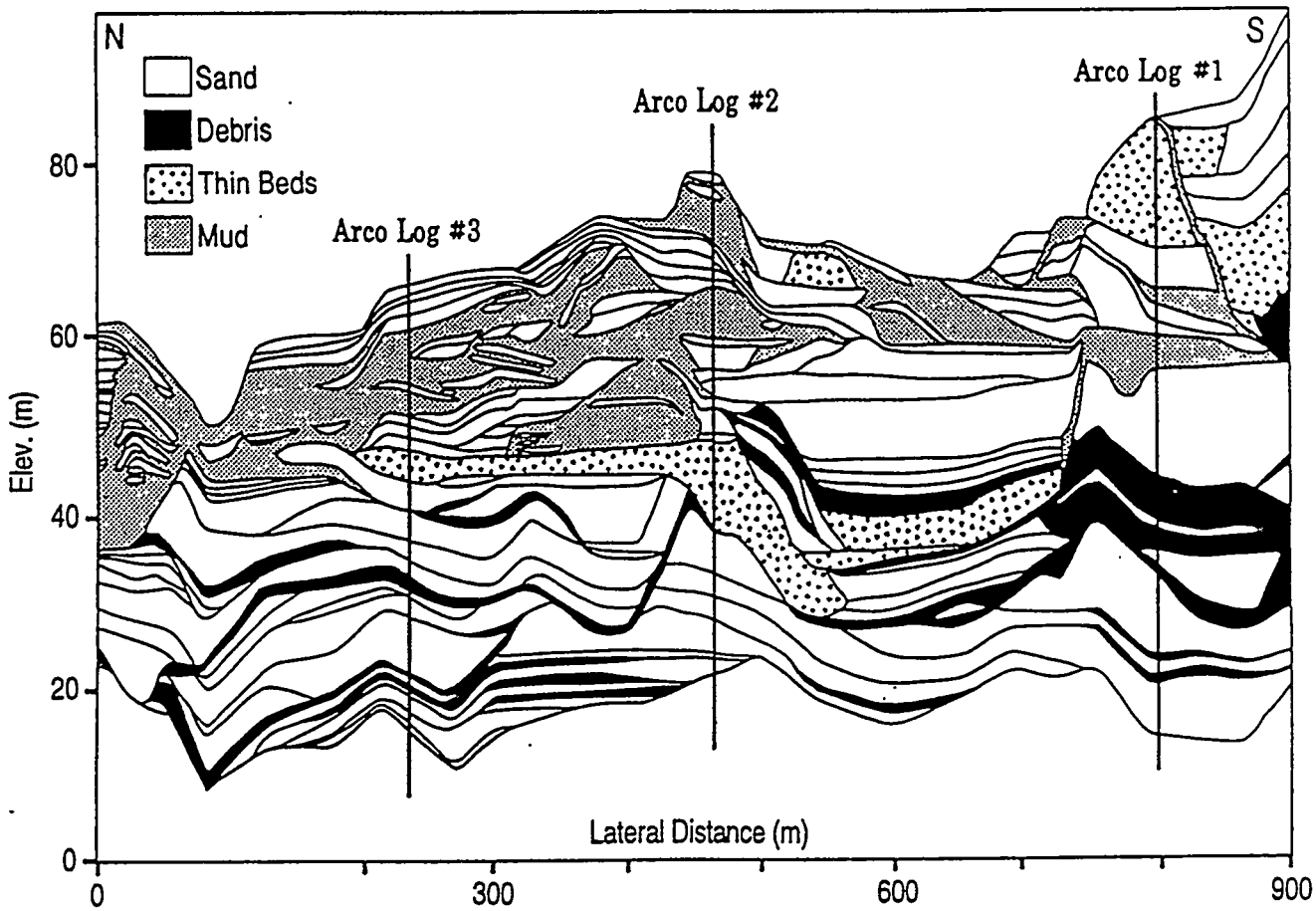


Figure 25. Lithofacies architecture of the wall in Big Rock Quarry, North Little Rock, Arkansas. The three ARCO logs are gamma-ray logs obtained from a truck-mounted probe. Shell drilled a core near ARCO Log #2. The proprietary software computer program used four offshore lithologies, that replaced the quarry sediments, in order to plot this reservoir simulation model of this outcrop (After Cook et al., 1994).

mudstones (muddy shales) that suddenly becomes less prevalent in the southern half. Sandstones that alternate with the muds are mostly isolated while many of the sandstones are in communication in the southern half.

ARCO obtained three gamma-ray profiles from a truck-mounted logging probe (Jordan et al., 1991, 1993; Cook et al., 1994) and Shell Research Company drilled a core near the ARCO #2 location. The study was conducted to better understand the complexity of the architecture of this site. Later it became obvious that it also could be used in the development of the fine-grained submarine fan model.

TANQUA KAROO SUBBASIN, ECCA GROUP, SOUTH AFRICA

The uplifted Permian Tanqua Karoo subbasin submarine fan deposits are the best in the world to study a fine-grained basin-floor fan complex because there is no tectonic tilt in N-S direction and only 3-4° tilt to the east. The series of five submarine fans was deposited in a subsiding basin against the western branch of the Cape Fold Belt and the Hex River-Baviaans River Anticlinorium. During or just before deposition of the last submarine fan, uplifting took place with the result that the overlying shale series gradually merges into prodelta deposits, followed by prodelta and delta front (Wickens, 1994; Wickens and Bouma, 1995).

The five submarine fans range in thickness from about 12m to 200m and are separated by shale series of equal or more thickness. The lower two fans only display outer fan deposits, number 3 is a complete basin floor fan, numbers 4 and 5 reveal outer midfan and outer fan (Fig. 26). Paleocurrent directions are from the southern sector, except for Fan #4 which was fed from the west. The majority of cliff type outcrops are facing west with smaller ones running E-W in the south, center and north. The irregular configurations of the outcrops of each fan makes it possible to study the deposits in a 3-D mode (Fig. 26).

The fine-grained nature of the sediments indicates that the sediment source area was a considerable distance away from the actual depositional area. That means that either major fairways existed through the Cape Fold Belt or that the belt had not yet a surface expression on the sea floor. A second subbasin, located between the southern branch of the Cape Fold Belt and the Hex River-Baviaans River Anticlinorium, the Laingsburg subbasin, was not an open and broad foredeep but a narrow and long trough. The fill is comprised of four submarine fans that are strongly folded. A comparison between the two subbasins will provide information about the deposits being deposited during a quiescent period in a broad foredeep or during a more tectonic

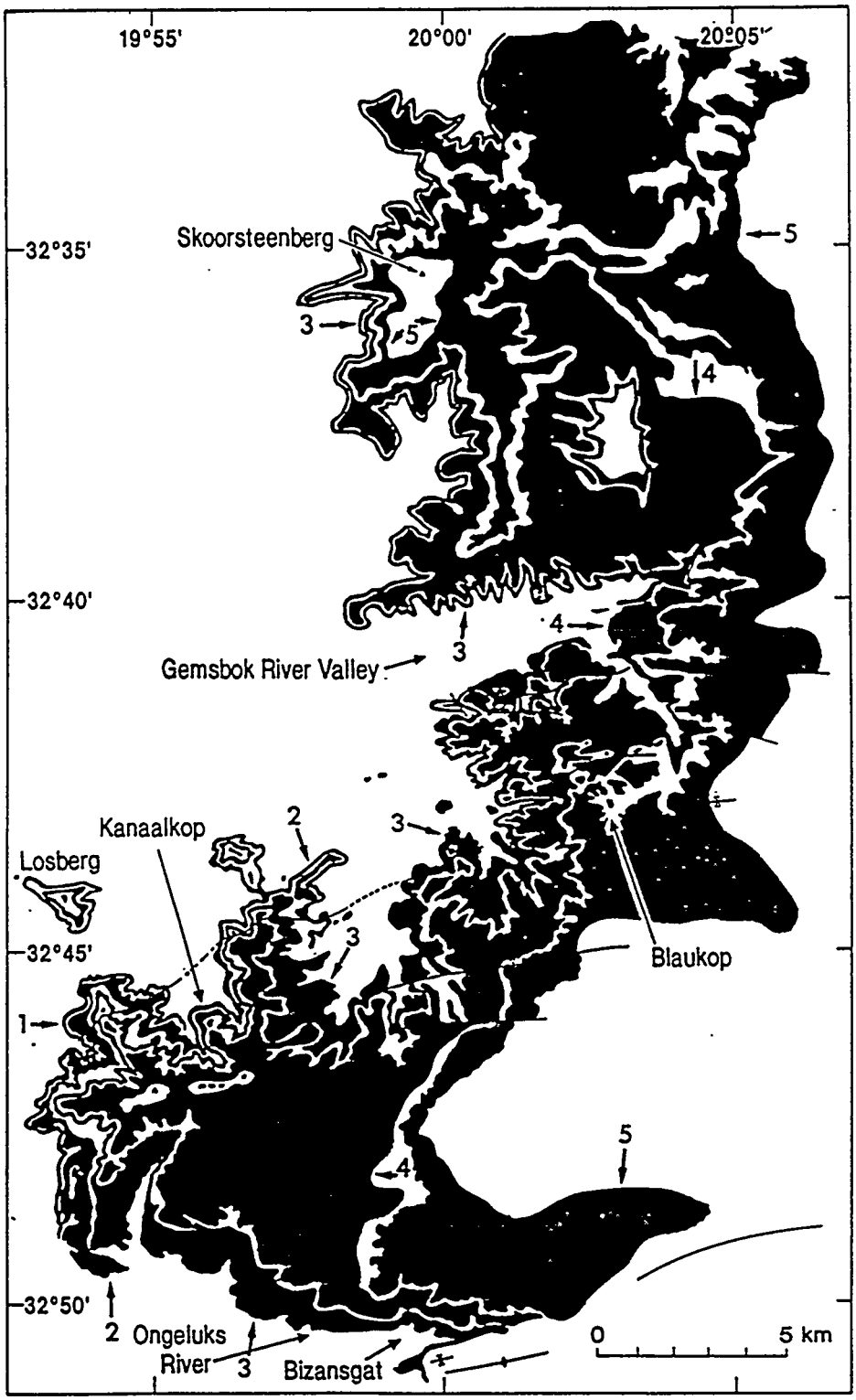


Figure 26. Outcrop map of the five Tanqua Karoo basin-floor fans (in black, numbered 1 through 5 in stratigraphic order). The individual fans are numbered on the drawing and the locations of a few localities are presented. The white between the individual fans represents shale (basin shales as well as shaley turbidites) (From Bouma and Wickens, 1991, 1994).

active time in a trough. Although the setting is an active margin in a tectonic sense, the fine grain size provides the idea that at least the Tanqua Karoo subbasin mimics a passive margin depositional style.

Fan #3 is the best example to study a basin floor fan (Bouma and Wickens, 1991, 1994; Wickens et al., 1992; Bouma, 1992; Wickens, 1994; Bouma et al., 1995a, b). Three depositional styles can be recognized: a channel complex in the south (Ongeluksrivier outcrop), a channel-levee complex occupying the southern part of the outcrop area (example Kanaalkop), and sheet sands in the north (Skoorsteenberg area) (see Fig. 26).

The channel complex along the Ongeluks River can be compared to Big Rock Quarry in Arkansas. It is comprised of channel fills, most of them amalgamated sandstones, with or without zones or irregular pockets of concentrated or scattered shale clasts (rip-up clasts) along the contacts. Younger channels cut into older ones. The base of a channel cut often is characterized by a laminated sand-rich silty shale or a zone of rip-up clasts. Sandstone-on-sandstone contacts can also be observed. Figure 27 shows a major part of the outcrop in two parts at a vertical exaggeration of 13.5 times (Bouma and Wickens, 1994; Bouma et al., 1995b). The illustration reveals that the channel fills show a high width/thickness ratio and a general change of the paleocurrent direction to the northern sector followed by a direction more to the east. A time succession of the different channel fills has yet to be established. The numbers in Figure 27 show one possibility.

Leveed-channels can be observed at many points. It was noticed in Fan #5 at Bloukop (see Fig. 26) that the complex consists of massive channel fills comprised of amalgamated sandstones, and bedded deposits of slightly finer-grained sandstones revealing normal current-ripple lamination, climbing ripple lamination, parallel lamination or very thin bedding, and long wavelength flat ripples. The latter are typical for layers 4-7cm thick, the other three for layers ranging in thickness from 15-60cm. Layers thinner than 2-3cm normally show parallel lamination and sometimes current ripple lamination. Two of the layers could be followed into the massive channel sands, indicating that the massive sandstones and bedded sandstones are related and time equivalent. Because the massive sandstones are interpreted as channel fills, the bedded sandstones therefore are levee deposits. (NOTE: the lack of any surface convexity of the bedded sandstones is not surprising. The channels were shallow and wide, the levees must have been low and wide. Later differential compaction decreased any convexity even more).

The levee sandstones show the typical tractional structures. That implies that part of the

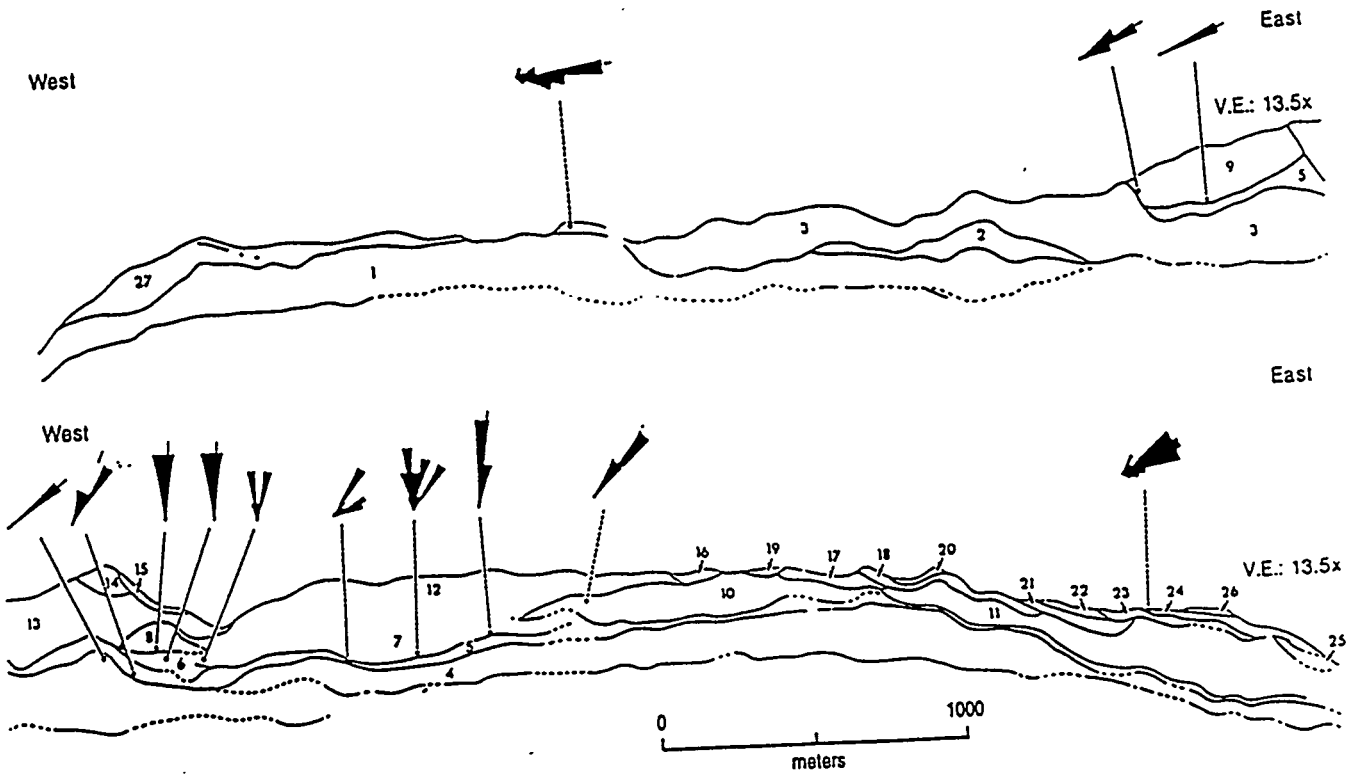


Figure 27. Drawing based on field measurements of (Fan #3 at Ongeluks River, Tanqua Karoo subbasin, South Africa. Lower drawing is a continuation of the upper part. Vertical exaggeration is 13.5 times. The channels have a high width/depth ratio and shift laterally to make use of steeper gradients. The numbering of the channels does not indicate the order of shifting. Note the variation and general change in paleocurrent directions (Field observations by O. van Antwerpen; after Bouma and Wickens, 1994; Bouma et al., 1995b).

turbulent density current overflowed the channel margins and changed to traction currents. Also the paleocurrent direction of the bedded deposits differs from the main channel direction by about 30° which indicates the different forces involved: overflowing to the side, forward momentum, lack of restriction to the side, and the dipping surface of the levee-overbank deposits.
(NOTE: a similar configuration has been found in the Upper Brushy Canyon Formation in the Delaware Basin - west Texas and New Mexico - along the road from El Paso to Carlsbad near the rest area SW of El Capitan).

Fan #3 in the Kanaalkop location can be studied in a U-shaped outcrop (Fig. 26). Fan #2 is overlain by basin shales which sharply change into bedded sand-rich shales which, in turn, are interrupted by a channel sandstone (Fig. 28). According to the Mutti and Ricci Lucchi (1972, 1975) the bedded shales should be interpreted as distal deposits across which the channel progressed suddenly, starved and became overlain again by outer fan deposits. The west side of the U-shaped outcrop also contains a massive sandstone package. The presence of that channel fill and the sedimentary structures in the bedded sandstones, being similar to those at Blaukop, supports the interpretation that Fan #3 in the Kanaalkop outcrop represents channel and levee-overbank deposits.

Other observations on Fans #3 and 5 show that channels are conduits for density currents, leaving some sand behind and building up levees. Consequently it takes some time for a channel to be filled. It is suggested that a large density current, possibly representing a new beginning of activity (relative sea level lowering and consequently the major construction of a deltaic body near or in the shelfbreak or head of the submarine canyon area), may cause a significant erosion of an "active" channel. It seems that such erosion often involves a lateral shifting. The new channel goes through a similar cycle (Fig. 29). Finely the channel fills up, topped by high shale content deposits, and a new major current will switch to a new position with a steeper local gradient.

It is not necessary that each current deposits a layer of sand in the central part of the channel with a lateral continuation onto the channel margin, the levee and overbank area. It is the head of the density current that deposits most of the sediment that is left in the channel while the body of a turbidity current may overflow and is responsible for the levee-overbank deposits. That explains why the channel sandstones are somewhat coarser than those of the levee-overbank sediments. Continuity of channel sands onto the levee may thus not be too common.

It was also noted that the channel sands are not only a little coarser than the levee

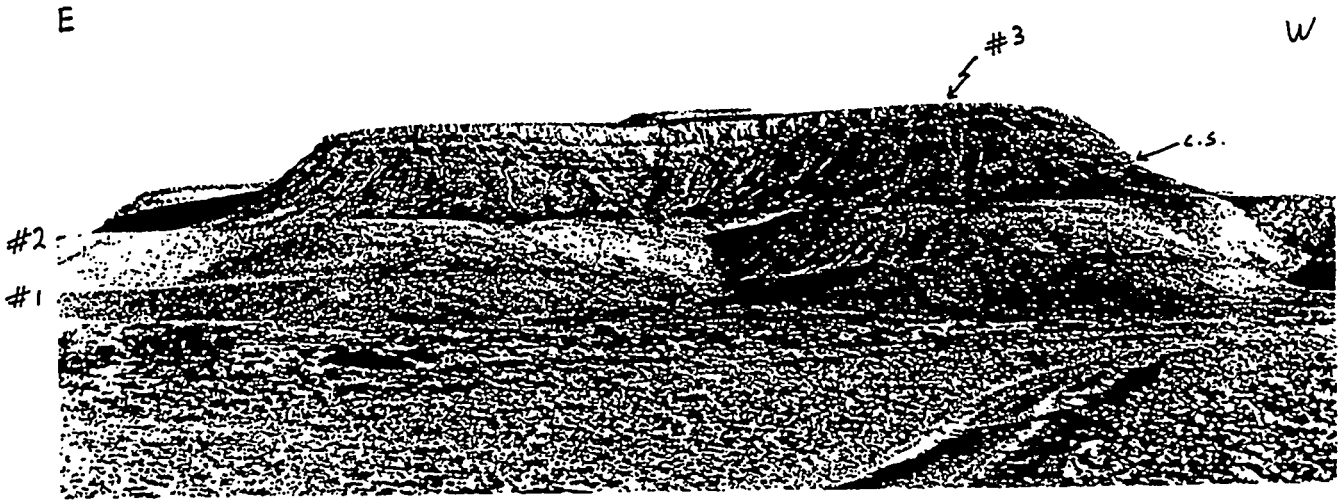


Figure 28. Photograph of the front of the U-shaped Kanaalkop outcrop. Fans # 1, 2 and 3 are shown. Notice that Fan # 2 is overlain by "homogeneous" shales (basin shales) that abruptly change into "bedded shales" (levee-overbank deposits belonging to a channel on the right-hand side of the U-shaped outcrop. A channel has cut into these bedded sandstones. Channel width: 508 m; channel fill thickness in the center: 20m; c.s.: condensed section containing nodules at the top.

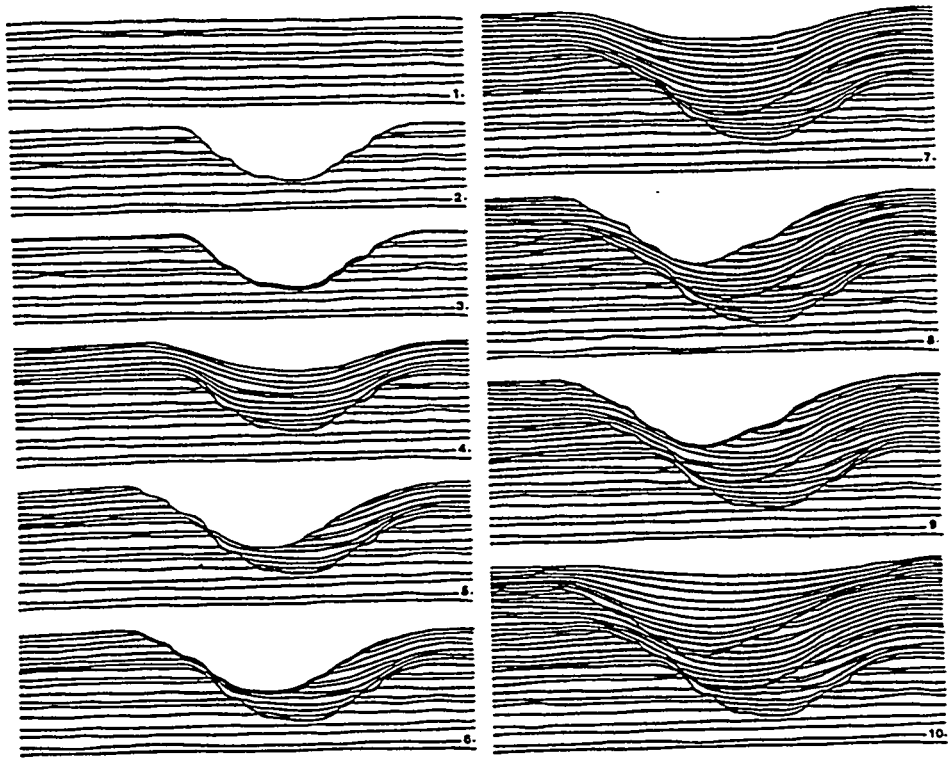


Figure 29. Schematic representation of the formation of a channel complex comprised of alternating phases of erosion often with shale deposition, and transport/deposition of sand-rich sediment through the channel from the nose of the density current. The upper part of the body of the current flows over the levee and deposits thin sand beds via traction currents, alternating with shale deposition. The sequence can repeat itself several times till a shaling out of the channel fill terminates the use of this channel complex (After Bouma, 1992; Bouma and Wickens, 1994).

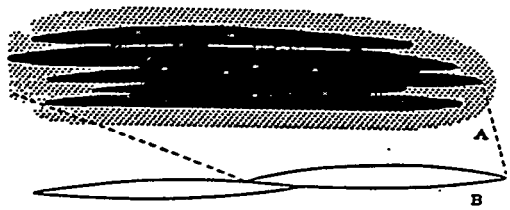


Figure 30. Schematic explanation of the formation of stacks of sheet sands.

A: a number of successive turbidity currents, coming down the same path and each depositing a sand layer overlain by mud, form an amalgamated stack of sandstone layers (black). Each succeeding density current erodes the center part of the exposed mud layer away. That results in an amalgamated contact that changes into a shale laterally. The thickness of the shale increases outward because the erosive strength decreases in those directions. Strong vertical exaggeration

B: two sandstone packages onlap onto each other (After Bouma, 1995).

sandstones but that the channel sands contain a little more clay, thus reflecting density currents vs. traction currents. The thin-bedded levee sandstones (low-contrast, low-resistivity sandstones according to Darling and Sneider, 1992) can reach tremendous total thicknesses and can be excellent hydrocarbon reservoirs, due to their high permeability.

The sheet deposits or depositional lobes can best be studied in the Skoorsteenberg area using Fan #4 because Fan #3 is too thin (about 14m). The deposited sandstones give an internally massive, parallel bedded appearance with shale separations. Closer observations reveal that the sandstones are the product of turbidity currents. The major part of a sandstone can be massive in appearance. If that should be called a T_a division or a debris flow deposit is up to the investigator. However, field observations do not favor the debris flow interpretation. Graded bedding is not possible because of the lack of a range in grain size of the original sands.

A combination of drawings made from photo-mosaics and field observations shows that amalgamated contacts in the sandstones change into thin shales in lateral direction. The thickness of the shales increases laterally (Fig. 30). The following explanation can be provided (Bouma, 1991, 1995; Bouma and Wickens, 1994): A number of succeeding turbidity currents follow the same channel path (middle fan channel and distributary channel). That means that each of those currents is pushed in the same direction once they leave the mouth of the distributary channel. Each current, whatever its size, will deposit a very flat lenticular sand layer that will be covered with mud that falls out of the tail of the current. The next current has sufficient energy to remove that mud, and may be some sand, from the central part of the previous deposit. That results in an amalgamated sand-on-sand contact. This stacking, either vertically, offlapping to one side, or randomly will continue till either the stack gets too high and the downdip gradient too low, or updip a major current breaks through the levee of the old channel, and a new direction is formed. Figure 30B shows how two stacks of amalgamated sandstones can onlap onto each other (For stacking variations see Fig. 31). The width of an individual sandstone layer can be 0.5km or more, making it nearly impossible to observe this in outcrop. The compensation of seafloor topography is very sensitive but likely does not always follow the upward thickening sequences proposed by Mutti and Sonnino (1981). Observations in the Tanqua Karoo subbasin deposits suggest that any sequence can be expected (thickening-upward, thinning-upward, bimodal, or no sequence).

DISCUSSION OF THE FINE-GRAINED SUBMARINE FAN MODEL

Figure 31 shows that a minimum of three depositional areas exist on the basin floor fan that can be called end members: 1) base-of-slope area with the channel complex, 2) middle fan with channel-levee-overbank deposits, and 3) lower fan with sheet sand deposits (depositional lobes) (Bouma, 1991, 1995; Bouma et al., 1995a, b). All three end members are the result of individual transport-deposition density currents. The size of each end member and the size of the total deposit varies depending on initial volume and velocity of each density current and the gradients of the basin floor. Observations on the Tanqua Karoo deposits suggest that the basin-floor fan system results from a rapid progradation followed by avulsion of channels and consequent lateral switching of sheet sand deposition. Once the supply of sediment reduces during a continued rise of relative sea level or results from a climatically or tectonically controlled reason in the sediment source area, a general regression will start. That regression will likely be a pulsating affair with a general decrease in both grain size and layer thickness of the deposits. Channels and other depressions will be filled before a general coverage of mud-rich sediments may result (see Fig. 7). Lastly the upper fan channel (basin slope conduit or fan valley) will be filled with fining-upward sediment.

The above presented reasoning eliminates the slope fan as a channelized depositional unit, because all parts (end members) belong to the basin-floor fan. The actual slope fans of a fine-grained submarine fan complex are basically shaly with sometimes large sandy slump blocks of deltaic material and/or shelf sand at its basis where it merges with the base-of-slope sandstones. Because of the many scenarios possible, one can expect several variations on the upper fan part of the model presented in Figure 31.

A suggested outline of the original coverage of Fan #3 is presented in Figure 32. Black dots along the western side of the outcrop location map indicate where vertical profiles were measured. The illustration shows changes in the paleocurrent direction. The bottom rose diagram is based on channel fill and channel bottom measurements, the top two on sole markings from the sheet sand deposits on the outer fan, and the central ones are primarlily based on ripple troughs and fore-set bedding found on upper bedding planes and in vertical sections of the bedded levee deposits, hence a difference in direction.

The vertical profiles, shown in Figure 33, reveal that there are several changes in the sand/shale ratio and bedding characteristics of a basin floor fan going from updip in downdip direction. Profiles from the Ongeluks River outcrop, directly west of Bizansgat (Fig. 32) are nearly

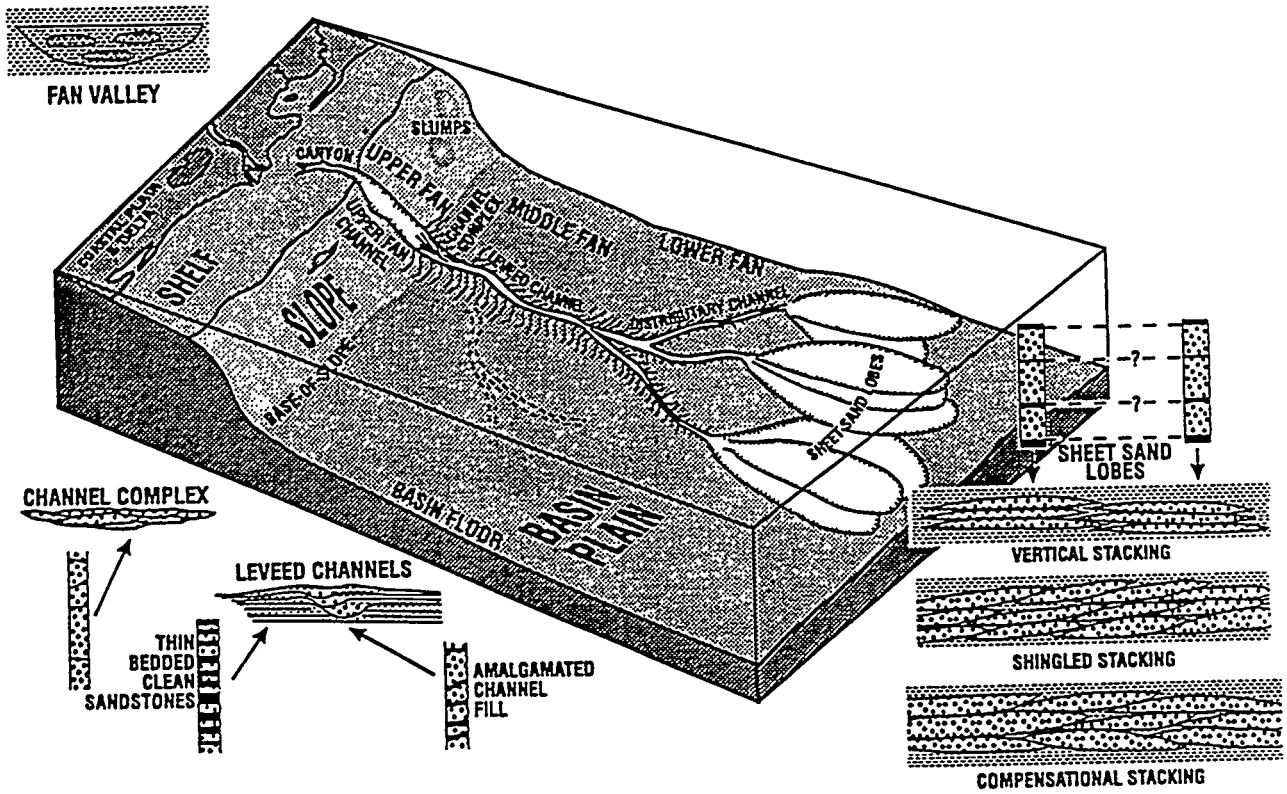


Figure 31. Proposed model for a fine-grained submarine fan. The fan itself is sand-rich except for the overbank areas on the middle fan. Note the large conduit on the upper fan (basin slope): upper fan channel. The channel complex is located at the base-of-slope area where the upper fan channel changes into the basin plain with leveed channels. In the lower fan area the active channel starts a distributary pattern. Only one channel and one distributary is active at a given time. The distributary shallows and finally looses its retaining influence on the head of the density current and sheet deposits will be formed. The stacking of the sheet sands can occur in several modes: vertical stacking of small piles of sheet sands with the piles onlapping to each other, singled stacking or random compensational stacking (After Bouma, 1995; Bouma et al., 1995a, b).

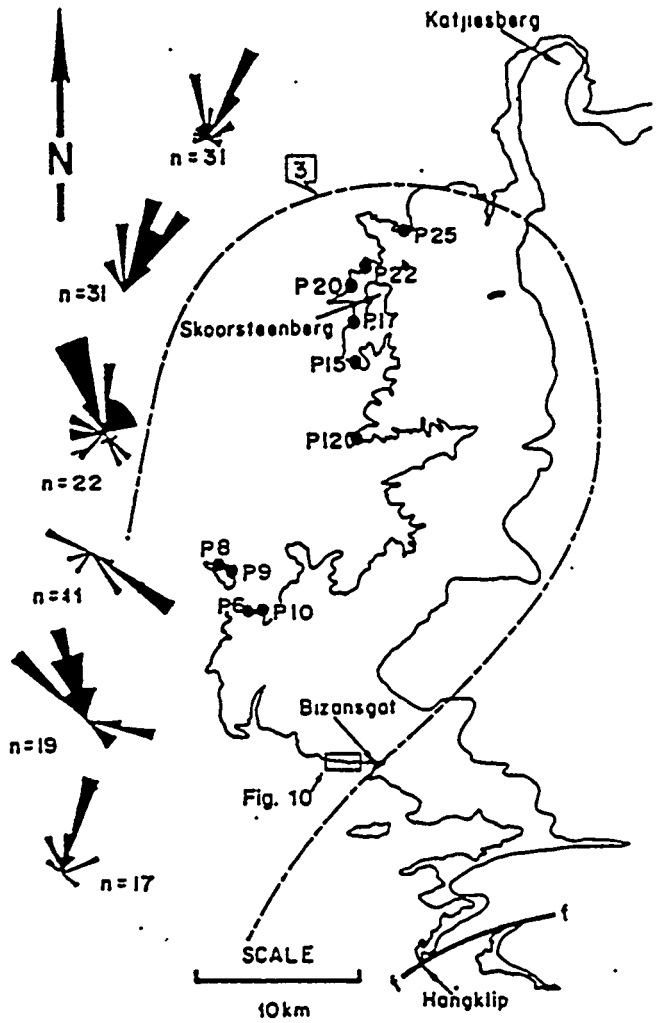
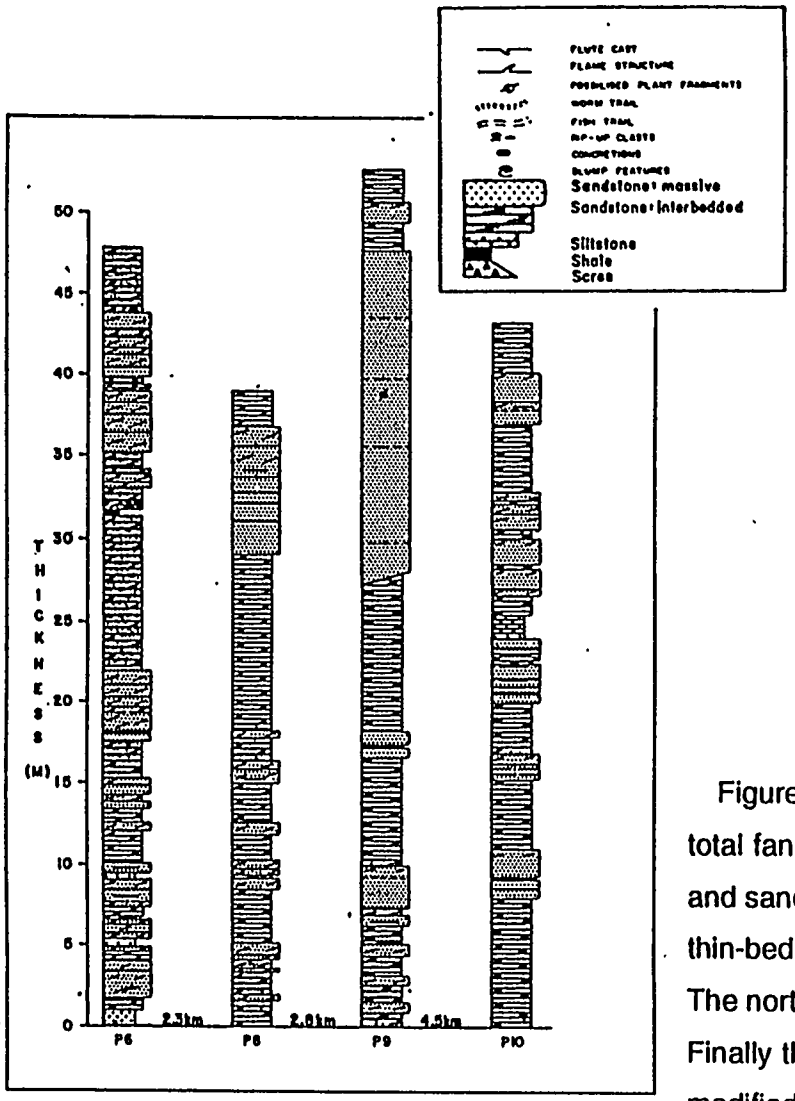


Figure 32. Outcrop distribution map and inferred original areal coverage of Fan # 3, Tanqua Karoo subbasin, South Africa. Rose diagrams present the results of measured paleocurrent directions. The differences in direction are the result of the different features measured. The bottom one reflects channel base measurements primarily of the base-of-slope channel complex along Ongeluks River (west of Bizansgat). The next two diagrams are based on measurements of ripple troughs and some foresets in the levee deposits, and therefore do not represent the overall direction of flow. Rose diagram No. 4 represents measurements from the P8-P9 area getting closer to the side of the original basin. The top two diagrams are based on sole markings of the sheet sand deposits. P: location of measured vertical profile; n: number of paleocurrent readings (Courtesy of Soekor; modified after Wickens et al., 1990).



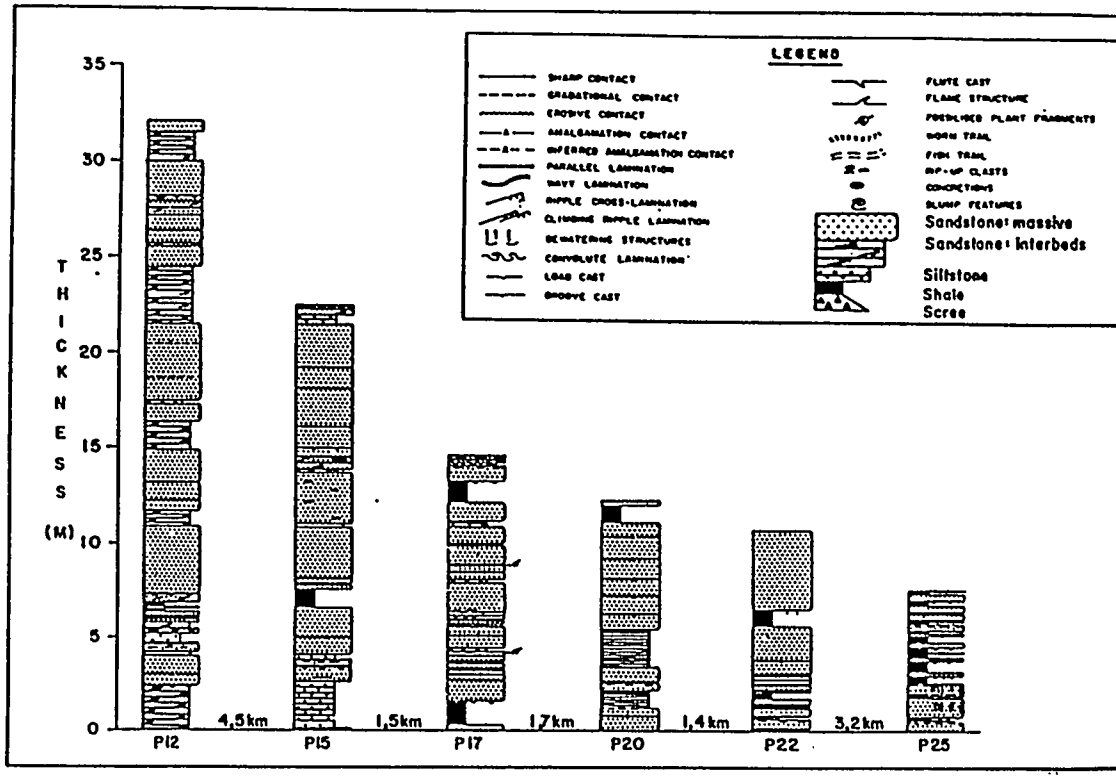


Figure 33. South to north distribution of measured vertical profiles showing a thinning of th total fan # 3 to the north (downdip direction) and changes in the overall layering characteristic and sand/shale ratio. The southern half represents the channel-levee-overbank deposits, main thin-bedded series (slightly low sand/shale ratio) interrupted by massive channel fill sandstones The northern part displays a higher sand/shale ratio of the non-channelized sheet sand deposit Finally the fan thins drastically. For locations of the profiles see Figure 31 (Courtesy of Soeko modified after Wickens et al., 1990).

massive sands, separated by thin sand-rich shales (not shown). The channel-levee deposits show that they are comprised of thin-bedded levee deposits that are interbedded by massive channel fill sandstones. The total sand/shale ratio is somewhat lower than that from the updip and down-dip areas. When a core would represent the real overbank areas the sand/shale ratio would be very low (see DSDP Leg 96 Site 620: Bouma et al., 1985a, c).

Channel Complex at the Base-Of-Slope

Density currents coming down the upper fan channel may start to deposit part of their load because of decreasing velocity due to the decrease in gradient. Typically, the first mass flow(s) and density current(s), that carved out the upper fan channel, will be succeeded by density currents of smaller volumes that cannot cover the entire width of the lower part of the fan valley. Many density currents probably start with erosion, followed by deposition of part of their load. This results in amalgamated channel sandstones with sand-rich levees and sometimes minor overbank deposits (Fig. 31). Much of the latter two will be removed by subsequent currents (Fig. 34). Density currents seek the maximum gradient available which causes a sweeping of the fan valley floor from one side to the other. The end product of the deposition consists of a very sand-rich deposit with many amalgamated contacts and scattered remnants of sandy/shaly levee-overbank sediments (Bouma and Wickens, 1994; Bouma, 1995; Bouma et al., 1995a, b). A core drilled through these deposits will reveal massive sandstones separated by 2-10cm thick "shale" series. The shales typically are comprised of 2-6mm thick sandstones or siltstones separated by 1-2mm thick muddy shales. The sandstones may contain low amplitude bedforms that can be several meters across. Locally in a channel axis one may find a lag deposit that is comprised of subangular rip-up clasts and sand. An FMS log will likely show some low angle dips in different directions (channel base) and low-medium angle dips in a more organized manner, indicating bedforms.

Channel-Levee-Overbank Deposits

Once the constricted lower fan valley changes into the more unrestricted basin plain, the mode of deposition changes into a well-developed channel with levee and overbank sedimentation. Levees focus the direction of the head of density currents while part of the main body of the current spills over the levees, causing accumulation on the levee and overbank (interchannel) area. The layers show a thinning and a sand/mud ratio decrease away from the

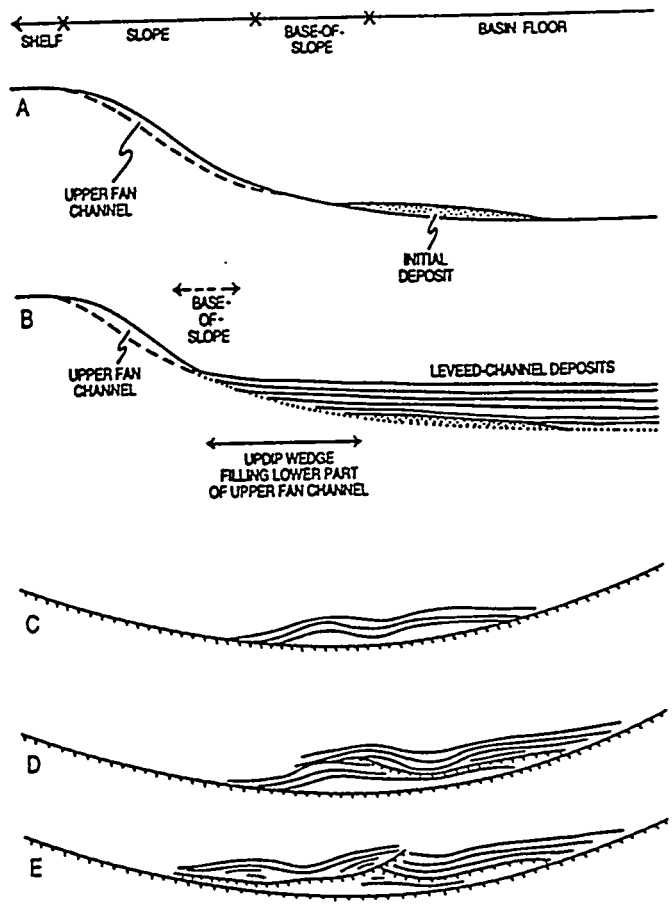


Figure 34. Schematic representation of the construction of the sand-rich updip wedge of the channel complex in the base-of-slope area.

A: dip line revealing the relationship of the upper fan channel, formed by excavation of a major depression by a large slump, and the detached deposition on the basin floor of that excavated mud-rich sediment;

B: transport of sediment through the upper fan channel with deposition of basin-floor fan sediments. It shows the aggrading of the updip onlapping onto the upper fan channel bottom, necessary to maintain a downdip gradient;

C-E: strike sections with different stages of channel formation: building-up, switching accompanied by erosion and again followed by a constructive phase, etc. Barbed line: erosional contact; full line: amalgamated contact (After Bouma et al., 1995b).

channel. Outcrops in South Africa, southern France and other locations indicate that channel transport/deposition often occurs in cycles where small flows are more constructive and add to the accumulation, whereas larger, stronger currents often erode. Each time a major erosional cycle begins the channel may migrate laterally, removing part of the underlying channel fill and levee deposits. The result is an amalgamated, laterally accreted channel fill (Fig. 31). Moreover, the fine grain size makes it difficult to detect several individual channel fill events. The massive channel fill commonly is slightly dirty (clayey); its upper fill usually consists of dirty incomplete turbidites (Bouma and Wickens, 1991).

The levee deposits are comprised of alternating sandstones and shales. The sands are deposited by traction currents and thus normally are cleaner than channel deposits. Current ripples and climbing ripples are common, showing a direction of flow away from the channel and the general downdip direction (see Fig. 32). Grain orientation supports paleoflow directions obtained from the sedimentary structures. These thin-bedded, low-contrast, low-resistivity sandstones (Darling and Sneider, 1992) are too thin to detect on seismic reflection records and on most routine well logs. Therefore, they are easily classified on logs as (slightly) sandy shales. However, they can be excellent reservoirs with extremely high permeabilities (Bouma and Wickens, 1994).

When midfan deposits are observed in large outcrops, an abundance of thin-bedded sandstones with a scattering of a few massive channel fills are commonly found (see Fig. 33). Older models placed those thin-bedded units at the outer fan fringe with channel fills providing an indication of rapid channel progradation. However, the above-mentioned observations and the few findings of a direct connection of a thin levee sandstone to the channel fill, suggest more lateral switching than frequent progradation. Bifurcation is not uncommon and occasionally can be very intensive (see also Weimer, 1989, 1991) (Fig. 22).

The sand/shale ratio of the channel fills often is 97-100%, the highest of the fine-grained submarine fan. The levees have a variable sand/shale ratio from high (80-90%) very near the channel to very low the farther away from the channel onto the overbank deposits. Any outcrop, core or set of well logs thus can reveal a variety of sand/shale ratios, bedding characteristics and thicknesses and sedimentary structures (Fig. 31).

Sheet Sand or Depositional Lobes

A very significant amount of sediment, especially sand, is transported through the

channel(s) of the midfan onto the outer fan when dealing with a high-efficiency fine-grained submarine fan. The lack of levee confinement of a density current causes it to overflow and "fan out", forming an elongated sheet sand. The length/width ratio of the sheet depends on factors such as current velocity, sand/mud ratio, bottom gradients, and available basin-floor space. Natural slope variations appear to become important where gradients of 0.1° or 0.2° mean a deepening of 1.75 or 3.50m for each 1000m travelled, respectively. Compensation of seafloor topography thus is a very sensitive aspect.

Typically, sheet sand deposition may result in various configurations (Fig. 31). Vertical stacking means that several amalgamated sets of sandstone beds form one major depositional lobe or sheet with dimensions on the order of 0.5-1.5km in width, 3-20m in thickness, and may be 3-5km in length. Because succeeding density currents may travel down the same channel, they will be guided in the same direction. Consequently the deposits may stack vertically until the effect of downdip gradient is lost and a lateral shift results. This shift will either form an independent mound or an onlap onto previous deposits. It was noted in the Tanqua Karoo that many packages of sandstone are comprised of amalgamated sandstones in the center, whereas the amalgamations widen laterally into a shale wedge (Bouma and Wickens, 1994). This widening suggests that each succeeding density (turbidity) current deposits a sand layer that is overlain by a clay. It also suggests that the axis of the succeeding current is sufficiently strong to remove the soft clayey cover in the center of the density current that results in an amalgamated contact (Bouma and Wickens, 1994). A longer time period between currents may prevent complete erosion and thus the formation of an amalgamated contact. If the gradient does not permit additional aggradation, the current will swing to the side, either onlapping the previous deposits or seeking the maximum gradient as a response to depositional seafloor compensation (Fig. 31). Any stacking system may result depending on the factors involved, and it is assumed that more than one stacking system can be found in anyone basin fill. An important issue, but not known at this time, is the degree of connectivity that results from each of the suggested stacking patterns. However, initial observations give the impression that connectivity is very good with varying degrees of tortuosity.

Occasionally, a channel-shaped erosional depression was documented either at the base of outer fan sheet sands or within a sheet sand package. The latter occurrence suggests that an occasional strong density current prograded further than the majority of the density currents and started sheet sand deposition in the down-dip area, similar as indicated in Walker's (1978)

model.

Figure 31 shows that the various stacking arrangements of the sheet sands likely can not be distinguished in cores. It is possible that FMS logs from two or three neighboring wells may provide a decent answer. As long as connectivity between individual sheet sands or packages is acceptable the stacking pattern may not be an important industrial question.

CONCLUSIONS

No model can be applied universally to similar types of deposits in different areas, but general characteristics may well be applicable. Basin size and gradients, climatological and tectonic activities in the area where rocks are eroded into sedimentary particles, the length and time involved to bring that sediment to the coast line, the sand/mud ratio of the sediment passing through the deltaic distributary mouth, current and tidal influences at the delta shore line, width of the shelf and the slope toward the receiving basin, and the relative sea level fluctuations present at that time, will influence the construction and characteristics of a submarine fan. In spite of all of these variations a model is proposed for a fine-grained, single entry point, basin-floor fan that is part of a mud-rich submarine fan complex.

At the entry to the basin floor, in the base-of-slope zone, a very sand-rich channel complex is constructed comprised of channel fills that cut into each other (erosional events) and are often separated by thin sand-rich, laminated zones, often identified as sandy shales. That channel complex changes into channel-levee-overbank deposition once the gravity-driven density currents enter the less- or non-restricted basin floor. A main channel progrades rapidly onto the basin floor, after which total accumulation is the result of local vertical accumulation and frequent lateral switching as the sediment pile reduces the local gradient too much.

The channel gradually shoals and finally looses its constraining influence on the head of the density current. The turbidity current will fan out and an elongate sheet sand will be deposited. Succeeding sheet sands may stack vertically, form a shingling set of layers or a compensational arrangement.

As a general rule, the basin-floor fan increases in thickness in the updip area of the basin and then gradually thins downdip and laterally. The base-of-slope channel complex migrates upwards into the lower part of the upper fan channel in order to maintain a downdip gradient

when the submarine fan aggrades. The sand/shale ratio is very high in the base-of-slope area, lower and variable in the channelized area (mid-fan) and high again on the lower fan with its sheet sand deposition.

Seismically the channelized area is the easiest to recognize. Differential compaction can create good reservoirs. The base-of-slope area might be an important reservoir target but it is more difficult to distinguish on seismic records. Careful palinspastic reconstruction of fan surfaces may indicate how far the updip wedging into the upper fan channel took place. The ideal sheet sand area may have all the characteristics necessary for a reservoir sand but may lack a trapping structure or may not have retained hydrocarbons because of updip migration.

The complexity of fine-grained submarine fan deposits is not different from any other depositional system. A good understanding and interdisciplinary approach is the most constructive means to be successful economically.

REFERENCES

Bally, A.W. (Ed.), 1989. Atlas of Seismic Stratigraphy. American Association of Petroleum Geologists Studies in Geology No. 27, v. 3, 244 p.

Barnes, N.E. and Normark, W.R., 1985. Diagnostic parameters for comparing modern submarine fans and ancient turbidite systems. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p. 13-14 and separate map.

Berg, O.R. and Woolverton, D.G. (Eds.), 1985. Seismic Stratigraphy II: An Integrated Approach to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 39, 276 p.

Bouma, A.H., 1962. Sedimentology of Some Flysch deposits, A Graphic Approach to Facies Interpretation. Elsevier, Amsterdam, 168 p.

Bouma, A.H., 1972. Leveed-channel deposits, turbidites, and contourites in deeper part of Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions, v. 23, p. 368-376.

Bouma, A.H., 1991. Models and characteristics of submarine fan channels. South Texas Geological Society Bulletin, v. 32, p. 11-21.

Bouma, A.H., 1992. Locations and characteristics of thin bedded turbidites in passive margin setting submarine fans. Gulf Coast Association of Geological Societies Transactions, v. 42, p. 425-432.

Bouma, A.H., 1995. Geological architecture of fine-grained submarine fans. Corpus Christi Geological Society and Coastal Bend Geophysical Society Bulletin, March 1995, p. 11-19.

Bouma, A.H., Coleman, J.M., and DSDP Leg 96 Shipboard Scientists, 1985c. Mississippi Fan: Leg 96 program and principal results. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p. 247-252.

Bouma, A.H., Coleman, J.M., Meyer, A.W., and Leg 96 Scientists, 1986. Initial Reports of the Deep Sea Drilling Project Leg 96. U.S. Government Printing Office, Washington, D.C., 824 p.

Bouma, A.H., Coleman, J.M., Stelting, C.E., and Kohl, B., 1989. Influence of relative sea level changes on the construction of the Mississippi Fan. Geo-Marine Letters, v. 9, p. 161-170.

Bouma, A.H., Lee, G.H., Van Antwerpen, O., and Cook, T.W., 1995b. Channel complex

architecture of fine-grained submarine fans at the base-of-slope. Gulf Coast Association of Geological Societies Transactions, v. 45, p. 65-70.

Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), 1985a. Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, 351 p.

Bouma, A.H., Normark, W.R., and Barnes, N.E., 1985b. COMFAN: Needs and initial results. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p. 7-11.

Bouma, A.H. and Treadwell, T.K., 1975. Deep sea dune-like features. Marine Geology, v. 19, p. M53-M59.

Bouma, A.H. and Wickens, H.DeV., 1991. Permian passive margin submarine fan complex, Karoo Basin, South Africa: possible model to Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions, v. 41, p. 30-42.

Bouma, A.H. and Wickens, H.DeV., 1994. Tanqua Karoo, ancient analog for fine-grained submarine fans. In: Weimer, P., Bouma, A.H., and Perkins, B.F. (Eds.), Submarine Fans and Turbidite Systems: Sequence Stratigraphy, Reservoir Architecture and Production Characteristics, Gulf of Mexico and International. Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation 15th Annual Research Conference Proceedings, p. 23-24.

Bouma, A.H., Wickens, H.DeV., and Coleman, J.M., 1995a. Architectural characteristics of fine-grained submarine fans: a model applicable to the Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions, v. 45, p. 71-75.

Carminatti, M. and Scarton, J.C., 1991. Sequence stratigraphy of the Oligocene turbidite complex of the Campos Basin, offshore Brazil: An overview. In: Weimer, P. and Link, M.L. (Eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems. Springer-Verlag, New York, p. 241-246.

Carter, L., and Carter, R.M., 1988. Left-bank levees in the southern hemisphere - a case study from the Bounty Trough, New Zealand. Marine Geology, v. 78, p. 185-197.

Chapin, M.A., Davies, P., Gibson, J.L., and Pettingill, H.S., 1994. Reservoir architecture of turbidite sheet sandstones in laterally extensive outcrops, Ross Formation, western Ireland. In: Weimer, P., Bouma, A.H., and Perkins, B.F. (Eds.), Submarine Fans and Turbidite Systems: Sequence Stratigraphy, Reservoir Architecture and Production Characteristics; Gulf of Mexico and International. Gulf Coast Section Society of Economic

Paleontologists and Mineralogists Foundation 15th Annual Research Conference Proceedings, p. 53-68.

Christie-Blick, N., 1991. Onlap, offlap, and the origin of unconformity-bounded depositional sequences. Marine Geology, v. 97, p. 35-36.

Christie-Blick, N. and Driscoll, N.W., 1995. Sequence Stratigraphy. Annual Review of Earth and Planetary Sciences, v. 23, p. 451-478

Coleman, J.M., Prior, D.B., and Lindsay, J.F., 1983. Deltaic influences on shelf-edge instability processes. In: Stanley, D.J. and Moore, G.T. (Eds), The Shelfbreak: Critical Interface on Continental Margins. Society of Economic Paleontologists and Mineralogists Special Publication No. 33, p. 121-127.

Cook, T.W., Bouma, A.H., Chapin, M.A. and Zhu, H., 1994. Facies architecture and reservoir characterization of a submarine fan channel complex, Jackfork Formation, Arkansas. In: Weimer, P., Bouma A.H., and Perkins, B.F. (Eds.), Submarine Fans and Turbidite Systems: Sequence Stratigraphy, Reservoir Architecture and Production Characteristics; Gulf of Mexico and International. Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation 15th Annual Research Conference Proceedings, p. 69-81.

Damuth, J.E., 1975. Echo character of the western equatorial Atlantic floor and its relationship to the dispersal and distribution of terrigenous sediments. Marine Geology, v. 18, p. 17-45.

Darling, H.L. and Sneider, R.M., 1992. Production of low resistivity, low contrast reservoirs, offshore Gulf of Mexico basin. Gulf Coast Association of Geological Societies Transactions, v. 42, p. 73-88.

Department of Energy, 1993. A Review of Slope-Basin & Basin Clastic Reservoirs in the United States. U.S. Department of Energy, Contract DE-AC22-93BC14964, Bartlesville Project Office, 174 pp.

DeVries, M.B. and Bouma, A.H., 1991. Correlation trends in thin-bedded turbidites, Jackfork Group, DeGray Lake, Arkansas. Gulf Coast Association of Geological Societies Transactions, v. 41, p. 184-186.

Edwards, D.E., Leeder, M.R., and Best, J.L., 1994. On experimental reflected density currents and interpretation of certain turbidites. Sedimentology, v. 41, p. 347-461.

EEZ Scan 86 Scientific Staff, 1987. Atlas of the Exclusive Economic Zone, Gulf of Mexico and Eastern Caribbean Seas. U.S. Geological Survey Miscellaneous Investigation Series I-

1864-a, 104 p.

Flint, S.S. and Bryant, I.D. (Eds.), 1993. The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogs. Internal Association of Sedimentologists Special Publication 15, 269 p.

Flood, R.D., Piper, D.J.W., Klaus, A., et al., 1995. Proceedings of the Ocean Drilling Program, Initial Reports, 155. College Station, TX (Ocean Drilling Program), 1233p.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists Bulletin, v. 73, p. 125-142.

GCSSEPM, 1990. Sequence Stratigraphy as an Exploration Tool; Concepts and Practices in the Gulf Coast. Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation 11th Annual Research Conference, 409 p.

Haq, B.U., Hardebol, J. and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science, v. 235, p. 1156-1167.

Hess, G.R. and Normark, W.R., 1976. Holocene sedimentation history of the major fan valleys of Monterey Fan. Marine Geology, v. 22, p. 233-251.

Jordan, D.W., Lowe, D.R., Slatt, R.M., Stone, C.G., D'Agostino, A.,Sheihing, M.H., and Gillispie, R.H., 1991. Scales of geological heterogeneity of Pennsylvanian Jackfork Group, Ouachita Mountains, Arkansas: Applications to field development and exploration for deepwater sandstones. Guidebook Dallas Geological Society Field Trip #3 (American Association of Petroleum Geologists Convention), 142 p.

Jordan, D.W., Slatt, R.M., Gillispie, R.H., D'Agostino, A., and Stone, C.G., 1993. Gamma-ray logging of outcrops by a truckmounted sonde. American Association of Petroleum Geologists Bulletin, v. 77, p. 118-123.

Kneller, B., 1995. Beyond the turbidite paradigm: physical models for deposition of turbidites and their implications for reservoir prediction. In: Prosser, D.J. and Hartley, A. (Eds.), Reservoir Characterization of Deep Marine Clastic Systems. Geological Society of London Special Publication 94, p. 31-49.

Kneller, B.C. and Branney, M.J., 1995. Sustained high-density turbidity currents and the deposition of thick massive sands. Sedimentology, v. 42, p. 607-616.

Kuenen. Ph.H., 1951. Properties of turbidity currents of high density. Society of Economic Paleontologists and Mineralogists Special Publication 2, p. 14-33.

Lee, G.H., Watkins, J.S., and Bryant, W.R., 1996. Bryant Canyon fan system: an unconfined, large-river turbidite system in the northwestern Gulf of Mexico. American Association of Petroleum Geologists Bulletin, v. 80, p. ...

Link, M.H. and Stone, C.G., 1986. Jackfork Sandstone in the abandoned Big Rock Quarry, North Little Rock, Arkansas. In: Stone, C.G. and Haley, B.R. (Eds.), Sedimentary and Igneous Rocks of the Ouachita Mountains of Arkansas. Guidebook Geological Society of America Annual Meeting, San Antonio, p. 1-8.

Loucks, R.G. and Sarg, J.F. (Eds.), 1993. Carbonate Sequence Stratigraphy. American Association of Petroleum Geologists Memoir 57, 545 p.

Lowe, D.R., 1979. Sediment gravity flows: Their classification and some problems of application to natural flows and deposits. Society of Economic Paleontologists and Mineralogists Special Publication 27, p. 75-82.

Lowe, D.R., 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. Journal Sedimentary Petrology, v. 52, p. 279-297.

Macdonald, D.I.M. (Ed.), 1991. Sedimentation, Tectonics and Eustacy. Sea Level Changes at Active Margins. International Association of Sedimentologists Special Publication 12, 518 p.

Middleton, G.V., 1966. Experiments on density and turbidity currents. I. Motion of the head. Canadian Journal of Earth Sciences, v. 3, p. 523-546.

Middleton, G.V., 1967. Experiments on density and turbidity currents. III. Deposition of sediment. Canadian Journal of Earth Sciences, v. 4, p. 475-505.

Middleton, G.V., 1970. Experimental studies related to the problems of flysch sedimentation. Geological Society of Canada Special Paper 7, p. 253-272.

Middleton, G.V. and Hampton, M.A., 1973. Sediment gravity flows: Mechanics of flow and deposition. In: Middleton, G.V. and Bouma, A.H. (Eds.), Turbidites and Deep-Water Sedimentation. Society of Economic Paleontologists and Mineralogists Pacific Section, p. 1-38.

Middleton, G.V. and Hampton, M.A., 1976. Subaqueous sediment transport and deposition by sediment gravity flows. In: Stanley, D.J. and Swift, D.J.P. (Eds.), Marine Sediment Transport and Environmental Management. Wiley, New York, p. 197-218.

Mitchum, R.M.Jr., 1985. Seismic stratigraphic expression of submarine fans. In: Berg, O.R. and

Woolverton, D.G. (Eds.), Seismic Stratigraphy II: An Integrated Approach to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 39, p. 117-136.

Mutti, E., 1977. Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-Central Pyrenees, Spain). Sedimentology, v. 24, p. 107-131.

Mutti, E., 1979. Turbidites et cones sous-marins profonds. In: Homewood, P. (Ed.), Sedimentation Detritique (Fluviatile, Littorale et Marine). Institut de Géologie, Université de Fribourg, Switzerland, p. 353-419.

Mutti, E., 1985. Turbidite systems and their relations to depositional sequences. In: Zuffa, G.G. (Ed.), Provenance of Arenites. D. Reidel, Dordrecht, p. 63-93.

Mutti, E., 1992. Turbidite Sandstones. Agip, S. Donato Milanese, Milan, 276 p.

Mutti, E., Barros, M., Possato S., and Rumenos, L., 1980. Deep-sea fan turbidite sediments winnowed by bottom currents in the Eocene of the Campos Basin, Brazilian offshore. International Association of Sedimentologists 1st European Meeting, Bochum, Germany, p. 114 (abstract).

Mutti, E. and Normark, W.R., 1987. Comparing examples of modern and ancient turbidite systems: Problems and concepts. In: Leggett, J.K. and Zuffa, G.G. (Eds.), Marine Clastic Sedimentology: Concepts and Case Studies. Graham and Trotman, London, p. 1-38.

Mutti, E. and Normark, W.R., 1991. An integrated approach to the study of turbidite systems. In: Weimer, P. and Link, M.L. (Eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems. Springer-Verlag, New York, p. 75-106.

Mutti, E. and Ricci Lucchi, F., 1972. Le torbiditi dell'Appennino Settentrionale: Introduzione all'analisi di facies. Memorie della Società Geologica Italiana, v. 11, p. 161-199 (Translated into English by T.H. Nilsen, 1978, International Geological Review, v. 20, p. 125-166.

Mutti, E. and Ricci Lucchi, F., 1975. Turbidite facies and facies associations. In: Mutti, E., Parea, G.C., Ricci Lucchi, F., Sagri, M., Zanzucchi, G., Ghibaudo, G., and Iaccarino, S. (Eds.), Examples of Turbidite Facies Associations from Selected Formations of Northern Apennines. Nineth International Congress International Association of Sedimentologists, Nice, France, Field Trip A 11, p. 21-36.

Mutti, E. and Sonnino, M., 1981. Compensation cycles: A diagnostic feature of turbidite sandstone lobes. International Association of Sedimentologists, 2nd European Regional

Meeting, Bologna, Italy, p. 120-123.

Normark, W.R., 1970. Growth patterns of deep-sea fans. American Association of Petroleum Geologists Bulletin, v. 54, p. 2170-2195.

Normark, W.R., 1978. Fan valleys, channels, and depositional lobes on modern submarine fans: Characters for recognition of sandy turbidite environments. American Association of Petroleum Geologists Bulletin, v. 62, p. 912-931.

Normark, W.R., Barnes, N.E., and Bouma, A.H., 1985. Comments and new directions for deep-sea fan research. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p. 341-343.

Normark, W.R. and Hess, G.R., 1980. Quaternary growth patterns of California submarine fans. In: Field, M.E., Bouma, A.H., Colburn, I., Douglas, R.G., and Ingle, J.C. (Eds.), Proceedings of the Quaternary Depositional Environments of the Pacific Coast: SEPM Pacific Section, Pacific Coast Paleogeography Symposium, part 4, Los Angles, p. 201-210.

Normark, W.R., Hess, G.R., Stow, D.A.V., and Bowen, A.J., 1980. Sediment waves on the Monterey fan valley: A preliminary physical interpretation. Marine Geology, v. 37, p. 1-18.

Normark, W.R. and Piper, D.J.W., 1969. Deep-sea fan-valleys, Past and present. Geological Society of America Bulletin, v. 80, p. 1859-1866.

Normark, W.R., Piper, D.J.W., and Hess, G.R., 1979. Distributary channels, sand lobes, and mesotopography of Navy Submarine Fan, California Borderland, with applications to ancient fan systems. Sedimentology, v. 26, p. 749-774.

Nummedal, D. and Remy, R. (Eds.), 1989. Cretaceous Shelf Sandstones and Shelf Depositional Sequences, Western Interior Basin, Utah, Colorado and New Mexico. 28th International Geological Congress Field Trip Guidebook T 119. Washington, D.C., American Geophysical Union, 87 p.

Payton, C.E. (Ed.), 1977. Seismic Stratigraphy-Applications to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 26, 516 p.

Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Ricci Lucchi, F., and Smith, R.D.A. (Eds.), 1995. Atlas of Deep Water Environments, Architectural Style in Turbidite Systems. Chapman & Hall, London, 333 p.

Posamentier, H.W. and Mutti, E. (Convenors), 1994. Second High-Resolution Sequence Stratigraphy Conference. International Union of Geological Sciences and Global

Sedimentary Geology Program, 221 p.

Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allen, G.P. (Eds.), 1993. Sequence Stratigraphy and Facies Associations. International Association of Sedimentologists Special Publication 18, 644 p.

Postma, G., 1986. Classification of sediment gravity flows based on flow conditions during sedimentation. Geology, v.14, p. 291-294.

Postma, G., Nemec, W., and Kleinspehn, K., 1988. Large floating clasts in turbidites: a mechanism for their emplacement. Sedimentary Geology, v. 58, p. 47-61.

Reading, H.G. and Richards, M., 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. American Association Petroleum Geologists Bulletin, v. 78, p. 792-822.

Shanmugam, G. and Moiola, R.F., 1994. An unconventional model for the sandstones of the Jackfork Group (Pennsylvanian), Ouachita Mountains, Arkansas and Oklahoma. In: Weimer, P., Bouma, A.H., and Perkins, B.F. (Eds.), Submarine Fans and Turbidite Systems: Sequence Stratigraphy, Reservoir Architecture, and Production Characteristics, Gulf of Mexico and International. Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation 15th Annual Research Conference, p. 311-326.

Shanmugam, G. and Moiola, R.F., 1995. Reinterpretation of depositional processes in a classic flysch sequence (Pennsylvanian Jackfork Group), Ouachita Mountains, Arkansas and Oklahoma. American Association of Petroleum Geologists Bulletin, v. 79, p. 672-695.

Shepard, F.P. and Dill, R.F., 1966. Submarine Canyons and Other Sea Valleys. Rand McNally & Co., Chicago, 381 p.

Sloss, L.L., 1988. Forty years of sequence stratigraphy. Geological Society of America, v. 100, p. 1661-1665.

Sloss, L.L., 1991. The tectonic factor in sea level change: a countervailing view. Journal of Geophysical Research, v. 96, p. 6609-6617.

Sloss, L.L., Krumbein, W.C., and Dapples, E.C., 1949. Integrated facies analysis. In: Longwell, C.R. (Ed.), Sedimentary Facies in Geologic History. Geological Society of America Memoir 39, p. 91-124.

Stelting, C.E. and DSDP Leg 96 Shipboard Scientists, 1985. Migratory characteristics of a mid-fan meander belt, Mississippi Fan. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p.

283-290.

Stone, C.G. and Haley, B.R., 1986. Sedimentary and Igneous Rocks of the Ouachita Mountains of Arkansas. Arkansas Geological Commission Guidebook 863, 100 p.

Stow, D.A.V., 1985. Deep-sea clastics: where are we and where are we going. In: Brenchley, P.J. and Williams, B.J.P. (Eds.), Sedimentology: Recent Developments and Applied Aspects. Geological Society of London Special Publication 18, p. 67-93.

Stow, D.A.V., Howell, D.G., and Nelson, C.H., 1985. Sedimentary, tectonic, and sea-level controls. In: Bouma, A.H., Normark, W.R., and Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, p. 15-22.

Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy. Part I: Seismic stratigraphy interpretation procedure. In: Bally, A.W. (Ed.), Atlas of Seismic Stratigraphy. American Association of Petroleum Geologists Studies in Geology No. 27, p. 1-10.

Vail, P.R., Mitchum, R.M., and Thompson, S., III, 1977. Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy-Application to Hydrocarbon Exploration. American Association of Petroleum Geologists Memoir 26, p. 83-97.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies. American Association of Petroleum Geologists Methods in Exploration Series No. 7, 55 p.

Walker, R.G., 1978. Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. American Association of Petroleum Geologists Bulletin, v. 62, p. 932-966.

Walker, R.G. and Mutti, E., 1973. Turbidite facies and facies associations. In: Middleton, G.V. and Bouma, A.H. (Eds.), Turbidites and Deep-Water Sedimentation. Pacific Section SEPM Short Course Notes, Anaheim, California, p. 119-157.

Weimer, P., 1989. Sequence stratigraphy of the Mississippi Fan (Plio-Pleistocene), Gulf of Mexico. Geo-Marine Letters, v. 9, p. 185-272.

Weimer, P., 1991. Seismic facies and depositional variations in channel evolution, Mississippi Fan (Plio-Pleistocene), deep Gulf of Mexico. In: Weimer, P. and Link, M.H. (Eds.), Seismic Facies and Sedimentary Processes of Modern and Ancient Submarine Fans. Springer-Verlag, New York, p. 323-347.

Synthetic Seismic Modeling of a Fine-Grained Submarine Fan Complex, Tanqua Karoo, South Africa

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Introduction

One of the limitations of seismic studies is vertical resolution. Terrigenous clastic sequences less than 15 m thick can be laterally extensive for many kilometers but undetectable on seismic profiles. A submarine fan complex of the Permian Skoorsteenberg Formation in the southwestern Karoo was used to examine the consequences of underestimating the extent of submarine fans on seismic sections. The fan complex crops out over 640 km^2 and consists of five submarine fans separated by basin shales (Bouma and Wickens, 1991, 1994).

The objective of this study is to illustrate the seismic response of the thin individual fans, belonging to the Tanqua submarine fan complex, to a high-frequency (40 Hz) wavelet signal. A profile running approximately N-S along the western edge of the outcrop area was used for performing seismic modeling of the fans (Fig. 1). The ultimate goal is to evaluate the lower limits of vertical seismic resolution through modeling of turbidite sequences. The twenty-six vertical stratigraphic sections, from which the synthetic seismic models are derived, come from Scott (1993).

Techniques

Stratigraphic variations can be detected by reflection seismic data acquisition when there is a relatively high acoustic impedance contrast across a lithologic boundary. Synthetic seismograms can be created to provide the link between the depth horizons of stratigraphic sections and the time reflectors of geophysical data. The seismic character (i.e. amplitude, frequency and continuity of reflections) depicts the changes in the internal reflection characteristics of the rock strata with these parameters, depending on the boundary contrast in density and compressional wave velocity across individual layers (Cant, 1992).

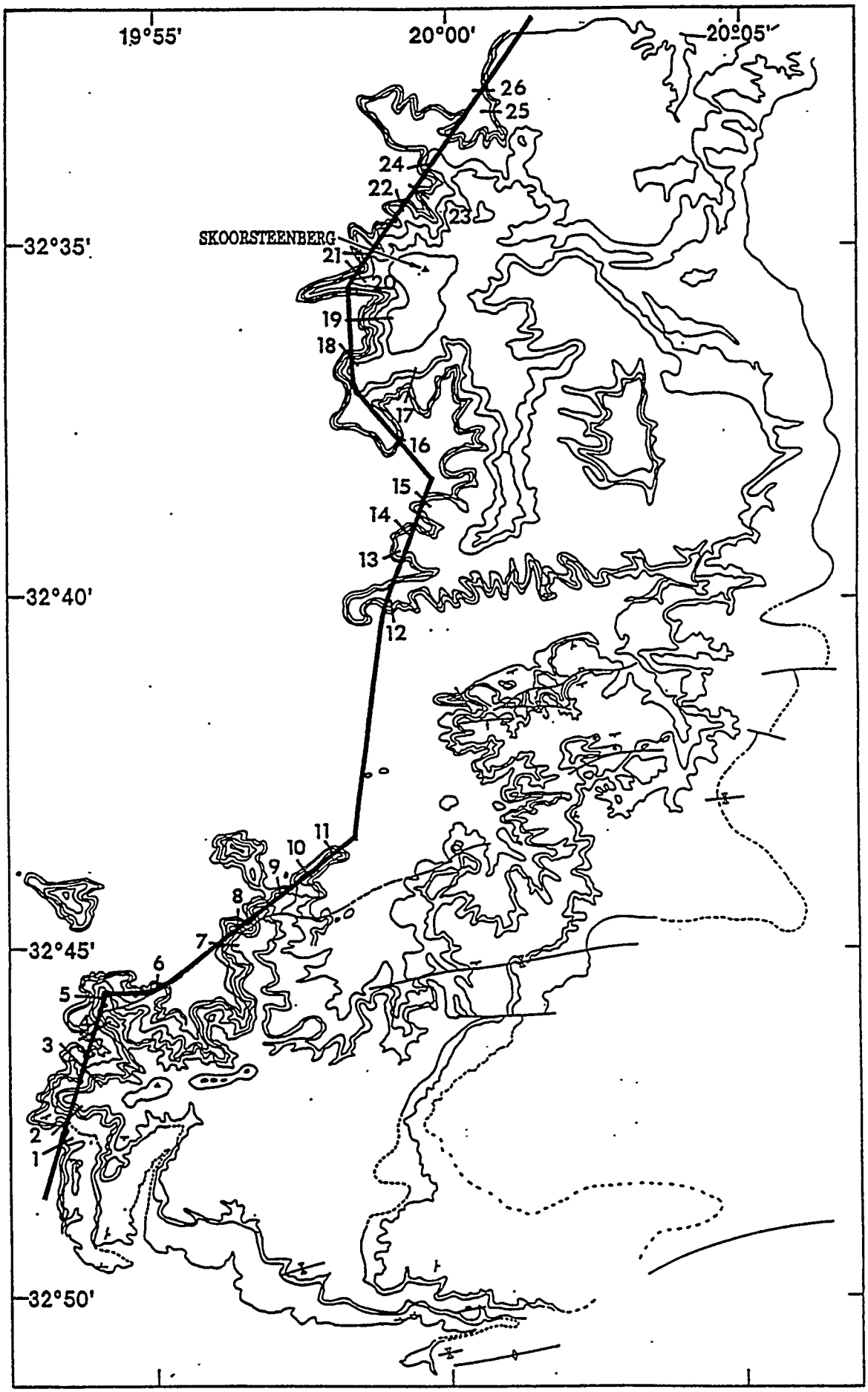

Figure 1. Outcrop map of the Tanqua Submarine Fan complex. Wavy line indicates the location of the profile shown in Figure 2. Numbers along this line reveal the locations of the measured vertical sections.

The impedance values used in the modeling are calculated using tabulated values (Telford et al., 1994, Table 2.2). Average densities of 2.35 g/cm^3 for sandstone and 2.40 g/cm^3 for shale are used, and seismic velocities are extrapolated (Telford et al., 1994, p.160) using the above assumed density values. Compressional wave velocities of 4 km/s and 3.45 km/s were used to model sandstone and shale layers, respectively. A Ricker wavelet was used.

Synthetic seismograms were obtained by applying a one-dimensional filter approach (Peterson et al., 1955), assuming that the returning reflected wavelet has the same shape as the incident wavelet. Therefore, the seismogram records the succession of acoustic impedance discontinuities. The reflection coefficient was calculated for each model layer interface as a function of two-way travel time (Lorenzo and Hesselbo, 1996). The reflection coefficients measure the returning reflected wave relative to the original incident wave.

The reflectivity coefficient changes versus depth were calculated for every 1 m interval and then converted to coefficient series values versus time. Thus, stratigraphic (depth) picks were correlated to the synthetic seismic (time) picks. The synthesized wavelet shows a positive (white) pick at the shale/sandstone interface and a negative (black) pick at the sandstone/shale interface.

Reflecting interfaces in many turbidite facies are often more closely spaced than the seismic wavelength, and therefore the obtained waveshape represents a composite of several reflection interfaces. The capability of identifying separate reflection events determines the practical vertical resolution of the seismic model. The construction of several seismograms from various sandstone layers with thicknesses ranging from 1 to 100 m leads to the conclusion of a 7-10 m tuning thickness being ideal for proper bed recognition. Below these thickness values the base of any bed can not be resolved and the seismic response reflects the average of more than one layer.

Procedure

Synthetic seismograms of the Tanqua submarine fan complex were made using a 40 Hz Ricker wavelet and a 1 ms sampling rate. Since most stratigraphic sections consist of alternating layers of sandstone and shale, sections with sandstones at their top and base are assumed to be bordered by shale units. For example, a three layer section of sandstone-shale-sandstone is represented by four interface boundaries (shale-sandstone, sandstone-shale, shale-sandstone, and sandstone-shale). Vertical sections 9, 18 and 23 differ from the rest by having shale at their top (Fig. 2). In these instances, a sandstone horizon capping the shale is assumed when modeling the sections.

Final synthetic seismograms for each measured vertical stratigraphic section and their correlated picks are shown to true horizontal scale in Figure 2. The seismic response of "sandstone 3" (Fan 3), a representative submarine fan of the Tanqua Complex, is portrayed separately on the same plate in order to emphasize the vertical resolution changes within the fan distribution.

Results

Only one of the fan units, "sandstone 4" (Fan 4), can be completely resolved with the synthetic seismograms as its thickness varies from 12 to 59 m (Table 1). These thickness values fall within the estimated tuning limit of 7-10 m. The remaining four submarine fans are only partially resolved. For example, the base of "sandstone 1" (Fan 1) becomes difficult to recognize in the vertical section 3 where the fan thickness decreases to 7 m, the predicted limit. The base of Fan 2 (sandstone 2) can not be resolved in vertical sections 10 and 11, where the unit has a thickness of 3 and 2.5 m, respectively. Similarly, the base of Fan 3 becomes difficult to distinguish when the unit's thickness dropped below 5-6 m (vertical sections 22, 25, and 26). In these cases, each synthetic seismogram represents a composite of the two interfaces which correspond to the top and base of the individual unit.

Conclusions

The practical vertical resolution of the turbidite sequences is 5-7 m when using 40 Hz wavelet and a 1 ms sampling rate. Below this limit the base of any fan cannot be resolved. Thus, this study reveals the limitation of the seismic modeling when detecting the lateral extent of turbidite sequences on seismic sections. As shown in Figure 2, Fan 2 extends for 2 km and Fans 1 and 3 each continue for approximately 4 km after they become unrecognizable on the synthetic seismogram panel. However, the lateral sand/shale ratio variations associated with the architectural changes within a submarine fan should always be accounted for. These variations may alter the seismogram behavior of the fan in dip direction. Therefore, seismic data should be applied with caution when estimating the lateral extent of turbidite facies.

The Tanqua Karoo example may not be an exceptional example, as most of the individual submarine fans are rather thin. Nonetheless, it can be expected that many basins have thin submarine fans sandwiched between thicker ones. Hence, careful analysis of lateral changes in seismic response may lead to recognizing some of those, especially when a set of well logs is available.

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Tanqua Fan	Stratigraphic section thicknesses /m/																								
Sequences	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
SS 5	13						4	26		15																
SH 4/5	65						89	74	66	24																
SS 4	50	45	49		45	46	45	59	59	47	35	34	33	26	30				25	22		12	28	25	18	
SH 3/4	22	11	16	16	18	18		20	22.5	22	20	20	22	22	18				33	21		36	25	35	48	
SS 3	2.5	3	6	10	5	5		8	12.5	23	21	21	23	24	32	32	20		43	65		31	36	44	38	
SH 2/3																52	70	61	60	90		71	52	44	58	
SS 2																2.5	3	13	20	12	15	31	17	24	20	13
SH 1/2																				20	15	18	23	18	24	16
SS 1																					6	4	6	7	14	8
Total /m/	153	59	71	26	68	69	138	187	160	131	76	75	78	72	80	86.5	93	74	181	230	36	203	187	197	220	37

Table 1. Thickness variations of the sandstone-dominated portions of the submarine fans ("SS") and the shale series ("SH") between the fan sequences. Each shale series is comprised of a basin shale unit together with the thin-bedded sandy shales that belong to a submarine fan sequence. Numbers 1 through 5 following "SS" indicate the corresponding fan numbering within the Tanqua complex from the lower to the upper one. The shale series between the fans are shown as ratios (e.g. "SH 1/2" means the shale series between fans 1 and 2).

References

Bouma, A.H., and Wickens, H. De V., 1991, Permian passive margin submarine fan complex, Karoo Basin, South Africa: possible model to Gulf of Mexico: Gulf Coast Assoc. Geol. Scientists Transactions, v. 41, p. 30-42.

Bouma, A.H., and Wickens, H. De V., 1994, Tanqua Karoo, Ancient analog for fine-grained submarine fans: GCSSEPM Foundation 15th Annual Research Conference: Submarine Fans and Turbidite Systems, Dec. 4-7, 1994, p. 23-34.

Cant, D.J., 1992, Subsurface facies analysis: *in* Walker, R.G., and James, N.P., eds, Facies Models: Response to Sea Level Change: Geological Association of Canada, p. 27-45.

Lorenzo, J.M., and Hesselbo, S.P., 1996, Seismic-to-well correlation at Ocean Drilling Project Leg 150 Continental slope sites: Proceedings of the ODP, Scientific Results, Leg 150, in press.

Peterson, R.A., Fillipone, W.R., and Coker, F.B., 1955, The synthesis of seismograms from well log data: Geophysics, v. 20, p. 516-538.

Scott, E.D., 1993, Lateral variations in the Tanqua submarine fan complex along a "seismic scale" profile: Tanqua Karoo: Fluvially-dominated, shale-rich submarine fan complex: Geo-Marine Consultants, Inc., v. I, p. 15.1-15.6.

Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1994, Applied Geophysics: Cambridge University Press, 2nd ed., 770 p.