Clinoform stacking patterns, shelf-edge trajectories and facies associations in Tertiary coastal deltas, offshore Norway: Implications for the prediction of lithology in prograding systems

Scott Bullimore, Sverre Henriksen, Frode M. Liestøl & William Helland-Hansen

Bullimore, S., Henriksen, S., Liestøl, F. M., & Helland-Hansen, W.: Clinoform stacking patterns, shelf-edge trajectories and facies associations in Tertiary coastal deltas, offshore Norway: Implications for the prediction of lithology in prograding systems. *Norwegian Journal of Geology*, Vol. 85, pp. 169-187. Trondheim 2005. ISSN 029-196X.

Regional uplift of Scandinavia in the Late Cenozoic resulted in widespread deltaic shelf progradation on the mid-Norwegian continental shelf. This deltaic complex, called the Molo Formation, is readily recognised on seismic cross-sections by a series of high angle, westward prograding clinoforms. High quality three-dimensional seismic data allow for the detailed mapping of parts of this deltaic-complex. Recent advances in the field of three-dimensional seismic imaging have led to an increased ability to interpret depositional sedimentary environments from seismic attribute maps and time-slices. Seismic interpretation combined with seismic attribute mapping of selected clinoforms has allowed for the identification of a variety of depositional environments along the depositional profile.
The shelf-edge trajectory concept is used in conjunction with high quality three-dimensional seismic data to determine the existence of a relationship between varying rates and directions of shelf-edge progradation, depositional environments encountered in the coastal-plain/shelf environment, and the character and geometry of slope/basin-floor deposits. Steep-positive shelf-edge trajectories, indicating an increased rate of aggradation, appear to be associated with barrier/lagoonal deposits in the lower coastal plain. Flat-negative (forced regressive) shelf-edge trajectories are associated with topset truncation and slumping at the shelf-edge. Strongly negative (forced regressive) shelf-edge trajectories are associated with bypass of the shelf and slope, and the deposition of basin-floor fan deposits. Low angle-positive shelf-edge trajectories are associated with the preservation of fluvial depositional systems with meandering channel-belt geometries behind the shelf-break and the deposition of lobate deltas at the shelf-edge.

Scott Bullimore, Frode M. Liestøl, William Helland-Hansen, University of Bergen, Department of Earth Science, Allegt 41, NO-5007 Bergen, Norway; Sverre Henriksen, Statoil Research Center, Rotvoll, NO-7005 Trondheim, Norway; Scott Bullimore present address, Statoil, Exploration and Production, NO-5020, Bergen, Norway; Frode M. Liestøl present address, Norsk Hydro, Exploration and Production, NO-5020, Bergen, Norway.

Introduction

This investigation focuses upon the Late Tertiary Molo Formation, a sedimentary prism that prograded at least 25 kilometres into the Norwegian Sea from the easterly Norwegian mainland (Figs. 1 & 2). The Molo Formation (Fig. 2) consists of a coarse-grained (Eidvin et al. 1998), steeply dipping clinoform package attributed to deposition during the progradation of a deltaic complex (Henriksen & Vorren 1996; Henriksen & Weimer 1996). The deltaic deposits occur offshore mid Norway where they may be followed laterally for a distance of approximately 600 km (Fig. 1). The age of these deposits has been disputed; both Oligocene and Early Pliocene ages have been suggested by Eidvin et al. (1998) and Henriksen & Vorren (1996), respectively. The chronostratigraphy in the area is currently under review (T. Eidvin, pers. comm. 2004).

The data analysed in this study constitute part of a commercial, three-dimensional (3-D) seismic survey covering an area of 1190 km^2 (Fig. 3). The seismic survey is positioned between 66°43'N-67°19'N and 10°10'E-11°15'E offshore of western Norway, more specifically on the edge of the Trøndelag Platform, between the Træna sub-basin and the Vestfjorden Basin (Fig. 1). Within the area of investigation, water depth varies between 250 metres and 450 metres. An average seismic velocity of 2200 metres/second is applied to the delta-complex and vertical seismic resolution is calculated to be approximately 15 metres. Apparent truncation, thinning and merging of seismic horizons and intervals may thus be an effect of limited seismic resolution. This is taken into consideration in the subsequent interpretations and models.

Large scale faulting in the area, now defined as the Trøndelag Platform, largely came to an end after rifting in Late Jurassic- Early Cretaceous time (Blystad et al. 1995). The adjacent Vestfjorden Basin (Rønnevik & Navrestad 1977; Jørgensen & Navrestad 1979, 1981) is an asymmetric, fault-bounded basin that formed in response to the same tectonic movements (Blystad et al. 1995).

The Late Jurassic - Early Cretaceous (Cimmerian

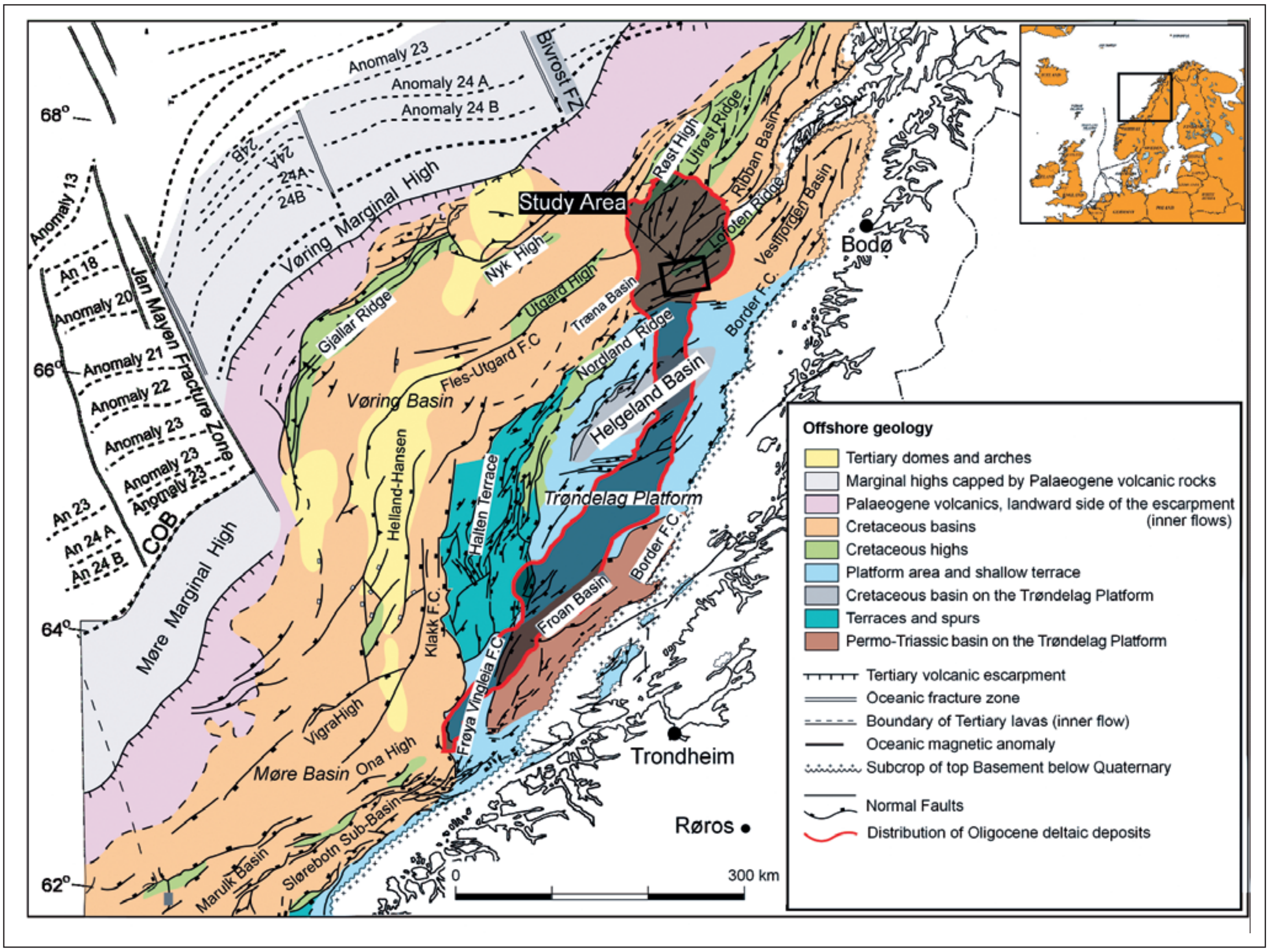


Fig. 1. Location of the study area within the Norwegian Sea (Modified from Mosar et al. 2002).

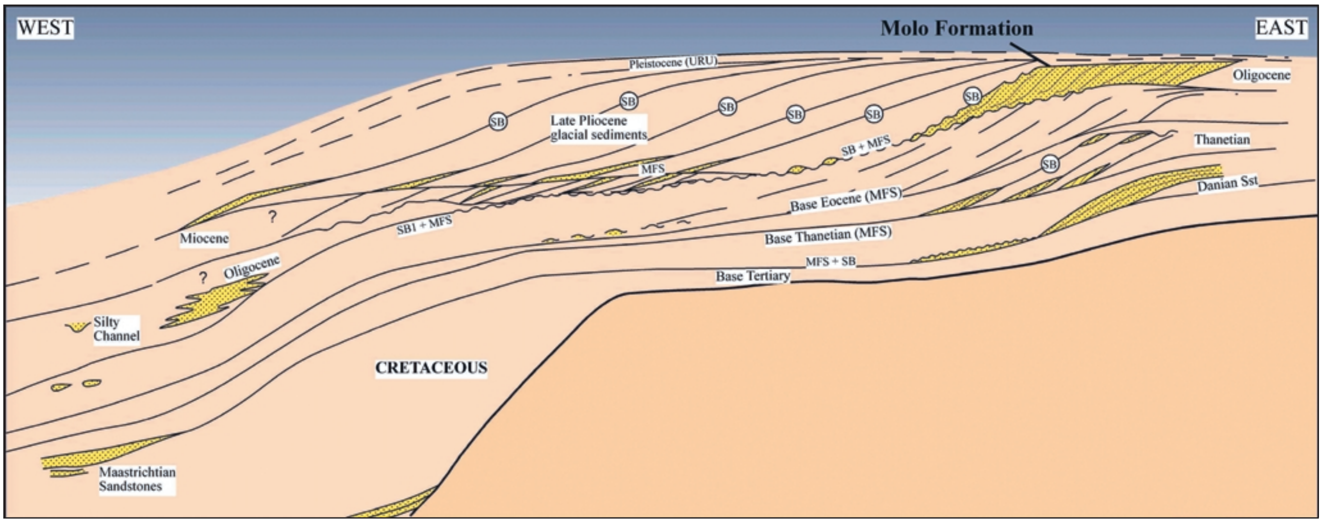


Fig. 2. Schematic diagram of the Tertiary stratigraphy of the Norwegian Sea area (From Henriksen et al. 2002).

rifting pulse) resulted in significant subsidence in the Møre and Vøring Basins (shown in Fig. 1) and the Halten Terrace area on the mid-Norwegian shelf (e.g. Dorè et al. 1999; Brekke 2000). Subsequent rifting during the Late Mesozoic/Early Cenozoic led to continental break up and the formation of oceanic crust (e.g. Talwani & Eldholm 1977; Dorè et al. 1999; Brekke 2000).

While rifting occurred in the west during the Early Tertiary, differential uplift and erosion are reported

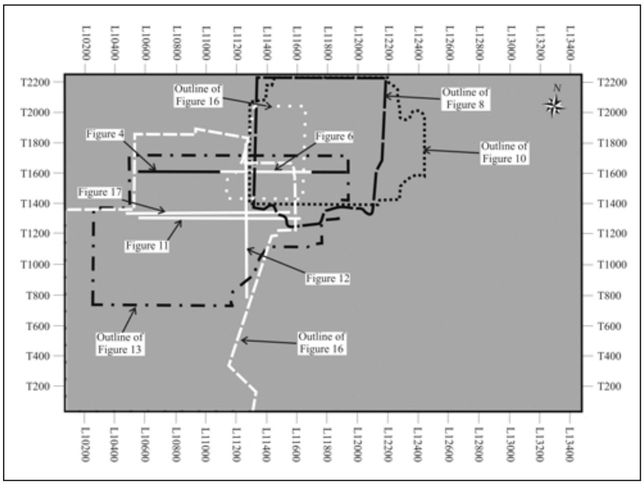
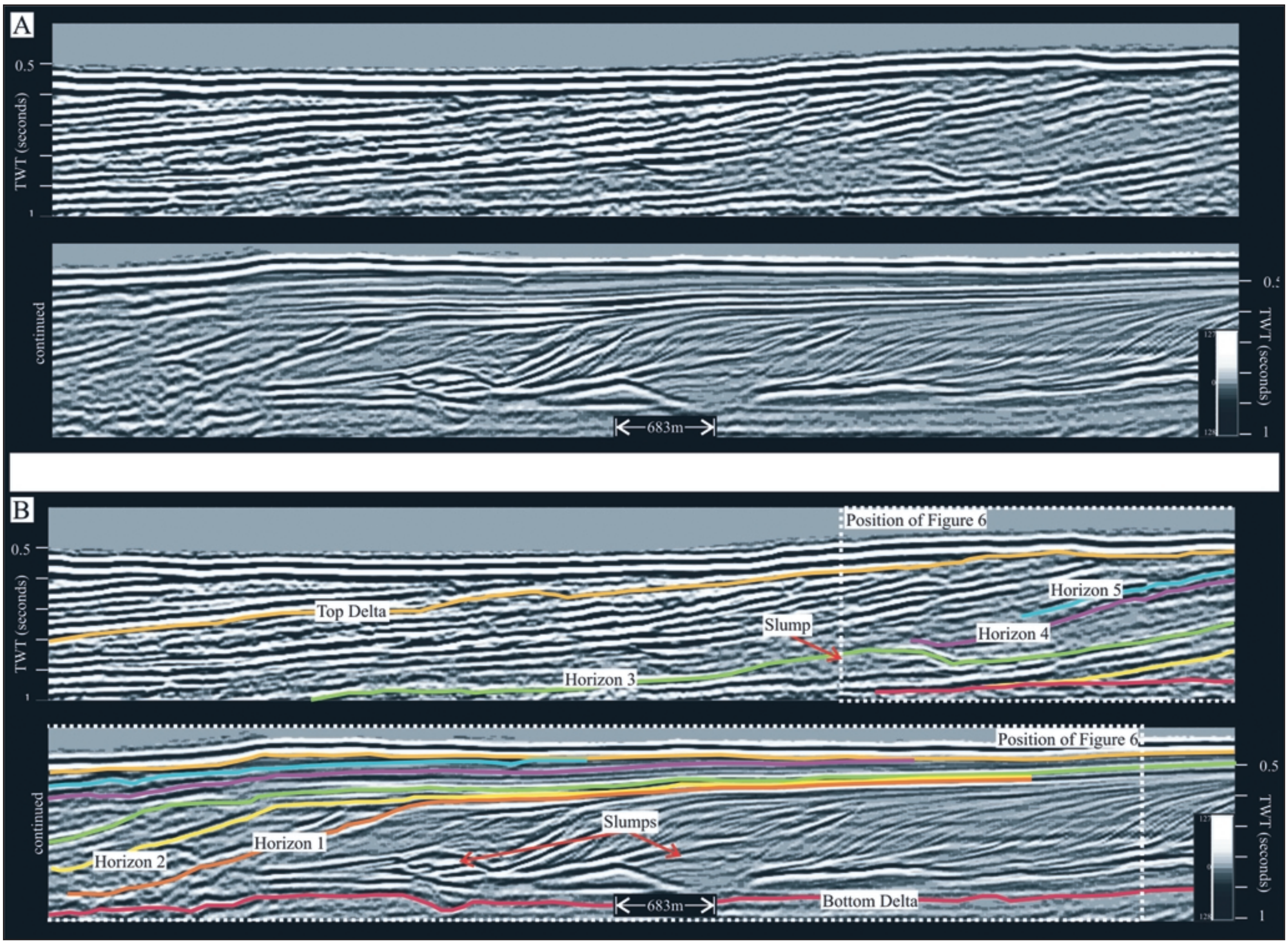


Fig. 3. *Position of seismic attribute maps and cross-sections within the 3-D seismic survey.*

Fig. 4. *Dip orientated cross-section showing the progradational nature of the delta-complex.*
4A: Without interpretation.
4B: With interpretation. See Figure 1 for location.



from the Fennoscandian mainland to the east (Torske 1972; Riis & Fjeldskaar 1992; Brekke et al. 2001), and from structurally high areas in the Lofoten and Vøring Basins (e.g. Skogseid et al. 1992; Hjelstuen et al. 1999; Brekke et al. 2001). Following continental break up at 53 Ma (e.g. Skogseid et al. 1992) the mid-Norwegian shelf experienced two periods of intermittent uplift in the Palaeogene and the Neogene (e.g. Riis 1996; Mogensen et al. 2000; Japsen & Chalmers 2000).

Clinoform or shelf-slope systems such as the ones investigated in this study (Fig. 4) are capable of developing in a wide range of depositional settings (Swift & Thorne 1991). However, well data (cuttings, sidewall cores) available from equivalent deposits outside the study area, indicate that these units were deposited in a sandy coastal environment (e.g. Eidvin et al. 1998), probably a wave-dominated deltaic setting (Rokoengen et al. 1995). Palynological evidence suggests that underlying units were deposited in an open shelf environment

(Poole & Vorren 1993), while overlying Upper Pliocene sediments are of glaciogenic origin (Riis & Fjeldskaar 1992; Henriksen & Vorren 1996; Ottesen et al. 2001).

Traditional sequence stratigraphic analysis of a given interval of the rock record involves the allocation of stratigraphic units to various types of regressive or transgressive systems tracts in order to form predictive models. The shoreface and shelf-edge trajectory concepts (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1996; Mellere et al. 2002; Steel & Olsen 2002) allow traditional systems tracts to be viewed as part of a more continuous spectrum. Studies of trajectory trends and the systematic occurrence of various facies associations within a stratigraphic succession hold the potential for defining a simplified and more accurate method for prediction of lithologies.

This methodology is here applied to 3-D seismic data in order to obtain an improved understanding of the relationship between specific depositional environments and the progradational, aggradational or transgressive nature of a given depositional system.

This study has a threefold purpose. Firstly, to use detailed seismic interpretation to resolve sequence stacking patterns and identify different shelf-edge trajectory scenarios. Secondly, to generate seismic attribute maps from shelf, shelf-edge/slope, and basin settings that enable the interpretation of depositional environments in these respective settings. Thirdly, to couple these attribute maps and the shelf-edge trajectory concept to investigate the dynamic nature of the depositional system and determine the presence and nature of a relationship between differing shelf-edge trajectories and depositional environments along the depositional profile.

Shelf-edge trajectory concept

Given sufficient sediment supply and water depths, the basinward progradation of coastal prisms and clastic wedges results in deposition of clinoforms (Fig. 5) on either an individual delta/shoreface scale (tens of metres), or on a shelf margin scale (hundreds of metres) (Pirmez et al. 1998; Steel & Olsen 2002). In a depositional, dip-orientated profile, the successive positions of the shoreline along delta and shoreface-scale clinoforms, in a stratigraphic succession allow identification of the shoreline trajectory (Fig. 5) (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1996). This concept permits the stratigraphic record to be divided into several systems tracts (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1996). With larger, shelf margin-scale clinoforms the migration of the shelf-slope break (Steel & Olsen 2002), alternatively termed the offlap break (Vail et al. 1991) and the shelf-edge/shelf margin (Vail & Todd 1981; Vail et al. 1984), may be used to determine a trajectory which becomes evident when the successive position of this "point" is viewed in a dip-orientated profile (Fig. 5a-d). This trajectory is termed either the shelf-edge trajectory (Mellere et al. 2002), or the clinoform trajectory (Steel & Olsen 2002). Progradational (both forced regressive and normal regressive), aggradational, and retrogradational shelf-edge trajectories have previously been recognised (Steel el al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002; Plink-Björklund & Steel 2002; Steel & Olsen 2002).

While the shoreline trajectory is determined by the interplay between sediment supply, 4th and 5th order relative sea-level changes, and basin physiography (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1996), the shelf-edge trajectory is influenced by 3rd-order changes of relative sea-level and sediment supply rates (R. Steel pers. comm. 2002). Shelf transit times (Burgess & Hovius 1998; Muto & Steel 2002) influence the supply of sediment to the edge of the shelf, and therefore also affect the shelf-edge trajectory (Porobski & Steel 2003). Outcrop investigations (Steel el al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002; Plink-Björklund & Steel 2002; Steel & Olsen 2002) suggested that flat/negative shelf-edge trajectories are associated with more fluvially dominated depositional systems and that aggradational (positive) shelf-edge trajectories are associated with wave-dominated processes.

Methods

Seismic data analysis has played an important role in the development of sequence stratigraphic principles since early sequence-stratigraphic studies were published by workers at the Exxon Research Center (e.g. Vail & Mitchum 1977; Mitchum et al. 1977a,b). More recently, the development of 3-D seismic data has enhanced the ability of geoscientists to image the stratigraphic record within specified time intervals (seismic time-slice) or along chosen horizons (using seismic attribute maps). Although the potential use of seismic images for the interpretation of depositional environments has been recognised for some time (e.g. Brown 1985, 1991), programming limitations regarding seismic resolution and processing time, have inhibited the use of these images for such purposes. However, recent advances in program technology have now made it possible to use seismic time-slice and attribute map images to infer depositional architecture and environments for given data sets (e.g. Weimer & Davis 1996; Miall 2002; Posamentier 2002).

In this study, the generation of attribute maps relies upon the calculation of amplitude values for a given seismic

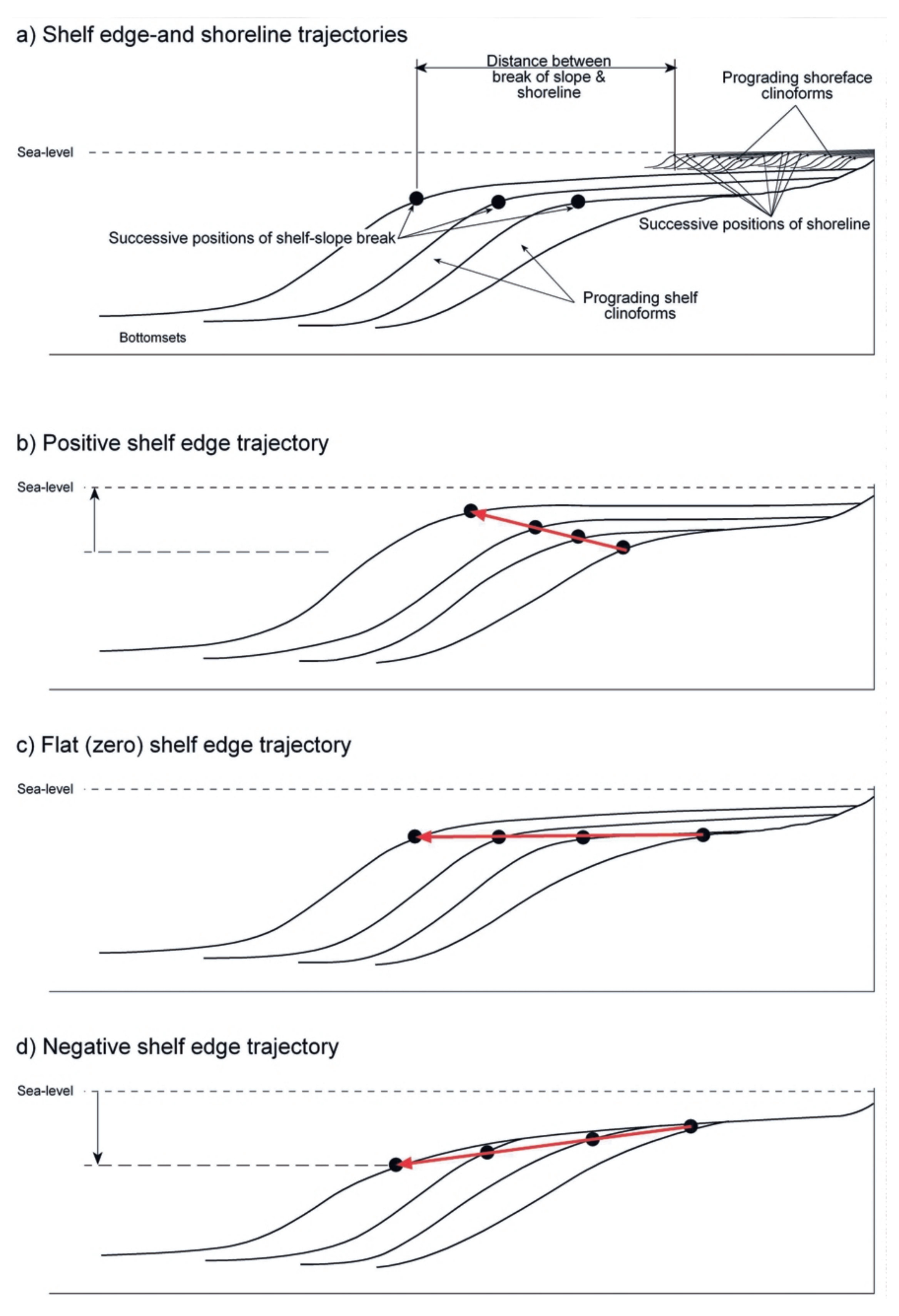


Fig. 5. Schematic diagram showing the different scaled prograding shoreface and prograding shelf clinoforms. Note that the successive positions of the shoreline allows for the identification of a shoreline trajectory, which, in this example, shows both forced regressive and normal regressive trends. The shelf-edge trajectory is determined by the successive positions of the migrating shelf-slope break and may exhibit a) a very-low angle positive trend; b) high angle positive trend; c) flat and d) negative (high /low angle) trend (modified from Steel & Olsen 2002).

interval around a pre-determined seismic horizon. The advantage of this methodology, as opposed to using amplitude maps generated from single trough or peak reflectors, is that it allows for the analysis of seismic energy from an interval rather than from just one seismic event. The seismic intervals chosen for the studied horizons vary, as each interval is calculated specifically to give the best possible attribute image of features observed along each horizon.

The identification of shelf-edge trajectories within the study area involves examining cross-sections orientated parallel to the depositional-dip direction of the deltaic-complex. A line drawn through each break-in-slope of successive clinoforms will determine the subsequent position of the shelf-edge break and indicate the angle of the shelf-edge trajectory.

Core data or coastal outcrop data have not been available to substantiate the depositional environments interpreted from the seismic data in the study area. However, well data (cuttings, sidewall cores) are available from the Molo Formation in wells located outside the study area and are used to infer a general deltaic depositional setting (Rokoengen et al. 1995; Eidvin et al. 1998). The same core data enable the age of these units to be estimated. The primary methodology used in this investigation involves the recognition of geologically significant features (e.g. clinoforms, channels) along seismic profiles and the mapping of these features with the aid of seismic attribute maps. Specifically, depositional environments are interpreted and recorded from geometries observed within attribute maps and associated seismic sections. A relationship between shelf-edge trajectories and depositional settings may then be proposed by comparing the position of the depositional environments along the depositional profile under varying shelf-edge trajectory conditions.

On black and white seismic cross-sections (Figs. 4, 6, 11, 12 and 17), a grey colour scale is used where different shades of grey represent different amplitudes, lithologies and degrees of compaction. In these seismic sections, darker shades (e.g. black) are generally associated with a soft seismic response (typically more shale-rich lithologies) and lighter shades with a hard seismic response (typically more sand-rich lithologies). On coloured attribute maps (Figs. 7, 8, 9, 10, 13, 14, 15 and 16) a red-white-black colour scale is applied, where darker colours reflect a soft (shale-rich) seismic response and white to red colours reflect progressively harder (more sand-rich) seismic responses.

Sequence stacking patterns and shelf-edge trajectories

In the studied seismic data set it is possible to identify four different classes of shelf-edge trajectory trends. Note that although the terms high-angle and low angle negative shelf-edge trajectory are used below, these are

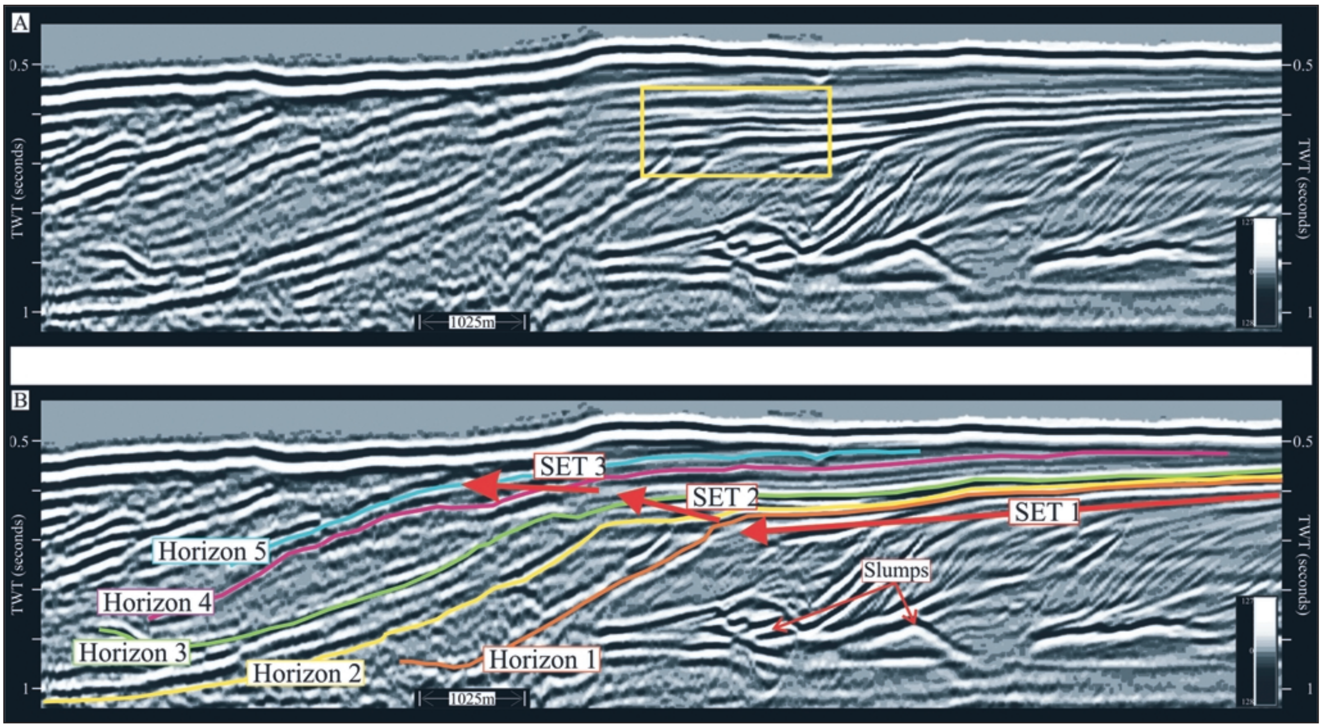


Fig. 6. Enlarged image of delta-complex showing interpreted seismic horizons (Horizons 1 to 5) and low angle negative (SET 1), high angle positive (SET 2), and low angle positive (SET 3) shelf-edge trajectory trends. Rectangle in Figure 6A shows the position of preserved topsets associated with SET 1. Vertical exaggeration is 400 times. (See Figure 3 for location).

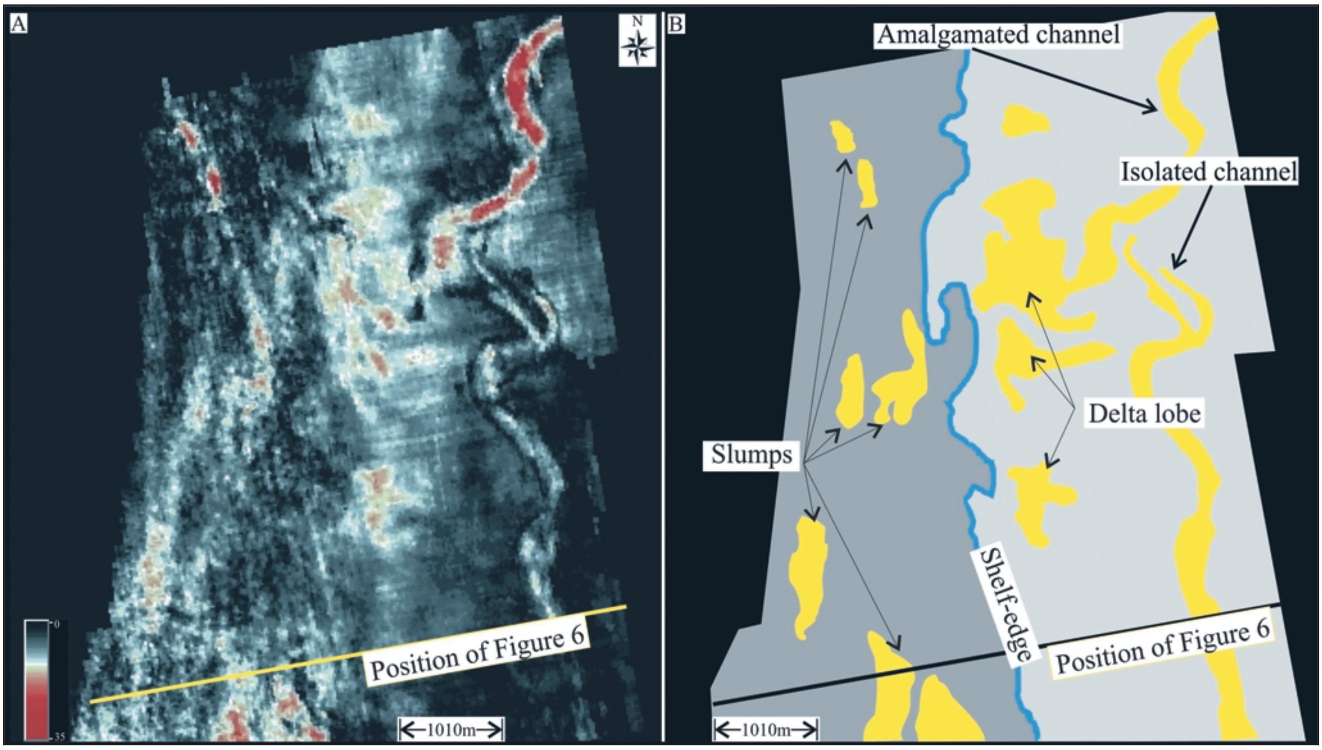


Fig. 7. Attribute map of channel geometries associated with the low angle positive shelf-edge trajectory. 7A: Attribute map generated from seismic Horizon 5 (window 4ms up and 3ms down from the horizon). 7B: Interpretation of 6A showing amalgamated and isolated channels and high amplitude delta deposits at the shelf-edge. See Figure 3 for location.

relative terms. The angles of both trajectory trends are relatively low. Further analysis of clinoform topsets, foresets and bottomsets related to each of these shelf-edge trajectory trends indicates that there is a distinct relationship between shelf-edge trajectories and depositional environment

Low angle positive shelf-edge trajectory

The low angle positive shelf-edge trajectory (Set 3, Fig. 6) is typified by a package of clinoforms that are strongly progradational and where each successive break of clinoform slope is positioned slightly above and more basinward than the previous one. This shelf-edge trajectory is interpreted to represent progradation during rising relative sea-level where deltaic units are deposited and preserved in the topset area. The ratio of accommodation space to sediment supply (A:S ratio) in the topset area is relatively low, although still larger than 1. In the study area, it is possible to interpret two seismic horizons in topset areas that are associated with low angle positive shelf-edge trajectories (horizons 4 and 5, Fig. 6).

An attribute map generated from Horizon 5 reveals the presence of high amplitude features on the slope and in topset areas (Fig. 7A). The basinward interpretation of this horizon and imaging of basin-floor areas is hampered by poor data quality. High amplitude, sinuous reflectors seen on the shelf in Figure 7A are interpreted to represent either isolated or amalgamated channel-belt sandstones (Fig. 7B). These channels are orientated northeast-southwest and north-south (approximately parallel with the shelf-edge). Further south, Horizon 5 is truncated by a Quaternary erosion surface. The orientation of these channel deposits suggests a more prominent north or northeast sediment source area and a southern depocentre that has been removed by later erosion. However, in Figure 7A, one channel appears to terminate at one of several high amplitude lobate features situated at the shelf-edge. Low amplitude (presumed muddy) deposits are observed on the slope (seaward of the shelf break) and surrounding channels in topset areas.

The overall clinoform geometry for this interval precludes a deep-water origin for these channels and suggests a fluvial setting. The sinuous nature of the channelised sandstones and the occurrence of surrounding low amplitude (presumed mud-rich) deposits support an interpretation of a meandering channel-belt succession and surrounding floodplain units. Based upon their geographic position (in relation to channel deposits and the shelf margin) their geometric shapes, and high amplitude (presumed sandy) lobate reflectors occurring at the basinward termination of channels are interpreted as small delta lobes situated at the shelf-edge (Fig. 7B). Although not revealed in the study area

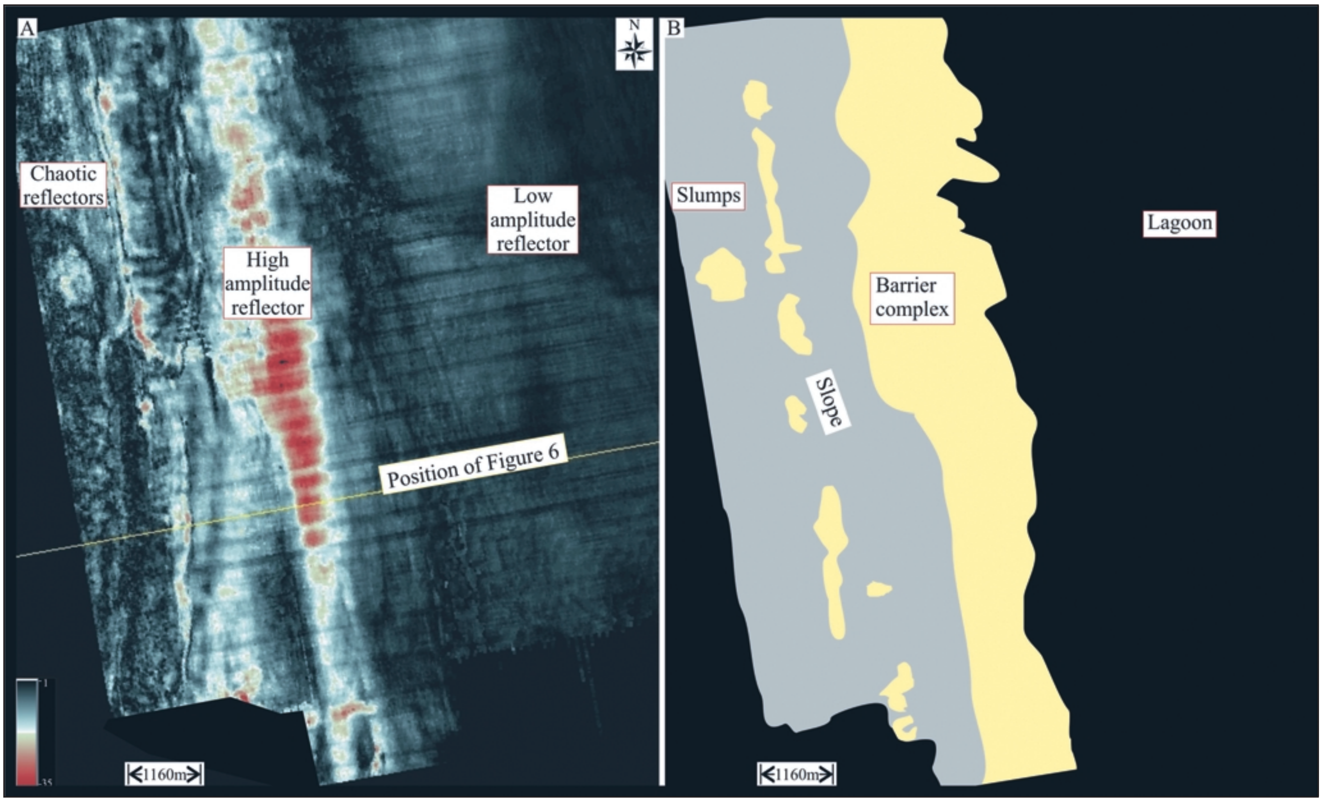


Fig.8. Attribute map generated from a window 8ms up and 8ms down from seismic Horizon 3 (Fig. 8A) and the interpretation of a barrier-complex (Fig. 8B) associated with the high angle positive shelf-edge trajectory. Yellow colours represent high amplitudes and grey colours represent low amplitudes. (Note: striped lines parallel with the position of Figure 6 in Fig. 8A result from the interpretation technique used and are not a reflection of geological events). See Figure 3 for location.

lateral delta lobe switching is expected to lead to the deposition of an extensive sand sheet at the delta front over time. Analysis of plan-view attribute maps indicates that slope failure (slumping) is sometimes associated with this low angle positive shelf-edge trajectory. Discontinuous, high amplitude reflectors observed seaward of the shelf break are interpreted as small slump structures situated on the slope (Fig. 7B).

High angle positive shelf-edge trajectory

Similar to the low-angle positive shelf edge trajectory, the high- angle positive shelf-edge trajectory (Set 2, Fig. 6), builds upward and basinwards. As with the low angle positive shelf-edge trajectory (above), this shelf-edge trajectory represents progradation under normal regression where coastal plain units are deposited and preserved in the topset area. The A:S ratio is considered to be significantly higher than that associated with the low angle positive shelf-edge trajectory and is considered to be dominated by sediment supply rates. With the high angle positive shelf-edge trajectory, the amount of accommodation space created behind the shelf-edge is probably higher than for the low angle.

Two seismic horizons have been interpreted throughout the topset, foreset and bottomset areas (horizons 2 and 3, Fig. 6) in association with this high angle positive shelf-edge trajectory. In plan view (Fig. 8) a high amplitude (presumed sand-rich) reflector with a hard seismic response is imaged as a linear feature orientated parallel to the shelf break and perpendicular to the dip direction of the delta-complexes. This linear feature is positioned approximately 200 metres landward of the shelf break, has a maximum width of ca. 1.5 kilometres and a minimum length of 12 kilometres in a north-south direction. The seismic response indicates a sandy lithology. There are no apparent distributary systems landward of the sandy linear feature (although smaller distributaries may occur below the limits of vertical seismic resolution) and sand, therefore, is interpreted to have been transported alongshore from the north or the south. Significant alongshore drift and the linear nature of this system suggest that the basinal regime was wave-dominated at the time of sand deposition. The assumed dominance of wave processes in the basin at the time of deposition, the linear nature of the high–amplitude (presumed sandy) feature, deposited during overall rising relative sea-level (as indicated by the shelf-edge trajectory), and an orientation parallel to the shelf-edge enable the sandy feature seen in Figure 8A to be interpreted as a barrier-complex. The width of the barrier-complex is analogous to widths of modern

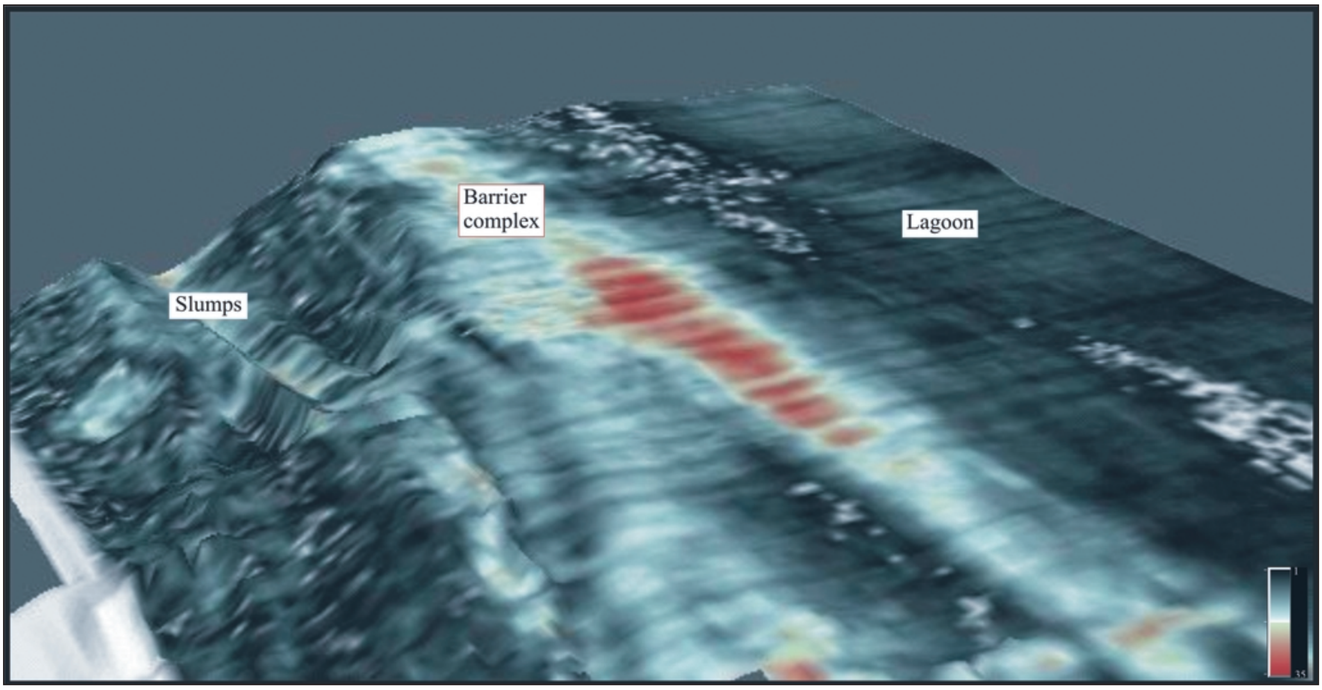


Fig. 9. Three-dimensional image of the barrier-complex associated with the high angle positive shelf-edge trajectory. (Note: striped lines crossing the shelf, perpendicular to the orientation of the barrier-complex result from the interpretation technique used and are not a reflection of geological events).

barrier-complexes reported from the Gulf Coast of Texas, USA (e.g. Morton et al. 1995; McBride et al. 1996).

Landward of this proposed barrier-complex, a very low amplitude area is observed on the shelf (Fig. 8). The interpretation of a barrier-complex near the shelf-edge suggests that the area directly to the east (landward) occupied by a low amplitude area relates to mud deposited in a lagoonal setting (Fig. 8B). Seaward of the barrier-complex, and parallel with the slope, lie a series of chaotic, high-amplitude (presumed sandy) seismic reflectors (Fig. 8A). Three-dimensional imaging of this amplitude map (Fig. 9) suggests that the chaotic reflectors represent the product of slumping along an oversteepened shelf-edge. On seismic cross-sections, a large slump structure is also observed directly below Horizon 3, at the foot of the slope (Fig. 4).

Low angle negative shelf-edge trajectory

In sequence sets with low angle negative shelf-edge trajectories, the tops of clinoforms are often planed off by erosion, especially in proximal areas (SET 1, Fig. 6). Topsets may be preserved in the most basinward areas (insert in Fig. 6A) where the shelf-edge trajectory flattens out prior to its subsequent climb as a high angle positive shelf-edge trajectory. This low angle negative shelf-edge trajectory is suggested to represent progradation during falling and subsequent early rise of relative sea-level. Deposits would then be traditionally attributed to a forced regressive - falling stage systems tract (Hunt & Tucker 1992; Nummedal et al. 1992; Helland-Hansen & Gjelberg 1994; Plint & Nummedal 2000), or a lowstand wedge systems tract (e.g. Van Wagoner et al. 1988; Posamentier & Vail 1988; Posamentier et al. 1988). It should be noted that in cross-section, inferred slump deposits are observed at the foot of some clinoforms (Fig. 6B). These slump deposits suggest that an unstable slope may be associated with this low angle negative shelf-edge trajectory.

One seismic reflector has been interpreted in association with this shelf-edge trajectory (Horizon 1, Fig. 6). An attribute map generated from the "topset area" shows linear features parallel to the trend of the clinoform-break in more proximal areas (Fig. 10A). These linear features (Fig. 10B) represent the truncated tops of clinoforms, and not a horizon time-slice, as they penetrate upwards through the interpreted horizon. Note that the NW-SE orientated linear feature that penetrates many of the clinoforms in Figure 10A is interpreted as the seismic shadow of an underlying fault and is not considered to represent a primary depositional feature.

As already stated, topset deposits are preserved in basinal areas where the angle of the shelf-edge trajectory probably flattens out before climbing (rectangle in Fig. 6A). These deposits occur in a shelf-break setting characterized by a change from falling to rising relative sea-level, and their stratigraphic position indicates that they may include both shoreface and lower coastal plain deposits. The preservation potential of sediments

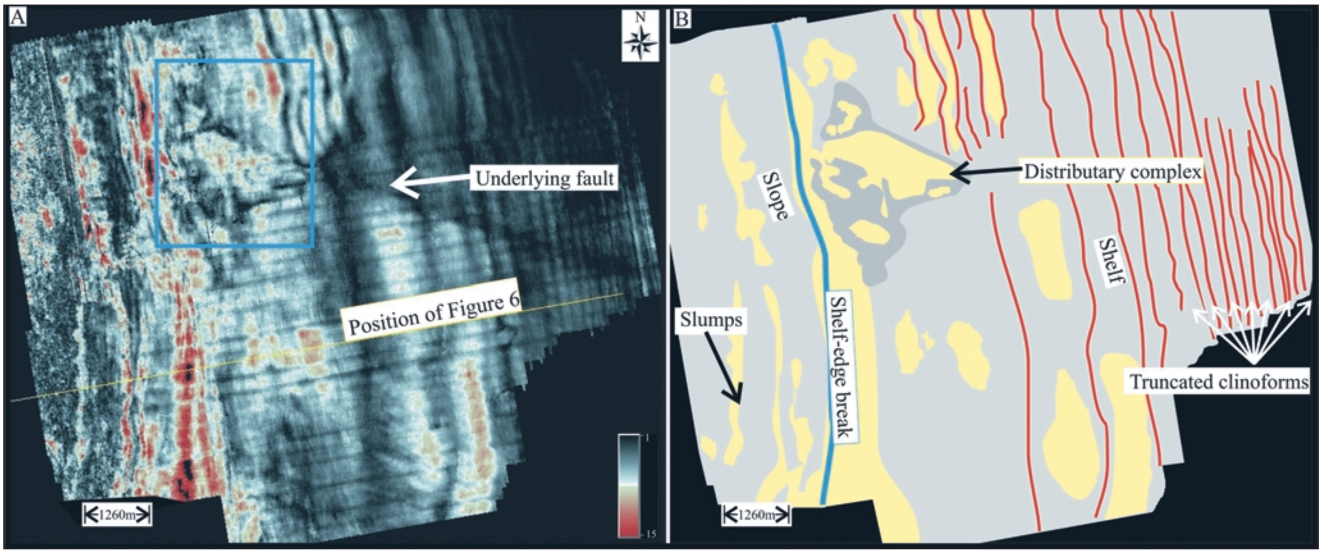


Fig. 10. Attribute map generated between 7ms and 26ms below seismic Horizon 1 (Fig. 10A), and the depositional environments associated with the low angle negative shelf-edge trajectory (Fig. 10B). Yellow colours represent high amplitudes and grey colours represent low amplitudes. (Note: striped lines parallel with the Position of Figure 6 in Fig. 10A result from the interpretation technique used and are not a reflection of geological events). See Figure 3 for location of attribute map.

deposited in this stratigraphic position is expected to be relatively high due to the following rise in shelf-edge trajectory, and the resultant increase in shelf/coastal plain accommodation space.

In plan view it is possible to identify predominantly high amplitude (presumed sandy) lithologies, although some low amplitude deposits are observed at the shelf-edge (Fig. 10). These differences in amplitude (reflecting different lithologies) enable the identification of two low-amplitude semi-linear features that appear to originate from the same area in the east. Basinward, at the shelf-edge, these features terminate in triangular, high and low amplitude structures several hundred metres in length (Insert, Fig. 10A). The geometric size and shape of these triangular structures and the fact that they terminate at the shelf-edge, the likely position of the shoreface at this time, allow them to be interpreted as mouth bar deposits fronting mud-filled distributary channels. The area within the rectangle in Figure 10A is therefore tentatively interpreted as a distributary channel complex. Traditionally, these deposits may be attributed to the lowstand wedge systems tract of Helland-Hansen & Gjelberg (1994). An important observation is the apparent lack of deep-water basin-floor fan deposits on attribute maps of this area (Fig. 10) or on cross-sections of basinward located areas (Fig. 4). Deep-water fan deposition may not, therefore, be associated with this low angle negative shelf-edge trajectory, despite a fall of the relative sea-level.

High angle negative shelf-edge trajectory

The high angle negative shelf-edge trajectory (Set 4, Fig. 11) is typified by complete bypass of the topset/shelf region and erosion into previously deposited clinoform deposits in both slope and topset areas. This erosion suggests that the relative sea-level was falling and that sediments were supplied from both the hinterland region and from cannibalised topset/foreset regions. As with the low angle negative shelf-edge trajectory (above), this high angle negative shelf-edge trajectory would traditionally be attributed to a falling stage systems tract. Two seismic reflectors have been interpreted in association with this shelf-edge trajectory (horizons 6 and 7, Fig. 11). In strike orientated sections (Fig. 12), it is possible to recognise a 60-70 metres deep incised feature associated with these two reflectors. The incision has a total width of approximately 2.5 kilometres, and a length that is restricted to 8 kilometres (in an east-west direction) due to truncation from a Quaternary erosion surface in the updip direction.

In plan view (Figs. 13 and 14) and in a three-dimensional perspective (Fig. 15), high amplitude (presumed sandy) deposits within the incision are seen to be predominantly surrounded by an area of lower amplitudes, interpreted as shelf mud (Fig. 13). This incised feature appears to stop at the shelf margin and its geographic position (at the shelf-slope break) implies that it may represent a transition between an incised valley, in the most landward parts, and a submarine canyon near the shelf-slope break. In Figure 14, it is possible to identify internal valley/canyon structures such as abandoned channel structures and slumping from the walls. Quarternary truncation indicates that the incised valley system originally had a much greater eastward extent and that the total amount of fluvial incision may be greater than the 60-70 metres measured from seismic cross-sections. As well as being incised, the slope is also considered to have been subject to large scale slumping (Figs. 13 and 15).

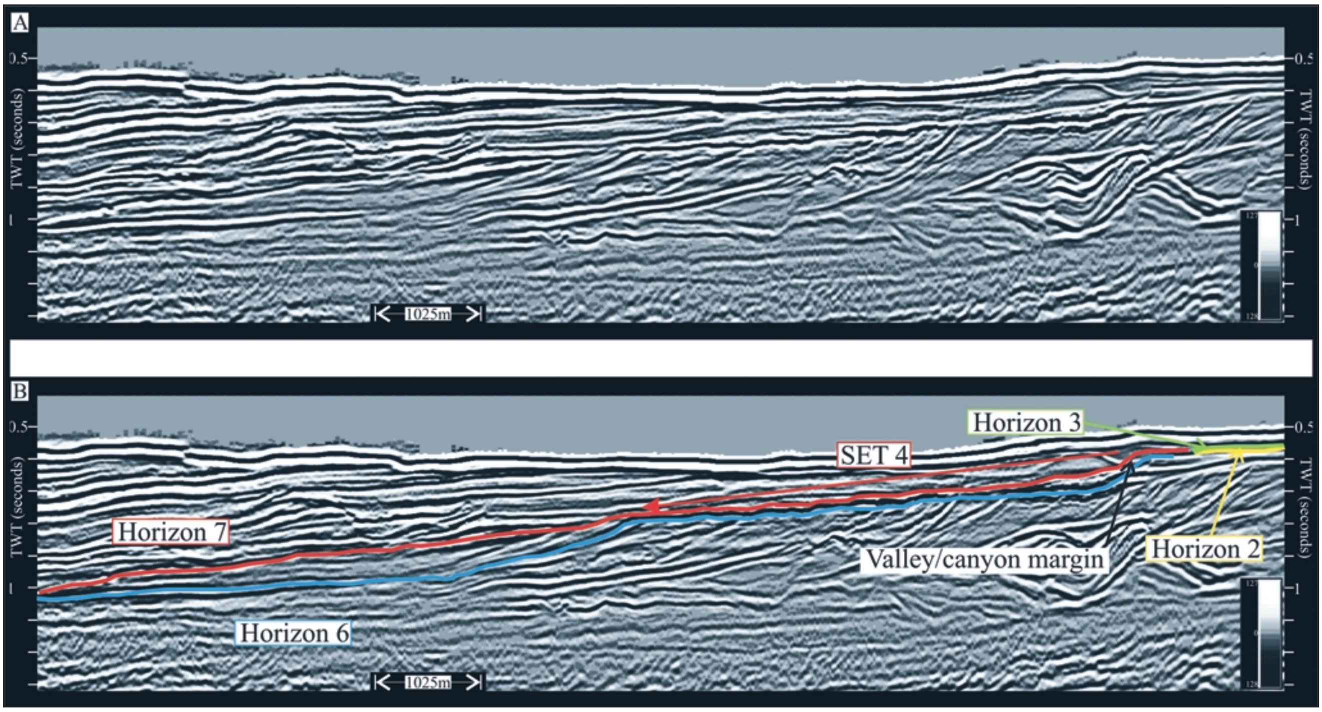


Fig. 11. Seismic horizons 6 and 7 are associated with the high angle negative shelf-edge trajectory (SET 4). Horizon 6 truncates Horizon 2. Vertical exaggeration is 600 times. (See Figure 12 for location).

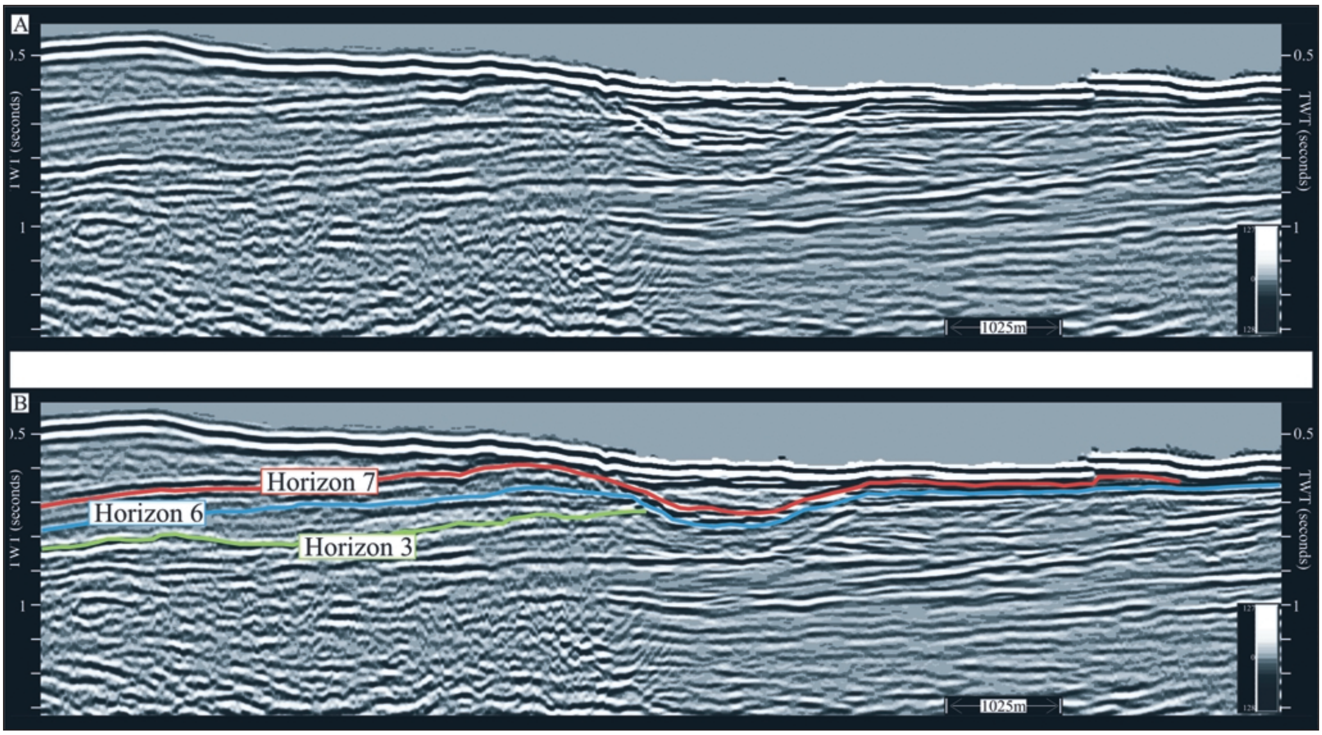


Fig. 12. Strike orientated cross-section showing valley/canyon incision and related seismic horizons 6 and 7 (Horizon 3 is truncated by Horizon 6). Vertical exaggeration is 400 times. (See Figure 12 for location).

Failure of the slope and shelf-edge incision, especially by what is interpreted to be a fluvial system, is expected to result in bypass of shelf margin shoreface environments and the deposition of sand-rich slump and turbidite deposits directly on to the slope and basin-floor. High amplitude (sandy) deposits on the basin floor and slope (Figs. 13 and 15) are tentatively interpreted to represent slump and basin-floor fan deposits (although fan geometries are not clearly visible on attribute maps, possibly due to effective sediment dispersal and/or reduced seismic quality/resolution at this depth). It is possible that initial slope failure resulted in slumping and the development of submarine canyons (e.g. Coleman et al. 1983; Goodwin & Prior 1989; Posamentier et al. 1991). Landward migration of these canyons during falling relative sea-level would encourage their linkage with basinward migrating fluvial systems and, where sea-level falls below the shelf-edge, the development of incised valley systems. This in turn, results in a point-sourced sediment supply to the deeper basinal areas and the deposition of basin-floor fans at the seaward extent of the incised valleys/submarine canyons.

Figure 15 indicates that there is a considerable bypass of the slope by sediments expelled from the mouth of the valley/canyon (situated at the shelf-break) and deposited as basin-floor fans. The inferred fan-complex appears to be detached from the incised valley and shelf system. However, slightly higher amplitude reflections on the slope indicate that it is possible that a sediment

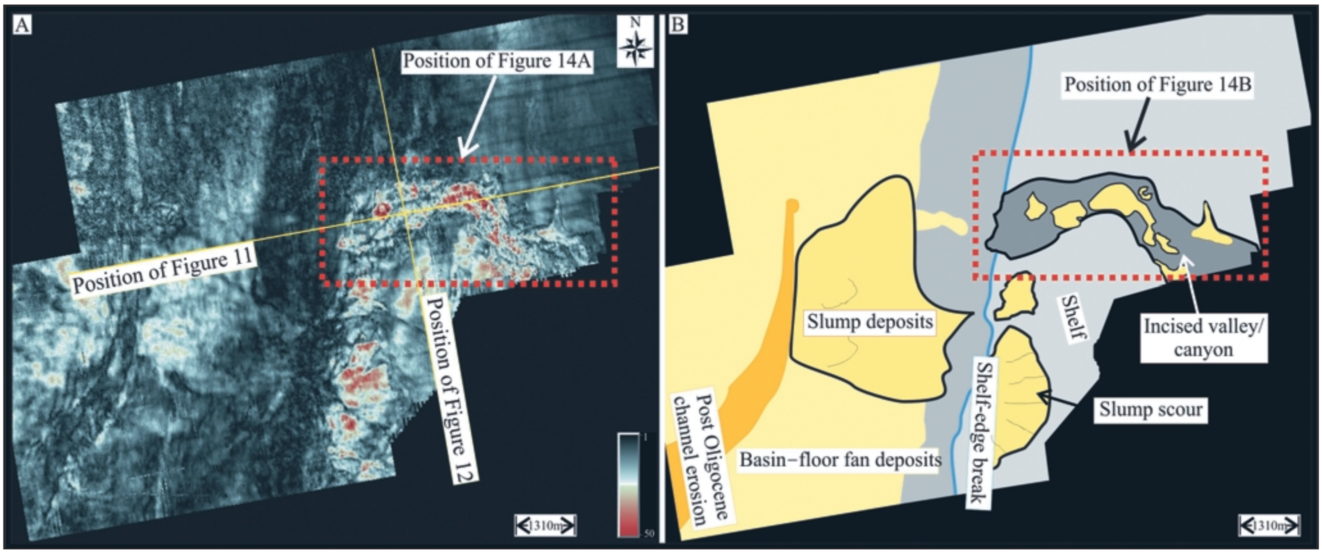


Fig. 13. Attribute map generated 25ms either side of Horizon 6 (Fig. 13A), and the depositional environments associated with the high angle negative shelf-edge trajectory (Fig. 13B). (Note: striped lines parallel with the position of Figure 11 on the shelf in Fig. 13A result from the interpretation technique used and are not a reflection of geological events). Yellow colours represent high amplitudes and grey colours represent low amplitudes. See Figure 3 for location of attribute map.

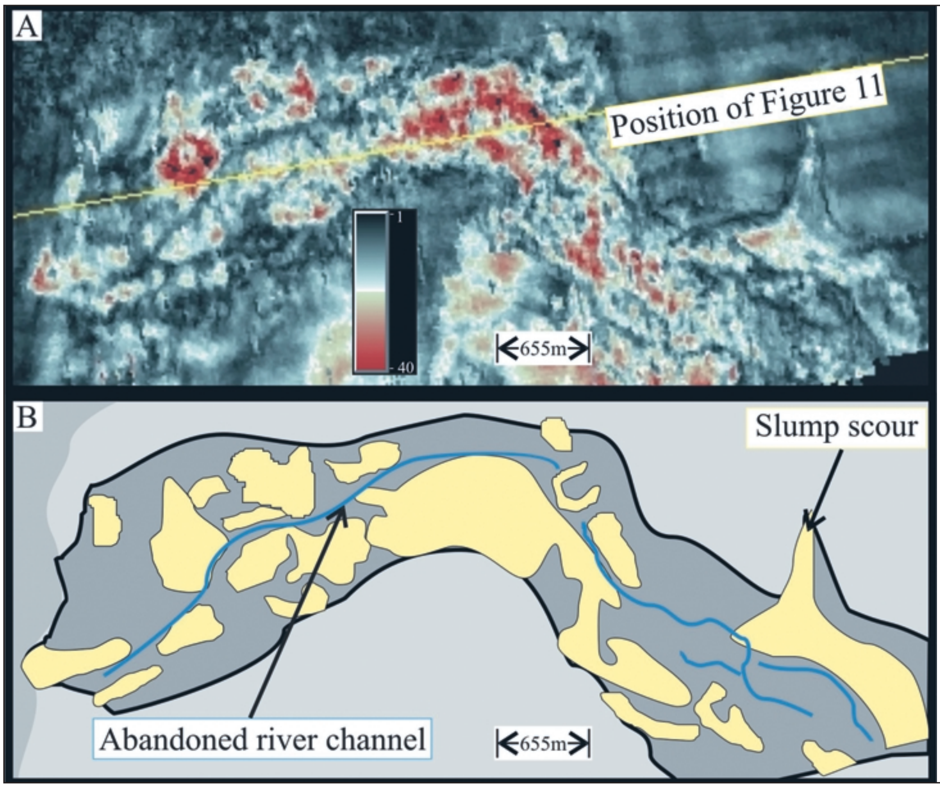


Fig. 14. Enlarged view of the valley/canyon seen in Figure 13. Slump structures and abandoned channel structures (Fig. 14B) may be interpreted from the seismic attribute map (Fig. 14A). Yellow colours represent high amplitudes and grey colours represent low amplitudes. See Figure 3 for location.

transport fairway, from the shelf to the basin-floor, existed on the lower slope (Figs. 13 and 15). The shelf and basin-floor systems may also be connected by deposits occurring on the slope below the limits of seismic resolution.

When an attribute map is constructed around Horizon 7, small slope-fans are clearly observed at the slope to basin-floor transition zone (Fig. 16). From Figure 16 it becomes apparent that these fan deposits originate

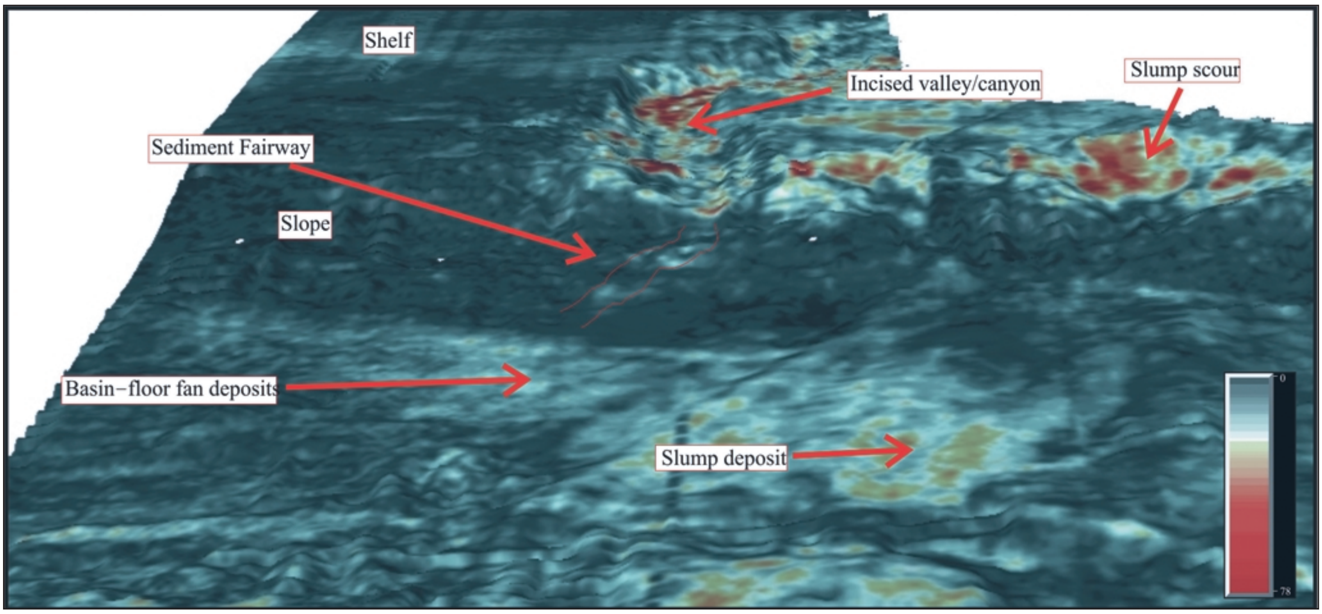


Fig. 15. Three-dimensional image of the incised valley/canyon and slope failure shown in Figures 13 and 14.

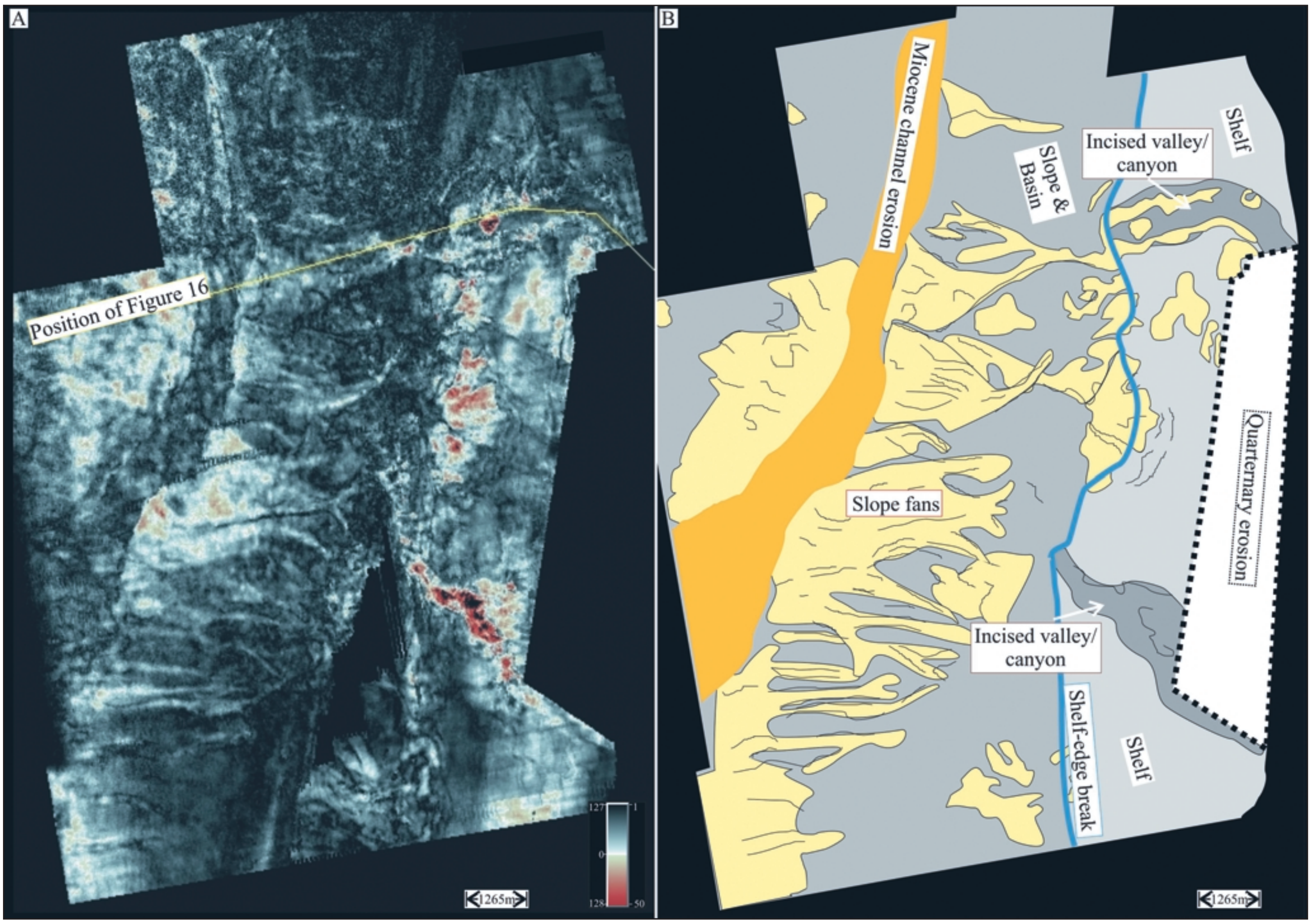


Fig. 16. Attribute map generated 25ms either side of Horizon 7 (Fig. 16A), and the depositional environments associated with the high angle negative shelf-edge trajectory (Fig. 16B). Yellow colours represent high amplitudes and grey colours represent low amplitudes. See Figure 3 for location of attribute map.

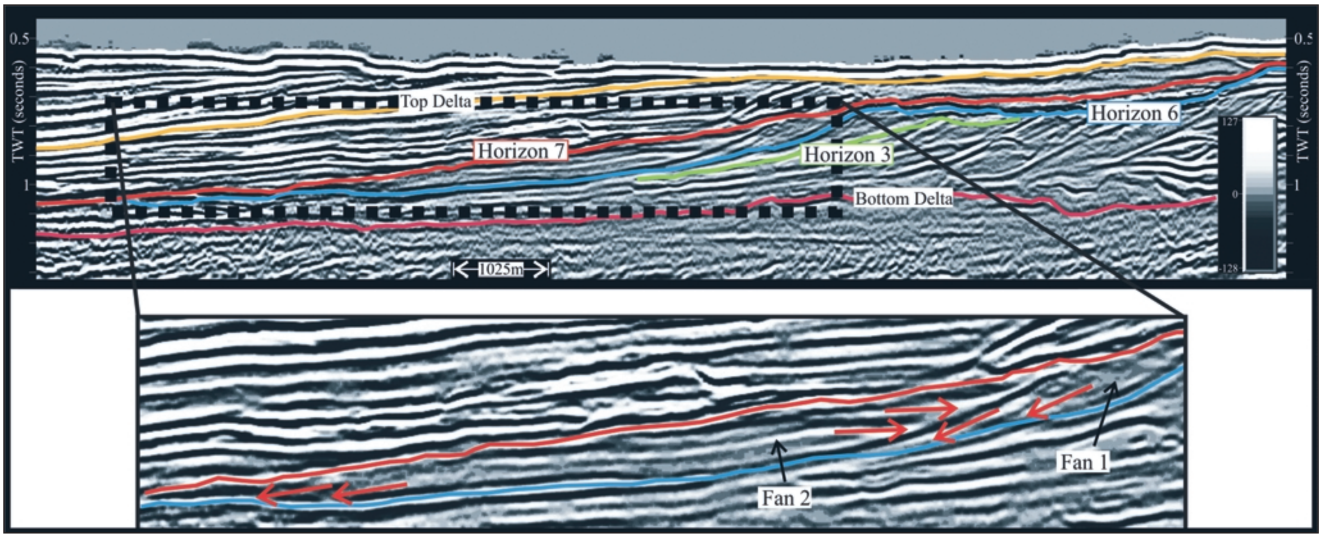


Fig. 17. Cross-section showing the internal onlap and downlap patterns observed within slope fan deposits. For position of cross-section see Figure 3.

from a line source (as opposed to a point source) and they are sourced from both incised valleys and inter-valley slump areas. In cross-section, these deposits appear as several high amplitude reflectors that onlap the slope and downlap the basin-floor. In Figure 17, a slope fan (Fan 1) is onlapped at its most distal extent by a more basinward located fan (Fan 2). This is interpreted to suggest progradation of the slope-fan succession, and is supported by Liestøl (2001), who attributes these deposits to a lowstand systems tract. The intermittent transgression required to shift the focus of deposition from the basin-floor back on to the shelf is not evident on the seismic data.

A predictive relationship

In general terms, factors that influence the shelf-edge trajectory of a given depositional system are rates of sediment supply and changes of relative sea-level (e.g. Muto & Steel 2002; Steel & Olsen 2002). Results from this study imply the existence of a probable relationship between different shelf-edge trajectories and associated depositional environments at various locations along the depositional profile (Fig. 18). It is here postulated that the trends between shelf-edge trajectories and depositional environments permit the definition of a method that may be used to predict lithology in areas beyond well control, outcrop or seismic control.

During normal regression, available accommodation space in the shelf area is reflected by the angle of the shelf-edge trajectory. A dominance of the rate of sediment supply over the rate of relative sea-level rise, as indicated by a low angle positive shelf-edge trajectory (D in Fig. 18), results in rapid progradation, a low amount of accommodation space in the topset/shelf area and the prediction of fluvially influenced (or dominated) delta front sandstones, and thin channel/channel-belt and floodplain deposits in the lower coastal plain area (9 in Fig. 18). A high angle positive shelf-edge trajectory (B in Fig. 18) reflects a closer balance between the rates of sediment supply and relative sea-level rise. This results in increased accommodation space in the coastal-plain (shelf) area and the formation of wave-dominated (?) barrier-island and lagoonal units (2 and 3 in Fig. 18).

Conversely, negative shelf-edge trajectories (A and C in Fig. 18) are associated with bypass and erosion in the prograding shelf margin foreset and topset areas. However, not all negative shelf-edge trajectories are associated with the emplacement of basin-floor fan deposits. This study indicates that the amount, and rate of relative sea-level fall (a negative shelf-edge trajectory results from a fall of relative sea-level) exerts a pronounced influence upon the presence or absence of basin-floor fan deposits, the existence of which is considered to be dependent upon: 1) fall of relative sea-level below the shelf-slope break, and: 2) incision of the slope. This theory is supported by previous investigations from other areas (Jervey 1988; Posamentier & Vail 1988; Van Wagoner et al. 1988; Steel et al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002; Muto & Steel 2002; Plink-Björklund & Steel 2002).

Where rates and amounts of relative sea-level fall are sufficiently low, and basinal processes sufficiently effective, sediments may be dispersed at the shelf-edge and not channelled into deeper waters. It is tentatively suggested that the low angle negative shelf-edge trajectory (A in Fig. 18) represents a situation where a lack of incision at the shelf-slope break may result in the storage of all sediment on the slope, and a lack of basin-floor fan deposits can be predicted (Fig. 18).

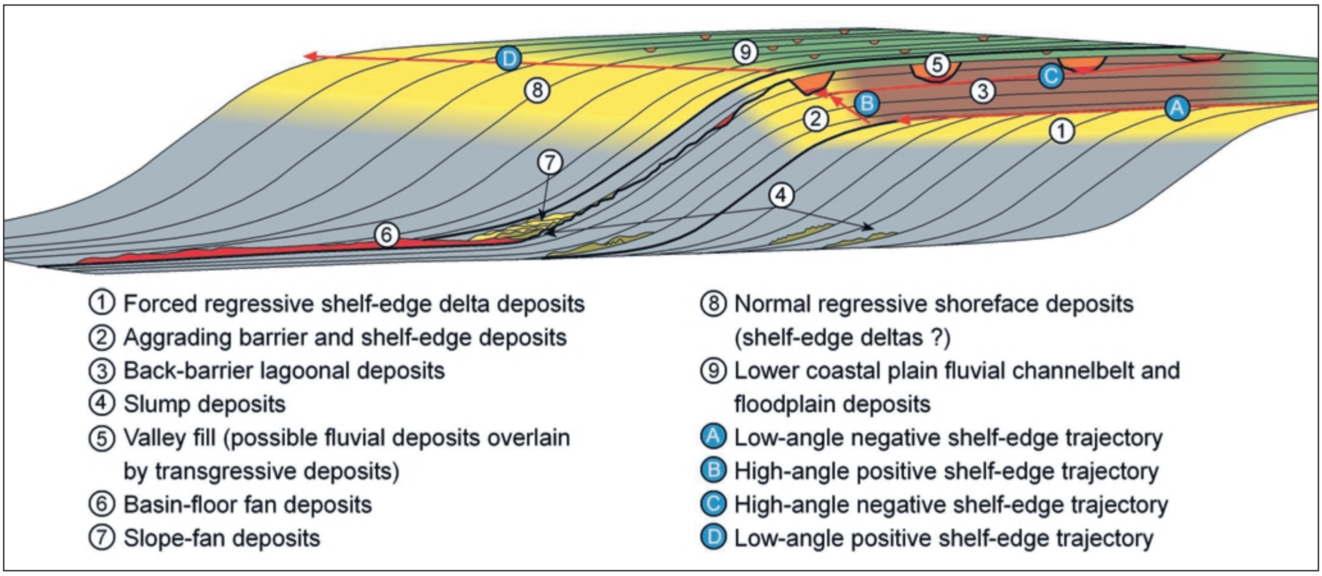


Fig. 18. Schematic diagram showing the relationship between different shelf-edge trajectories and related depositional environments (see text for explanation).

Studies from other areas by Steel et al. (2000), Plink-Björklund et al. (2001), Mellere et al. (2002) and Plink-Björklund & Steel (2002) seem to confirm the general validity of this observation.

The high angle negative shelf-edge trajectory (C in Fig. 18) is presumably associated with a larger, possibly more rapid, sea-level fall beyond the position of the shelf-slope break and resultant shelf and slope incision (5 in Fig. 18), and basin-floor fan deposition may be inferred (6 in Fig. 18). This interpretation is supported by studies from other areas regarding the timing of basin-floor fan deposition and the magnitude of relative sea-level change (e.g. Posamentier & Vail 1988; Steel et al. 2000; Steel & Olsen 2002). The occurrence of distributary systems and incised valleys/canyons at the shelf-edge generally appears to be associated with negative shelf-edge trajectories. Previous studies by Steel et al. (2000) and Steel & Olsen (2002) support our observations and involve similar shelf-edge trajectories being dominated by fluvial processes at the shelf-slope break.

Implications for petroleum exploration

The results from this study, provide an improved understanding of the relationship between specific facies associations and various shelf-edge trajectories. This may have important implications for the exploration of petroleum reservoirs, and also for an improved understanding of proven petroleum plays.

As demonstrated in this and other studies, not all falls of relative-sea level result in the deposition of basin-floor fan deposits (e.g. Jervey 1988; Muto & Steel 2002; Plink-Björklund & Steel 2002) Where rates of relative sea-level fall are sufficient to allow the truncation of clinoforms over a large area (Fig. 10), but not large enough to incise the shelf-edge, basin-floor fan deposits (i.e. potential deep water reservoirs) may be lacking. Additionally, it may be speculated that shoreface sandstones associated with a low angle negative shelf-edge trajectory most likely will be thin and of relatively poor reservoir quality due to slumping. The best reservoir sands associated with this shelf-edge trajectory will be found at the maximum basinwards extent of the shelf-edge (Figs. 6A and 10) where a flattening of the shelf-edge trajectory, prior to the subsequent sea-level rise will allow thicker sand deposits (shelf-edge deltas) to accumulate and be preserved. However, slumping may also be a detrimental factor to reservoir thickness and/or preservation.

It is here postulated that high angle positive shelf-edge trajectories offer the best potential for good reservoir sands in a shelf-edge setting. The positive nature and high aggradation rate associated with the high angle shelf-edge trajectory suggest that deltas prograde the shoreline to the shelf-edge where wave dominated barrier-complexes and shelf-edge deltas develop. Outcrop studies of similar deposits (Steel el al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002; Plink-Björklund & Steel 2002; Steel & Olsen 2002) indicate storage of significant amounts of sand on the shelf-edge and upper slope. Aggradation of these "perched" deltas may result in the development and preservation of a potential reservoir body, which would generally be expected to consist of sand-rich, relatively narrow but thick, shore-parallel linear features. The reservoir quality of this sand-prone interval may be reduced where the shelf-edge trajectory is the product of several parasequences and consists of several shoreline trajectories (i.e. a composite shoreline trajectory) separated by transgressive ravinement surfaces and possibly thin shale beds, or alternatively, where slumping transports sand downslope.

The low angle positive shelf-edge trajectory may represent the presence of shelf-edge deposits of intermediate-to-good reservoir quality. Due to the lower relative rate of aggradation, the sandstones inferred to be associated with this shelf-edge trajectory will probably be thinner than those associated with the high angle positive shelf-edge trajectory. The total sand interval in the shoreface package is, however, likely to be preserved (i.e. it is not eroded or compressed by forced regression) and there is less chance for intermittent ravinement surfaces and shale intervals that may act as barriers to (hydrocarbon) migration. Inferred sandstones associated with this low angle positive shelf-edge trajectory would probably be related to the deposition of a laterally extensive sandstone sheet deposit that may result in an extensive reservoir. There is also a potential for additional sandstone reservoirs in fluvial deposits situated on the shelf.

Discussion and conclusions

Analysis of seismic data from the Neogene off mid-Norway has resulted in the interpretation of depositional sedimentary environments based on cross-sectional profiles and geometries observed in seismic attribute maps. Seismic images of large-scale clinoforms, representing shelf margin progradation, have allowed differentiation of four types of progradational shelf-edge trajectories. These shelf-edge trajectories are defined by the successive position of the break-in-slope between clinoform topsets and foresets. Based upon results from this investigation, it is possible to identify several trends related to differing shelf-edge trajectories and associated shelf/coastal plain depositional environments. It also appears possible to make certain generalisations regarding different shelf-edge trajectories and the stability of the shelf slope, as well as the emplacement of basin-floor fan deposits. Liestøl (2001) indicates that within the Molo Formation, frequent, small scale slope failure is associated with a highstand of relative sea-level, while slumps are larger, but less frequent during a falling stage and lowstand of relative sea-level.

This study indicates that it is possible to infer a relationship between shelf-edge trajectories and depositional environments (Fig. 18). Falling relative sea-level results in topset bypass and erosion, and the deposition of sediments at or beyond the shelf-slope break (Fig. 18). Progradation during rising relative sea-level is not associated with deep-water fan deposition, and may result in the deposition of either fluvial channel deposits or barrier/lagoon-complexes on the shelf (Fig. 18).

Several explanations are offered for shelf failure and the occurrence of slump deposits. Incision of fluvial systems at the shelf break results in a more focussed delivery of sediment on to the slope, which, in turn, often results in collapse of the shelf-edge (Steel et al. 2000) and may lead to the formation of canyons on the slope. This offers a feasible explanation for the occurrence of large slump deposits in association with the high angle negative shelf-edge trajectory (Figs. 13 and 15). Slumps associated with the low angle negative shelf-edge trajectory (Fig. 6) may have a similar origin. A fall of relative sea-level evidently resulted in the positioning of fluvial systems at the shelf-edge (as indicated by the distributary system seen in Figure 10), but not necessarily below it. This may have resulted in significant amounts of coarse-grained sediment being deposited directly on to an unstable slope and subsequently to slope failure.

Given a narrow shelf, deltas may also prograde to the shelf-edge during stages of rising relative sea-level (Muto & Steel 2002; Porobski & Steel 2003), as observed in Figure 7, and slope failure may occur due to the deposition of coarse sands on unstable slope muds, as discussed above. Helland-Hansen & Gjelberg (1994) stipulate that rising relative sea-level, and a climbing shoreline trajectory in a ramp setting will eventually result in oversteepening of the delta front and subsequent slope failure. Although this occurs at an order of magnitude lower than the shelf margin progradation observed in this study, the observation of slump deposits in association with a high angle positive shelf-edge trajectory (Figs. 8 and 9) implies that the same principle may be applied to prograding shelf margin systems, as suggested by Ross et al. (1994). Sediment grain-size influences the steepness of the beach profile (e.g. Walker & Plint 1992) and the steepness of clinoform foresets (e.g. Pirmez et al. 1998; Steel & Olsen 2002). Coarser grained sediments lead to more steeply dipping clinoform foresets than fine-grained sediments and this may therefore have an influence on the stability of the slope.

The concept of a relationship between differing shelf-edge trajectories and depositional environments (facies and facies associations) has important implications for an improved understanding of the dynamic nature of a given depositional system. Such a relationship implies that changing facies association trends will be reflected in changing shelf-edge trajectories and that the identification of such a relationship may enable systematic variations in facies association trends to be used in a more predictive manner. This study indicates that such a relationship does exist and that careful analysis of high quality seismic data may allow the prediction of lithological and facies association changes in either a landward or seaward direction of any given location along the depositional profile. As such, this relationship represents a powerful tool for the prediction of potential hydrocarbon reservoirs in both shallow and deep-water settings.

Acknowledgements: Thanks to Egil Rundhovde for organising access to the seismic data at Statoil's Bergen office, thus eliminating many months of travelling for S.B. Conversations about seismic interpretation with Marc Ryan and many geologists at Statoil, Bergen, were enlightening and very helpful. Permission to publish results of the study was granted by Statoil ASA, ENI Norge AS and Amerada Hess Norge AS. VISTA and Statoil ASA provided financial support for this study. Jane Ellingsen is kindly thanked for drafting an earlier version of Figure 2. Per Terje Osmundsen and Erik Lundin critically reviewed the manuscript, and offered constructive advice leading to improvement of both text and figures.

References

Blystad , P., Brekke, H., Færseth, R. B., Larsen, B. T., Skogseid, J. & Tørudbakken, B. 1995. Structural elements of the Norwegian continental shelf. Part II The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin No 8*, 45pp.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre basins. *In* Nøttvedt, A. et al. (ed.), *Dynamics of the Norwegian margin.* Geological Society London, Special Publication 167, 327-378.

Brekke, H., Sjulstad, H. I., Magnus, C. & Williams, R. W. 2001. Sedimentary environments offshore Norway - an overview. *In* Martinsen, O. J. & Dreyer, T. (eds.), *Sedimentary Environments Offshore Norway - Palaeozoic to recent.* Norwegian Petroleum Society Special Publication 10, 7-37.

Brown, A.R. 1985. The role of horizontal seismic sections in stratigraphic interpretation. *In* Berg, O.R. & Woolverton, D.G. (eds.), *Seismic stratigraphy II; an integrated approach to hydrocarbon exploration.* American Association of Petroleum Geologists, Memoir 39, 37-47.

Brown, A.R. 1991. Interpretation of three-dimensional seismic data. *American Association of Petroleum Geologists Memoir 42*, 341 pp.

Burgess, P.M. & Hovius, N. 1998. Rates of delta progradation during highstands; consequences for timing of deposition in deep-marine systems. *Journal of the Geological Society of London 155*, 217-222.

Coleman, J.M., Prior, D.B. & Lindsay, G.F. 1983. Deltaic influences on shelf edge instability processes. *In* Stanley, D.J. & Moore, G.T. (eds.), *The Shelf break: critical interface on continental margins.* Society of Economic Paleontologists and Mineralogists Special Publication 33, 121-138.

Doré, A.G., Lundin, E.R., Jensen, L.N, Birkeland, Ø., Eliassen, P.E. & Fichler, C. 1999. Principal tectonic events in the evolution of the northwest European Atalntic margin. *In* Fleet A.J. & Boldy, S.A.R (eds.), *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference.* Geological Society, London, 41-61.

Eidvin, T., Brekke, H., Riis, F. & Renshaw, D.K. 1998. Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64 degrees N-68 degrees N. *Norwegian Journal of Geology 78*, 125-151.

Goodwin, R.H. & Prior, D.B. 1989. Geometry and depositional sequences of the Mississippi Canyon, Gulf of Mexico. *Journal of Sedimentary Petrology 59*, 318-329.

Helland-Hansen, W. & Gjelberg, J.G. 1994. Conceptual basis and variability in sequence stratigraphy; a different perspective. *Sedimentary Geology 92*, 31-52.

Helland-Hansen, W. & Martinsen, O.J. 1996. Shoreline trajectories and sequences; description of variable depositional-dip scenarios. *Journal of Sedimentary Research 66*, 670-688.

Henriksen, S. & Vorren, T.O. 1996. Late Cenozoic sedimentation and uplift history on the mid-Norwegian continental shelf. *Global and Planetary Change 12*, 171-199.

Henriksen, S. & Weimer, P. 1996. High-frequency depositional sequences and stratal stacking patterns in lower Pliocene coastal deltas, mid-Norwegian continental shelf. *American Association of Petroleum Geologists Bulletin 80*, 1867-1895.

Henriksen, S., Fichler, C., Grønlie, A., Henningsen, T., Løseth, H., Ottesen, D. & Prince, I. 2002. The Norwegian Sea during the Cenozoic. *In* Hurst, A. (ed.), *Onshore - Offshore Relationships on the Nordic Atlantic Margin*, 93-95. Abstracts and Proceedings of the Norwegian Geological Society: Norwegian Geological Society, Trondheim, Norway.

Hjelstuen, B.O., Eldholm, O. & Skogseid, J. 1999. Cenozoic evolution of the northern Vøring margin. *Geological Society of America Bulletin 111*, 1792-1807.

Hunt, D. & Tucker, M.E. 1992. Stranded parasequences and the forced regressive wedge systems tract; deposition during base-level fall. *Sedimentary Geology 81*, 1-9.

Japsen, P. & Chalmers, J.A. 2000. Neogene uplift and tectonics around the North Atlantic; overview. *Global and Planetary Change 24*, 165-173.

Jervey, M.T. 1988. Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. *In* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J. & Kendall, C.G.St C. (eds.), *Sea-level changes; an integrated approach.* Society of Economic Paleontologists and Mineralogists Special Publication 42, 47-69.

Jørgensen, F. & Navrestad, T. 1981. The geology of the Norwegian shelf between 62 degrees N and the Lofoten Islands. *In* Illing, L.V., & Hobson, G.D. (eds.), *Petroleum geology of the continental shelf of North-West Europe.* Proceedings of the second conference, 407-413. Heyden and Son, London.

Jørgensen, F. & Navrestad, T. 1979. Main structural elements and sedimentary succession on the shelf outside Nordland (Norway). *Norwegian Sea Symposium*, 1-20. Tromsø, Norway.

Liestøl, F. M (2001). Seismisk stratigrafi og sekvensstratigrafi av et tidlig pliocent deltakompleks, midtnorsk sokkel. *Unpublished Cand. scient. thesis, University of Bergen, Norway.*

McBride, E.F., Abel, W.A. & McGilvery, T.A. 1996. Loss of sand-size feldspar and rock fragments along the South Texas barrier island, USA. *Sedimentary Geology 107*, 37-44.

Mellere, D., Plink-Björklund, P. & Steel, R. 2002. Anatomy of shelf deltas at the edge of a prograding Eocene shelf margin, Spitsbergen. *Sedimentology 49*, 1181-1206.

Miall, A.D. 2002. Architecture and sequence stratigraphy of Pleistocene fluvial systems in the Malay Basin, based on seismic time-slice analysis. *American Association of Petroleum Geologists Bulletin 86*, 1201-1216.

Mitchum, R.M., Jr., Vail, P.R. & Sangree, J.B. 1977a. Seismic stratigraphy and global changes of sea level; Part 6, Stratigraphic interpretation of seismic reflection patterns in depositional sequences. *In* Patyon, C.E. (ed.), S*eismic stratigraphy; applications to hydrocarbon exploration.* American Associations of Petroleum Geologists Memoir 26, 117-133.

Mitchum, R.M., Jr., Vail, P.R. & Thompson, S., III 1977b. Seismic stratigraphy and global changes of sea level; Part 2, The depositional sequence as a basic unit for stratigraphic analysis. *In* Patyon, C.E. (ed.), *Seismic stratigraphy; applications to hydrocarbon exploration.* American Association of Petroleum Geologists Memoir 26, 53-62.

Mogensen, T.E., Nyby, R., Karpuz, R. & Haremo, P. 2000. Late Cretaceous and Tertiary structural evolution of the northeastern part of the Vøring Basin, Norwegian Sea. *In* Nøttvedt, A. et al. (ed.), *Dynamics of the Norwegian margin.* Geological Society of London, Special Publication 167, 379-396.

Morton, R.A., Gibeaut, J.C. & Paine, J.G. 1995. Meso-scale transfer of sand during and after storms; implications for prediction of shoreline movement. *Marine Geology 126*, 161-179.

Mosar, J., Eide, E. A., Osmundsen, P.T., Sommaruga, A., & Torsvik, T. H. 2002. Greenland-Norway separation: A geodynamic model for the North Atlantic. *Norwegian Journal of Geology 82*, 281-298.

Muto, T. & Steel, R.J. 2002. In defense of shelf-edge delta development during falling and lowstand of relative sea level. *Journal of Geology 110*, 421-436.

Nummedal, D., Riley, G.W., Cole, R.D. & Trevena, A.S. 1992. The distribution of depositional systems within falling sea level and lowstand systems tracts; examples from the Gallup Sandstone. *In* Ethridge, F.G. (ed.), *SEPM 1992 theme meeting; Mesozoic of the Western Interior; abstracts, 50.* Society of Economic Paleontologists and Mineralogists, Tulsa, OK, United States.

Ottesen, D., Rise, L., Rokoengen, K. & Sættem, J. 2001. Glacial processes and large-scale morphology on the mid-Norwegian shelf. *In* Martinsen, O. J. & Dreyer, T. (eds.), *Sedimentary Environments Offshore Norway - Palaeozoic to recent.* Norwegian Petroleum Society Special Publication 10, 441-449.

Pirmez, C., Pratson, L.F. & Steckler, M.S. 1998. Clinoform development by advection-diffusion of suspended sediment; modeling and comparison to natural systems. *Journal of Geophysical Research, B, Solid Earth and Planets 103/B10.* 24,141-24,157.

Plink-Björklund, P., Mellere, D. & Steel, R.J. 2001. Turbidite variability and architecture of sand-prone, deep-water slopes; Eocene clinoforms in the Central Basin, Spitsbergen. *Journal of Sedimentary Research 71*, 895-912.

Plink-Björklund, P., & Steel, R. 2002. Sea-level fall below the shelf edge, without basin-floor fans. *Geology 30*, 115-118.

Plint, A.G. & Nummedal, D. 2000. The falling stage systems tract; recognition and importance in sequence stratigraphic analysis. *In* Hunt, D. & Gawthorpe, R.L. (eds.), *Sedimentary responses to forced regressions.* Geological Society of London Special Publication 172, 1-17.

Poole, D.A.R. & Vorren, T.O. 1993. Miocene to Quaternary paleoenvironments and uplift history on the mid Norwegian shelf. *Marine Geology 115*, 173-205.

Porobski, S.J. & Steel, R. J. 2003. Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands. *Earth-Science Reviews 62*, 283-326.

Posamentier, H.W. 2002. Ancient shelf ridges; a potentially significant component of the transgressive systems tract; case study from offshore Northwest Java. *American Association of Petroleum Geologists Bulletin 86*, 75-106.

Posamentier, H.W. & Vail, P.R. 1988. Eustatic controls on clastic deposition; II, Sequence and systems tract models. *In* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J. & Kendall, C.G.St C. (eds.), *Sea-level changes; an integrated approach.* Society of Economic Paleontologists and Mineralogists Special Publication 42, 125-154.

Posamentier, H.W., Jervey, M.T. & Vail, P.R. 1988. Eustatic controls on clastic deposition; I, Conceptual framework. *In* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J. & Kendall, C.G.St C. (eds.), *Sea-level changes; an integrated approach.* Society of Economic Paleontologists and Mineralogists Special Publication 42, 109-124.

Posamentier, H.W., Erskine, R.D. & Mitchum, R.M., Jr. 1991. Models for submarine-fan deposition within a sequence-stratigraphic framework. *In* Weimer, P. & Link, M.H. (eds.), *Seismic facies and sedimentary processes of submarine fans and turbidite systems*, 127-136. Springer-Verlag, New York.

Riis, F. 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change 12*, 331-357.

Riis, F. & Fjeldskaar, W. 1992. On the magnitude of the late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea. *In* Larsen, R.M., Brekke, H., Larsen, B.T. & Talleraas, E. (eds.), *Structural and tectonic modelling and its application to petroleum geology.* Norwegian Petroleum Society Special Publication 1, 163-185.

Rokoengen, K., Rise, L., Bryn, P., Frengstad, B., Gustavsen, B., Nygaard, E. & Sættem, J. 1995. Upper Cenozoic stratigraphy on the mid-Norwegian continental shelf. *Norwegian Journal of Geology 75*, 88-104.

Ross, W.C., Halliwell, B.A., May, J.A., Watts, D.E. & Syvitski, J.P.M. 1994. Slope readjustment; a new model for the development of submarine fans and aprons. *Geology 22*, 511-514.

Rønnevik, H. & Navrestad, T. 1977. Geology of the Norwegian Shelf between 62 degrees N and 69 degrees N. *Geo Journal 1*, 33-46.

Skogseid, J., Pedersen, T. & Larsen, V.B. 1992. Vøring Basin: subsidence and tectonic evolution. *In* Larsen, R.M., Brekke, H., Larsen, B.T. & Talleraas, E. (eds.), *Structural and tectonic modelling and its application to petroleum geology.* Norwegian Petroleum Society Special Publication 1, 55-82.

Steel, R., Cranbaugh, J., Schellpeper, M., Mellere, D., Plink-Björklund, P., Deibert, T. & Løseth, T. 2000. Deltas versus rivers on the shelf edge: their relative contributions to the growth of shelf margins and basin-floor fans (Barremian and Eocene, Spitsbergen). *In: GCSSEPM Foundation 20th Annual Research Conference, Deepwater Reservoirs of the World*. 981-1009. Houston.

Steel, R. & Olsen, T. 2002. Clinoforms, Clinoform Trajectories and Deepwater Sands. *In* Armentrout, J.M. & Rosen, N.C. (eds.), *Sequence Stratigraphic models for exploration and production: Evolving Methodology, Emerging Models and Application Histories*. 367-381. Special Publication GCS- Society of Economic Paleontologists and Mineralogists.

Swift, D.J.P. & Thorne, J.A. 1991. Sedimentation on continental margins; II, Application of the regime concept. *In* Swift, D.J.P., Oertel, G.F., Tillman, R.W. & Thorne, J.A. (eds.), *Shelf sand and sandstone bodies; geometry, facies and sequence stratigraphy.* International Association of Sedimentologists Special Publication 14, 33-58.

Talwani, M. & Eldholm, O. 1977. Evolution of the Norwegian-Greenland Sea. *Geological Society of America Bulletin 88*, 969-999.

Torske, T. 1972. Tertiary Oblique Uplift of Western Fennoscandia; Crustal Warping in Connection with Rifting and Break-up of the Laurasian Continent. *Norges Geologiske Undersøkelse Bulletin 273*, 43-48.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N. & Perez, C.G. 1991. The stratigraphic signatures of tectonics, eustacy and sedimentology; an overview. *In* Einsele, G., Ricken, W. & Seilacher, A. (eds.), *Cycles and events in stratigraphy*, 617-659. Springer Verlag, Berlin.

Vail, P.R., Hardenbol, J. & Todd, R.G. 1984. Jurassic unconformities, chronostratigraphy, and sea-level changes from seismic stratigraphy and biostratigraphy. *In* Schlee, J.S. (ed.), *Interregional unconformities and hydrocarbon accumulation.* American Association of Petroleum Geologists Memoir 36, 129-144.

Vail, P.R. & Mitchum, R.M., Jr. 1977. Seismic stratigraphy and global changes of sea level; Part 1, Overview. *In* Payton, C.E. (ed.), *Seismic stratigraphy; applications to hydrocarbon exploration.* American Association of Petroleum Geologists Memoir 26, 51-52.

Vail, P.R., Mitchum, R.M., Jr. & Thompson, S., III 1977. Seismic stratigraphy and global changes of sea level; Part 3, Relative changes of sea level from coastal onlap. *In* Payton, C.E. (ed.), *Seismic stratigraphy; applications to hydrocarbon exploration.* American Association of Petroleum Geologists Memoir 26, 63-81.

Vail, P.R. & Todd, R.G. 1981. Northern North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy. *In* Illing, L.V. & Hobson, G.D. (eds.), *Petroleum geology of the continental shelf of North-West Europe; Proceedings of the second conference*, 216-235. Heyden and Son, London.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Jr., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J. 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. *In* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J. & Kendall, C.G.St C. (eds.), *Sea-level changes; an integrated approach.* Society of Economic Paleontologists and Mineralogists Special Publication 42, 39-45.

Walker, R.G. and Plint, A.G. 1992. Wave- and storm-dominated shallow marine systems. *In* Walker, R.G. & James, N.P. (eds.), *Facies models; response to sea level change*, 219-238. Geological Association of Canada. St, Johns, NF, Canada.

Weimer, P. and Davis, T.L. 1996. Applications of 3-D seismic data to exploration and production. *American Association of Petroleum Geologists Studies in Geology 42*, 270 pp.