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Submarine channels controlled by salt tectonics: Examples from 3D seismic data offshore Angola

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Abstract

The interaction between salt tectonics and sedimentation, offshore Angola has created a complex slope geometry of submarine channels, intra-slope basins and diapiric salt structures. There are a wide range of slope channel styles in close stratigraphic and geographic proximity, although the controls on these changes are not fully understood. Channels often follow complicated routes downslope, and have developed highly variable channel geometries, with narrow, erosional confined systems, and aggradational, broader systems as end members. Many channels are organised into stacked channel complexes. Rapid transitions in channel geometry are observed where channel systems pass through constrictions in salt wall structures or encounter decreases in slope gradients, for example within intra-slope depressions. Decreases in gradient and the exit points of incised channels mark the transition from narrow, well-defined linear or sinuous channels to broad, weakly confined channels. Important seismic facies changes are also observed where channels approach salt structures that created positive features on the seafloor. Results presented here show that linear, high gradient channels exhibit distinctive geometry changes around salt structures, often forming discreet depositional forms in planview. Lateral changes in sedimentary architecture within depositional lows record salt movement, as facies migrate relative to growing salt structures.

Keywords: Turbidity currents; Submarine channels; Salt tectonics; 3D Seismic; Channel levees; Angola

1. Introduction

The use of 3D seismic techniques has significantly advanced our understanding of deep-water sedimentary processes. During the past few years, there has been a renewed interest in the seafloor processes that create submarine channels and transport material downslope from shallower to deeper water (e.g. Roberts and Compani, 1996; Beaubouef and Friedmann, 2000; Kolla et al., 2001; Sikkema and Wojcik, 2000; Navarre et al., 2002; Deptuck et al., 2003; Samuel et al., 2003; Posamentier, 2003; Broucke et al., 2004; Saller et al., 2004). The term 'submarine channel' is here used to describe an incised conduit for downslope sediment transport, without any implication for process or flow type. Channels from the offshore region of Angola are often organised into incised complexes and may be associated with levees deposited outside the channel (e.g. Mayall and Stewart, 2000). Before 3D seismic geomorphology was developed, Damuth et al. (1988) recognised that submarine channels were the principal depositional element of large submarine fan systems. They provide a potentially valuable record of submarine fan evolution and display interesting temporal and spatial variations in geometry which are controlled by sea level changes, sediment flux variations, tectoni forcing and climate change. A key weakness is that we have little understanding of the links between channel geometry and the processes that create channels. This paper investigates specific poorly understood aspects of submarine channel behaviour in the vicinity of salt structures, where there is complex slope topography.

Existing models of deep-water erosionally confined channel complexes for Angola are based on 3D seismic, drill and core data (Mayall and Stewart, 2000; Sikkema and Wojcik, 2000). These models show a basal erosion surface underlying a bypass facies of sandy debrite, slumps and muddy debrite at the channel base, overlain by sand-rich stacked channels, low sinuosity channels and sand-poor channel levee complexes, respectively. The bypass facies might contain local slumped material in addition to coarse pebbles which suggest a more distant source. The uppermost stage is characterised by sand

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rich, highly sinuous channel–levee complexes. Angolan channel geometry is highly controlled by slope gradient, resulting in complex flow pathways. Small scale faulting also has an important local control, resulting in channel bends (Mayall and Stewart, 2000). Another continental margin affected by salt tectonics is the Gulf of Mexico where diapiric salt structures have created numerous intraslope mini-basins. Deep-water channel models from the Gulf of Mexico (Satterfield and Behrens, 1990; Beaubouef and Friedmann, 2000) describe successive downslope basin filling by channelized turbidity currents. As basins fill with sediment they spill, bypass and deposit into the next basin downslope and erode some of the upslope sediments. Such sediment bypass initiates intra-basin channels.

In this paper, we use 3D seismic data to show the geometry and facies of deep-water channels from two subsurface study areas on the continental slope within block 17 offshore Angola. We recognise channels using seismic geometry, amplitude, published seismic, drill and core data (e.g. Mayall and Stewart, 2000; Sikkema and Wojcik, 2000) and describe some of the seismic complexity of different channel types in the vicinity of salt structures. These data are used to develop a general conceptual model of the slope during the Late Miocene. We also present new and detailed observations of a linear, high gradient channel adjacent to a salt dome and show how channel geometry and facies are controlled by salt movement. Finally, we discuss some of the controls on channel geometry and facies, their relationship to salt tectonics and the possible behaviour of flow types that deposit and erode slope sediments. Two way travel times are converted to metres using a reasonable seismic velocity (unpublished well data) of 2000 m/s for the interval in which the channels are located.

2. Geological setting

There is a large sand-rich Tertiary turbidite system preserved in the subsurface offshore Angola. The study area (Fig. 1) covers a small area of this fan system and contains a dense network of turbidite slope channels (e.g. Mayall and Stewart, 2000; Sikkema and Wojcik, 2000; Kolla et al., 2001) and an extensive mass transport complex (Gee et al., 2005). The channel systems are typically <200 m thick, 1–5 km wide and can be traced for tens of kilometres within the 3D seismic data. They can be sand rich, incised systems characterised by complex amalgamated and often highly sinuous channel sand bodies (Beydoun et al., 2002; Abreu et al., 2003). Deposition, controlled by gradient, confinement and sediment load, was focussed in slope depressions. The fan system developed as a result of uplift of the African margin, sea level changes and increased river runoff (Lavier et al., 2001). Mayall and Stewart (2000) showed evidence of the large variety of channel geometries present in the area and how they were related to the complex slope morphology. Highly sinuous incised and aggradational channel systems converge into salt-related depressions.

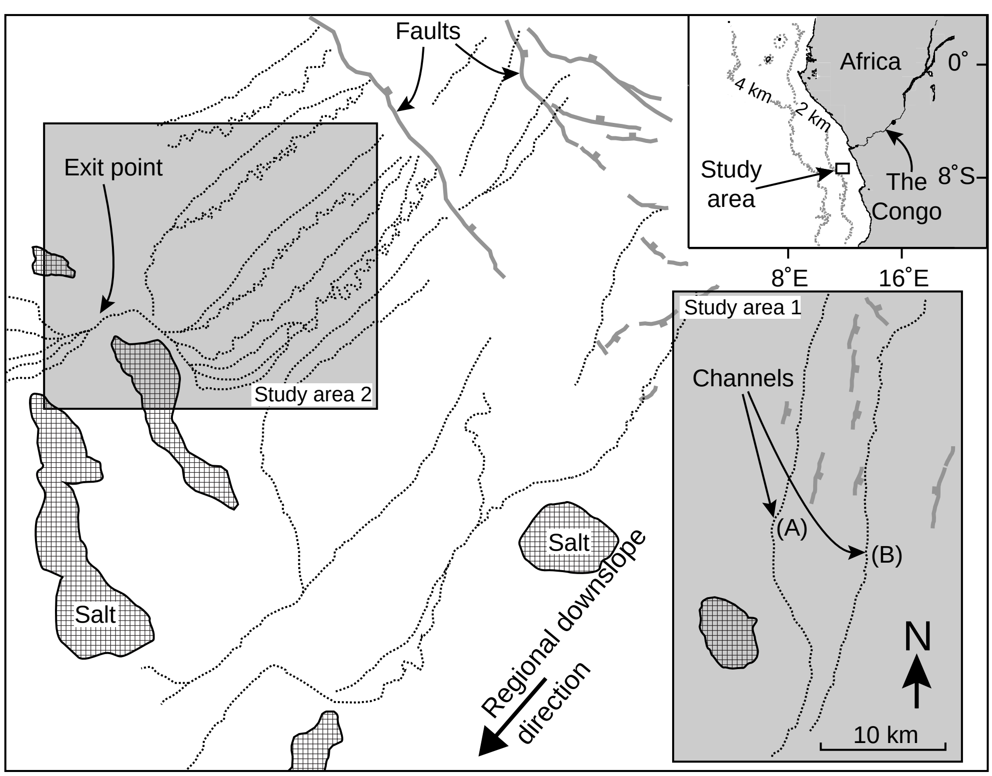

Fig. 1. Basemap of region showing two study areas and locations of subsurface channel systems (dashed lines), faults (solid bold lines) and salt intrusions (hatchured). Salt intrusions outcrop on the current seafloor and channels shown are buried up to 500 m below the present seafloor. Downslope direction is towards the SW.

Numerous channels of different ages become amalgamated within depressions and topographic constrictions around salt structures (Mayall and Stewart, 2000). The typical elements of such channel systems include terraces, levees, crevasse splays, sheet-like sands, gravel-rich lag deposits, debris flows and a high seismic amplitude channel base.

The West African margin is affected by salt tectonics causing growth faulting and salt flow (Duval et al., 1992). The salt layer which underlies the Tertiary fan sediments is Aptian in age and in places is ~1000 m thick beneath the Congo and Angolan margins. Deformation of this salt layer has resulted in faulting and seaward rafting of large sections of stratigraphy (Uchupi, 1992; Lavier et al., 2001). In the SW part of the slope, diapiric salt has penetrated the stratigraphy and deflected channels passing down the slope. Upslope, normal growth faults with displacements >200 m have formed (Fig. 1). Large-scale faulting and folding has, in many cases, significantly affected channels, producing complex planform geometries (Fig. 1). The gradients of channels are often modified by later faulting, although planform geometry, e.g. sinuosity, tends to be preserved. Withdrawal of salt from beneath the upper part of the margin has created a diapiric province farther seaward around which turbidity currents and debris flows have deposited sediments.

The Angolan margin displays a complex interplay between tectonics and channel formation. Evidence for tectonic activity coinciding with channel formation may include avulsion events, and lateral and vertical shifts in the channel location on the slope. Channels preserve a record of tectonics and other controls such as sea level change, climate variation and changes in sediment discharge. Salt structures form walls and domes in the subsurface, some of which outcrop on the present seafloor. Individual domes are typically 3–5 km across and are associated with flanking depressions, arcuate normal faults and deformed strata. Salt domes appear to affect the geology up to a radius that is approximately twice the diameter of the salt structure itself. On the Angolan margin, circular slope depressions and a complex pattern of normal faults usually exist around salt structures. Similar, but larger mini-basins are well known from the Gulf of Mexico and are extremely efficient sediment traps, into which turbidity currents deposit sands that can be high quality hydrocarbon reservoirs (Beaubouef and Friedmann, 2000 and refs within).

Using 3D seismic data, a spectrum of sinuous channel types, including their geometry, vertical aggradation and meander migration, was presented by Kolla et al. (2001). Similar observations were made from the stratigraphically deeper Dalia Field, Block 17, offshore Angola using higher resolution (>75 Hz) 3D seismic data (Abreu et al., 2003). In addition to highly sinuous systems, two early Pliocene linear channel levee systems <250 m wide from the deep-water subsurface off West Africa were described by Fonnesu (2003). The channels were flanked by high seismic amplitude levees of thin-bedded sands and associated with high seismic amplitude lobes. Such channels are prone to avulsion and able to deposit sheet sands, lobes and form levees.

3. Slope channel observations

In seismic section, the Tertiary fan sediments are characterised by discontinuous and continuous high amplitude reflections, complex geometries, with numerous terminations and lateral discontinuity, suggesting large numbers of erosional channel-levee complexes and erosional bypass. Abrupt changes in channel geometry are often observed as channels enter slope depressions flanking salt intrusions. Channels approaching salt diapirs are observed to rapidly broaden and thicken often forming distinctively-shaped structures in plan-view. These broad, depositional systems are characterised by high seismic amplitudes and a relatively high sand content. They form a recently and poorly defined slope reservoir class described as a weakly confined channel. Transitions between the two types of channel style are often characterised by weaker seismic amplitudes and steeper channel gradients which indicate erosional flow behaviour typical of hydraulic jumps.

3.1. Study area 1

Two contrasting channel systems that formed in a similar stratigraphic setting are described from study area 1 (A and B, see Fig. 1 for location). They have been traced from a major salt-cored growth fault upslope, to the limits of the 3D survey ~40 km downslope. These two channel systems both have levees, are <4 km wide, aggradational and show small amounts of basal incision along the channel axis (<60 m). Channel A has a relatively high gradient and a linear, narrow channel axis where sediments reach thicknesses of ~80 m. In contrast, channel B is highly sinuous over most of its mapped extent and is associated with high seismic amplitudes and greater thicknesses (<200 m) of channel sediments. In their distal regions, channels A and B pass through a salt-withdrawal slope depression.

Seismic cross sections show the main axis of channel A is weakly incised (40 m) and has an irregular basal reflection when compared with channel B (Fig. 2). There are several smaller incisional notches outside the main channel axis. In the upper part of its reach, channel A has a small, well-defined channel axis and reaches a maximum thickness of ~80 m over the channel axis. Approximately, 4–5 km away from the channel axis, channel–levee thicknesses decrease to <40 m. The internal geometry is characterised by high, irregular seismic amplitudes across a broad zone which decrease downslope. Downslope, channel A is more lens-shaped in cross–section which is largely because of differential compaction of the finer grained sediments flanking the main channel axis. Closer to the salt dome the channel is thicker over a broader area (Fig. 2, Section 3). The basal reflector also becomes less irregular and lacks incised notches, indicating less basal erosion. A seismic section through the lower part of the salt-related depression (Fig. 2, Section 4) shows channel A is much narrower (<5 km), although part of the eastern levee of channel A in the SE sector of depression, has been eroded by a debris flow. Channel A is not currently located in the lowest

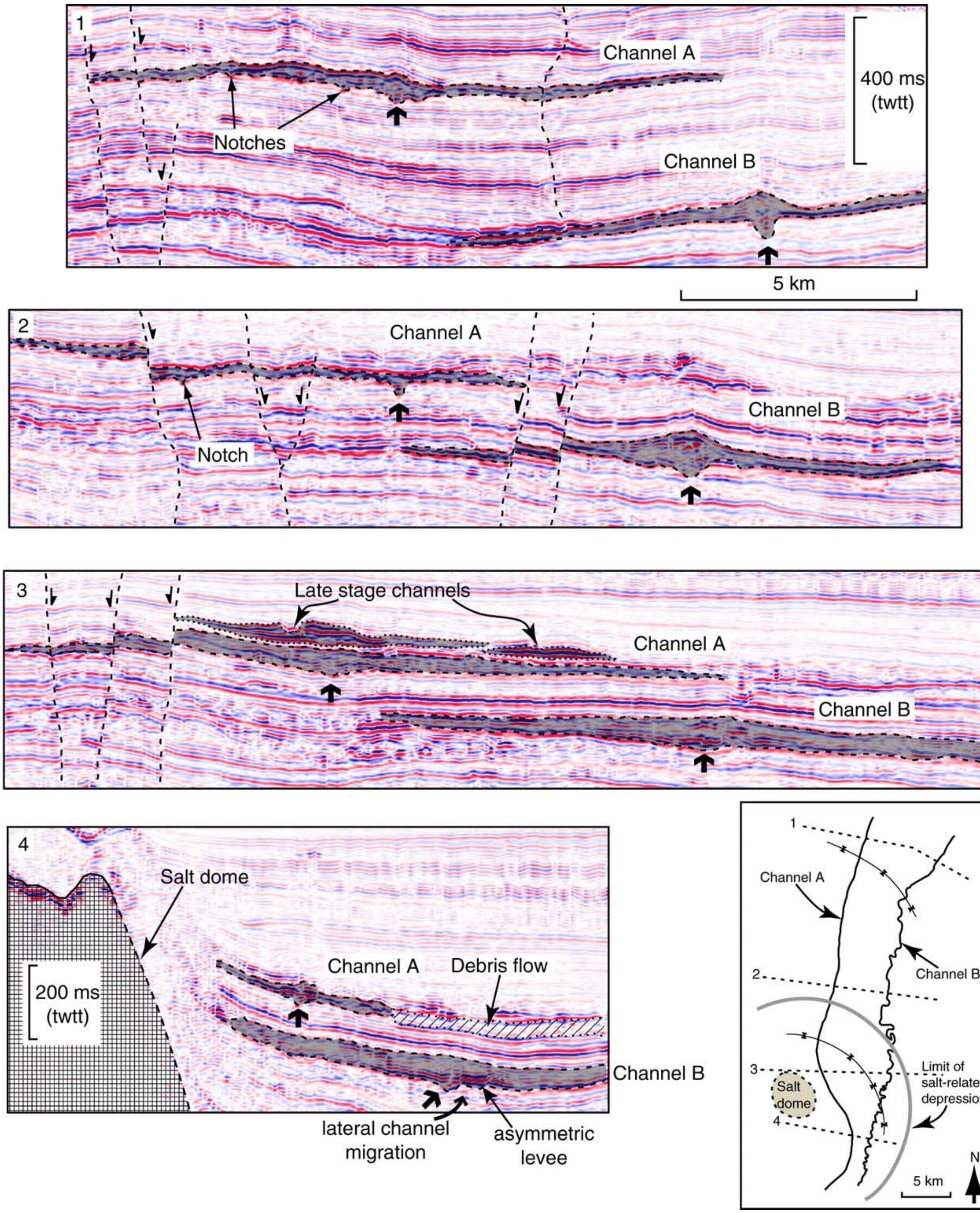

Fig. 2. Seismic cross sections of a young system (channel A) and a more mature system (channel B). Short black arrows indicate location of main channel axis. See small inset and Figs. 4 and 6 for location. Channels are cut but not affected by later normal faults. Note the change in channel geometry from 1 to 4 as the channels approach the salt dome.

point of the salt-related depression indicating it has been uplifted by the salt dome. Two late-stage, aggradational channel systems with well-formed, high seismic amplitude levees, are present above channel A, although these appear to have only deposited sediment locally around the salt structure (Fig. 2, Section 3). Cross sections of channel B show thicker sediments, decreasing downslope from ~130 m to <70 m. A well-defined channel axis and significant differential compaction is observed in Sections 1 and 2 (Fig. 2). High amplitude and continuous reflectors extend away from the main channel axis for >3 km (Fig. 2). Differential compaction of the channel axis region and immediate overbank channel

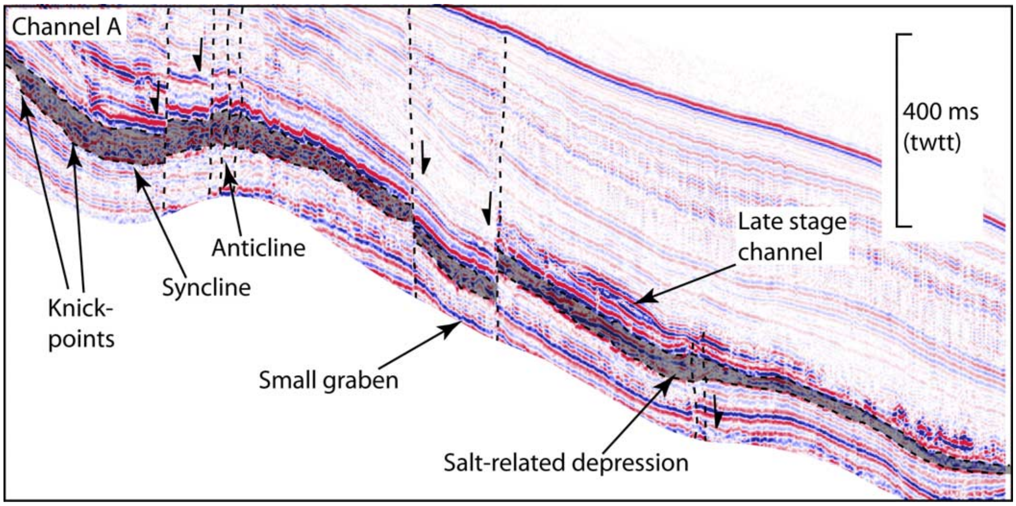

Fig. 3. Long profile of channel system A illustrating internal seismic facies and thickness changes downslope. Channel thickens into the salt-related slope depression. See Figs. 2 and 4 for location.

areas, indicate sand-rich sediments. In Sections 3 and 4, channel B becomes a much broader system with thicker levees and a less well-defined channel axis. In Section 4 (Fig. 2), the channel axis and levees have an asymmetric geometry which is evidence for lateral channel migration away from the salt dome.

3.2. Channel A

A long profile seismic section down the main axis of channel A shows significant variations in internal seismic amplitude, gradient and channel thickness. Channel A is initially steep and has two apparently erosional knick-points in its basal profile (Figs. 2 and 3). The channel sediments reach a maximum thickness of ∼80 m within the syncline. Passing out of the syncline, a series of minor post-channel faults offset the channel sequence, and therefore formed later. As the channel is traced downslope over an anticline, the channel thickness and internal seismic amplitude decreases. A small graben has displaced the channel axis post-channel formation. As the channel passes into the slope depression surrounding the salt dome, its internal seismic amplitude and thickness increases

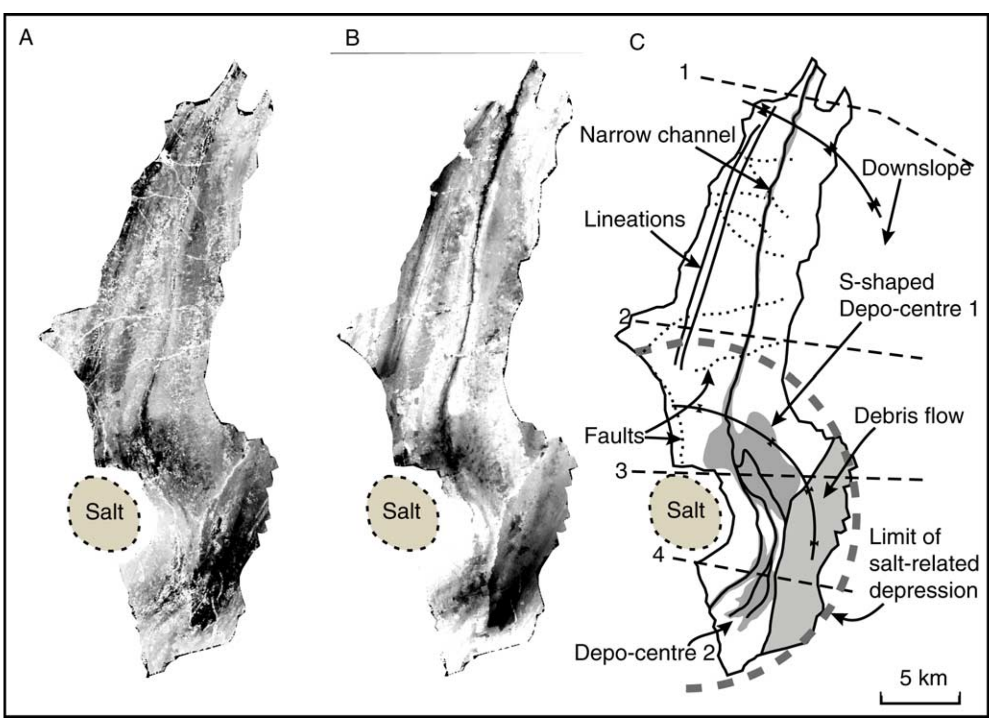

Fig. 4. Seismic amplitude map (A), isochore map (B) and interpretation (C) for the relatively young channel system A, illustrating the complex channel architecture of discrete depocentres connected by up to three feeder channels in the salt-related depression. The grey-shaded isochore map shows two way travel times for the channel (black = maximum twtt, 90 ms).

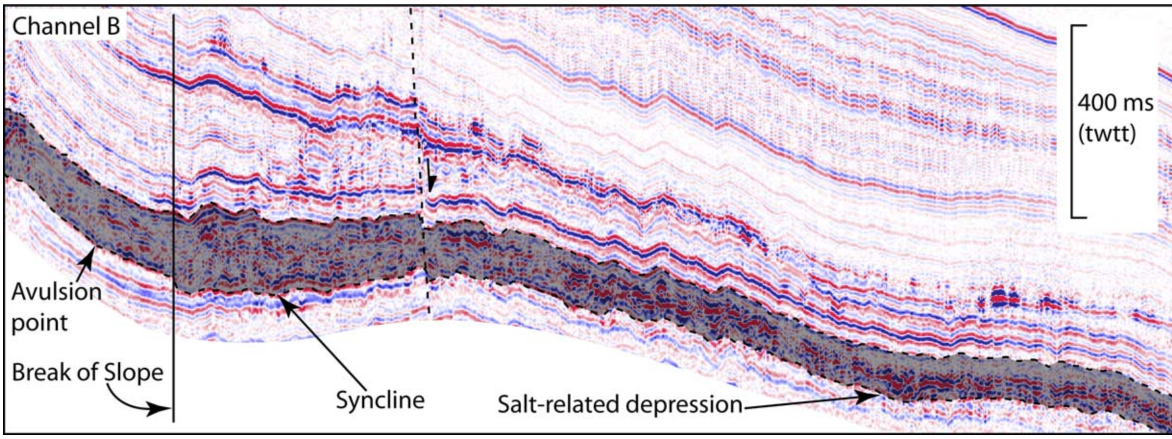

Fig. 5. Long profile of channel B illustrating internal seismic facies and thickness changes downslope. Channel thickens into the syncline on the upper part of the slope. See Figs. 2 and 6 for location.

dramatically. One of the late-stage aggradational channels can be seen above the interpreted channel sequence. This late-stage channel developed in the low gradients of the syncline in the depression surrounding the salt dome and is characterised by high seismic amplitude levees.

Channel A is narrow and linear; it broadens from <200 m to >4 km and thickens over a distance of 1–2 km as it enters the depression surrounding the salt dome (Fig. 4). Within this depression, significant variations in channel geometry are observed. This section of channel appears weakly confined, forms a broad depositional body in plan view and is limited to the NE sector of the salt-related depression. Extending from the lower edge of this depositional body are two small channels which lead to a second smaller, possibly older, depositional body in the southern sector of the salt-dome depression. Outside the channel there are a number of high amplitude and linear features on the slope which run parallel to the main channel. Some of these appear to have slightly erosional bases (see notches, Fig. 2) with thin, linear overlying deposits. A large and erosive debris flow sourced in the NE has removed part of channel related sediments in the eastern part of the salt-dome depression (Figs. 2 and 4).

3.3. Channel B

A long profile seismic section of channel B shows that the first ~ 7 km of channel B is ~ 130 m thick, and has a relatively high gradient (Fig. 5). At ~ 7 km a slope-break marks an

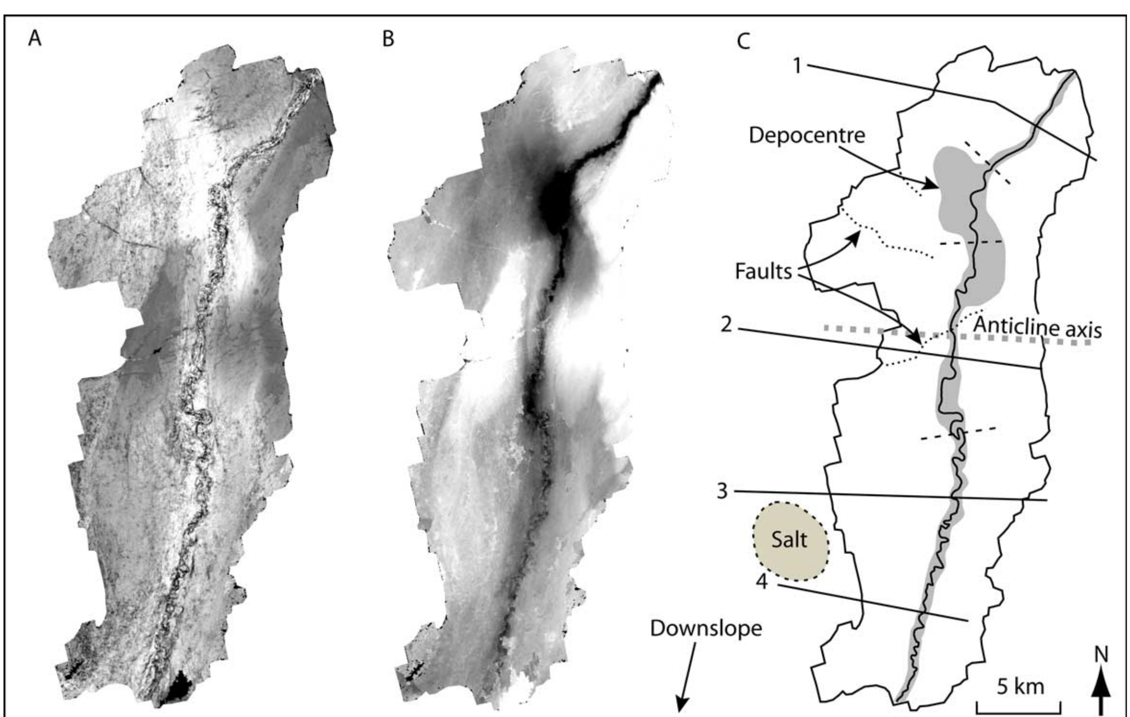

Fig. 6. Amplitude map (A), isochore map (B) and interpretation (C) for channel B. The grey-shaded isochore map shows two way travel times for the channel (black = maximum twtt, 190 ms). Note that in plan view there appears to be relatively little influence on channel shape from the salt dome.

increase in the thickness of the channel sediments to ~160 m. Exiting the syncline the channel appears to run upslope for a few km, although this is clearly due to post-channel uplift (Fig. 5). Downslope, the channel thickness decreases gradually to <90 m. At the farthest end of the channel within the syncline surrounding the salt dome, there is an increase in seismic amplitude but no corresponding increase in channel thickness (see salt-related depression, Fig. 5).

In plan view, channel B has a moderate to highly sinuous channel axis for all but the initial 7 km length (Fig. 6). Within the upper slope syncline the channel system broadens to ~3 km, although downslope, the channel levees become narrower. As the channel passes over the anticline axis it becomes less sinuous with lower seismic amplitudes (Fig. 6). Downslope of the anticline the channel broadens gradually and is characterised by moderate seismic amplitudes and higher sinuosities. Farther downslope, in the region of the slope depression surrounding the salt dome, the planview data show no obvious variation in geometry (Fig. 6).

In the upper reaches (0–4.5 km) of channel B, there is evidence for a single avulsion event (Fig. 7). Here, the main channel is narrow, steep, straight and incised relative to the channel farther downslope. A second channel is observed to lead from the avulsion point towards the southwest (channel 2, Fig. 7). This second channel has about ~20 m incision at its base which is about half that observed for the main

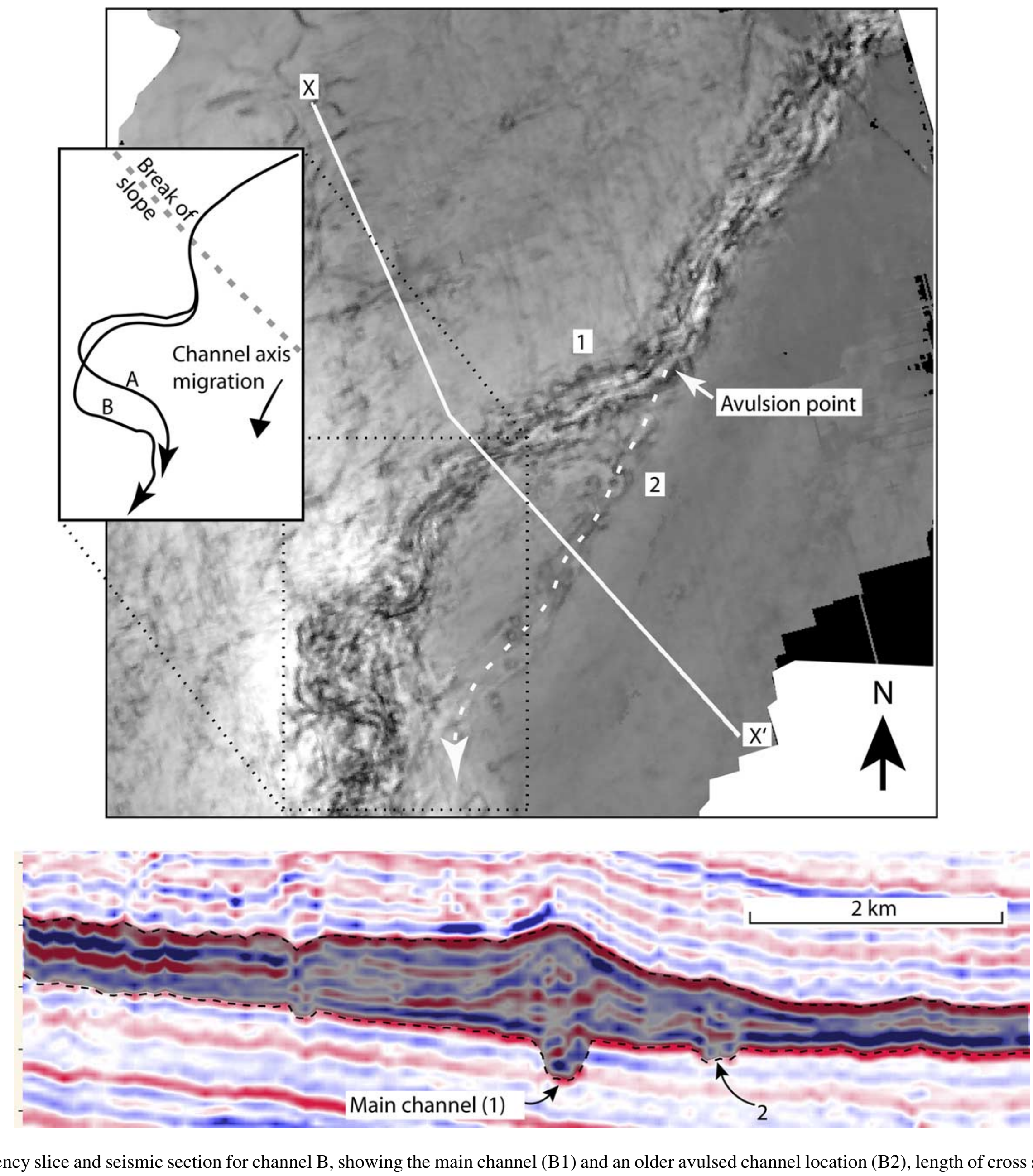

Fig. 7. Coherency slice and seismic section for channel B, showing the main channel (B1) and an older avulsed channel location (B2), length of cross section is 8 km. The main channel axis exhibits meandering behaviour and downslope channel migration after the break of slope. (See inset). Thickest part of channel B1 is approximately 200 ms twtt.

channel. We interpret channel 2 (Fig. 7) as an older abandoned channel. The apparently younger channel heads to the SW then swings round to rejoin the old channel. Avulsion appears to have occurred because of tectonic structuring and rotation of the maximum dip direction to the SW. At ~4.5 km along channel 1 there is a distinct break of slope where the channel is observed to start meandering and migrating downslope (Fig. 7). A knick point with ~20 m of incision is also observed at the base of slope, which might indicate flows spreading as they exit the incised channel, and experienced hydraulic jumps (Komar, 1971). Beyond the break of slope there is an increase in channel width and thickness with evidence for significant overbank deposition.

Compared with channel A, channel B has a lower overall gradient characterised by a more sinuous channel axis, a greater thickness of channel axis and levee sediments, and a broader overall channel system width (Fig. 6). Channel A shows minimal response to the upper syncline, but in contrast, channel B becomes four times broader (Fig. 6) and one and a half times thicker (Fig. 5). In the salt-related depression, channel B shows minimal variation in geometry, but channel A becomes eight times broader and increases slightly in thickness. Several small faults affect both channels with no obvious effect on geometry. These observations indicate that the syncline was active during channel formation and that the faults formed later. The more variable geometry of channel A

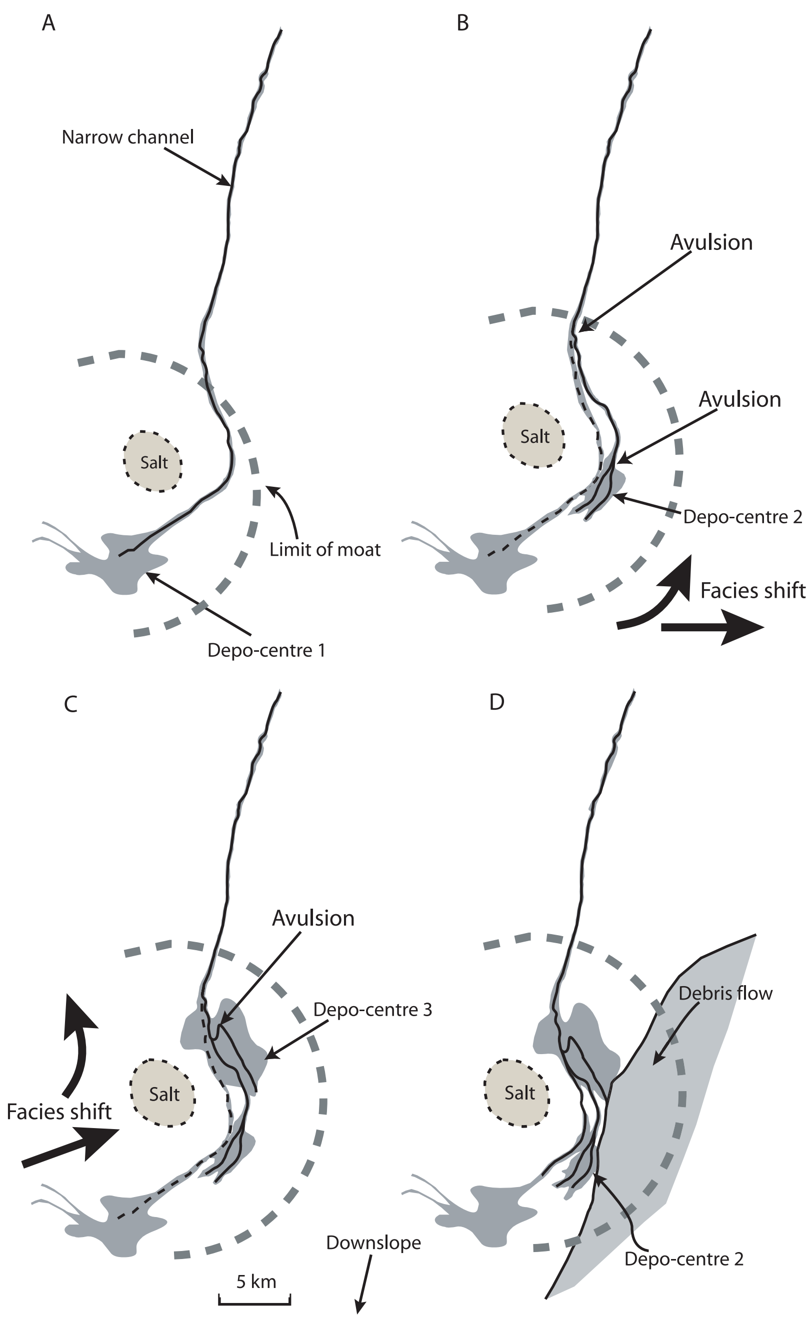

Fig. 8. Interpretation of channel A formation. (A) oldest to (D) youngest. See text for discussion.

and underlying seismic reflections indicate that the slope depression surrounding the salt dome was deeper during formation of channel A. However, the greater thicknesses, lower gradients and higher sinuosities of channel B suggest that it is a more mature channel system.

3.4. Interpretation of channels A and B

The development of channel A is interpreted to be closely related to the growth of a local salt structure. A simple model for the evolution of this channel system is shown in Fig. 8. Turbidity currents flowing into the salt-related slope depression deposited two discrete sediment bodies. These sediment bodies appear to be part of a continuous channel system which extends farther downslope. No evidence for sediment ponding is observed around the salt structure. As the salt dome grew and the rim syncline widened, it appears to have forced a series of channel avulsions and caused a new sediment body to form. In general, the salt movement caused a shift in the channel facies to the N and NE within the slope depression.

An E–W striking anticline intersects channel B upslope of the salt-dome depression (Fig. 6). The anticline appears to have been propagating south-eastwards when the channel was active, resulting in channel avulsion and the creation of the syncline depocentre immediately downslope. Farther downslope around the salt dome, the lack of variation in channel geometry indicates there may have been only a weakly developed slope depression present at the time. However, the channel axis shows some evidence for lateral migration away from the salt dome, and a preferentially developed eastern levee, indicating a channel response to initial salt dome growth (Fig. 2).

3.5. Study area 2

Up to seven separate incised channels at different stratigraphic intervals converge towards, and exit to the SW through a large salt wall (Fig. 9). This salt wall extends from the NW to the SE beyond the study area, and is ~500 m high and ~6 km wide in the subsurface. A low point in the salt wall provided a major exit for flows passing downslope (Fig. 9). As the channels reach the slope depression upslope of the salt wall, they exit their confined channels and become broader, linear, weakly-confined systems. Within the depocentre, channels are more amalgamated and have significantly higher seismic amplitudes. Through the low point in the salt wall, channels are indistinguishable from each other, and it appears that significant post-channel deformation has occurred due to salt flow. Downslope of the salt wall exit point, there is a second

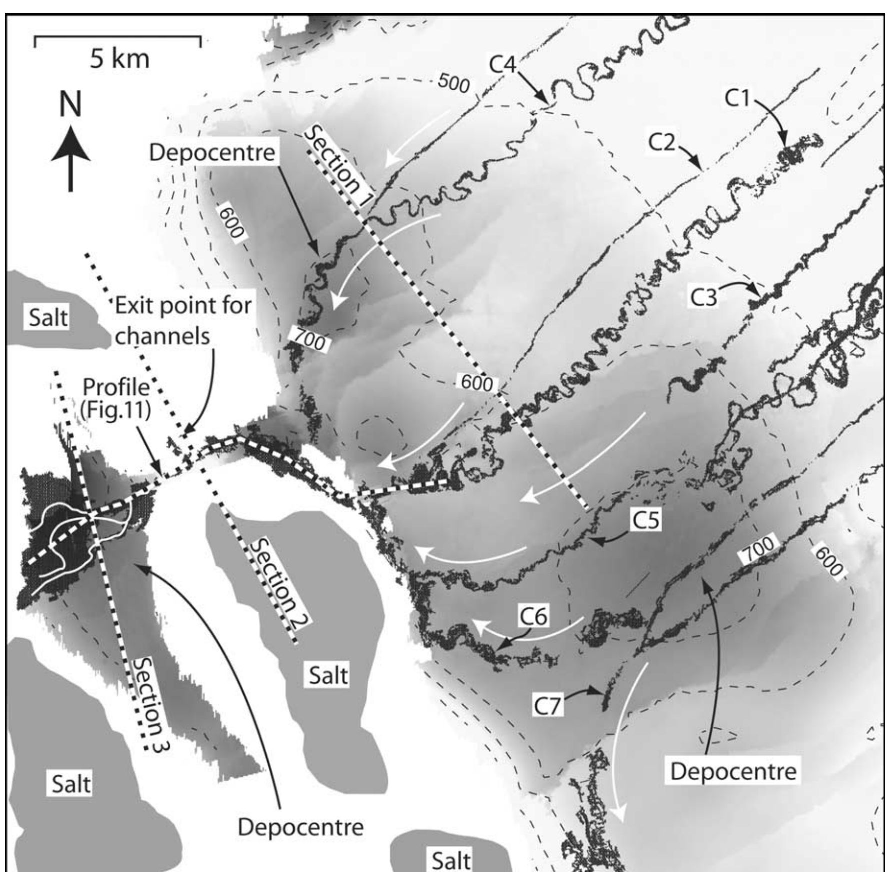

Fig. 9. Basemap of study area 2 showing an isochore map of lower slope interval containing near surface channel systems which converge towards a major exit point in the salt wall. Dark shades indicate thicker sediments. Channel systems are shown in black. Locations of seismic sections are shown as thick dashed lines (Figs. 10 and 11).

depocentre. Here, the channel system broadens again, and several sinuous high amplitude channel axis loops are observed in plan view (Fig. 9).

Three seismic sections oriented perpendicular to slope, illustrate the internal geometry and seismic facies of four channel systems which converge through the exit point in the salt wall (Fig. 10). Four channels numbered in stratigraphic order from C1 to C4 are briefly described (Figs. 9 and 10A, Section 1). The largest channel (C1) is ∼1 km wide and ∼250 m deep and appears at the highest stratigraphic level in the section. It has a relatively chaotic, low amplitude seismic reflection fill characterised by some high amplitude channel axis reflections at its base and weaker reflections dipping towards the channel centre. Some high amplitude reflections outside the channel appear either to have been truncated by channel C1 and may represent levees associated with an older channel system. Channels C3 and C4 are incised ∼200 m into the slope and show slightly higher amplitude reflections in their fill. The smallest channel system is C2 (∼40 m wide and ∼30 m deep) which has small 'gull wing' style levees extending a few hundred metres laterally from the channel. Channel 1 is younger than channel C2 as it cuts the levee of channel 2. Channel C2 appears to be younger than channels C2 and C3. The more incised channels (C1, C3 and C4) display either weakly developed levees or no obvious sign of levee formation. This appears to reflect the efficiency of incised channels in confining turbidity current flows passing through them.

A seismic section, through the salt wall (Fig. 10B, Section 2) shows a very bright top-salt reflection and deformed strata cut by a deep v-shaped channel. Channel axis sediments within this v-shaped, incised salt wall exit can be recognised as discontinuous, high amplitude and offset, vertically stacked reflections adjacent to a low amplitude, chaotic seismic facies.

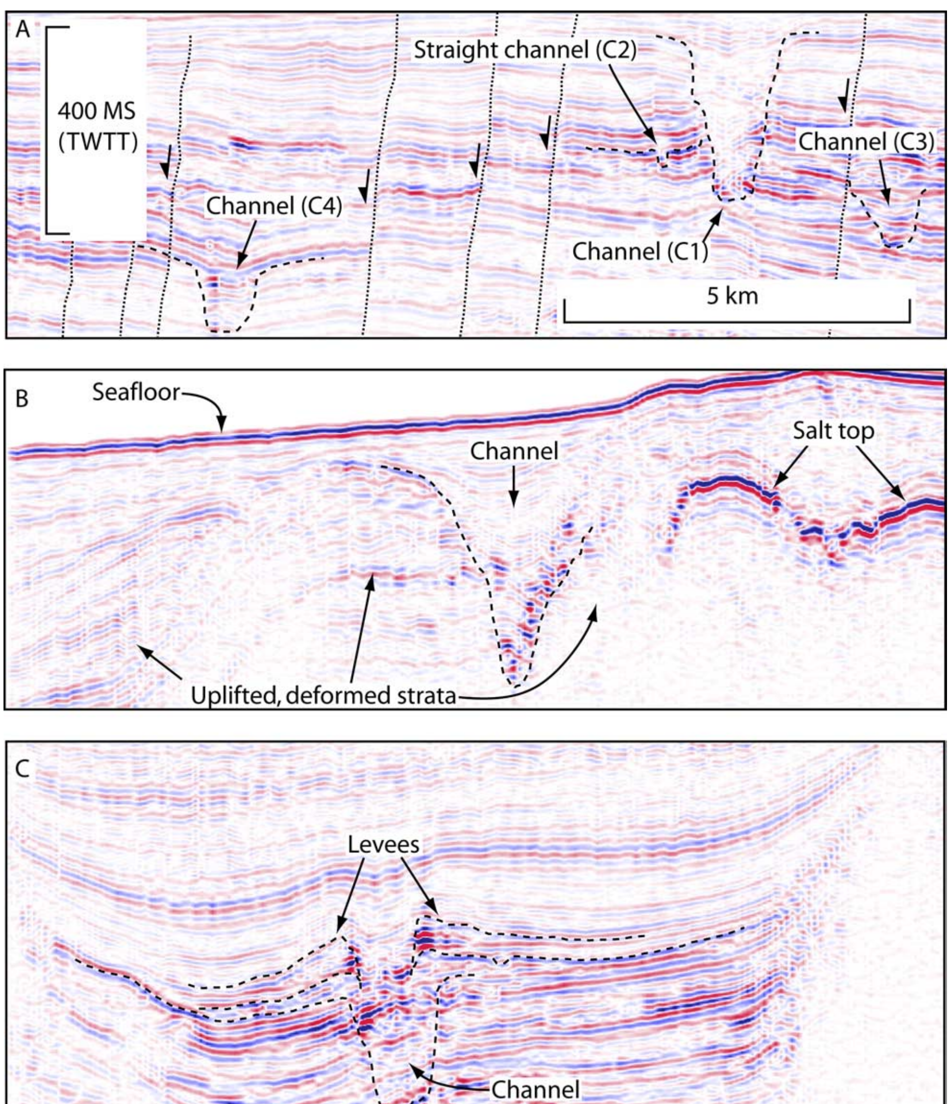

Fig. 10. Proximal to distal seismic sections, oriented NW (left) to SE (right), showing variation in channel geometry around the salt wall in Fig. 9. (A) Section 1, showing up-dip channels distributed verticall and laterall on the slope. (B) Section 2, exit point across salt wall. (C) Section 3 downslope of salt wall with well developed channel-levee complex.

This v-shaped structure forms part of the exit route through the salt wall where numerous channels merge. Downslope of the salt wall, high amplitude reflections located within the channel axis become more distinct and continuous, and large levees ~100 m thick, with gull-wing geometries extend for ~4 km either side of the main channel axis (Fig. 10C, Section 3). The seismic data immediately downslope of the salt wall consists of smoother, more laterally continuous, higher seismic amplitude reflections.

3.6. Long profile of seismic section C1

A long profile seismic section of one channel axis shows variation in channel geometry from the open slope, into the salt-related depression and through the exit in the salt wall (Fig. 11, see Fig. 9 for location). The upper channel surface is defined by a weak, but continuous reflection which marks a change to layered, laterally continuous reflections interpreted as fine-grained, hemipelagic sediment drape. The depocentres associated with salt withdrawal are ~400 m thick on either side of the salt wall, the upslope depocentre being associated with a normal fault with ~400 m displacement to the SE. Channel sediments thicken towards the fault indicating coeval deposition and fault activity. The low gradients encountered by turbidity currents adjacent to the salt wall appear to have controlled sediment deposition, with bright amplitudes and several hundred metres of channel sediment deposited in the depocentre upslope of the salt wall. In general, the depocentres upslope of the salt wall are thicker and more extensive than downslope (see Fig. 9).

Through the salt wall the channel sediments are interpreted to be much thinner, and the high seismic amplitude reflections associated with channel axis sediments are highly discontinuous, indicating erosion. The top of the channel is characterised by a low amplitude generally chaotic seismic character, indicating a fining upward channel fill.

3.7. Planform variation around the salt wall

Seven channel systems are recognised in four planview seismic variance maps sampled at different horizons from the upper 500 ms (Fig. 12). These channels converge to the narrow (2 km) exit point in the salt wall, apart from channel C7, which passes through a separate exit in the salt wall to the south. Channel C7 is deeply incised (>340 m) and although best observed on the horizon slice at 160 ms (below seafloor), can be observed down to 500 ms (Fig. 12). Channels have eroded 200 to >340 m upslope of the salt wall, although there is less basal erosion in the depressions closer to the exit point. Channel C1 (Fig. 12) has a highly sinuous erosional geometry with scalloped walls and a sinuous channel axis at its base. The 200 ms horizon slice shows that channel axis of channel C1 is more sinuous at depth. Several dip-orientated, normal faults are observed to intersect the channels and might have influenced channel morphology. The sinuous channel geometry suggests that there has been no significant lateral or downslope channel migration of the channel axis.

The short segment of channel C7 imaged on the 160 ms slice has larger channel wall scallops, especially on the outer bend of the channel, indicating collapse of the channel walls (Fig. 12). At the 200 ms horizon slice there is a straight, narrow channel and several straight, dip-orientated, weakly incised lineations upslope of the salt wall (Fig. 12). These may be embryonic channels which develop to form systems such as C2. The 250 ms horizon slice images the deeper section of the channel C1 to show a narrow, highly sinuous channel axis which is erosional across the lower gradients approaching the salt wall. This is interpreted as a lowering of the equilibrium profile of the C1 channel, perhaps by a breach in the salt wall. At 500 ms below the seafloor, three older channels are imaged (C4, C5 and C6, Fig. 12) converging towards the salt wall. Channel C4 converges from the north towards the exit point. It is a simple, highly sinuous channel that also appears

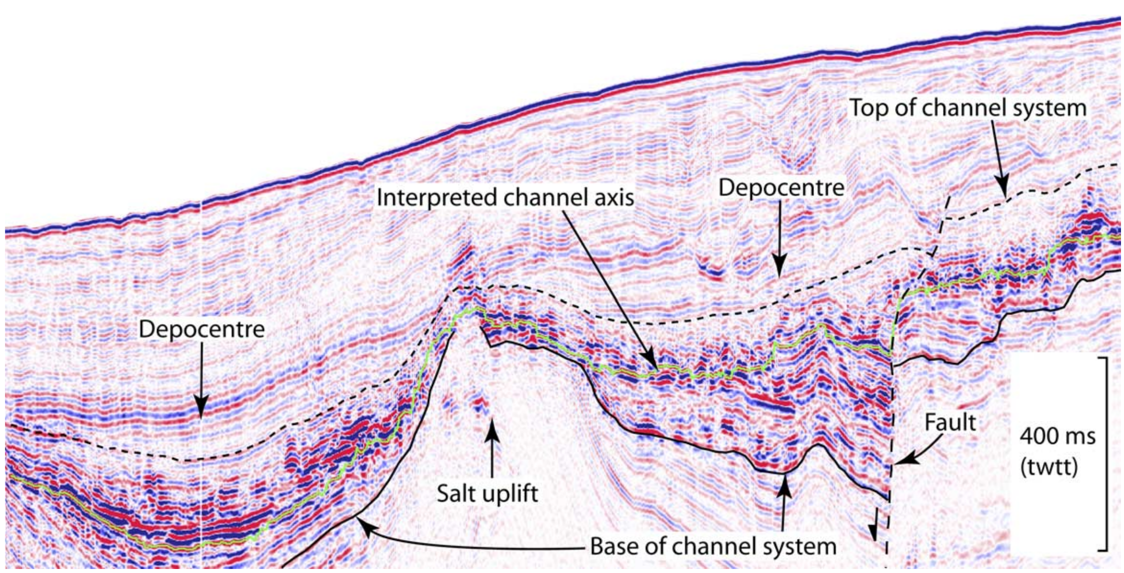

Fig. 11. Long profile of channel 1 as it passes through the mini-basins and constriction in the salt wall (see Fig. 9 for location). The channel has clearly been uplifted and deformed by later salt movement (see Fig. 9 for location). Length of section is c.14 Km.

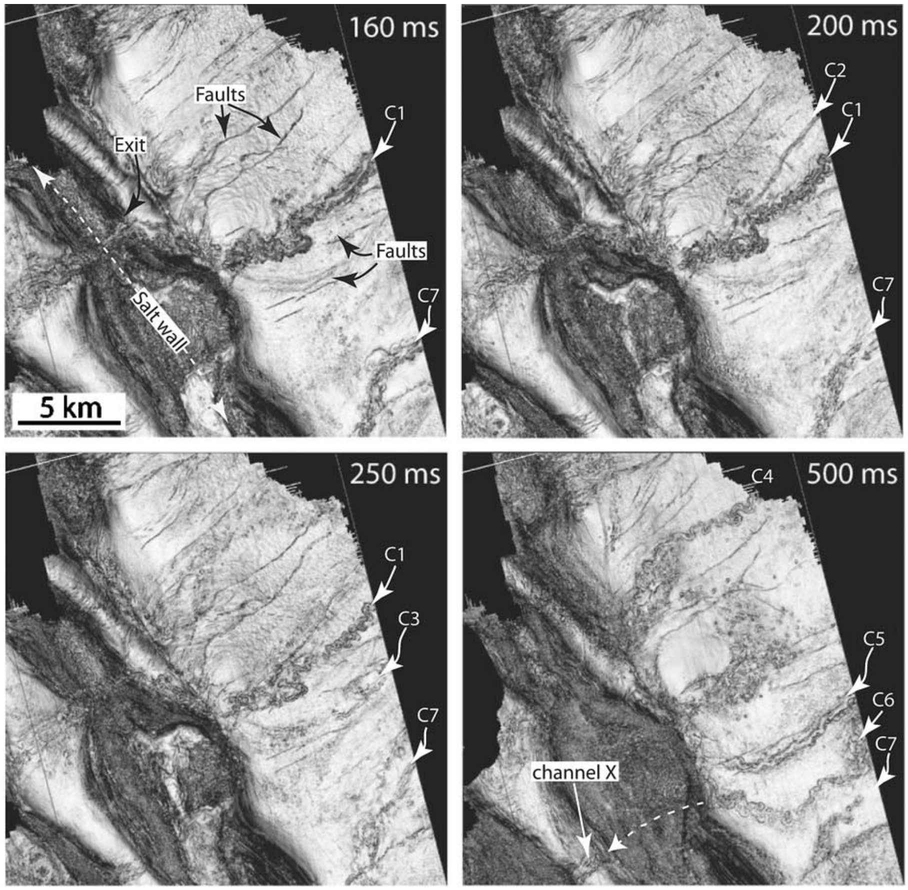

Fig. 12. Horizon slices of seismic coherence data at four different travel times showing channels converging and passing through an exit point in the salt wall (cf. Fig. 9).

to have experienced no significant lateral or downslope migration. Channel C3 has a broader, less sinuous channel which is poorly defined by the variance data. Channel C6 has a narrow incised geometry with lower sinuosity in the upslope part and higher sinuosity where the gradient is lower closer to the salt wall. There is no obvious exit point in the salt wall at deeper levels (>250 ms). Below 500 ms no channels are observed.

Immediately downslope of the salt wall, several sinuous channel loops are visible, associated with a general broadening of the channel system. Downslope of the salt wall, the channel appears to have experienced minor lateral and downslope migration (Fig. 12) and has well-developed levees (Fig. 10, Section 3). Another channel is observed appearing downlope of the salt wall, although there is no obvious exit point through the salt wall (channel x, Fig. 12).

3.8. Interpretation of channels passing through salt wall exit

There appears to have been erosion of the salt structure which might have resulted from turbidity currents accelerating and becoming erosive within the exit constriction. Ongoing salt uplift has altered the palaeoslope as the present day gradients of the upper surface of the channel system run upslope as they approach the salt wall. There has probably been at least 200 m of post-channel uplift. The salt appears to have been deforming as turbidity currents flowed through the exit point. This deformation may in part be due to the development of local depocentres which loaded the underlying salt. The apparently random occurrence of another channel system downslope of the salt wall without an obvious exit point indicates post channel salt movement.

4. Discussion

4.1. Miocene Angolan slope model

Variations in along channel geometry reveal a dynamically evolving slope environment with abrupt temporal and spatial shifts in the channel network. The variations in channel geometry may be controlled by factors such as gradient and slope configuration, or factors such as flow type and sediment supply. It is not possible to make direct inferences about the flow type using seismic data. However, there is a strong relationship between the different channel geometries and slope gradient and configuration. Figure 13 illustrates a schematic reconstruction of how the seafloor might have looked during the late Miocene. Salt structures are shown on the lower slope and five different channel systems. These five systems are considered as analogues for typical slope reservoir classes encountered on a slope in a high state of disequilibrium.

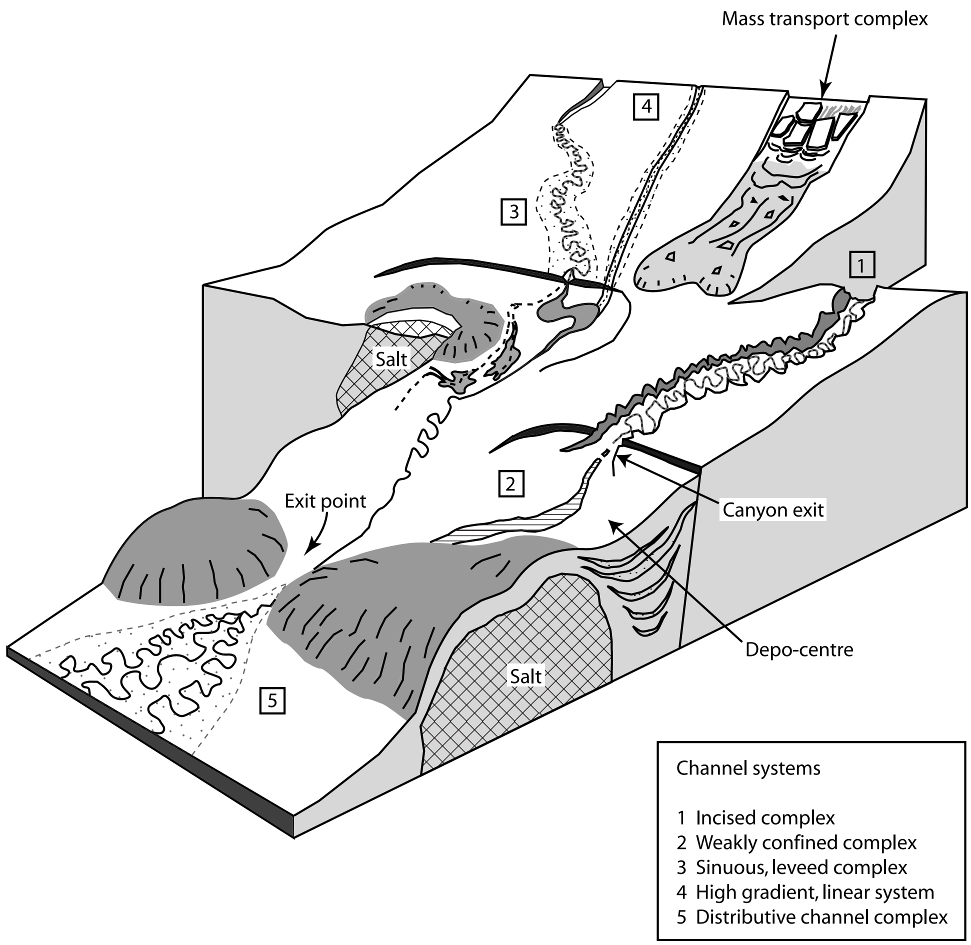

Fig. 13. Conceptual slope model illustrating range of channel types occurring within study area and the style of salt tectonics.

Mass transport (landslide) complexes are also common features of the late Miocene slope environment (Gee et al., 2005).

Channels respond to salt-driven uplift by locally eroding channels ~200–300 m deep and <3 km wide. These systems have 'scalloped' walls which appear to have formed as a result of lateral channel migration and bend enlargement (e.g. Deptuck et al., 2003). Large channel wall collapse events appear to have been rare as indicated by the lack of slump features on channel walls. However, industry drilling results from channels in the area indicate slump material and muddy debris flows were probably derived from channel walls (Mayall and Stewart, 2000). Aggradational channels are also common, forming where the slope is below grade. They are capable of depositing broad, amalgamated and often highly sinuous, sand-rich channels which vary markedly with changing slope morphology. Levees are typically well-developed and may extend for more than 3 km either side of the channel, characterised by occasional avulsion channels. Where channels pass through narrow constrictions in salt walls, individual channels can be highly amalgamated and difficult to distinguish from one another (Mayall and Stewart, 2000). Within exit points in salt wall structures flows may become focussed, accelerate and become erosional (e.g. Gee et al., 2001). Episodes of uplift and salt deformation tend to close the constriction forcing the channel to reroute. As flows exit intersalt constrictions they expand, decelerate and can build laterally migrating channels with well-defined levees to form distributary complexes (Fig. 12, channel system 5). Straight channels observed in the study area appear to represent preserved immature channel systems characterised by narrow, thin channel sequences and higher gradients. The model (Fig. 13) presents a static view of the seafloor. However, ongoing work suggests the slope may be acting as a self organizing system with dynamic feedbacks between turbidity current and debris flow deposition and the underlying mobile salt. As flows erode deep channels they focus sediments into slope depressions between salt ridges. These sediment accumulations appear to cause local deformation in the salt ridges, resulting in the development of new exit points and abrupt changes in the network of clastic channels on the slope.

A large submarine landslide has been described in the area which may have developed as a result of fault activity (Gee et al., 2005). Landslides significantly modify the seafloor topography by removing tens of cubic kilometres of material. This can create accommodation space upslope and remove channels and influence subsequent channel geometries and pathways by filling in slope depressions downslope. Landslide complexes appear to be closely related to the smaller linear, high gradient channels, although it is not clear whether early channel development precedes major seabed instability.

Slope depressions are commonly associated with salt structures and are important regions where channels exhibit significant geometric changes. Channels may pond within slope depressions, but on the Angolan margin, they often flow straight through, forming complex depositional geometries in the process. Seismic data show how linear channels <100 m wide entering slope depressions respond by broadening rapidly to form discreet deposits up to several kilometres across and tens of metres thick (Figs. 2 and 4). Several such depositional bodies may form individually within slope depressions surrounding salt structures, recording lateral and radial shifts in early depositional facies (Fig. 8).

Tectonic activity related to salt movement in the subsurface appears to be the dominant control on the large variety of planform geometries observed in the study area. Submarine channel systems from areas affected by high rates of tectonic activity have been documented from the Gulf of Mexico (Berryhill et al., 1987; Satterfield and Behrens, 1990; Beaubouef and Friedmann, 2000; Badalini et al., 2000; Pirmez et al., 2000), the Niger Delta (Deptuck et al., 2003) and Angola (Kolla et al., 2001; Sikkema and Wojcik, 2000; Abreu et al., 2003). Many of these studies also highlight the complexity of deposits left by different sediment flow types, for example debris flows and turbidity currents. The Gulf of Mexico has a slope morphology characterised by numerous, deep mini-basins (Bryant et al., 1990; Bouma and Bryant, 1994; Diegel et al., 1995). Slope depressions on the Angolan margin are much smaller without evidence for ponding, therefore are not true mini-basins. Channels in the Gulf of Mexico are similar to Angola channels inasmuch as they are typically complex, characterised by abrupt changes in sinuosity, incision and levee development (Badalini et al., 2000; Beaubouef and Friedmann, 2000). Prather (2000) classified Gulf of Mexico submarine slopes into above-grade slopes with intraslope basins, or stepped depositional profiles and graded slopes that lack significant topography. Intraslope basins in the Gulf of Mexico fill up progressively in a downslope direction (Satterfield and Behrens, 1990; Winker, 1996; Prather et al., 1998). As each basin reaches fill point, the channel spills over into the next basin and re-equilibrates, eroding the sill dividing the two basins. Badalini et al. (2000) demonstrated the influence that external, climatic factors have on minibasin architecture in the Gulf of Mexico. Due to high rates of sedimentation during the late Miocene on the Angolan margin, channel architecture provides a partial record of salt-related tectonic movements, although so far it has not been possible to measure the influence of external climate controls.

Channels are effective recorders of tectonics and flow processes including immature, linear systems which have not yet built thick channel axis and levee sediments. In a study of low sinuosity channels, in the West Africa deep-offshore, Fonnesu (2003) reported the syn-sedimentary influence of fold structures on the deposition of channel lobes. Fold and faults which formed after channels are easily distinguished as they do not affect channel sediment thickness. Channel avulsion (this study) is another good indicator of syn-sedimentary channel activity, especially in depressions surrounding salt domes. If there is a relatively high sedimentation rate, the architecture of sediments surrounding salt domes may reveal the growth history of the salt dome because channel avulsion causes facies to migrate around and away from the salt dome. Accomodation space is often created in slope depressions as salt structures grow, resulting in sedimentary packages which may thicken towards faults related to salt movement.

4.2. Channel equilibrium

Channels evolving in highly tectonic areas are subject constantly to dynamic adjustments in their long profile and cross channel geometry, for example, the long profiles and channel geometries of many West African submarine channels are complex (e.g. Pirmez et al., 2000). Pirmez et al. (2000) showed how a submarine channel appears to adjust its sinuosity, gradient, width and depth in response to flow and sediment discharge and evolve a smooth, concave-up long profile of the channel axis. The evolution of a sinuous channel with reduced gradients means that turbidity currents flowing through the channel could tend towards sub-critical flow conditions (Froude number <1) and become less erosive.

The results of this study indicate that avulsion events are rare. This may reflect the ability of channels to rapidly incise and establish their position on the slope. Where observed, it is interpreted that avulsions result from structural changes in the maximum slope dip direction, perhaps close to faults where fault slip may cause a channel to seek out a newly created low point in the topography. Aggrading channels are more likely to experience avulsion due to levee instability. When a channel avulses, the new channel profile is straight and steep relative to the parent channel (e.g. Pirmez et al., 2000; Babonneau et al., 2002). Avulsions often leave knick-points in long channel profiles and cause erosion to occur updip of the knick-point and deposition to occur downdip (Pirmez et al., 2000). However, the recognition of erosion and deposition relating to avulsions is difficult in the study area. Disruption of the channel equilibrium profile is greatest close to salt structures where channels deposit sediment in slope depressions. Abrupt transitions between erosional and depositional channel behaviour observed where confined channels exit into the lower gradients of slope depressions may be the result of hydraulic jumps affecting flows. Flows exiting confined channels may experience hydraulic jumps as they spread laterally and dissipate energy. Hydraulic jumps are associated with flow velocity decrease, increase in flow depth and deposition, where erosion may occur followed by rapid deposition (Komar, 1971; Macias et al., 1982). Channel aggradation and levee building occurring directly downslope of constrictions in salt walls might also be related to hydraulic jumps.

Channels appear to be able to quickly re-adjust their profiles after gradient changes have been imposed on the system (Pirmez et al., 2000). In areas of high tectonic activity, channels may be dynamically adjusting at many locations simultaneously; one part of a channel may remain static with rapid changes occurring a short distance away (Deptuck et al., 2003). Tectonic influence is high on the Angolan margin with strong evidence for dip directions changing in response the growth of salt structures and subsequent salt withdrawal beneath the slope. Pirmez et al. (2000) noted that channel incision is the dominant response of flows to a local gradient increase. Where a channel is eroding because of local gradient increase, it follows that the eroded sediments will be delivered downstream resulting in a local increase in sediment load. Incised channels are more likely to confine turbidity current flows within them thus transporting sediments farther downslope to depocentres.

5. Summary

The Angolan margin provides a very good opportunity to study the evolution of channel systems in areas of complex topography. Salt tectonics have created complex seafloor folding and faulting which have resulted in significant temporal and spatial changes in channel geometry. Abrupt increases in channel width and thickness are observed in the vicinity of salt structures where channels encounter low gradients in slope depressions surrounding salt domes and walls. In particular, linear, high gradient channels appear to be highly sensitive to slope topography. The geometry of channels within slope depressions is complex, and records the phases of movement of adjacent salt bodies. A linear, high gradient channel leading towards a slope depression surrounding a salt diapir has deposited two discreet depositional forms linked by avulsed feeder channels. The lateral migration of channel sediments records the movement of the salt diapir.

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