SEISMIC GEOMORPHOLOGY AND EVOLUTION OF HIGHLY SINUOUS SUBMARINE CHANNELS: EXAMPLES FROM THE ANGOLAN CONTINENTAL MARGIN

M. J. R. GEE[1], R. L GAWTHORPE[1], K. PEDERSEN[3], AND S. J. FRIEDMANN[2]

1 Basin and Stratigraphic Studies Group, Department of Earth Sciences, The University of Manchester, Manchester M13 9PL, UK
Tel:+44 (0)161 275 3838
Email: martin.j.gee@man.ac.uk *(corresponding author)
2 Energy & Environmental Directorate, Lawrence Livermore National Laboratory, Livermore CA, 94550
3 Norsk Hydro Research Center, Sandsliveien 90, Bergen, 5020, Norway

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ABSTRACT: A wide range of incised turbidite channel geometries are observed in the subsurface off Angola. Analysis of 3D seismic data indicate that channels evolve from initially straight, low sinuosity systems into highly sinuous, incised systems with gentle channel axis gradients. However, the early evolutionary stages of incised channels are poorly understood due to erosional enlargement. We quantify relationships between channel sinuosity, gradient and amount of incision and show a simple evolutionary model. Results indicate thresholds for channel geometry formation and characterise the evolution of incised, sinuous channels. Two end members are recognised: i) low sinuosity systems characterised by 'gull winged' levees and narrow channels, and ii) sinuous, incised systems with enlarged, complex channel geometries and weakly developed levees. The rarest form of channel system identified has moderate incision, low to medium sinuosity and a moderate channel axis gradient. It appears to represent a fast evolving, intermediate channel stage with low preservation potential. Results show a good correlation between incision and curvature of channel axis profiles. Incised channels appear to remove, 'convex-up' curvature from the original slope as the channel axis profile tends towards an equilibrium profile. Incision and development of a highly sinuous channel may be a rapid process, as many straight, high gradient and sinuous, low gradient systems are observed relative to intermediate forms. Linear, high amplitude features, and

weakly incised ‘furrows’ identified on open slope between channels are believed to precursors of new channels. The results improve our ability to predict subsurface channel geometries and recognise key trends in channel evolution.

INTRODUCTION

Channels are important to study because they respond to sea-level change, sediment flux, tectonics and climate and have a significant impact on the sedimentary architecture of continental margins. They are also important oil and gas exploration targets. Despite this, many aspects of channel evolution and the processes that control their geometries are poorly constrained. Incised channel systems have a poor 'memory' of their early evolutionary stages due to the numerous flows which erode and enlarge the channel system. However, by examining separate channels with different incisional geometries it is possible to recreate their early temporal evolution. By substituting space for time, the early erosional channel history can be recreated and used to build predictive frameworks for channel development.

The use of 3D seismic data in deep water slope settings has revealed subsurface turbidite channels in unprecedented detail (e.g., Roberts and Compani 1996; Kolla et al. 2001; Sikkema and Wojcik., 2000; Badalini et al. 2000 Friedmann and Beaubouef. 1999, Deptuck, et al. 2003, Samuel et al. 2003, Posamentier et al. 2003). Numerous turbidite channels have been described in the shallow subsurface off Angola (Fig. 1) which are highly effective analogues for deeper hydrocarbon reservoirs (Kolla, 1998; Sikkema and Wojcik, 2000; Mayall and Stewart., 2000; Fonnesu, 2003). The Angolan continental margin has been strongly influenced by salt tectonics (Lavier et al. 2001), and channels exhibit an extraordinary range of geometries. Some systems have simple linear channels while others are highly complex, consisting of broad, entrenched valleys (up to 200-300 meters deep) filled with numerous highly amalgamated sinuous channels with a high net to gross sand content (e.g. Mayall and Stewart, 2000; etc.). Channels may be incisional or aggradational,

with low and high sinuosities, with or without well developed levees. These various geometries can often be observed along profile within the same channel system over a few kilometers distance.

The deepwater subsurface off West Africa is a unique location to study submarine channels as a large number of channels have been abandoned and preserved in different stages of evolution. This allows a unique insight into the early, erosional phase of channel development. This paper addresses the poorly understood, early stages of incisional channel formation and builds a quantitative framework for understanding their evolution. We quantify the geometry of subsurface Angolan deepwater channels in terms of sinuosity, gradient and incision. We identify linear channels in their early stages of formation, and a single channel which appears to represent a transitional phase between a weakly entrenched, straight system and a deeply entrenched, highly sinuous system. Channels in the study area appear to have evolved from high gradient, linear systems, into highly sinuous, lower gradient systems, which are incised by <300 m. A total of 13 channels were analysed within the study area in terms of gradient, incision, channel width and sinuosity. From these we selected four channels preserved in different stages of evolution to recreate the early evolution of incisional channel history. The four channels are located on a broad anticline (Fig. 2a) with an axis trending roughly NE-SW. Figure 2a shows evidence for some erosion of the uplifted area in the form of reflection events which are cut by the current seafloor. Channels are incised by <300 m into the underlying strata and are recognised on the basis of their 'V' or 'U-shaped' geometry and distinctive seismic facies (Fig. 2b). Cross-cutting channel relationships (Fig. 2b) indicate the relative ages of the channel systems but not maturity of the respective systems; Channel 4 formed first, followed by Channels 2, 1 and 3. Channels are numbered according to the amount of incision, sinuosity and interpreted maturity, i.e., Channel 1 is a straight, weakly incised, immature system and Channel 4 is a highly sinuous, deeply incised, mature system.

Equilibrium, grade and baselevel

The concept of grade, or equilibrium profile has been fundamental for understanding fluvial river systems and associated landforms for many years (Gilbert, 1877; Davis, 1902 and Mackin, 1948). Rivers constantly adjust their profiles by aggrading and degrading, tending towards a concave-up profile which has a decreasing slope from source (Davis, 1902). The fluvial system is primarily controlled by baselevel, which for nearly all systems is the sealevel, below which the lands cannot be eroded (Powell, 1875). Gilbert (1877) recognised that a change at any point in a river can be transferred thoughout the fluvial system. Rivers adjust their gradient, width, planform and roughness in response to changes in flow discharge, sediment discharge and calibre (Mackin, 1948; Leopold and Bull, 1979).

The concept of equilibrium is readily applied to submarine channels. It has been demonstrated that submarine channels mutually adjust their geometry (sinuosity, gradient, width and depth) in response to tectonics and the flow and sediment discharge in the system and tend towards a concave-up long profile (Pirmez et al. 2000, Prather et al. 2000, Beaubouef et al. 2000). Pirmez et al (2000) showed that channel systems in areas where tectonic deformation was low (e.g. Amazon Fan), were closer to grade or equilibrium profile. If the submarine slope is above equilibrium, flows will accelerate and erode. Conversely, if slope is below equilibrium, flows will deposit and steepen the slope. The flows considered in this study are all incisional and therefore above equilibrium grade. The effects of flows within the channel systems are largely unknown, although the response to such factors can be evaluated by measuring channel geometry and considering and contrasting different systems and along-channel changes in geometry. The most complex long channel profiles are found in areas of high tectonic forcing (e.g. The Gulf of Mexico, Pirmez et al. 2000; Badalini et al. 2000). The channels in this study are in an active tectonic setting and all above grade, but appear to have been able to respond rapidly to uplift by adjusting their geometry. The relative abundance of channels with different amounts of incision, records tectonic activity and may

indicate the rate of uplift.

Geological setting of the submarine channels

The study area is located on the passive margin slope about 100 km off the coast of Angola, in water depths of ~1.5 km (Fig. 1). High rates of river fed sediment supply and margin uplift resulted in progradation of the Angola margin and deposition of the sand-rich Tertiary Congo Fan (Amaral et al. 1998). During the late Miocene, a large, drainage network of submarine channels was actively transporting clastic sediment towards the southwest (Fig. 1). Channels are dissected by large growth faults trending NW-SE (Fig. 1), which extends to the current seafloor of the continental slope and are related to deformation above a mobile salt layer. The salt is Aptian in age and in many places has pierced through the overlying stratigraphy (see Fig. 1) to the current seafloor (e.g. Uchupi 1992). These salt structures (diapiric domes and walls) have resulted in the formation of complex channel geometries, which are highly variable over small distances. Where channels are within a few km of upstanding salt structures, they deviate around and converge through the complex structures (Fig. 1). On the lower part of the slope, several channels converge and can be tracked through the salt at two exit points. The time travel thicknesses (grey-shades, Fig. 1) are shown for the near surface seismic interval (~500 ms below seafloor), which contains the channel sequences. Darker grey shades (Fig. 1) indicate depocenters, which are related to the location of slope grabens, divided by a series of small normal faults trending downslope. Many channel systems especially those lower down in the section, flow into these slope grabens and have filled them with sediment. This pattern of sedimentation is similar to the 'fill and spill' of salt withdrawal minibasins described from the Gulf of Mexico (e.g. Beaubouef and Friedmann, 2000).

Methodology and database

Channel systems were interpreted from 3D seismic data using Schlumberger Geoframe 4 and Paradigm Geophysical VoxelGeo. The 3D seismic data was acquired for the purposes of oil and

gas exploration off Angola and has an inline spacing of 12.5 m. For analysis, xyz data generated from the 3D seismic data were gridded at ~15m using GMT software (Wessel and Smith, 1991). Gradient and sinuosity were measured for each channel at 2 km intervals from the gridded seismic data. Sinuosity is defined as the ratio of thalweg length to the valley length (Schumm, 1977). In this study, the channel axis length was measured. Gradients were measured in ms(twtt)/km along the channel axis, and sinuosity was measured as the ratio between channel axis length and valley length. Where possible, two way travel times are converted to meters using a reasonable seismic velocity (unpublished well data) of 2000 m/s for the landslide interval. Channel incision was measured by fitting a least squares, spline curvature across the top of the channel margin and sampling the same points as used for the channel axis below. Incision was calculated as the vertical difference between the top and base of the channel. Long profile channel axis and incision profiles were sampled from the seismic grid at 50 m intervals.

SEISMIC FACIES AND GEOMORPHOLOGY

Seismic Facies

Three simple seismic facies are defined for the channel systems, (Fig. 2b) based on reflection amplitude, geometry and lateral continuity that describe the channel axis sediments, internal channel valley fill and levee deposition. Facies 1 is a low amplitude, seismically chaotic or weakly layered channel 'fill'. It is best developed within the upper ~140 ms of Channel 3 and the upper ~45 ms of Channel 2 (Fig. 2b). Facies 1 is interpreted as fine-grained, generally structureless channel fill. It is likely that a proportion of this facies was derived from local valley wall slumping, especially at bends in the channel axis (e.g. Mayall and Stewart. 2000; Samuel et al. 2003). Facies 2 consists of high amplitude, detached, short seismic reflection events or 'couplets' usually at the base of channel complexes. This facies is variable, but easily recognised as it has very high, discontinuous amplitudes and is often located at the lowest points of each channel valley system. Facies 2 occurs at the base of all channels, although for Channel 2, it extends across the channel

base and has a simple stacked style. Within the deeply incised (~180 ms twtt) and wider (<3 km) Channel 4 system, Facies 2 occurs at the base and also higher up within the channel (Fig. 2b). The seismic 'fill' of Channel 4 is more complex, probably resulting from several phases of re-incision. Facies 3 is characterised by high amplitudes, and often laterally continuous reflection events adjacent to the channel which diminish in amplitude and relief away from the channel axis (Fig. 2). Facies 2 is interpreted as high net:gross channel axis sands and gravels and Facies 3 as overbank deposits which form channel levees (e.g. Kolla et al. 2001; Mayall and Stewart 2000). Facies 3 is typically stratigraphically higher up than Facies 1, although differential compaction of channel axis sediments for some systems may give the impression that levees formed at a lower level.

Smaller channels, more frequently observed in the upper part of the section, have well-developed 'gull wing' levees (Facies 3, Fig. 2b). Channel 1 is a good example of this type and although appears to be aggradational, has incised slightly into the underlying seafloor (Fig. 2b). Channel levees are best developed in channels 1 and 2, although are progressively weaker in amplitude and have lower relief in channels 3 and 4 (Fig. 2b).

Along channel axis profiles (Fig. 3) illustrate the distribution of seismic Facies 1 and 2. Channel 1, has a simple but relatively continuous, high amplitude reflection event at its base (Facies 2). This channel system is too narrow and shallow for any channel ‘fill’ (Facies 1) to be resolved by seismic. Channel 2 displays limited and highly variable development of Facies 2 along its channel axis. For this channel, higher amplitudes characterise lower channel gradients downslope of a slope break. There are two sections affected by steeper gradients (Fig. 3, Channel 2). Amplitudes degrade over these higher gradient sections, and increase in strength and continuity at or shortly downslope of the break-of-slope (Fig. 3). The degradation of amplitudes is possibly due to flows accelerating and depositing less sediment over the convex-up slopes before decreasing in energy over low gradients downslope of the break-of-slope. It may also reflect a change in lithology from coarse to finer

grained deposit (Sullivan et al. 2000; Morend et al. 2002). In contrast, the highly entrenched channels (3 and 4) show better developed Facies 2. The Facies 1 of Channel 3 is characterised by very low amplitudes and highly chaotic reflection events, which show little variation along channel axis.

Seismic geomorphology of channels

The four channels systems are shown in plan view superimposed on an isochore map of the stratigraphic interval which contains the channels (Fig. 4a). Channel 4 correlates with a depocenter, although channels 1,2 and 3 appear not to correlate, which might indicate that channels 1,2 and 3 were delivering sediment farther downslope and did not accumulate sediment within the study region. Slope maps of the four channel systems show the interpreted channel axis relative to the channel valley systems (Fig. 4b), illustrating the evolution from a narrow (~40 m), linear system to a wider (~3 km), sinuous system with a more irregular valley wall morphology. Valley incision, which is believed to be a proxy for channel maturity, ranges from tens of meters, (Channel 1), to >200 meters, (Channel 4).

Channel 1

Channel 1 is a striking example of a high gradient, low sinuosity system with a simple high amplitude main channel about ~40-60 m across (Fig. 5). This channel is partly confined by levees and also by some incision (~15 m) into the underlying substrate. It has well developed and relatively continuous, high amplitude levees, that diminish in amplitude and relief up to ~1-2 km from the channel axis. This indicates that flows have regularly overtopped the channel to form levee deposits. Channel 1, although apparently straight, appears to have developed a slightly sinuous main channel within its straighter valley. The main channel axis is clearly identified by a thin (~40 m), high amplitude feature (Fig. 5) which has a wavelength of ~1 km. Outside the channel to the NW there are a series of sub parallel, downslope-trending lineations or striations characterised by negative relief (<15 m) and higher amplitudes (Figs. 5 & 6). They are spaced

~100-300 m apart. We interpret them as open slope erosion by unconfined and perhaps large turbidity currents and suggest that this out-of-channel erosion of the open slope creates the initial conditions for channel formation (see discussion).

Channel 2

Channel 2 is moderately incised (50-100 m), and has low to intermediate sinuosity. However, the higher amplitudes within the channel valley (interpreted as channel axis sediments) are highly variable and relatively discontinuous. The channel valley geomorphology is irregular, especially on the SE flank, although there is a clear trend for channel width increase and incision decrease downslope (Fig. 6 & 7). The flanking morphology of Channel 2 is characterised by low to moderate amplitudes, which in places indicate weakly developed levees and channel overspill. At the distal part of Channel 2 on the outer bend there is a region of higher amplitudes, indicating flow overspill. (Fig. 6).

Channel 3

Channel 3 is a deeply incised system (~200 m) with the highest sinuosity of the four channels (average ~2). It is a little narrower than Channel 4 suggesting, 1) a higher rate of incision 2) more stable valley walls or, 3) less lateral channel migration. The channel axis is easily recognised by its high amplitude, sinuous loops and adjacent, contrasting low amplitudes. The channel valley is relatively straight with 'scalloped' flanks (e.g. Deptuck et al. 2003) that are not as irregular as channels 2 and 4. The radius of these 'scallops' is similar to channel axis loops. The channel overspill of Channel 3 appear to be well developed on the SE flank especially where the channel valley turns a corner at its' distal part (Fig. 6).

Channel 4

Channel 4 is deeply incised system (~190 m) with a highly sinuous channel axis (~1.8) and irregular valley morphology (Fig. 6). The channel walls on both sides have a characteristic arcuate

or 'scalloped' morphology. The SE valley wall geometry appears more irregular than the NW wall in plan view. The channel axis is asymmetric within its incised valley, running closer to the SE side of the channel valley margin compared with the other channels (see Fig. 4b). This indicates that Channel 4 experienced lateral migration towards the SE as result of being located on the eastern limb of the anticline (see Fig. 2). The whole channel system appears to have been tilted slightly to the East. More continuous amplitudes on the SE flank of Channel 4 indicate limited channel overspill, especially on the outer part of large 'scallops' in the SE channel flank where flows are more likely to breach the valley confines.

CHANNEL PARAMETRICS (GRADIENT, SINUOSITY AND INCISION)

Gradient sinuosity, channel axis profile and incision were plotted for the four channels (Fig. 7). Using the established channel classification scheme developed for subaerial channels (Leopold and Wolman, 1957), channel sinuosities range from straight (<1.1) for Channel 1 to highly sinuous (>2) for Channels 3 and 4. Maximum sinuosity is observed in Channel 3 (~3.2) and maximum channel width, in Channel 4 (~3km). For all channel systems, sinuosity is negatively correlated with gradient, with the lowest sinuosity system (Channel 1) having the steepest gradient. Channel 3 has a relatively constant valley width compared with Channel 4, which although having similar high sinuosity, is considerably more irregular. Channel 2 has a larger wavelength but smaller amplitude of sinuosity compared with Channels 3 or 4. This is interpreted to result from its lateral confinement within a narrow valley. The steeper channels (Channels 1 and 2) are also less incised, in contrast to the highly sinuous systems (Channels 3 and 4, Fig. 7). For all channels apart from Channel 4, incision decreases down-channel.

The channel axis of Channel 1 has gradients that start ~35 ms(twtt)/km, rising to ~55 ms(twtt)/km 9km down channel. Gradients reduce to 40ms(twtt)/km at 15 km, before finally rising to 60ms(twtt)/km at 20 km. Although apparently straight, the axis of Channel 1 is slightly sinuous

compared with its' straighter channel margins. Gradient and sinuosity appear to be correlated over short length-scales <4 km. Over length-scales of 20 km, the trend shows sinuosity fluctuating, but decreasing slightly against a gradient increase. Channel depth for Channel 1 is the lowest of all four channels, (<50 ms, twtt) and gradually decreases downslope. Although relatively continuous compared with the other channel systems, Channel 1 levees show important downslope variations. Levee development (Fig. 5) correlates with gradient increases of the channel axis (see ~8 km along channel axis, Fig. 7).

Channel 2 has low to moderate sinuosity (~1.3) and is incised by ~100 ms (twtt) upslope, decreasing to ~50 ms (twtt) >30 km downslope. Along Channel 2, normal faults intersect the channel, which have created higher channel axis gradients. This is reflected in the sinuosity, which decreases slightly then increases markedly over the lower gradients downslope of the slope break (Fig. 7). Therefore, faults and channel were active at the same time. Gradient and sinuosity appear negatively correlated over short (<4 km) length-scales, although, from 10 to 15 km, the sinuosity and gradient appear correlated.

Channel 3 has the highest sinuosity ratios (>3) and is the most incised system (>200 m). Channel incision, initially very high, gently decreases to <150 ms (twtt) 30 km downslope. The wavelength of the sinuous loops fills the whole channel floor and therefore appears to have been still eroding and widening the channel valley when last active. Gradients are relatively constant (~20 ms (twtt)/km) for the first 11 km, drop slightly to 15 ms (twtt)/km, then increase to ~30 ms (twtt)/km at 30 km distance. Sinuosity ratios are relatively high initially, rising from ~2 to a maximum of 3.2 at 13 km. From 13-30 km the ratios fluctuate but the trend is a decrease to ~1.5 over the last few km (Fig. 7). Over short length-scales of ~4 km, sinuosity and gradient appears correlated up to ~11 km, negatively correlated in the middle section (11-17 km), correlated from 17-22 km, and negatively correlated for the distal few km again. There is no discernible trend in width, sinuosity, or gradient

over the whole channel length.

Channel 4, the longest channel interpreted in this study, has a gently convex-up channel profile and a very high, relatively constant incision (~190 m), over a (Fig. 7). At ~35 km there is a break-of-slope, where the channel becomes straighter, and widens from ~60 m to <150 m (described as a weakly confined system). This part of the channel is characterised by very high amplitudes and lower gradients. There is a general increase in the sinuosity from 15-27 km with increasing gradient. From ~27 km the sinuosity rapidly decreases, as the gradient continues increasing. The point at which sinuosity sharply decreases (~27 km, Fig 7) corresponds not with the break-of-slope at ~35 km, but where the slope becomes more convex-up, i.e., gradually steeper. This indicates that some threshold might have been reached before the slope-break and that the channel could not adjust its gradient any more through sinuosity increase.

In general, our data show the steeper, weakly incised channels (e.g. Channel 1) have smoother, convex-up profiles. In contrast, the lower gradient channels (e.g. Channel 3) have rougher, less convex-up profiles. The profiles of the apparently more mature channels (3 and 4) have lower and relatively constant gradients along channel (Fig. 8). It appears that curvature along channel axis is removed by incision and sinuosity which results in lower gradients. Where channel incision is relatively high and constant, (e.g. Channel 3) the channel profile has effectively lost its original convexity. In contrast, the weakly incised and apparently immature Channel 1, still reflects the curvature of the slope it drains. It is likely that the evolutionary trend would be towards formation of a concave-up profile, as observed elsewhere for many modern submarine channels (e.g. Pirmez et al. 2000).

Long channel profiles for all 13 channels within the study area show two distinct groupings; a high gradient and a low gradient system (Fig. 8a). The high gradient systems tend to have smoother

profiles, but are more irregular over longer (>4 km) length-scales. In contrast, low gradient systems have smoother profiles over longer length-scales, but a short wavelength (<4 km) roughness. The short wavelength roughness may be due to sampling errors inherited from the gridding procedure, or may result from difficulties in sampling a highly sinuous channel axis. However, the smoother profiles appear to reflect the erosional work done by flows down the channel in removing slope irregularities as it approached its equilibrium profile. Figure 8b shows incision increasing from Channel 1 to 4. Sinuosity and gradient measurements were made for 13 channels within the study area and the results plotted (Fig. 8c). Sinuosity sharply increases with gradient up to a peak of 3.2 at ~14 ms(twtt)/km and then gradually decreases, until at gradients of ~38 ms (twtt)/km, channels are straight. Key thresholds for sinuosity development are at ~12 ms (twtt)/km and ~34 ms (twtt)/km. When these channel parameters are averaged for each channel and plotted (Fig. 8d) there is a simple correlation between sinuosity, incision and gradient. Results indicate that incision and sinuosity increase in a non-linear fashion as channel systems evolve. Channel 2 appears the most likely representative of an intermediate channel type.

DISCUSSION

The observations are summarised in a simple model (Fig. 9), which shows how an initially straight, high gradient channel evolves into a deeply incised and highly sinuous channel with low gradients. As sinuosity develops, channel gradient decreases and width increases. The mature system has a wide (~3 km) erosional valley ~200 m deep with a highly sinuous channel at its base. Despite erosional enlargement, the geometry of the mature, incised channel valleys still preserves some of the original linear channel geometry. The channel system may be filled and re-incised several times, creating complex fill geometry.

Initially, the immature channel has a high gradient, well-defined levees and a channel axis which is slightly incised into the underlying seafloor. The channel axis is developing a slight sinuosity

which correlates with gradient. The next stage is where the channel is rapidly increasing in width, depth and decreasing in gradient. A sinuous channel axis is recognisable and the valley walls are developing a 'scalloped' geometry due to slumping and lateral channel migration. It appears that slump events into the channel are relatively small, as the ‘scallops’ along the channel valley walls are of a similar size to channel axis loops. Channel levees and overbank deposits are recognisable but are diminished in relief and amplitude. In the mature stage a highly sinuous channel axis is easily identified within a wide, incised channel valley. The valley walls have a complex 'scalloped' morphology and slump structures may be observed. Levees are poorly developed, although there is flow overspill at bends in the channel valley. Levees are still probably evolving when the channel reaches its mature phase, although flow confinement means that only bigger flows are capable of depositing out of the channel and much of this is likely to be finer grained sediment which builds broader levees with gentle relief. Deeply incised channels (e.g., Channel systems 3 and 4, this study) were probably able to confine turbidity currents effectively, thereby focussing erosion and inhibiting overbank sedimentation (e.g. Pirmez et al. 2000). The mature stage is likely to be affected by repeat fill and incision which will create complex valley wall morphology and a highly variable channel fill architecture (e.g., Deptuck et al. 2003; Samuel et al. 2003).

The degree of incision appears to reflect the length of time that that channel has been active in relation to tectonic uplift of the region. The wider and more irregular geomorphology of the deeply incised valleys, suggests they are more mature than small, straight systems. The model (Fig. 9) assumes constant uplift for all channels, but the presence of an anticline indicates some variation in uplift. Channels in the center of the anticline (e.g., channel system 3) appear to have experienced relatively more incision. However, this effect is considered to be small compared to the total uplift affecting all the studied channels.

Observations of channel types indicate varying preservation potential for channels in different

stages of evolution. The scarcity of intermediate channel forms is interesting, although the reasons for it unclear. The apparent non-linear relationship between average incision, sinuosity and gradient (Fig 8d) indicates that there may have been a period of rapid tectonic uplift that was too fast to be recorded by channel formation, or an increase in flow discharge which resulted in faster erosion. It is likely that the preservation of weakly incised, immature channel systems is controlled by their sensitivity to avulsion, as they are confined mainly by levees at this stage which can easily be breached by large flow events. Deeply incised channels are less sensitive to avulsion, and more likely to change their course by lateral migration of the channel axis, which would cause preferential erosion of one channel margin. During the intermediate stages where there appears to be rapid incision, individual channel elements and their associated deposits appear to have a very poor preservation potential.

A channel evolving from straight to sinuous form for an aggrading system was described by Babonneau (2002) where avulsion creates an initially straight channel that is steeper than the parent channel. Babonneau et al. (2002) suggested that sinuosity evolution after avulsion (i.e., from a straight channel) was slow. In contrast, the incisional examples shown here from Angola appear to indicate that sinuosity may evolve rapidly. Where changes in the sinuosity are not reflected in the channel gradient or morphology, it may indicate either that deformation occurred after channel formation or that flow type (e.g. debris flow, turbidity current) changed. In this study, gradient changes appear to be reflected in the sinuosity indicating tectonic deformation coincident with channel formation.

While it is largely beyond the scope of this paper, the idea that meandering behaviour of submarine and fluvial systems can be compared is controversial (e.g., Peakall et al. 2000). Recent studies of laterally and vertically aggradational submarine channels show excellent examples of 'swing' and 'sweep' (lateral and downslope migration of channel loops), (e.g., Abreu et al. 2003, Posamentier,

2003, Deptuck et al. 2003). However, this study finds no evidence of significant channel migration. This may be due to the seismic resolution of the data or the fact that there are major differences in sinuosity evolution for aggrading and incising systems. For example it might simply indicate that the rate of incision was too fast to allow much channel migration.

If sinuosity is chiefly a function of gradient, then the temporal rate of gradient change should control sinuosity evolution. While it is assumed that the highly sinuous channels observed at the base of incisional valleys were responsible for carving the valleys, it is also possible that another type of flow caused the incision. The sinuous channel observed could result from the waning phase of a prolonged flow event, although recent high-resolution 3D seismic data published by Abreu, et al. (2003) show convincing evidence for erosion directly caused by sinuous channels.

Other submarine channels appear to respond to higher gradients by becoming more sinuous (Flood and Damuth 1987; Pirmez and Flood 1995). The high rate of incision relative to the rate of channel widening may inhibit lateral and downslope channel migration (Peakall, et al. 2000). Rapid incision also establishes the channel location on the slope, inhibiting channel bifurcation or avulsion (Baboneau et al. 2002). Once confined, the flows are likely to become more powerful and erosive, and therefore able to incise at a faster rate. However, this is far from clear as the low gradients and highly sinuous channel axis suggests steady-state flow.

Turbidity currents and other submarine mass flows respond strongly to tectonic forcing, as they are sensitive to gradient and gradient direction. In this study, the asymmetry of channel valley morphology of more incised, mature channels appears to record the growth of a local anticline related to regional uplift. Channel asymmetry could result from a process of lateral channel migration, which would preferentially erode the one valley wall by undercutting and slumping. As channels become progressively entrenched, they confine sediment-laden flows more effectively.

However, flows within more entrenched systems appear to have focussed overspill or levee deposition on the outer bends of channels due to the flow stripping or overspill of turbidity currents (Piper and Normark, 1983; Hiscott et al, 1997; Peakall et al. 2000). Progressive flow confinement would lead to levees becoming smaller and less continuous as channels become more incised.

Clarke et al. (1992) showed that each fan system had a unique threshold of maximum sinuosity. Compared to modern fan systems such as the Amazon, or Mississippi, peak sinuosity for Angolan channels is high although comparable with the modern Arguello fan system (Clarke and Pickering 1996). This high value for Angolan subsurface channels might be in part due to post-channel tectonic oversteepening. In addition, the examples we use are segments of much larger channel systems, which in turn form part of a large Miocene fan complex. A similar peak sinuosity value was found for older (Late Oligocene and Middle Miocene) channel systems, offshore Angola (Sperrevik 2002). The fluctuating relationship between sinuosity and gradient over short length-scales (<4 km) appears to indicate channel profiles that are out of phase with the flows that carve them. The effective work of channels is to reduce gradients along the path they transport sediment. They achieve this gradient reduction by differential incision and also by sinuosity increase. However, it is not clear whether temporal sinuosity evolution is a passive response to gradient change, or a driving, gradient reducing process. The observed trend for curvature reduction (from convex-up to linear) of channel profiles indicates how channel axis profiles are trending towards an equilibrium profile, which has a classic concave-up profile (e.g., Pirmez et al. 2000). A channel responds to higher gradients by becoming more sinuous, until it reaches a threshold. For Angolan channels with very high sinuosities (e.g., channels 3 and 4), this threshold is close or exceeded. High gradient, straight systems (e.g., Channel 1) appear to show good correlations between gradient and sinuosity, indicating they are farther from peak sinuosity threshold and maybe more in phase with their dominant mean flows. In this study, sinuosity increase and subsequent profound decrease (Channel 4, Fig, 8c) against steadily increasing channel gradient within one channel indicates that

such a threshold might have been reached. In other words the channel could not adjust it's gradient any more through sinuosity increase. Where channels flow over slopes with convex-up curvature, flows will respond by increasing in velocity. Results indicate that the threshold point for maximum sinuosity may be reached on a slope with gradually increasing gradient (i.e., convex-up slope) and not at a slope break. This has important implications for predicting channel geometry, as the point at which a channel cannot respond to a steepening slope by increasing its sinuosity, is where the channel may transform into a broad, weakly confined depositional system.

Results also indicate that there might be a threshold channel width, at which the channel reaches maximum sinuosity, as the widest channel system (Channel 4) has high, but not the highest sinuosity. A potential problem in relating geometry to process, is that channel morphology often appears not be in phase with the flows that carve them. There will be a lead and a lag in the time it takes for the channel to respond to tectonic deformation or flow changes. The relationships between sinuosity and gradient shown here for Angolan channels indicate that they are sometimes out of phase over short distances of <4 km, especially where channels encounter abrupt gradient increases. In a detailed study of channel belts from the Niger Delta and the Indus Fan, Deptuck et al. (2003) describes how some meander loops grow dynamically at the same time as others show little lateral migration. The alternation between sinuosity and gradient correlation and negative-correlation over short length-scales (<4 km) shows how these Angolan channels also adjust dynamically.

There is also tentative evidence shown here for the process by which channels initially form on the slope. The out-of-channel 'striations' we interpret to result from large, unconfined and erosive turbidity currents may be one mechanism by which seafloor imperfections are produced to 'seed' channels, but at this stage this must remain speculation. A similar mechanism for channel initiation on open submarine slopes was suggested by Elliott, (2000) where erosional megaflutes may have

created the conditions for channel formation. The development of straight or low sinuosity channels has been previously recognised (e.g., Fonnesau et al. 2003, Mayall and Stewart, 2000), although this study shows how the channel axis of an apparently straight channel is slightly sinuous. The development of early sinuosity appears to be controlled by the presence of levees and later by the valley walls as the channel becomes incised.

SUMMARY

Erosionally confined channels leave a poor record of their evolution. This study shows how this early history can be reconstructed by analysing channels in different stages of evolution. The Tertiary subsurface off Angola presents a unique opportunity to characterise channels and understand how they evolve from straight to mature, sinuous systems within geometrically complex confining valleys. Understanding the early phase of channel evolution is important because it helps constrain the processes and controls which create these complex channel geometries. Important gradient thresholds for rapid changes in sinuosity are recognised at ~34 ms (twtt)/km and 12 ms (twtt)/km, with peak sinuosity is ~16 ms (twtt)/km. Channels analysed in this study, show good relationships between sinuosity, incision and gradient.

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FIGURES

Figure 1: Basemap of area showing the near-surface salt dome tops, channels and faults interpreted from 3D seismic data. Channels flowed from NE to SW through complex salt structures on the lower slope. Grey shaded interval shows time travel thicknesses for the stratigraphic interval containing the channels. Darker shades = thicker sequences.

Figure 2. Two cross sections running along strike, intersecting numerous channel systems. See Fig. 1 for location. Section A is a longer regional line. Note the anticline structure and range of channel geometries and incisions. Section B shows the four channels analysed in this study, ranging from Channel 1 which is weakly incised with levees, to channels 3 and 4 which are highly incised without obvious levee development.

Figure 3. Seismic sections along channel axis for channels 1-4, illustrating internal seismic facies, decrease in gradient and increase in incision from 1 to 4.

Figure 4. Plan view geometry of channels 1-4. A = channels in relation to isochore map of the stratigraphic interval that contain the channels. B = planview images of four channels within their erosional valleys showing sinuosity increase with channel width from 1 to 4.

Figure 5. Amplitude and time structure map of Channel 1, showing highly linear valley containing a slightly sinuous channel and high amplitude levees adjacent to the channel. Note the out-of-channel lineations to the west of the main channel.

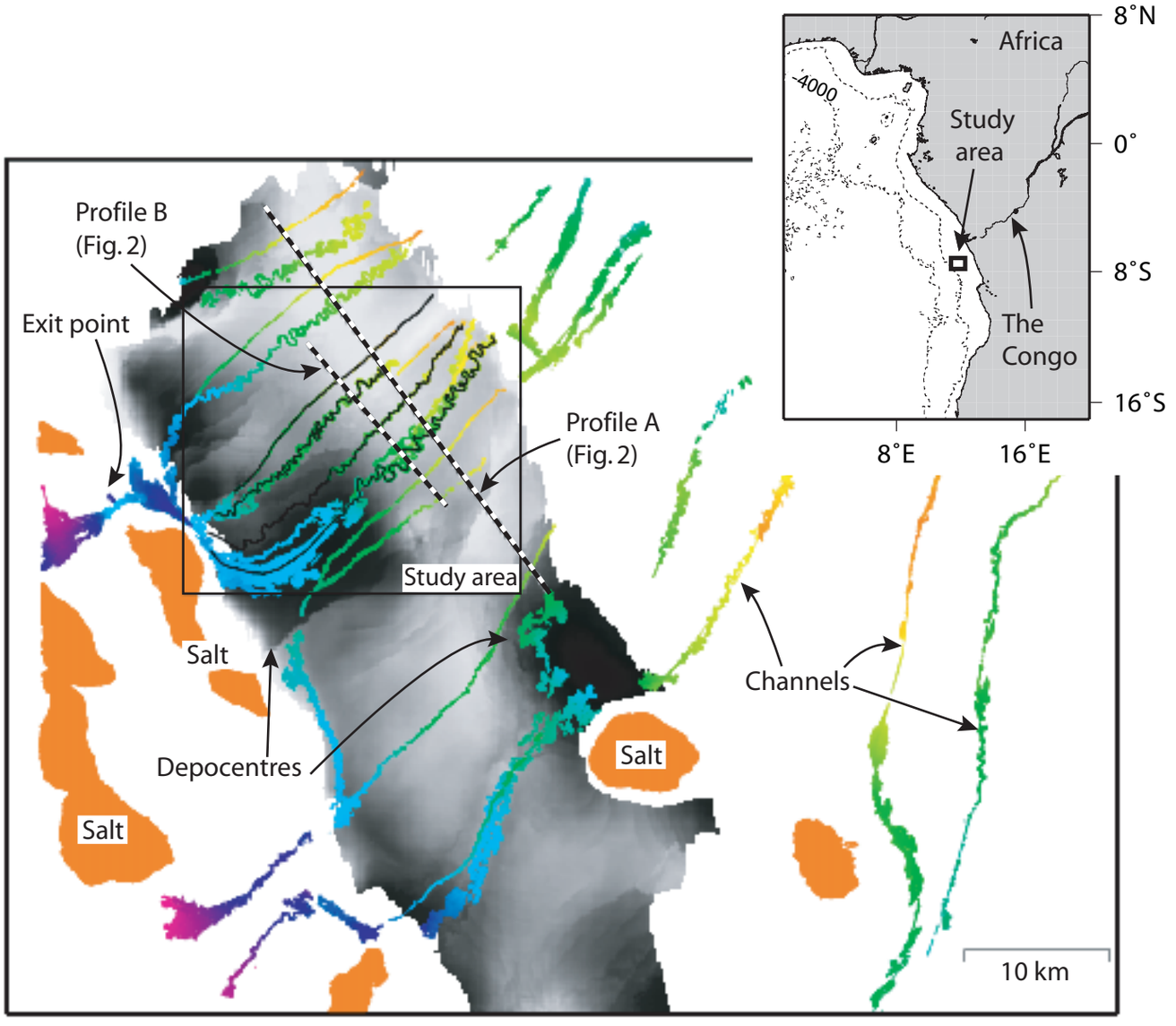
Figure 6. 3D seismic images of amplitude draped on time structure showing channels 1-4.

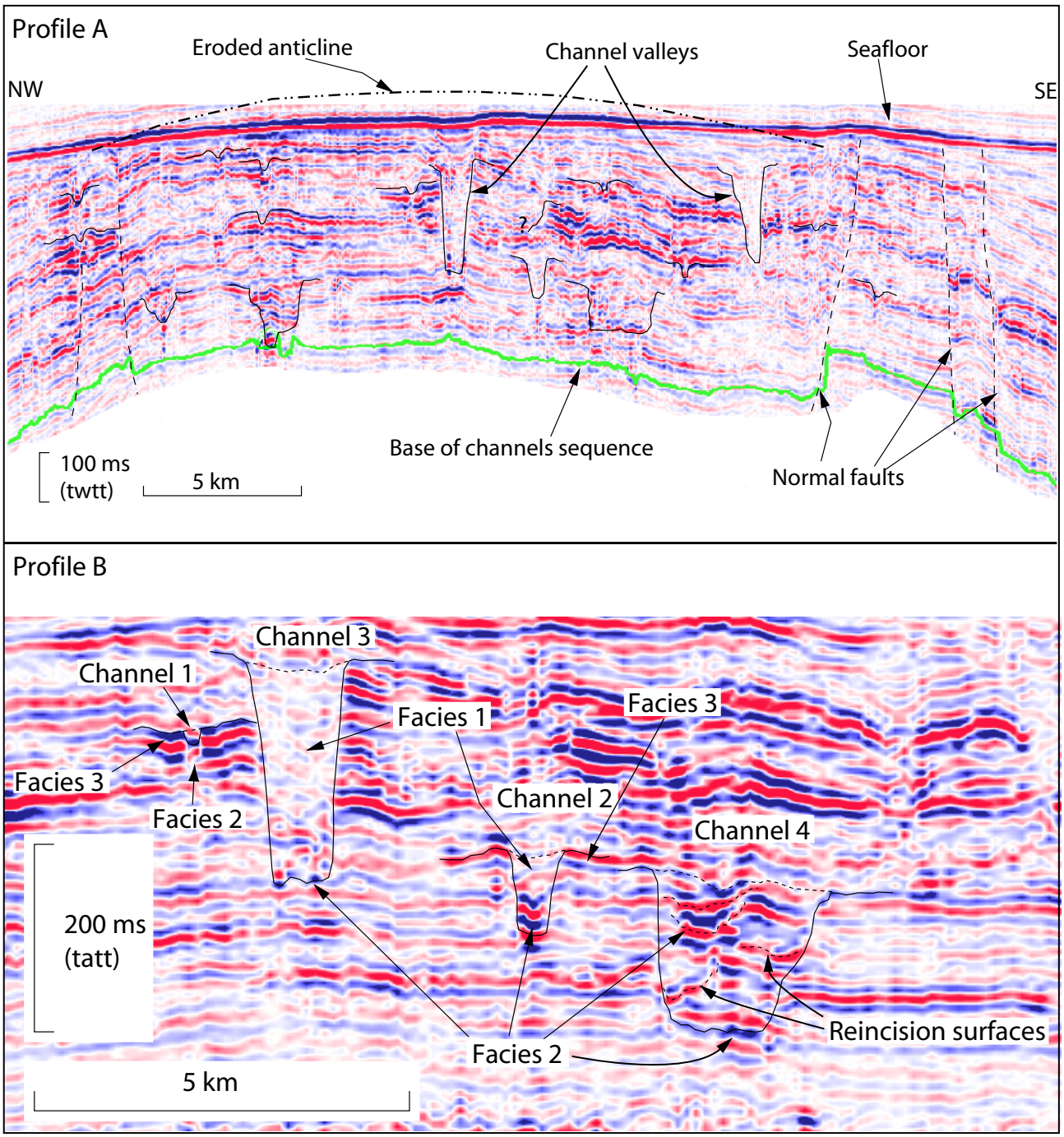
Figure 7. Channel parameters of gradient, sinuosity, profile and incision for channels 1-4. Channel

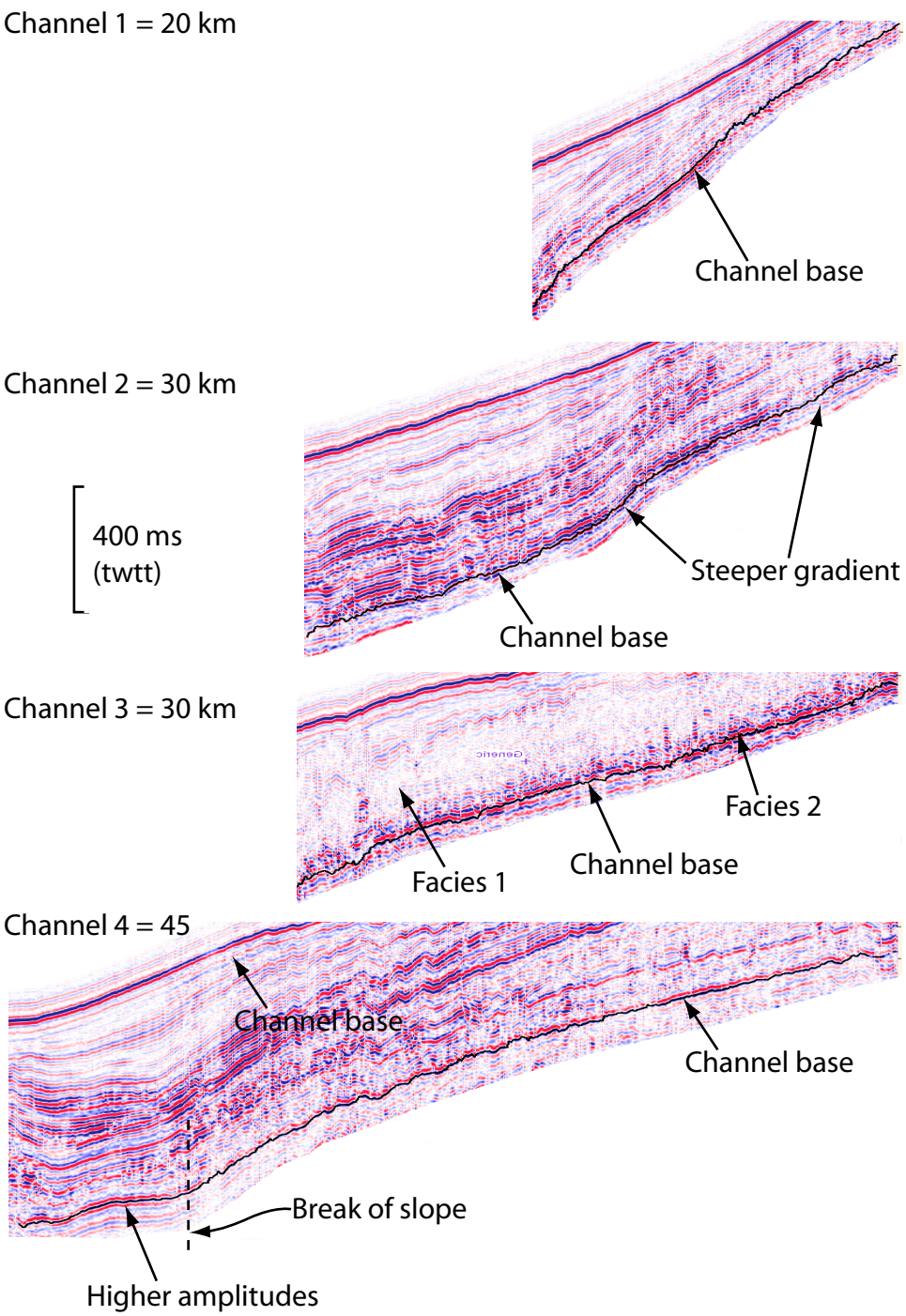
incision was calculated by fitting a minimum curvature surface across the top of the channel valley from one side to the other (dotted line). Gradient and sinuosity were measured along channel at 2 km intervals. Black triangles = sinuosity, open squares = gradient. Profiles were sampled every 100 m.

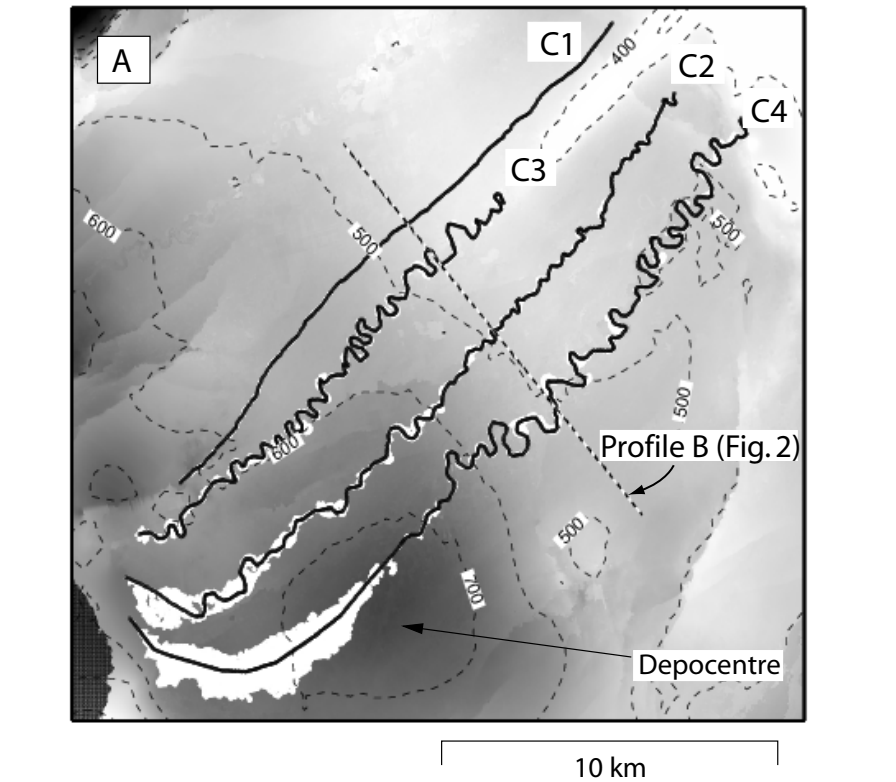
Figure 8. Channel parameters for channels 1-4. A = interpreted long profiles for numerous straight (dotted lines) and sinuous (solid lines). B = incision plotted along channel. C = sinuosity, gradient plot with key thresholds indicated. D = Relationship between incision, gradient and sinuosity for channels 1-4.

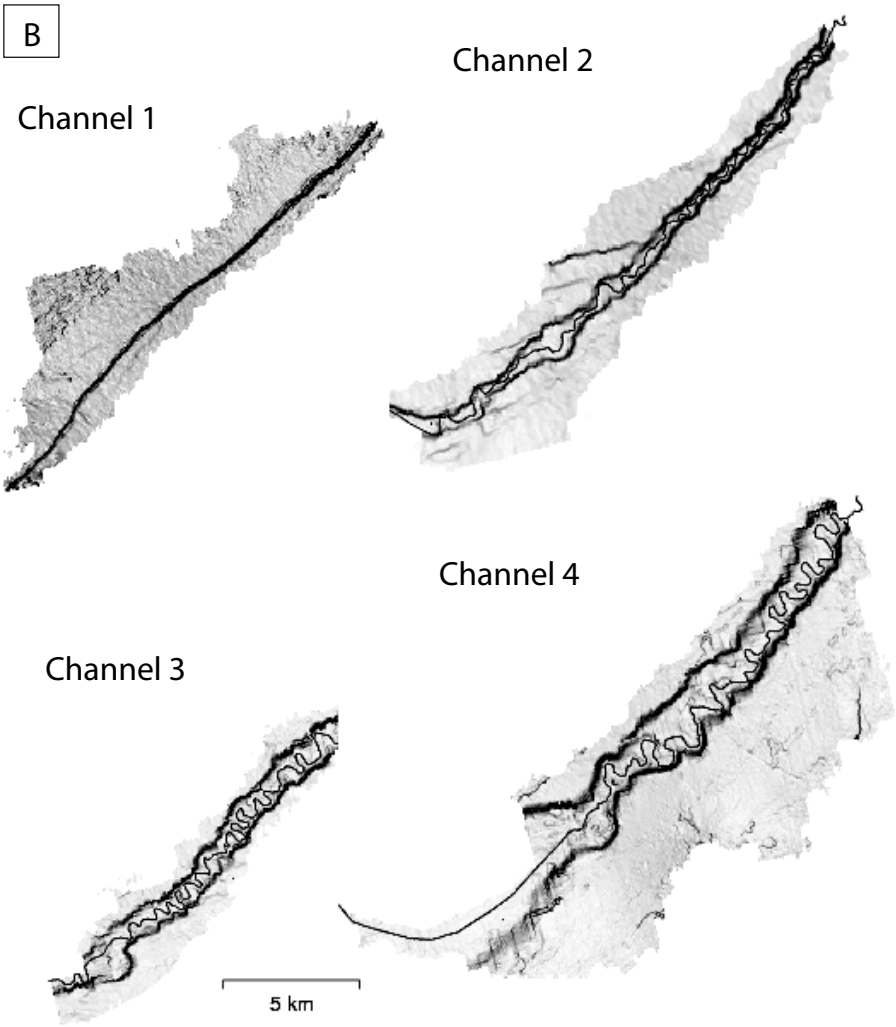
Figure 9. Model illustrating the evolution of incisional channels from a high gradient, low sinuosity immature system to a low gradient, sinuous, mature incisional system.

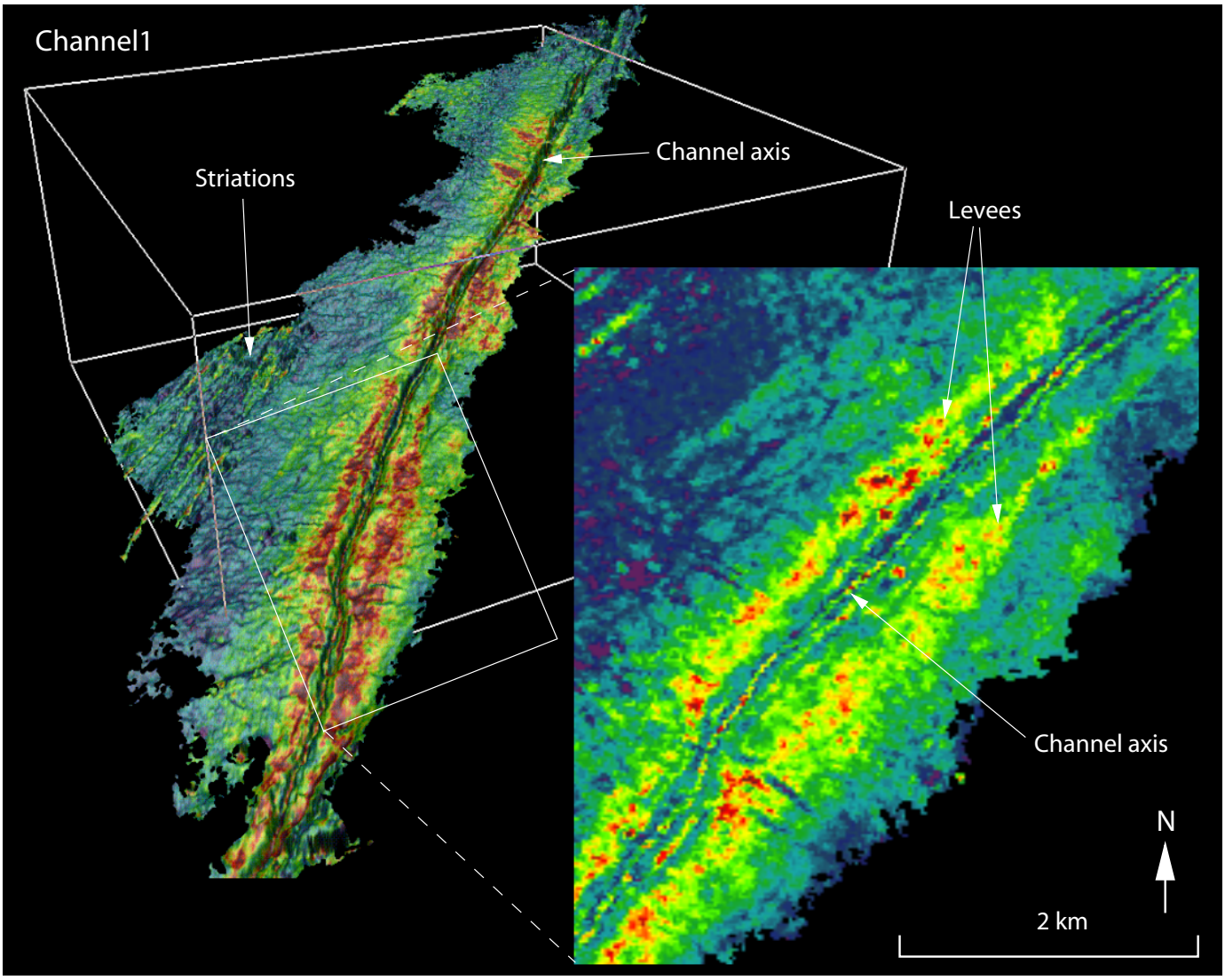

Profile B
(Fig. 2)
Exit point
Profile A
(Fig. 2)
Study area
Salt
Depocentres
Salt
Salt
Channels
10 km
Africa
4000
Study
area
The
Congo
8˚N
0˚
8˚S
16˚S
8˚E
16˚E

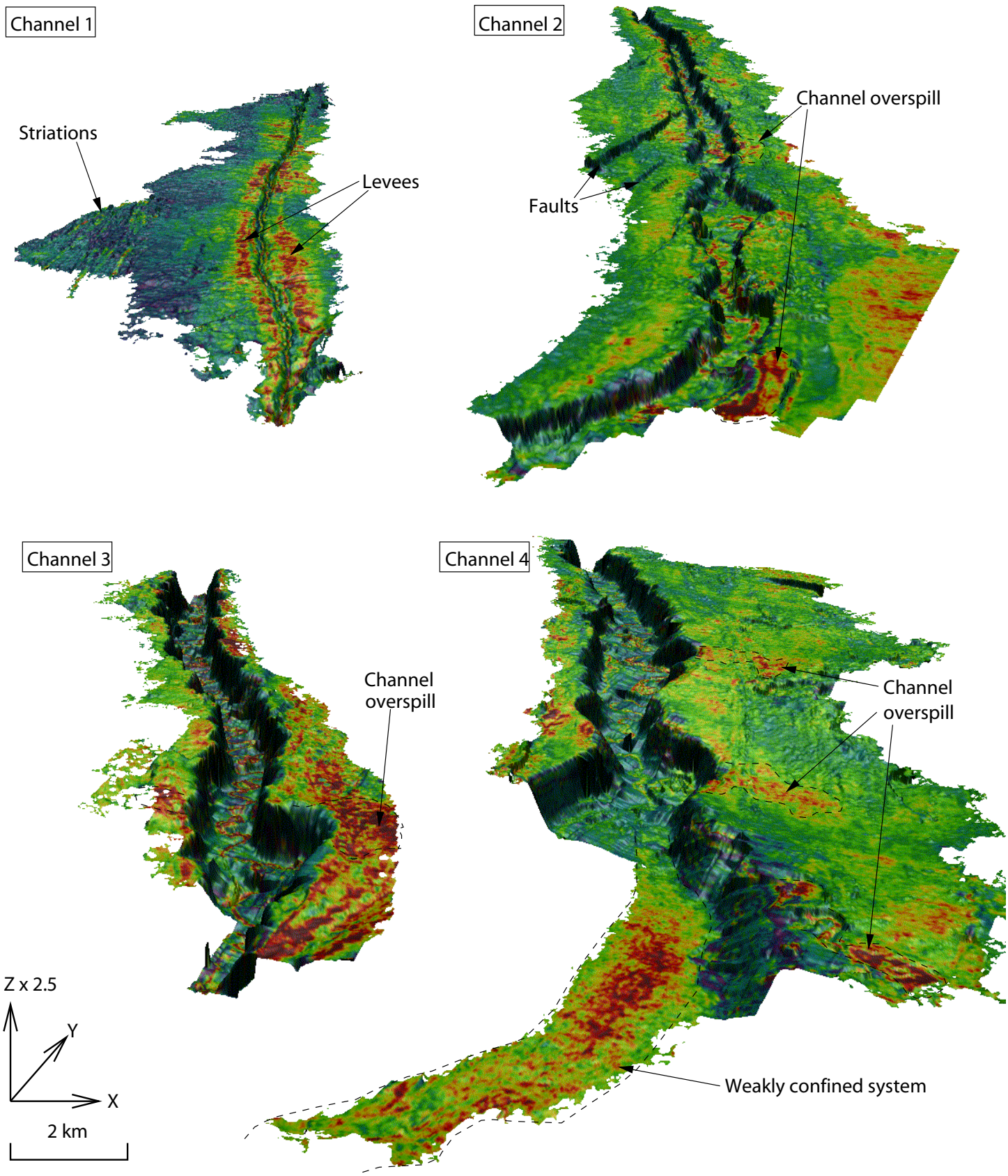

Profile A
Eroded anticline
Channel valleys
Seafloor
NW
SE
Base of channels sequence
Normal faults
100 ms
(twtt)
5 km
Profile B
Channel 3
Channel 1
Facies 1
Facies 3
Facies 3
Channel 2
Facies 2
Channel 4
200 ms
(tatt)
Reincision surfaces
Facies 2
5 km

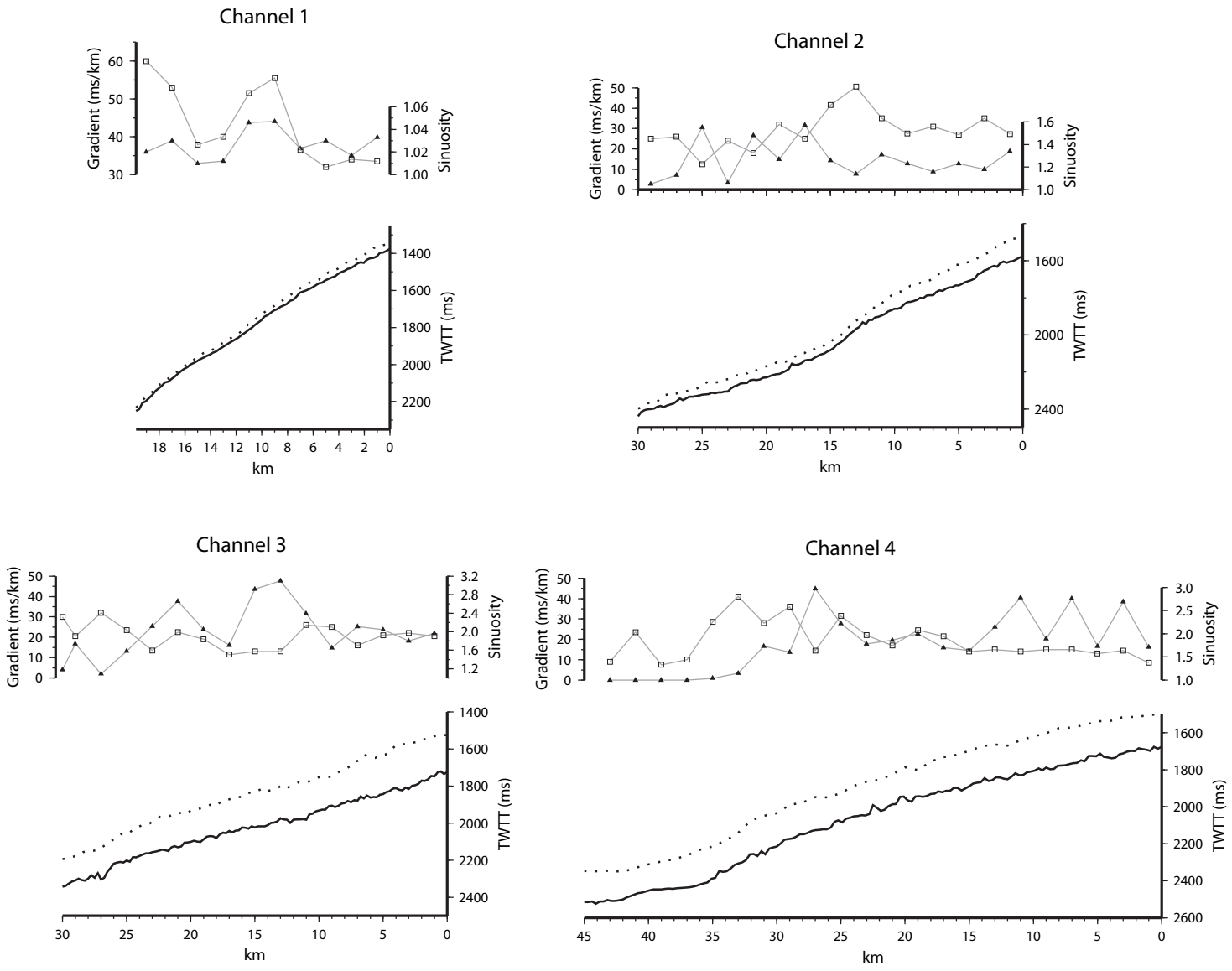

Channel 1 = 20 km
Channel base
Channel 2 = 30 km
400 ms
(twtt)
Steeper gradient
Channel base
Channel 3 = 30 km
Facies 2
Channel base
Facies 1
Channel 4 = 45
Channel base
Channel base
Break of slope
Higher amplitudes

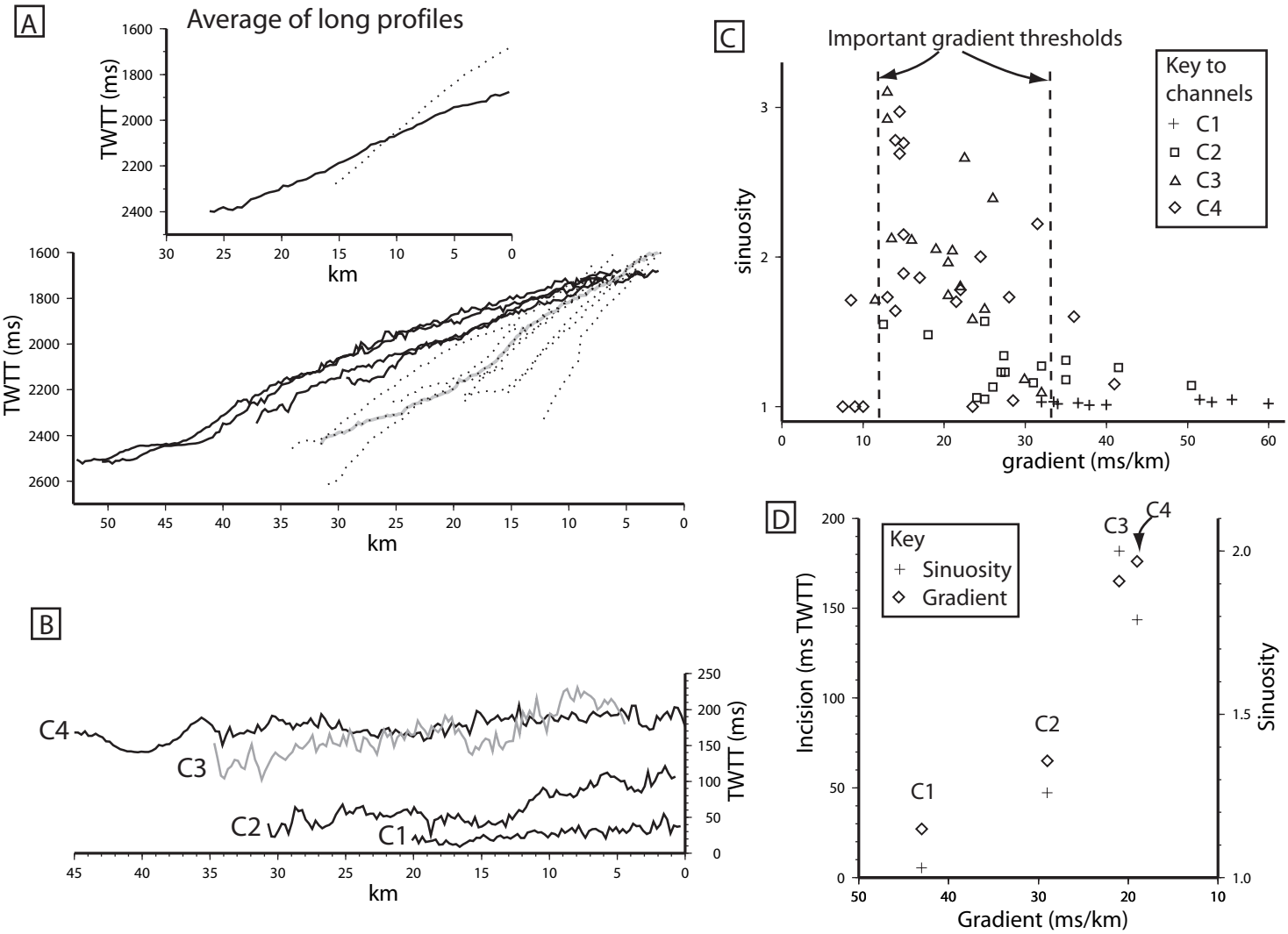

A
C1
C2
C3
C4
400
600
500
500
500
600
500
700
Profile B (Fig. 2)
Depocentre
10 km

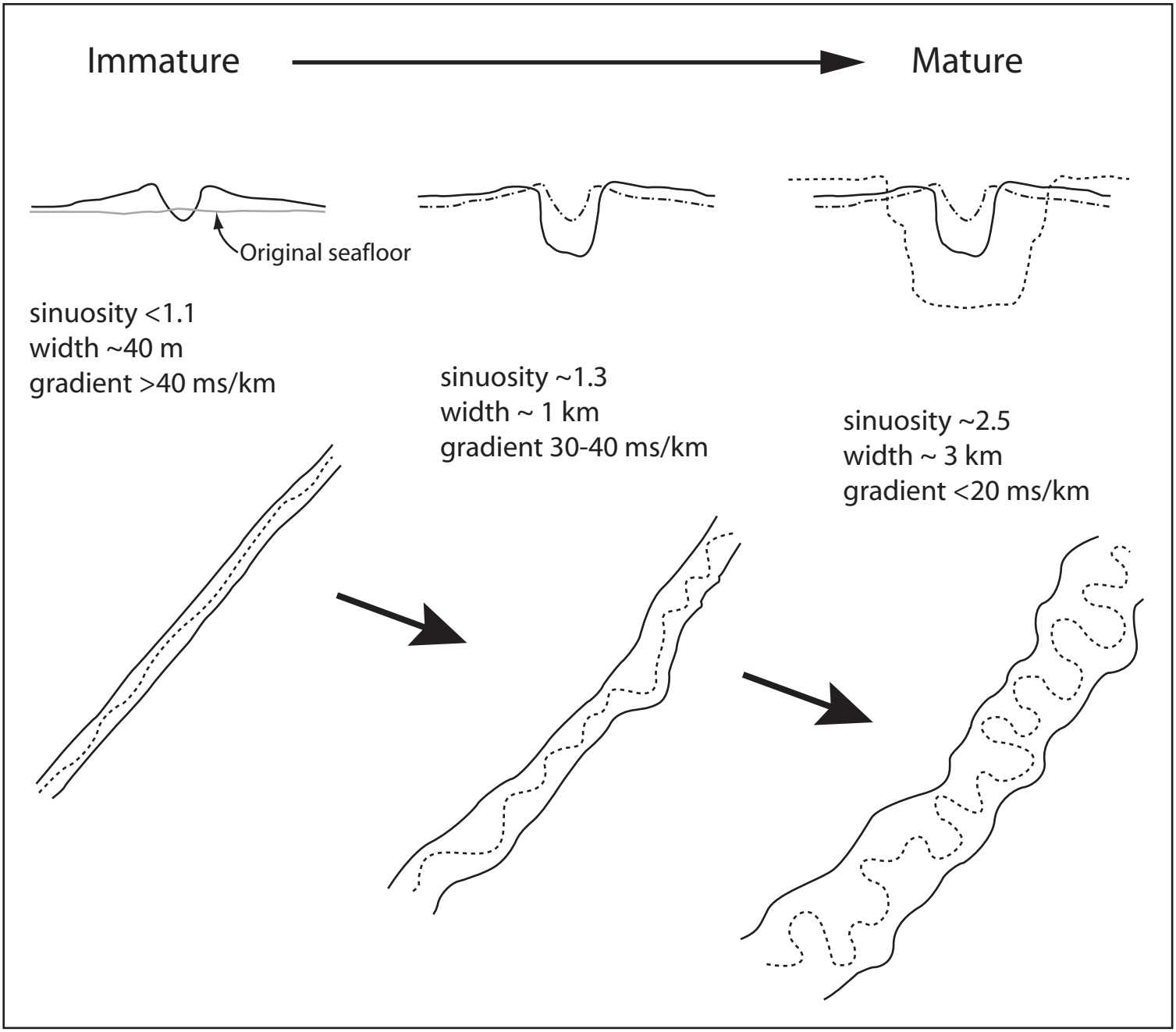

B
Channel 1
Channel 2
Channel 3
Channel 4
5 km


Channel1
Striations
Channel axis
Levees
Channel axis
N
2 km


Channel 1
Striations
Levees
Channel 2
Channel overspill
Faults
Channel 3
Channel
overspill
Channel 4
Channel
overspill
Weakly confined system
Z x 2.5
Y
X
2 km


Channel 1
Gradient (ms/km)
Sinuosity
TWTT (ms)
km
Channel 2
Gradient (ms/km)
Sinuosity
TWTT (ms)
km
Channel 3
Gradient (ms/km)
Sinuosity
TWTT (ms)
km
Channel 4
Gradient (ms/km)
Sinuosity
TWTT (ms)
km


A
Average of long profiles
TWTT (ms)
km
B
C4
C3
C2
C1
TWTT (ms)
km
C
Important gradient thresholds
Key to channels
C1
C2
C3
C4
sinuosity
gradient (ms/km)
D
Key
Sinuosity
Gradient
C1
C2
C3
C4
Incision (ms TWTT)
Sinuosity
Gradient (ms/km)


Immature
Mature
Original seafloor
sinuosity <1.1
width ~40 m
gradient >40 ms/km
sinuosity ~1.3
width ~ 1 km
gradient 30-40 ms/km
sinuosity ~2.5
width ~ 3 km
gradient <20 ms/km