Submarine fans in the Kribi-Campo sub-basin, offshore Cameroon: Geomorphology and stratigraphic evolution during the Late Cretaceous

Boris G. B. Secke [123]*, Yakufu Niyazi[4], Ovie Emmanuel Eruteya[1], Mbida Yem[2], Joseph Quentin Yene Atangana[2], Samuel Etame Makoube[5], Elias Samankassou[1]

[1.] Department of Earth Sciences, University of Geneva, Geneva 1205, Switzerland

[2.] Department of Earth Sciences, University of Yaoundé I, Faculty of Science, P.O. Box: 812, Yaoundé, Cameroon

[3.] Centre for Geological and Mining Research, P.O. Box: 333, Garoua, Cameroon

[4.] Minderoo-UWA Deep-Sea Research Centre, School of Biological Sciences and UWA Oceans Institute, the University of Western Australia, Perth 6009, Australia

[5.] National Hydrocarbon Corporation (NHC), P.O. Box: 955, Yaoundé, Cameroon

*Corresponding author: bsecke@yahoo.fr

Abstract

Submarine fans are deposits of sediments of continental origin in the deep sea, and are generally characterized by a complex depositional architecture, due to the multiple triggering mechanisms of deep-water sediment gravity flows. Consequently, this poses great challenges to deep-water petroleum exploration and development. We investigate the geomorphologic evolution and architecture of Campanian, deeply buried, submarine fans in the Kribi-Campo sub-basin, offshore Cameroon. Using a 3D seismic reflection data set and logs from two wells, we mapped horizons to produce seven strata slices including the fan base, fan top and five internal strata. In cross-section, the fan is characterized by high amplitude seismic facies exhibiting an aggradational pattern with parallel and continuous reflectors. The stacked fan-shaped morphology is up to 500 m thick, extends over an area of 600 km^2 and is oriented NE-SW, near the Kribi High. Analysis of the fan architecture reveals the presence of well-defined internal structures such as crevasse splay, a sinuous distributary channel and an elongated depositional lobe. The lobe whose beds are made up of sand, silt and mud. A detailed examination of the characteristics of the stratal slices has enabled us to propose a chronology of the Campanian submarine fan showing three phases of progression from its creation, and its growth to its abandonment. The detailed structure of this lobe has a finger-like morphology and is generally oriented at 90^o to the channel that delivered the sediment to the lobe. The finger-like features are interpreted as thick massive sands, formed as a result of gravity sedimentary flows which branched off the main flow eroding into pelagic clay substrate. It is important to note that the geomorphological evolution and architecture of the submarine fan were influenced by variations in sea level during the late Cretaceous and the underlying tectonics marked by the Kribi high. The 3D seismic geomorphological analysis of the submarine fan, as presented in this study, is essential to better understand their geometries, facies distribution, stacking patterns and depositional architecture to improve reservoir predictions.

Keywords: Seismic geomorphology, submarine fan, Campanian, Stratal slices, Kribi-Campo, offshore Cameroon.

1. Introduction

Submarine fans are recognised as sedimentary features generated mainly from the deposition of gravitational sedimentary flows (mainly turbidity currents and debris flows) as terrigenous and shallow marine sediments are transported and redistributed into deeper waters (Deptuck et al., 2018). They are characterised by erosion and redeposition, owing to the alteration of bed geometries and substrates during basin evolution (Gamberi and Rovere, 2011; Pickering et al., 2015; Zhang et al., 2015; Li et al., 2021). Submarine fans develop on the continental slope and may extend to the abyssal plain. They are generally fed by one or more canyons located off the outlet of fluvial systems (e.g. Amazon, Zaire, Rhone rivers), which are a source of large amount of sedimentary input to the marine realm (Deptuck et al., 2018). Indeed, the construction of submarine fans is governed by external factors, such as tectonics, sediment supply, sea level fluctuations, and climate. It is also influenced by internal factors, including topographic compensation, levee aggradation, meandering and channel overcutting, and channel avulsion (Pirmez et al., 2000; Prelat et al., 2010, 2009; Picot et al., 2016).

Deep-water fan systems are among the largest clastic sediment accumulations on the planet (Covault, 2011; Deptuck and Sylvester, 2018). Modern examples submarine fan-forming fluvial systems, such as the Bengal, Amazon, Indus, and Mississippi rivers, contribute sediment volumes up to hundreds of thousands of km^3 (Walker, 1992; Curray et al., 2002). These are intensively studied because they host many large offshore oil reservoirs that attracted the hydrocarbon industry to invest and explore in recent decades. In addition, submarine fans document the paleo-oceanographic and climatic records of the source and bypassing region (Picot et al., 2016). The evolution and internal architecture of these deep-water submarine fans developed during the Cenozoic were studied intensively (Yamassaki et al., 2022). Yet, the Cretaceous or older deeply buried submarine fans around the world remains poorly understood because of the paucity of high-resolution subsurface data coverage for these systems. More importantly, they have highly variable sizes, morphologies and lithological contents due to the complex impacts of both external and internal controlling factors, making it more difficult to comprehend their evolution history.

The West African continental margin is one of the most active and promising regions for hydrocarbon exploration because of the exceptional results obtained in the deep-water areas. These exceptional discoveries in the West African deep-water zone generally focused on the turbidite sandstone reservoirs. Most of the basins of this margin have high quality 3D seismic data and wells increasingly available (e.g. Navarre et al., 2002), allowing a better understanding of the development of submarine fans; for example in offshore Gabon (Wonham et al, 2000), the Zaire fan (Babonneau et al., 2002), Niger delta slope (Deptuck et al., 2007; Jobe et al., 2015), the Ceiba canyons in Equatorial Guinea (Dailly, 2002). On the contrary, the Kribi-Campo sub-basin, the southern component of the Douala/Kribi-Campo basin in the northmost part of the West African margin, remains relatively unexplored. Previous work in the deep-water Kribi-Campo sub-basin identified the submarine fans in different stratigraphic levels (Le, 2012, 2021 and Loule et al., 2018). A recent study published by Le (2021) highlighted the evidence of a Pliocene submarine fan deposits with a series of striations at their base, characterized by high amplitude reflections with bi-directional downlap on the base of the Pliocene sequence. Le (2012) documented an elongated Late Cretaceous fan system with a maximum thickness of around 450 m that likely be driven by interaction of the fault-related folds and Kribi High and dominated by sandstone within the intervening topographic lows. Loule et al. (2018) revealed submarine fans occur at multiple stratigraphic levels but are most clearly developed in the Campanian interval and suggested that these deep-water fans are demonstrably point-sourced, derived from short, steep feeder-slope channel systems that cut the shelf edge of the Kribi-Campo High. However, the initiation, evolution and controlling factors of this Late Cretaceous fan system and its morphological characteristics are still unclear. In this study, we aim to perform a finer-scale characterization of the geomorphologic evolution of Late Cretaceous (Campanian) deep-water submarine fan buried 4.5 km below the seafloor in the Kribi-Campo sub-Basin, offshore Cameroon. We applied horizon slicing techniques to the 3D seismic data to examine seven stratal slices associated with the submarine fan to i) delineate the fan internal architecture, lobe stacking pattern, and channel morphology, and ii) characterise the morphologic and depositional variation through time from submarine channel to fan initiation and to the demise of the fan. In addition, we discussed the possible controlling mechanisms on the initiation and evolution of this submarine fan system. Results of this study provides new insights into the geomorphological characteristics and development of submarine fan in deep marine settings, as well as possible interactions with environmental setting and geological mechanisms behind the formation and evolution of the Late Cretaceous submarine fans in the Kribi-Campo sub-Basin.

2. Geological Setting

The West African continental margin extends from the Walvis Ridge near the Namibi-Angola border to the edge of the Niger Delta in Cameroon (Rabinowitz and Labrecque, 1979; Benkhelil et al., 2002). It includes, from south to north, the major basins of Mocamedes, Kwansa, Bas-Congo, Gabon and Douala/Kribi-Campo. The Douala/Kribi-Campo Basin located offshore Cameroon is situated in the northernmost portion of a set of en echelon chain of West African Basins that developed from the Walvis Ridge in the south and the volcanic line of Cameroon to the north (Brownfield and Charpentier, 2006; Brownfield, 2016; Ntamak-Nida et al., 2008). These basins formed as the consequence of right lateral shear conditions (Coward et al., 1999) during the opening of the South Atlantic (115 Ma) in Early Cretaceous (Wilson et al., 2003). The Kribi-Campo sub-basin is the southern part of the Douala/Kribi-Campo Basin, which constitutes the northern end of the West African Coast salt basins. This sub-basin is limited to the north by the northern end of the Kribi fracture zone (KFZ), with possible Aptian salt structures, to the east by the Precambrian basement outcrops that occur close to the shoreline, to the south by the Campo high, which separates the Kribi-Campo sub-basin from the Equatorial Guinea basin, and to the west by the oceanic boundaries of Cameroon (Nguene et al., 1992; Meyers et al., 1996; Ntamak-Nida et al., 2010; Le et al., 2021 and Yugye et al., 2021). The study area is located along the continental slope of the Kribi-Campo sub-basin approximately 40 km off the coast of Cameroon. it covers an area of approximately 1500 km^2, between 2°20′ to 3°00′ N latitude and 9°00’ and 9°50′ E longitude (Fig. 1). The water depths in this area vary between 600 and 2000 m (Fig. 1).

The Kribi-Campo sub-basin formed during the breakup of Africa and South America. Rifting began in the Late Jurassic and lasted until the onset of seafloor spreading in Albian-Cenomanian time (Pauken, 1992). Following Early Cretaceous rifting, most circum-south Atlantic and West and Central African basins continued to evolve often as a consequence of thermal sag subsidence (Clifford, 1986; SPT/Simon Petroleum and Technology, 1995). Characterized by a post-rift sequence in a deep-water setting, the Kribi-Campo sub-basin contains a Mesozoic-Cenozoic sedimentary sequence attaining nearly 7500 m in thickness (Sterling, 2010). The post-rift sequence comprises the upper Mundeck Formation (Albian-Coniacian), Logbadjeck (Turonian-Campanian), Logbaba (Maastrichtian), N’Kapa (Paleocene-Eocene), Souellaba (Upper Oligocene-Middle Miocene), Kribi (Upper Miocene), Matanda (Pliocene-Pleistocene) and Wouri (Pleistocene-Recent)(Fig. 2). These formations are marked by major unconformities (Santonian ~ 85 Ma, K/T boundary ~ 70 Ma, Mid-Oligocene ~30 Ma, Mid-Miocene ~15 Ma, and Late Tertiary event ~5.3 Ma) (Lawrence et al., 2002; Iboum Kissaaka et al., 2016; Le, 2021; Mienlam Essi et al., 2021; Yugye et al., 2021 and 2022).

During Coniacian to Santonian times there was a tectonic readjustment along the elevated Kribi-Campo High area where it was uplifted in respect to the deep basinal area to the west and as a consequence substantial erosion occurred (SPT/Simon Petroleum and Technology, 1995). The result was the formation of the drift unconformity which has been bracketed at between 92 and 86 Ma (also known as the ‘Santonian unconformity’) and using seismic for palinspastic reconstructions suggests the thickness of the missing section was a minimum of 660 m of erosion (Turner 1999; Sterling, 2010). This Santonian tectonic event with its associated uplift led to the deposition of thick late Cretaceous clastics characterized by slope and basin floor fans containing multiple channel complexes (Sterling, 2010; Le, 2012, 2021). Renewed marine transgression and subsidence along the West African margin occurred during Late Cretaceous times (Campanian–Maastrichtian) as continental drift continued

(Sterling, 2010). New coarse clastics were input to the Kribi Campo High and study area (SPT/Simon Petroleum and Technology, 1995). These coarse clastics were being fed by palaeo-fluvio deltaic systems (Ntem, Nyong and Sanaga) that became organized into shallow marine sediments along the inner shelf area only to be remobilised into the deeper basin areas. These sediments remobilised as gravity flow deposits of turbidites and high density debrites in channels to fan geometries vis a vis submarine canyon feeder systems (Sterling, 2010). In the Late cretaceous, stacked fan-shaped features developed and have a maximum thickness up to 450 m. They have a relatively elongate shape due to the confinement by fault-related folds and the Kribi High. The fan system have been divided into upper and lower fan areas (Le, 2012). The upper fan contains leveed-feeder channels and the lower fan is characterized by increasingly sinuous channels

Basin deepening and continued input of sediments from the paleo-fluvial deltaic feeders continued through into the Tertiary and more submarine channel and fan turbidites formed across these West African basins and in particular in the study area of the Kribi-Campo sub-basin (Sterling, 2010; Le, 2012). During the Early Pliocene, a deep-water sandrich fan and channel were developed, and characterized by high amplitude reflections with bi-directional downlap on the base of the Pliocene sequence (Le, 2021). The channel exhibited an east to west flow on the High Gradient Slope (HGS), while the fan extended from NE to SW on the Low Gradient Slope (LGS). So, the fan and channel in the study area was supplied by two sediment sources, from northeast and east.

3. Data and methods

This study is primarily based on prestack time-migrated, three-dimensional (3D) seismic data acquired in 2003 by Amerada Hess Company, over an area of 1500 km^2 in water depths ranging from 600 m to 2000 m in the southern part of the Kribi-Campo basin. In addition to this two exploration wells were drilled in the basin (Fig. 1). The 3D seismic data was acquired using 10 streamers that are 5100 m long, with a 12.5 m group interval. The streamers was separated by 100 m, with a spatial resolution of 25 × 25 m. The shot interval is 50 m and the record depth is up to 8 s two-way travel time (TWT). The 3D data includes 1581 in-lines and 2051 crosslines with lines spacing of 25 m and a seismic recording sampling interval of 2 ms TWT. The studied interval is imaged with a dominant frequency of 17 Hz, and with an average velocity of 2400 m/s derived from the check-shot data in the interval of interest, this frequency gives a vertical resolution (λ/4) of ~28 m (Le, 2021 and Secke et al., 2022). The seismic survey was processed as zero-phase at the seabed and displayed using the Society of Exploration Geophysicists (SEG) normal polarity convention (Brown, 2004). Hence, a positive amplitude representing a downward increase in acoustic impedance is depicted by a red, orange or yellow peak. Negative amplitudes represent downward decreasing acoustic impedance and are depicted by a light blue trough.

The well log data from two wells (W1 and W2), is used for this study (Fig. 1). W1 is drilled down to the Campanian section with a total depth of 4747 m while W2 is drilled to a total depth of 4090 m below the seafloor (Secke et al., 2022). Available well log data for this study contains standard wireline logs suites e.g., gamma ray (GR), sonic time (DT), density, neutron porosity and other wireline logs. Only W1 has check shot data available for the current work. The check shot and well top of formation data provide the well to seismic correlation for geological age control (Fig. 3c).

The workflow started with the identification of seismic horizons in correlation with the geological ages available in wireline logs and seismic data. The classical seismic stratigraphic interpretation technique of Vail et al. (1977) that based on strata termination, truncation, toplaps, downlaps, and onlaps, was used in this study. Secke et al. (2022) established a seismic stratigraphic framework for this area and divided it into nine seismic sequences, separated by ten horizons (KC-1 to KC-9 and the seafloor). The interval of interest in the study area is the Late Cretaceous stratigraphy which is bounded by the KC-2 and KC-4 horizons at the base and top, respectively.

Identification and mapping of submarine fans were achieved using a strata slicing approach established by Zeng (2010), where the stratal or proportional slicing technique creates several evenly spaced time-slices that conform to the desired interval. Seismic attributes such as the root mean square (RMS) amplitude and variance were extracted from the stratal slices to illuminate and visualize sedimentary characteristics of the study interval and interpreted in accordance with the observed well log patterns and published literature (Posamentier and Kolla, 2003; Zeng et al., 2007; Niyazi et al., 2020; Wang et al., 2024). The RMS amplitude can boost high amplitudes in an interpreted interval, allowing the amplitude reflection related to sands within deep-water fans to be discriminated from their associated low amplitude masses (Omosanya and Alves, 2013). Variance is a volume attribute that measures the similarity of consecutive waveforms over a given sampling window, and it is useful for imaging lateral discontinuities, such as faults or channel margins (Chopra and Marfurt, 2007; Marfurt, 2015). Once the spatial extents of the submarine fans were mapped in strata slices, the geomorphologic features identified in map were then validated on seismic profiles following established submarine fans facies and sequence stratigraphic schemes proposed by Posamentier and Kolla (2003); Niyazi et al. (2018); Yamassaki et al. (2022); Bouchakour et al. (2023).

4. Results and interpretation

4.1. Seismic stratigraphic framework

The Late Cretaceous stratigraphy of the Kribi-Campo sub-Basin was subdivided into two seismic sequences named S1 (old) and S2 (young), based on the observed changes in seismic geometries and depositional environments (Fig. 4). S1 is bounded below by KC-2 and above by the KC-3 horizon. The KC-2 horizon is characterized by onlap above in the southeast area (Fig. 4). The horizon extends across almost all of the study area, but onlaps against the Kribi High in the east. KC-3 is top of sequence S1 and has a high-amplitude reflection with good continuity. The horizon is also characterized by the onlap above in the Kribi High area. It defines the top of the stack of high to bright amplitude reflection laterally migrating westward which extends from the east to the southern half of the study area (Fig. 4). Sequence S1 is Santonian to Campanian in age, consists of sub-parallel, low amplitude discontinuous reflections, but also contains discrete high to bright amplitude reflections observed to the east and to the base of horizon KC-3 (Fig. 4). The high to bright amplitude reflections observed are interpreted as a submarine fan. Below the high amplitude reflections, lateral offset stacking patterns are observed. These are interpreted as the product of laterally shifting vertical aggrading channels (Fig. 4). They are interpreted to be sinuous channel complexes evolving through time and constrained by the Kribi High to the east (Fig. 4). Sequence S2 forms the uppermost sequence in the Late Cretaceous and it is bounded by KC-3 at the base and the KC-4 surface at the top. S2 is Campanian to Maastrichtian in age (Secke et al., 2022) and corresponds to low to high amplitude. A large incision also occurs within this sequence (Fig. 3a), which is interpreted by Secke et al. (2022) as a submarine channel system.

4.2. Seismic facies and depositional elements

Four major seismic facies (submarine fan, submarine channels, levee deposits and hemipelagic sediments) were identified within the study interval, based on the recognition criteria established for the studies of deep-water depositional elements (Posamentier and Kolla, 2003; Deptuck et al., 2007; Niyazi et al., 2018; Lawal et al., 2022; Secke et al., 2022; Bouchakour et al., 2023) (Table 1).

4.2.1. Submarine channel system

This seismic facies has U- and V-shaped features of stacked, somewhat chaotic reflections, with medium to high amplitude at the base and low amplitude at the top (Table 1). Occasionally, this facies exhibits two stages of channel infilling. Smaller channel within the bigger one - a sort of younger generation type to the right. The maximum incision depth of 197 m (Secke et al., 2022), with the high and low amplitude reflections showing flat overlying reflections. This facies occurring as meandering ribbons in planview with low Variance amplitude (Table 1). Following previous studies on deep-water depositional systems (Posamentier and Kolla, 2003; Deptuck et al., 2007; Niyazi et al, 2018; Lawal et al., 2022), the high and low amplitude reflections of a U-shaped submarine channel are interpreted to be sand and mud-bearing infills, respectively.

4.2.2. Levee deposits

This facies has been found on either side of the submarine channel facies, and is characterized by higher amplitude reflections adjacent to the channel and low amplitude convergent reflectors in the distal part. Its seismic reflection amplitude varies laterally and, typically decreasing away from the channel axis before downlapping onto underlying deposits (Fig. 4). It also characterized by high RMS amplitude in planview extending out from the submarine channel system (Table 1). The geometry and reflection characteristics of this seismic facies has been recognised by other authors as external levees associated with channel system, formed when the height of turbidity currents exceeds the confinement of the channel form and spill sediment onto the areas surrounding the channel axis (Deptuck et al., 2007; Posamentier & Kolla, 2003; Lawal et al., 2022). Often this overspill is fine-grained due to flow stripping, resulting in a mud-dominated deposit and the low-amplitude response commonly observed in seismic reflection data (Table 1). This type of facies is already known in the study area, through the recent work of Secke et al., 2022.

4.2.3. Submarine fans

This seismic facies is composed of distinctive, sub-parallel continuous medium- to high-amplitude reflections displaying an aggradational pattern in cross-section and it has a maximum thickness of about 500 m, typically thinning and downlapping towards the outer edges (Table 1). In plan view, this facies occuring as low Variance amplitude lobate shapes and represent the fans with an internal distributary channel. These fan-shaped deposits have been observed along the slope through to basin-floor in deep-water settings (Posamentier & Kolla, 2003), and they are variably referred to as channelised lobes, frontal splays, sheet sands and submarine fans.

4.2.4. Hemipelagic sediments

The seismic facies are semi-transparent, low amplitude, discontinuous to continuous seismic reflections, that are parallel and conformable to underlying deposits (Table 1). In plan view, it is characterize by low amplitude RMS and it dominates the seismic volume and occurs outside the submarine fans. These seismic characteristics have been observed in many areas and correspond to pelagic and hemipelagic mud and silt during sediment starvation in low-energy environments (Secke et al., 2022; Bouchakour et al., 2023). In the well log data, this facies show moderate to high GR values and correspond to shaly deposits.

4.3. Submarine fans stratigraphy and morphology

The stratigraphy of the interval of interest shows that the submarine fan in the study area is framed at the base and top by two distinct channels. The lower channel is wider (5000 m), located within the older Santonian-Campanian sequence. In cross-section, it is U-shaped and these patterns are constrained between the Kribi High and a fault (Fig. 5a, 5b and 5c). Its mapping reveals a large amplitude sinuous pattern oriented in the NE-SW direction (Fig. 6a). Above this lower channel, the development of submarine fan deposit is clearly observed (Fig. 5d). The internal architecture and geometry of the submarine fan was analyzed by observing the cross-sections and seismic attribute maps, but also based on the integration of the W1 well logs. The submarine fans are buried at 4550 m below the seafloor and its large amplitude seismic facies shows an aggradation pattern with parallel reflectors and good continuity.

In cross sections, submarine fan reflectors onlap the slope face until the Kribi-Campo High, and the fan thins distally and laterally (Fig. 5). The stratal onlap is also observed against local slopes

(Fig. 5c and 5d), near the Kribi-Campo high, suggesting that relief already existed during submarine fan deposition. The fan-shaped stacked features are up to 500 m thick and locally contain U-shaped features of varying dimensions ranging from (10 km long, 2 km wide and 70 m depth), relatively linear upslope, to (20 km long, 0.2 km wide and 10 m depth), highly sinuous downslope (Figs. 6, 7 and 8). Prominent levees are observed on the larger scale features, decreasing high, and amplitudes away the channels (Fig. 5a).

In general, the extend of the of the submarine fan system cover an area of 600 km^2 and are oriented NE-SW, close to the. Seven mapped stratal slices reveal the morphology of seven distinct submarine fans labelled as fan A to fan G, highlighting their different evolutionary stages. Each submarine fan shows different lateral seismic characteristics in seismic sections with variations seismic reflection amplitudes. From SW to NE of the cross-sections, low amplitude reflectors (LARs) are observed, then the trend increases towards moderate amplitude reflectors (MAR) and high amplitude reflectors (HARs) near the channel (Fig. 5a). As moving away from the channel axis (Fig. 5a), the seismic reflections transit from the MARs to the LARs that strike the Kribi High to the east (Fig. 5c and 5d). On the stratal slice maps, the LARs correspond to low RMS amplitude and high variance. Conversely the HARs correspond to high RMS amplitude and low variance. (HAR) representing the filling of the fan with sandy-prone deposits (Zang et al., 2018), with a large area of low to medium reflection amplitude (LAR and MAR) which generally represent mud-prone deposits with some of silty-prone deposits (Zang et al., 2018) (Figs. 6,7 and 8).

Fans A and B are the base in the submarine fan system (Fig. 6b and 6c). Fan A is a low-amplitude and not clearly defined by seismic attributes (Fig. 6b). It also lies close to the lower large channel and has a base seal risk due to proximity to the lower channel (Figs. 5 and 6a). The fan has an elongate lobate geometry and it is interpreted to be stratigraphically trapped through shale plugging of the feeder channel, expressed by an absence or a low presence of a sand-prone attribute response. Fan B has similar morphological characteristics to fan A which lies above it. Fan B is large, with very high amplitudes on the SE margin, and weak amplitudes to the NW. The very high amplitude values on the SE margin may indicate thin cemented sandstones here. Both Fan A and B were not intersected the well. Well log data for the time period corresponding to these fans show high GR values dominated by fine-grained hemipelagic sediments (Fig. 9). The fan has a large lobate geometry and a sinuous distributary channel is present on the SE margin (Fig. 6c). This submarine fan shows an initial phase of submarine fan development that manifests itself as a prominent channel in the upslope area that slopes downwards in a NE-SW orientation, ending in a large-scale lobe in the southern area downslope (Fig. 6c). Thus, as it goes farther downslope, the channel is replaced by large-scale lobe, which may result from the varied seafloor topography. The geometry of the fan shows that sediment entry occurred from the east of the canyon (Fig. 6b and 6c). At its downstream end, high amplitudes stack from the SW area and are interpreted as a sand-prone lobe (Fig. 6b and 6c).

Fans C, D, and E are in the middle of the submarine fan system (Fig. 7a, 7b, and 7c). They are bright to high-amplitude reflectors with good continuity and are clearly defined in the cross-section (Fig. 5). The fan locally contains U-shaped features (Fig. 5a), and these U-shaped features are linear to sinuous in map view and interpreted as a channel in the upper slope. These submarine fans are relatively large compared to other submarine fans and have a prominent lobate geometry comprising a sinuous distribution channel radiating from the east feeder channel to a south-west downslope end (Fig. 7). The channel sinuosity is low in the upslope area, and increases gradually downslope, the feeder channel appears to be relatively constant in size and location during the evolution of the fan (Fig. 7). Thus, the submarine fans (C-E) mark the growth phase. Fan C is a large well-defined fan with high amplitudes on its SE margin, and weaker amplitudes to the NW (Fig.7a). The high amplitudes are likely to indicate more cemented sandstones. The Fan C geometry shows sediment entry was via the east canyon. The fan C also has a large lobate geometry and a sinuous distributary channel is present to the SE. It overlies Fan B and Fan A, and is itself overlain by the silt prone Fan D. Fan D shows an elongate lobe geometry and can be interpreted as a silt prone interval (Fig.7b). The variation of amplitudes within the feeder channel which suggest variable lithologies here (silt and sand prone sequences). Fan E is a large well-defined fan with bright amplitudes (Fig. 7c). The fan shows a high amplitude within the main fan channel and within an interpreted crevasse splay in the SE. The fan E has a large lobate geometry and a sinuous distributary channel on the SE side of the fan. The map for these fans shows separation of the fan amplitude from feeder channel and overbank amplitude updip. Furthermore, a remarkable observation of the lobe morphology during this phase is the presence of a series of relatively parallel elongated features. These series of relatively parallel high amplitude elongate features show finger-like terminations at the margin of the submarine fan, with the dimension of 0.5 to 5 km length and up to 2 km width (Figs. 5d and 7). branch off at high angles downslope, with an angle of up to 90^o to the overall transport direction. This feature is clearly visible in fan C, it is characterized by high RMS amplitudes and low variance amplitudes and is interpreted as thick massive sands, formed as a result of sedimentary gravity flows that deviate from the main flow and erode into a pelagic clay substrate.

Fans F and G are the youngest within the submarine fan system (Fig. 8a and 8b). Fan F is a large well-defined elongated fan. The amplitude map shows a prominent channel feature running down the axis of the fan then turning west (Fig. 8a). These fans are relatively small compared to the other submarine fans and probably represent a retreat/terminal phase of submarine fan development (Fig. 8a and 8b). At the top, the fan G is capped by a major Maastrichtian channel that comprises two episodes of erosion and infilling as indicated by the recent work of Secke et al., 2022 (Fig. 8c). The blocky GR log signature of the entire interval of interest suggests the nature of thick-bedded amalgamated sands and interbedded mud sets, showing a cylindrical shape consistent with channel fills within a submarine fan system (Fig. 9).

5. Discussion

5.1. Evolution of the submarine fan system

The submarine fan system consists of a single broad lobe fed from the east by a shelf incised canyon (Fig. 6b and 6c). As the fan system evolves, it exhibits variable planforms, sand content, stacking patterns and lithologic characters (Figs. 6, 7 and 8). This difference reflects the architectural evolution of a single submarine fan system, during an aggradation phase with a particular interaction with the underlying topography marked by the presence of the Kribi-high. Based on observation criteria such as fan shape, channel inclusion and difference in sand abundance within the submarine fan, we establish three-stage architecture evolution for submarine fan system (Zhang et al., 2018).

At the early stage of the fan evolution, deposition occurred as a minor submarine fan at the toe of slope fed by a single (narrow) feeder channel. Both Fan A and B developed in a stacking pattern with a lobed geometry and the presence of a channel within the submarine fan and can be interpreted as a channelized lobe (Fig. 6c). In the Well log W1, these fans are characterized by high-amplitude blocky GR log motifs and are interpreted as a sand-prone channel fill (Fig. 9). This stage represents the initiation of the submarine fan system (sensu Gardner et al., 2003, Hadler-Jacobsen et al., 2005).

In the second stage slope channel avulsion followed by submarine fan deposition at the toe of slope to proximal basin floor was initiated. Submarine fans C, D, and E are correspond to this stage and were formed associated with crevasse splay deposits and large volumes of sediments. Moreover, our results indicate the presence of a series of relatively parallel high amplitude elongate features with finger-like terminations at the margin of the submarine fan (Fig. 7). These finger-like terminations appear to be only developed on the lobe margin in the SE. The morphology and scale of the finger-like features are comparable to similar features described in the distal areas of Permian submarine fans preserved in the Tanqua Karoo Basin, South Africa (Klaucke et al., 2004) and also on the distal edge of the Mississippi submarine fan (Twichell et al., 2009). For instance, the distal Mississippi submarine fan also has a lobate morphology with finger-like dendritic terminations, elongated lobes, and splays that branch off from the main deposit (Twichell et al., 2009). The distal Mississippi submarine fan is very flat, with a surface slope of 0.08°, and also has low relief moderate sinuous channels(Gardner, 2007). It consists of mudstone facies with interbedded sand and silts, formed by abrupt deposition of channelized flows to form small lobes at their distal reaches (Nelson et al., 1992, Klaucke et al., 2004). Therefore, the high amplitude finger-like features in our study could be interpreted as a thick massive sands, formed as a result of sediment-gravity flows which branch off the main flow and erode into pelagic clay substrate (Le, 2012). Well W1 (Fig. 9) shows that submarine fans C to E consists of sandstone and subordinate claystone with blocky to funnel-shaped GR log motifs. This phase is interpreted as fan growth stage (sensu Gardner et al., 2003, Hadler-Jacobsen et al., 2005).

In the final stage, the submarine fan retreated and the feeder channel backfilling and significant slope overbank splay deposition as a function of reduced feeder-channel margin relief occurred. Although, the submarine fan F presents some similarities with fan E, it lacks finger-like features. Fan G is characterized by the absence of a feeding and distribution channel within this fan (Fig. 8b). Fan G is narrowing and tending to disappear to make way for a submarine channel system reported by Secke et al., 2022. Well W1 (Fig. 9) reveal that the submarine fans F to G are characterized by low-amplitude bell-shaped GR log responses and are interpreted as overbank.

This stage remarks the retreating phase of the submarine fan (sensu Gardner et al., 2003, Hadler-Jacobsen et al., 2005, Fig. 10).

5.2. Allogenic and autogenic controls on submarine fan architecture

According to Catuneanu and Zecchin, 2013, allogenic and autogenic processes both could contribute the evolution submarine fan deposits. Factors such as tectonics, sea level fluctuations, local topography and sediment input, probably controlled the development of the submarine fan in the study area.

During the Santonian (KC-02), the Atlantic Ocean is connected to the Tethys Ocean through a NE-SE trending shallow sea that separates the northwest African continent from the rest (Fig. 1b). Our study area is located in the northwestern corner of the continent. During this time, there was a tectonic readjustment along the Kribi-Campo High, which was uplifted relative to the deep basal zone to the west, resulting in significant erosion and leading to the deposition of thick Late Cretaceous clastics. It is characterized by slope and basin floor fans containing multiple channel complexes (Fig. 3; Sterling, 2010; Le, 2012; Secke et al., 2022). A series of eustatic depressions during the Campanian-Maastrichtian and Santonian uplift facilitated the episodic transport of major clastic sediments across the relatively narrow shelf into the deeper basin to the west (Secke et al., 2022). Following the fall of sea-level, increase of fluvial sediment supply, previously accumulated sediments on the shelf and sourced from the fluvial system were delivered to the deep basin, and formed a complex channel during the Santonian (Fig. 5 and 6a).

As sea level falls (Fig. 2), the shoreline migrates seaward for several kilometers, and may have caused a direct connection between shelf edge systems and slope canyon heads, which could facilitate the delivery of voluminous clastic material into the deep-water setting (Gong et al., 2016), and thus develop submarine fan sediments. The initiation of submarine Fan A atop the submarine channel system may suggest a relative rise in sea level, as the proximal (channel) part of the source to sink system was overlain by distal (fan) system (Gong et al., 2016). This was also evident by the well log that shows fining upward trend in GR values towards the Fan A (Fig. 9). Submarine fan B to C represent the continued development of the fans, and D has the largest areal coverage, indicating the low-order sea-level reached its relative peak during this time. In general, during the development of Fan A to Fan D, the low GR signatures are separated by high amplitude values, indicating the higher order sea level is fluctuating even though the general trend is a rising stage (Fig. 9).

Further subsidence along the West African margin occurred in the Late Cretaceous (Campanian-Maastrichtian) as continental drift continued (SPT/Simon Petroleum and Technology, 1995; Iboum et al., 2016). New coarse clastics were introduced into the Kribi-Campo high and the study area. These coarse clastics were fed by paleo-fluvial deltaic systems (Ntem, Nyong and Sanaga) that organized into shallow marine sediments along the inner shelf area, only to be remobilized into the deeper basin areas as gravity flow deposits of high density turbidites and debrites in fan channel geometries vis-à-vis submarine canyon feeder systems (Sterling, 2010; Secke et al., 2022). From Fan D to G, the areal coverage of the fans is decreasing, indicating a possible fall in lower order sea level. However, the GR shows an increasing trend, suggesting the sediments intersected by the wells are mainly fine-grained material. The fall in sea level is also evident by the observation of a channel system that developed atop of the Fan G (Figs. 8c and 9).

Although allogenic effects dominate the control of submarine fan architecture in the study area in the Late Cretaceous, autogenic factors may still exert some influence. Seafloor topography is an important autogenic factor that could influence the morphology of the submarine fan (Adeogba et al., 2005; Gervais et al., 2006; Prélat et al., 2010). For example, laterally confined topography may facilitate the development of submarine channel systems, while relatively unconfined topography may accommodate large-scale submarine lobe sediments, such as those observed in this study with an elongated shape and size around 600 km^2, falling in the lower range of the range dimensions (Pickering et al. (1989)). According to Janocko et al. (2013), frequent channel incision is another common autogenous process in the deep-water environment that may explain the diversity of submarine fan architecture. When channel incision occurs largely at one of the evolutionary stages, downstream submarine fan systems may be abandoned and end up with incomplete successions, as illustrated in this study (Fig. 8b).

5.3. Conceptual models of submarine fan

Campanian depositional form (primarily fans) was quite different from the large, well confined submarine channel of the Santonian. In Campanian times (KC-3), the dominant depositional form has been interpreted as large (Loule et al., 2018), relatively unconfined basin floor fans with well-defined internal structures such as channels, levee deposits, crevasse splay and breat-out fan lobes to the main basin floor fan (Sterling, 2010; Fig.10). The stage of evolution of these submarine fans, shows characteristics very similar to the Type I depositional system of Mutti (1985), where a vertical succession of aggradational fan lobes and channels produce a complex sedimentological mix of facies types and this is what would be expected in the Campanian of the study area (Fig.10). At the beginning of this period, the sea level coincides with a period of fall sea level which would have led to the development of the first stage of fan evolution (Fan A and B) marked by a single (narrow) feeder channel associated with a single sand-rich lobe (Gardner et al., 2003, Hadler-Jacobsen et al., 2005; Fig. 10a). During the growth phase (Fan D), the geometry of the fan increases with a more sinuous channel developing within the lobe (Fig. 10b). The slope channel avulsion was followed by the submarine fan deposition at the toe of slope. This suggests significant sediment supply to an expansive, unconfined basin floor area where is dominated by the fan channel and stacked lobes developed in a relatively lowest sea level period (Zhang et al., 2018). Immediately after this stage, as sea level rises, there is a upward trend in the GR log reading (Fig. 9) which is characterised by a decrease in the areal coverage of the lobe, and decrease in the slope gradient in its upslope feeder system. This period also accompanied by the incision of main channel (Fan G). A retreat of the submarine fan combined with feeder channel backfilling and significant slope overbank splay deposition as a function of reduced feeder-channel margin relief occurred (Gardner et al., 2003, Hadler-Jacobsen et al., 2005; Fig. 10c). The submarine fan becomes increasingly rich in fine sediment and poor in sand (Fig. 10c).

Overall, these are stacked, low relief sheets or lobes located outboard from the main feeder channel system in the eastern sector of the study area. The high amplitude reflection packages (HAR) give strong support for a mix of clastic types and there are evidence of compaction draping over the more sand-rich areas of the fans (Mutti, 1985, Sterling, 2010). The presence of erosive channels with moderately developed levees indicate the effects of turbidity flow processes that associated with the debris flow units (debrites) interbedded with sands and other rock assemblages (Sterling, 2010). With the onset of the Maastrichtian (KC-04), the dominant deep-water deposition system changed from a submarine fan series in the Campanian to a more confined and incised channel system (Secke et al., 2022; Figs. 8c and 9).

6. Conclusions

Detailed seismic geomorphological analysis of 3D seismic reflection and well data for the Late Cretaceous sequences studied in the Kribi-Campo basin, offshore Cameroon has enabled the internal architecture and geomorphological evolution of a deeply buried Campanian basin floor fan system to be described. The main conclusions of this work are as follows:

1) The submarine fan exists in stacked form and its depositional history has been reconstructed using seven strata slices and seismic attributes grouped into initiation, growth and abandonment phases.

2) The submarine fan is in the form of an elongated lobe-oriented NE-SW, the sediment of which entered via an east canyon probably originating from the Palaeo-Nyong fluvial system migrating through the area. This fan contains a sinuous distribution channel.

3) The sediments in the fan were mainly gravity-flow deposits of coarse-grained turbidite sandstone with minor interbedded fine-grained hemipelagics that were vertically stacked.

4) The evolution of the fan architecture was mainly conditioned by changes in sea level, tectonic readjustment along the Kribi-Campo High, which was uplifted relative to the deep basal zone to the west, resulting in significant erosion and leading to the deposition of thick Late Cretaceous clastics and the unconfined topography of the basin.

Acknowledgements

The authors would like to thank the National Hydrocarbon Corporation (NHC), Yaoundé, Cameroon, for providing the seismic data used in this study. BSBG is grateful to the Swiss Government Excellence Scholarship for awarding him an excellence scholarship ESKAS No. 2022.0697. SLB is acknowledged for granting the academic licence of Petrel to the University of Geneva used to interpret the dataset.

References

Adeogba, A.A., McHargue, T.R., Graham, S.A., 2005. Transient fan architecture and depositional controls from near-surface 3-D seismic data, Niger Delta continental slope. AAPG Bull. 89, 627–643.

Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Mar. Petrol. Geol. 19 (4), 445–467. https://doi.org/10.1016/S0264-8172(02)00009-0.

Beglinger, S.E., Doust, H., Cloetingh, S., 2012. Relating petroleum system and play development to basin evolution: west African South Atlantic basins. Mar. Petrol. Geol. 30, 1–25. https://doi.org/10.1016/j.marpetgeo.2011.08.008.

Benkhelil, J., Giresse, P., Poumot, C., Ngueutchoua, G., 2002. Lithostratigraphic, geophysical, and morpho-tectonic studies of the South Cameroon shelf. In: Marine and Petroleum Geology, 19, 499–517. https://doi.org/10.1016/ S0264-8172(02)00002-8.

Bouchakour, M., Zhao, X., Miclăus, C., Yang, B., 2023. Lateral migration and channel bend morphology around growing folds (Niger Delta continental slope). Basin research 35, 1154-1192. https://doi.org/10.1111/bre.12750.

Boulesteix, K., Poyatos-Moré, M., Flint, S., Hodgson, D.M., Taylor, K.G. and Parry, G.R., 2019. Sedimentary facies and stratigraphic architecture of deep-water mudstones beyond the basin-floor fan sandstone pinchout. EarthArXiv, July 9. https://doi.org/10.31223/osf.io/3qrew.

Brown, A.R., 2004. Interpretation of Three-Dimensional Seismic Data. American Association of Petroleum Geologists and the Society of Exploration Geophysicists.

Brown, A.R., 2011. Interpretation of Three-Dimensional Seismic Data, Seventh. ed. Society of Exploration Geophysicists and American Association of Petroleum Geologists. https://doi.org/10.1190/1.9781560802884

Brownfield, M.E., 2016. Assessment of Undiscovered Oil and Gas Resources of the West-Central Coastal Province, West Africa. U.S. Geological Survey, Reston, Virginia, p. 41p.

Brownfield, M.E., Charpentier, R.R., 2006. Geology and Total Petroleum Systems of the West-Central Coastal Province (7203), West Africa: U.S. Geological Survey Bulletin 2207-B, p. 52.

Catuneanu, O., Zecchin, M., 2013. High-resolution sequence stratigraphy of clastic shelves II: controls on sequence development. Mar. Petrol. Geol. 39, 26–38.

Covault, J.A., 2011. Submarine fans and canyon-channel systems: a review of processes, products, and models. Nature Education Knowledge 3 (10), 4.

Coward, M. P., Purdy, E. G., and Ries, A. C. et al. 1999. The distribution of petroleum reserves in basins of the South Atlantic margins. In: The Oil and Gas Habitats of the South Atlantic Geological Society of London Special Publications, 153, 101-131.

Curray, J.R., Emmel, F.J., Moore, D.G., 2002. The Bengal Fan: morphology, geometry, stratigraphy, history and processes. Mar. Petrol. Geol. 19 (10), 1191–1223. https:// doi.org/10.1016/S0264-8172(03)00035-7.

Dailly, P., Lowry, P., Goh, Gene, M., 2002. Exploration and Development of Ceiba Field, Rio Muni Basin, Southern Equatorial Guinea. The leading edge, November, pp. 1140–1146.

Deptuck, M.E., Steffens, G.S., Barton, M., Pirmez, C., 2003. Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea. Mar. Pet. Geol. 20, 649–676.

Deptuck, M.E., Sylvester, Z., 2018. In: Micallef, A., Krastel, S., Savini, A. (Eds.), Submarine Fans and Their Channels, Levees, and Lobes. Springer Geology. Springer, pp. 273–299. https://doi.org/10.1007/978-3-319-57852-1_15.

Deptuck, M.E., Sylvester, Z., Pirmez, C., O'Byrne, C., 2007. Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin major Canyon, western Niger Delta slope. Mar. Petrol. Geol. 24, 406–433.

Doughty-Jones, G., Mayall, M., Lonergan, L., 2017. Stratigraphy, facies, and evolution of deep-water lobe complexes within a salt controlled intraslope mini basin. AAPG (Am. Assoc. Pet. Geol.) Bull. 101 (11), 1879–1904. https://doi.org/10.1306/ 01111716046.

Gamberi, F., Rovere, M., Marani, M., 2011. Mass-transport complex evolution in a tectonically active margin (Gioia Basin, Southeastern Tyrrhenian Sea). Mar. Geol. 279, 98–110.

Gardner, M. H., Borer, J. M., Melick, J. J., Mavilla, N., Dechesne, M. & Wagerle, R. M. 2003. Stratigraphic process-response model for submarine channels and related features from studies of Permian Brushy Canyon outcrops, West Texas. Marine and Petroleum Geology, 20, 757–787.

Gervais, A., Savoye, B., Mulder, T., Gonthier, E., 2006. Sandy modern turbidite lobes: a new insight from high resolution seismic data. Mar. Petrol. Geol. 23, 485–502.

Gong, C., Steel, R.J., Wang, Y., Lin, C., Olariu, C., 2016. Shelf-margin architecture variability and its role in sediment-budget partitioning into deep-water areas. Earth Sci. Rev. 154, 72–101.

Hadler-Jacobsen, F., Johannessen, E. P., Ashton, N., Henriksen, S., Johnson, S. D. & Kristensen, J. B., 2005. Submarine fan morphology and lithology distribution. In: DORE´ , A. G. & VINING, B. A. (eds). Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference, 1121–1145. Petroleum Geology Conferences Ltd. Published by the Geological Society, London.

Hansen, L., Janocko, M., Kane, I., Kneller, B., 2017. Submarine channel evolution, terrace development, and preservation of intra-channel thin-bedded turbidites: Mahin and Avon channels, offshore Nigeria. Mar. Geol. 383, 146–167

Howlett, D.M., Gawthorpe, R.L., Ge, Z., Rotevatn, A., Jackson, C., 2020. Turbidites, topography and tectonics: Evolution of submarine. Basin Research. doi: https://doi.org/10.1111/bre.12506.

Iboum Kissaaka, J.B., Ntamak-Nida, M.J., Mvondo, F., Fowe Kwetche, P.G., Djomeni Nitcheu, A.L., Abolo, G.M., 2016. Postrift depositional evolution and sequence stratigraphy from offshore subsurface data of the Kribi-Campo sub basin (Cameroon, West African margin). Soc. Explor. Geophys. Am. Assoc. Petrol. Geol. 13, 79–101. https://doi.org/10.1190/INT-2015-0073.1.

Jobe, Z.R., Sylvester, Z., Parker, A.O., Howes, N., Slowey, N., Pirmez, C., 2015. Rapid adjustment of submarine channel architecture to changes in sediment supply. J. Sediment. Res. 85, 729–753. https://doi.org/10.2110/jsr.2015.30.

Klauche, I., Masson, D.G., Kenyon, N.H. & Gardner, J.V. 2004. Sedimentary processes of the lower Monterey Fan channel and channel-mouth lobe. Marine Geology, 206 (1-4), 181-198.

Kolla, V., Posamentier, H.W., Wood, L.J., 2007. Deep-water and fluvial sinuous channels characteristics, similarities and dissimilarities, and modes of formation. Mar. Petrol. Geol. 24, 388–405.

Lawal, M.A., Pecher, I., Bialik, O.M., Waldmann, N.D., Bialas, J., Koren, Z., Makovsky, Y., 2022. Multilevel Composition: A new method for revealing complex geological features in three-dimensional seismic reflection data. Marine and Petroleum Geology 146, 105938.

Lawrence, R.S., Munday, S., Bray, R., 2002. Regional Geology and Geophysics of the Eastern Gulf of Guinea (Niger Delta). The leading Edge, pp. 1112–1117.

Le, A.N., 2012. Stratigraphic evolution and plumbing system in the Cameroon margin, West Africa. In: Thesis for the Degree of Doctor of Philosophy. Faculty of Engineering and Physical Science, University of Manchester.

Le, A.N., 2021. Striations at the base of the paleo-fan and channel revealed by 3D seismic data, offshore Cameroon. Indones. J. Geosci. 8, 101–107.

Le, A.N., Huuse, M., Redfern, J., Gawthorpe, R.L., Irving, D., 2014. Seismic characterization of a Bottom Simulating Reflection (BSR) and plumbing system of the Cameroon margin, offshore West Africa. Mar. Petrol. Geol. 68, 629–647.

Li, P., Kneller, B., Hansen, L., 2021. Anatomy of a gas-bearing submarine channel-lobe system on a topographically complex slope (offshore Nile Delta, Egypt). Mar. Geol. 437, 106496 https://doi.org/10.1016/j.margeo.2021.106496.

Loule, J.P., Jifon, F., Angoua Biouele, S.E., Nguema, P., Spofforth, D., Carruthers, D., Watkins, C., Johnston, J., 2018. An opportunity to re-evaluate the petroleum potential of the Douala/Kribi-Campo Basin, Cameroon. Spec. Top.: Petrol. Geol. 36, 61–70. First break.

Meyers, J.B., Rosendhal, B.R., Groschel-Becker, H., Austin, J.J.A., Rona, P.A., 1996. Deep penetrating MCS imaging of the rift-to-drift transition, offshore Douala and north Gabon basins, West Africa. Mar. Petrol. Geol. 13, 791–835. https://doi:10.1016/0264-8172 (96)00030-X.

Mienlam Essi, M.F., Yene Atangana, J.Q., Abate Essi, J.M., Mbida, Yem, Angoua Biouele, S.E., Nguema, P., Tsimi Ntsengue, C., 2021. Stratigraphical nature of the Top Albian surface, from seismic and wells data analyses, in the south Sanaga area (Cameroon Atlantic margin): palaeogeographical significance and petroleum implications. Mar. Petrol. Geol. 129, 105073. https://doi.org/10.1016/j. marpetgeo.2021.105073.

Navarre, J.-C., Claude, D., Librelle, F., Safa, P., Villon, G. and Keskes, N., 2002. Deepwater turbidite system analysis, West Africa: sedimentary model and implications for reservoir model construction. The Leading Edge, 21, 1132–1139. https://doi.org/10.1190/1.1523754.

Nelson, C.H., Twichell, D.C., Schwab, W.C., Lee, H.J., Kenyon, N.H., 1992. Upper Pleistocene turbidite sand beds and chaotic silt beds in the channelized, distal, outer-fan lobes of the Mississippi fan. Geology, 20 (8)**,** 693-696.

Nguene, F.R., Tamfu, S., Loule, J., Ngassa, C., 1992. Palaeoenvironments of the Douala and Kribi/Campo sub-basins, in Cameroon, West Africa. In: Curnelle, R. (Ed.), Géologie Africaine, 1er Colloque de Stratigraphie et de Paléogéographie des Bassins Sédimentaires Ouest-Africains, 2e Colloque Africain de Micropaléontologie, Libreville, Gabon, 1991, Recueil des Communications: Boussens, pp. 129–139. Elf Aquitaine.

Niyazi, Y., Eruteya, O.E., Omosanya, K.O., Harishidayat, D., Johansen, S.E., Waldmann, N., 2018. Seismic geomorphology of submarine channel-belt complexes in the Pliocene of the Levant basin. Offshore Central Israel. Mar. Geol. 403, 123–128.

Ntamak-Nida, M.J., Baudin, F., Schnyder, J., Makong, J.C., Komguem, P.B., Abolo, G.M., 2008. Depositional environments and characterisation of the organic matter of thelower mundeck formation (Barremian?-Aptian) of the kribi-campo sub-basin (south Cameroon): implications for petroleum exploration. J. Afr. Earth Sci. 51, 207–219. https://doi.org/10.1016/j.jafrearsci.2008.01.006.

Ntamak-Nida, M.J., Bourquin, S., Makong, J.C., Baudin, F., Mpesse, J.E., Ngouem, C.I., Komguem, P.B., Abolo, G.M., 2010. Sedimentology and sequence stratigraphy from outcrops of the Kribi-Campo Sub-basin: lower Mundeck formation (lower Cretaceous, southern Cameroon). J. Afr. Earth Sci. 58, 1–18. https://doi.org/ 10.1016/j.jafrearsci.2010.01.004.

Oluboyo, A.P., Gawthorpe, R.L., Bakke, K., Hadler-Jacobsen, F., 2014. Salt tectonic controls on deep-water turbidite depositional systems: Miocene, southwestern Lower Congo Basin, offshore Angola. Basin Research. 26. 597-620.

Omosanya, K.O., Alves, T.M., 2013. A 3-dimensional seismic method to assess the provenance of Mass-Transport Deposits (MTDs) on salt-rich continental slopes (EspíritoSanto Basin, SE Brazil). Mar. Petrol. Geol. 44, 223–239. https://doi.org/ 10.1016/j. marpetgeo.2013.02.006.

Pauken, R. J. 1992. Sanaga Sud Field, offshore Cameroon, West Africa. In: Halbouty, M.T. (ed.) Giant Oil and Gas Fields of the Decade 1978-1988. Memoir. American Association of Petroleum Geologists, 54, 217-230.

Pickering, K. T., Hiscott, R. N. & Hein, F. J. 1989. Deep marine environments, clastic sedimentation and tectonics. Kluwer Academic Publishers Group.

Pickering, K.T., Corregidor, J. and Clark, J.D., 2015. Architecture and stacking patterns of lower-slope and proximal basin-floor channelised submarine fans, Middle Eocene Ainsa System, Spanish Pyrenees: An integrated outcrop-subsurface study. Earth-Science Reviews, 144, 47–81. https://doi.org/10.1016/j.earscirev.2014.11.017.

Picot, M., Droz, L., Marsset, T., Dennielou, B., Bez, M., 2016. Controls on turbidite sedimentation: insights from a quantitative approach of submarine channel and lobe architecture (Late Quaternary Congo Fan). Mar. Petrol. Geol. 72, 423–446.

Pirmez, C., Beaubouef, R.T., Friedmann, S.J. and Mohrig, D.C., 2000. Equilibrium profile and base level in submarine channels: examples from Late Pleistocene systems and implications for the architecture of deepwater reservoirs. In Weimer, P. (Ed.), Deep-Water Reservoirs of the World, Gulf Coast Section, 20th Annual Research Conference, Proceedings, Houston, SEPM, 782–805. https://doi.org/10.5724/gcs.00.15.0782.

Posamentier, H.W., Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. J. Sediment. Res. 73, 367–388. https:// doi.org/10.1306/111302730367.

Prélat, A., 2010. Evolution, Architecture and Hierarchy of Distributary Deep-Water Deposits: A High-Resolution Outcrop Investigation of Submarine Lobe Deposits from the Permian Karoo Basin. Thesis Ph.D, South Africa.

Prélat, A., Hodgson, D.M., Flint, S.S., 2009. Evolution, architecture and hierarchy of distributary deep-water deposits: a high-resolution outcrop investigation from the Permian Karoo Basin, South Africa. Sedimentology 56, 2132–2154.

Rabinowitz, P., LaBrecque, J., 1979. The Mesozoic South Atlantic Ocean and evolution of its continental margins. J. Geophys. Res. 84 (B11), 5973–6002.

Secke Bekonga Gouott, B., Mbida Yem, Yene Atangana, J.Q., Nkoa Nkoa, P.E., Angoua Biouele, S.E., Niyazi, Y., Eruteya, O.E., Seismic geomorphology of a Late Cretaceous submarine channel system in the Kribi/Campo sub-basin, offshore Cameroon. Marine and Petroleum Geology 145, 105865. https://doi.org/10.1016/j.marpetgeo.2022.105865.

SPT/Simon Petroleum and Technology, 1995. Petroleum Geology and Hydrocarbon Potential of Douala basin, Cameroon. (Unpubl. Non-exclusive report).

Sterling Cameroon Limited., 2010. Prospectivity review of the Ntem block (PH-78) in the Douala/Kribi-Campo Basin. (Unpubl. Non-exclusive report).

Turner, J. P. 1999. Detachment faulting and petroleum prospectivity in the Rio Muni Basin, Equatorial Guinea, West Africa. In: Cameron, N. R., Bate, R. H. & Clure, V. S. (eds) The Oil and Gas Habitats of the South Atlantic. Geological Society, London, Special Publication, 153, 303-320.

Twichell, D., Nelson, C.H., Kenyon, N., Schwab, W., 2009. The Influence of External Processes on the Holocene Evolution of the Mississippi Fan. External Controls on Deepwater Depositional Systems, vol. 92. Society for Sedimentary Geology Special Publication, pp. 145–157.

Vail, P.R., Mitchum, R.M., Thompson, S., 1977. Seismic stratigraphy and global changes of sea level, Part 4, Global cycles of relative changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration. AAPG Memoir. vol. 26. pp. 83–97.

Walker, R.G., 1992. Turbidites and submarine fans. In: Walker, R.G., James, N.P. (Eds.), Facies Models - Response to Sea Level Change. Geological Association of Canada, pp. 239–264.

Wang, J., Pang, X., Wang, H., Zhang, Z., Liu, B., La Croix, A.D., 2024. Seismic geomorphological analysis of submarine fan architecture in the Baiyun Sag, Pearl River Mouth Basin: Impact of second-order relative sea-level change. Marine Geology 469, 107234. https://doi.org/10.1016/j.margeo.2024.107234.

Wilson, P. G., Turner, J. P. & Westbrook, G. K., 2003. Structural architecture of the ocean-continent boundary at a transform margin through deep-imaging seismic interpretation and gravity modelling: Equatorial Guinea, West Africa. Tectonophysics, 374, 19-40.

Wonham, J.P., Jayr, S., Mougamba, R., Chuilon, P., 2000. 3D sedimentary evolution of a canyon fill (Lower Miocene-age) from the Mandorove Formation, offshore Gabon. Marine and Petroleum Geology 17: 175–197.

Yakufu Niyazi, Mark Warne, and Daniel Lerodiaconou 2020; Hectometer-scale, shallow buried honeycomb-like structures on the continental shelf of the Otway Basin, southeastern Australia. Interpretation 8(4). https://doi.org/10.1190/INT-2020-0039.1.

Yamassaki, H. S., Vesely, F. F., 2022. Timelapse of the geomorphologic and stratigraphic evolution of a Late Cretaceous deep-sea fan, northern Santos basin, Brazil. Marine and Petroleum Geology, 136, 105475.

Yugye, J.A., Mfayakouo Chavom, B., Chima K.I., N'nanga, A., Angoua Biouele, S.E., Nkoa Nkoa, P.E., Ngos III, S., 2022. Seismic-stratigraphic analysis and depositional architecture of the Cenozoic Kribi-Campo sub-basin offshore deposits (Cameroon): Seismic attributes approach and implication for the hydrocarbon prospectivity. Journal of African Earth Sciences 194, 104621. https://doi.org/10.1016/j.jafrearsci.2022.104621.

Yugye, J.A., Ngos III, S., Angoua Biouele, S.E., Nkoa Nkoa, P.E., 2021. Seismic stratigraphic interpretation and modeling of offshore synrift and postrift Cretaceous sequences in the Kribi-Campo sub-basin, southern Cameroon. AAPG (Am. Assoc. Pet. Geol.) Bull. 105 (11), 1–20. https://doi.org/10.1306/06092118040.

Zeng, H.L., Ambrose, W.A., 2001. Seismic sedimentology and regional depositional systems in Miocene Norte, lake Maracibo, Venezuela. Lead. Edge 20 (11), 1260–1269.

Zeng, H.L., Loucks, R.G., Brown, L.F., 2007. Mapping sediment dispersal patterns and associated systems tracts in fourth and fifth order sequences using seismic sedimentology: example from Corpus Christi Bay, Texas. AAPG Bull. 91, 981–1003.

Zhang, J., Wu, S., Hu, G., Fan, T.-e., Yu, B., Lin, P., Jiang, S., 2018. Sea-level control on the submarine fan architecture in a deepwater sequence of the Niger Delta Basin. Marine and Petroleum Geology. doi: 10.1016/j.marpetgeo.2018.04.002.

Zhang, J., Wu, S., Wang, X., Lin, Y., Fan, H., Jiang, L., Wan, Q., Yin, H., Lu, Y., 2015. Reservoir quality variations within a sinuous deep-water channel system in the Niger delta basin, offshore West Africa. Mar. Petrol. Geol. 63, 166–188.

Figure captions

Figure 1: Superimposed relief and bathymetric map of Cameroon, showing the location of the study area. Insert map on the right-hand corner of the map shows the location of Cameroon in the Gulf of Guinea. The 3D block, which we studied is white box, while the red cirles labelled W1 and W2, represent well locations (Modified from Secke Bekonga Gouott et al., 2022).

Figure 2: Stratigraphic column of the Kribi-Campo Sub-basin showing the tectono-sedimentary phases and global mean sea level (Secke Bekonga Gouott et al., 2022).

Figure 3: Seismic line through W1 well showing the entire basin successions and channel deposits identified within the dataset. Ten Horizon name (KC-1 to KC-9 and the seafloor) are identified in the study area based on Secke Bekonga Gouott et al. (2022). b) Seismic section through W2 well, taken perpendicular to regional dip, showing the channel complex deposits within the study interval. **c)** Depth conversion scheme.

Figure 4: The interpreted seismic stratigraphy of the slope Late Cretaceous showing the submarine fan, channel complex located within (S1) and the submarine channel system is located within sequence (S2) (based on Secke Bekonga Gouott et al., 2022).

Figure 5: Submarine fan external morphology and stratigraphy in the cross-section with indication of seven stratal horizons (Fan A to Fan G). a) dip-oriented seismic section showing incised channel within the submarine fan, b) strike-oriented seismic sections showing feeder channel within the submarine fan, c) and d) seismic section showing submarine fan between channel complex and channel system, e) seismic section showing a finger-lobe in the submarine fan.

Figure 6: RMS, Variance seismic attributes, and their interpretations, of the various stratal slice within the bottom and base submarine fan (see Fig. 5). a) The seismic attributes analysis shows the distribution of several types of sediments deposited of the channel complex. b) and c) The seismic attributes analysis shows the distribution of several types of sediments deposited during the initiation phase of the submarine fan (Fan A to B).

Figure 7: RMS, Variance seismic attributes, and their interpretations, of the various stratal slice within the bottom and base submarine fan (see Fig. 5.). a), b) and c) The seismic attributes analysis shows the distribution of several types of sediments deposited during the growth phase of the submarine fan (Fan C to E).

Figure 8: RMS, Variance seismic attributes, and their interpretations, of the various stratal slice within the bottom and base fan (see Fig. 5.). a) and b) The seismic attributes analysis shows the distribution of several types of sediments deposited during the retreat phase of the submarine fan (Fan F to G). c) The seismic attributes analysis shows the distribution of several types of sediments deposited of the channel system.

Figure 9: Well W1 showing lithological composition and GR log response of the major features. Approximate location of stratal slices which correspond to Fan A-G extracted from seismic data is indicated and the sea-level change during the time of the studied sequence

Figure 10: Conceptual submarine fan model in the Campanian time a) initiation phase, b) growth phase and c) retreat phase.

Table captions

Table 1: Description and the interpretation of the seismic facies observed within the study interval.

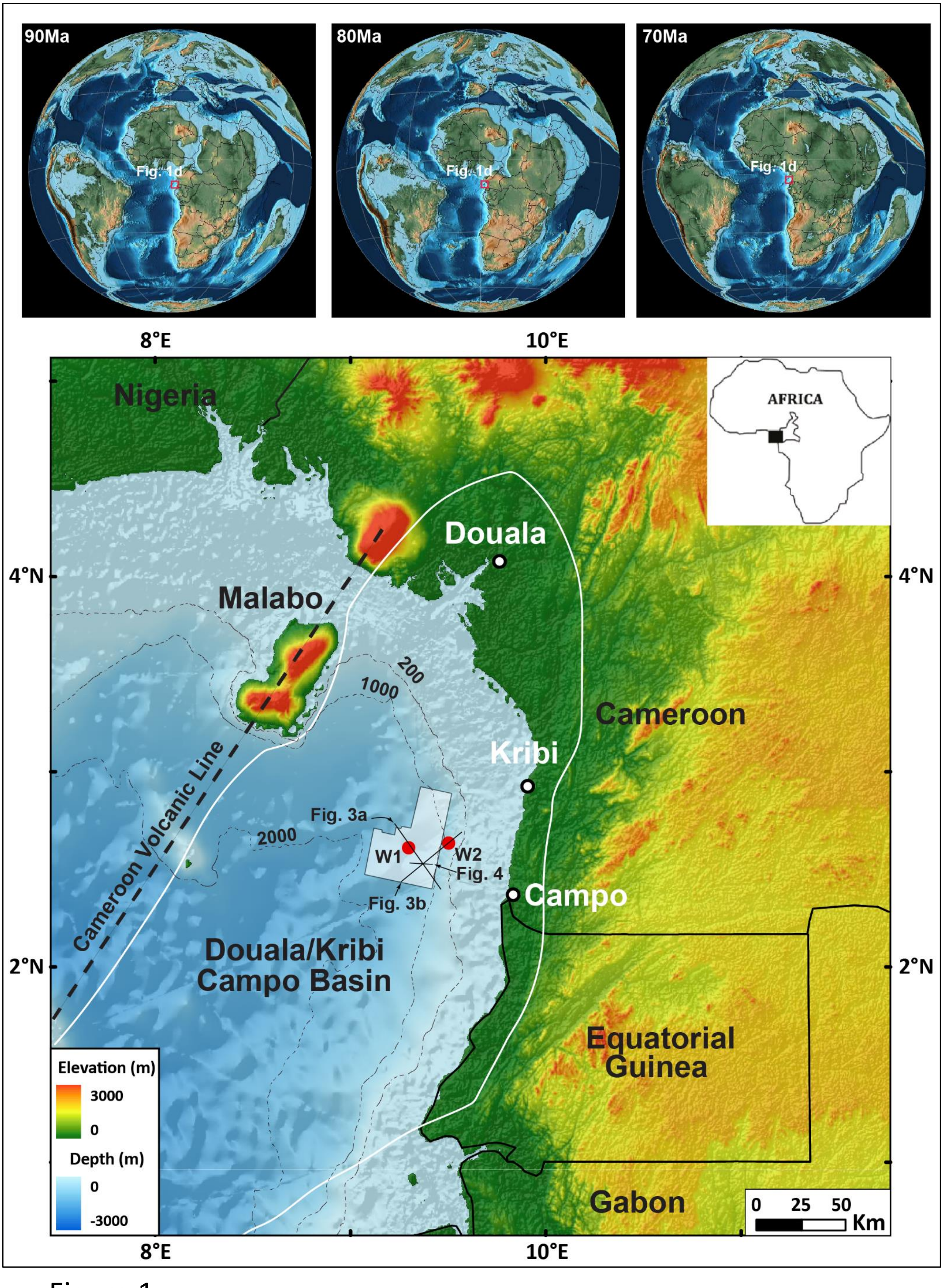
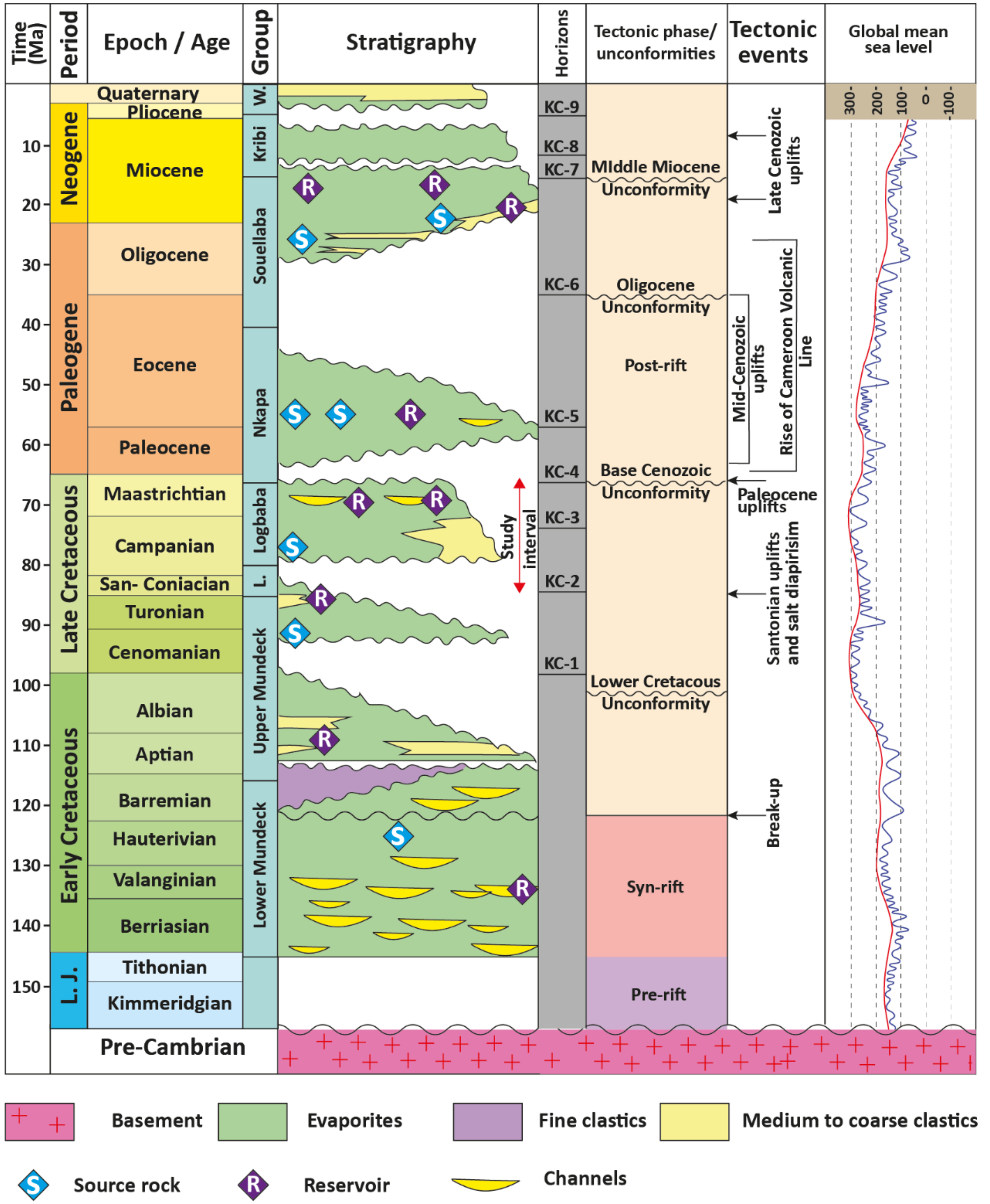

90Ma
80Ma
70Ma
Fig. 1d
8°E
10°E
4°N
2°N
Nigeria
AFRICA
Douala
Malabo
200
1000
2000
Cameroon
Kribi
Cameroon Volcanic Line
Fig. 3a
W1
W2
Fig. 4
Fig. 3b
Campo
Douala/Kribi
Campo Basin
Equatorial
Guinea
Gabon
Elevation (m)
3000
0
Depth (m)
0
-3000
0 25 50
Km

Figure 1



Time (Ma)
Period
Epoch / Age
Group
Stratigraphy
Horizons
Tectonic phase/ unconformities
Tectonic events
Global mean sea level
Quaternary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Maastrichtian
Campanian
San- Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
Kimmeridgian
Pre-Cambrian
Neogene
Paleogene
Late Cretaceous
Early Cretaceous
L. J.
W.
Kribi
Souellaba
Nkapa
Logbaba
L.
Upper Mundeck
Lower Mundeck
KC-9
KC-8
KC-7
KC-6
KC-5
KC-4
KC-3
KC-2
KC-1
Study interval
MIddle Miocene Unconformity
Oligocene Unconformity
Post-rift
Base Cenozoic Unconformity
Lower Cretacous Unconformity
Syn-rift
Pre-rift
Late Cenozoic uplifts
Mid-Cenozoic uplifts
Rise of Cameroon Volcanic Line
Paleocene uplifts
Santonian uplifts and salt diapirisim
Break-up
300-
200-
100-
0-
-100-
Basement
Evaporites
Fine clastics
Medium to coarse clastics
Source rock
Reservoir
Channels

Figure 2

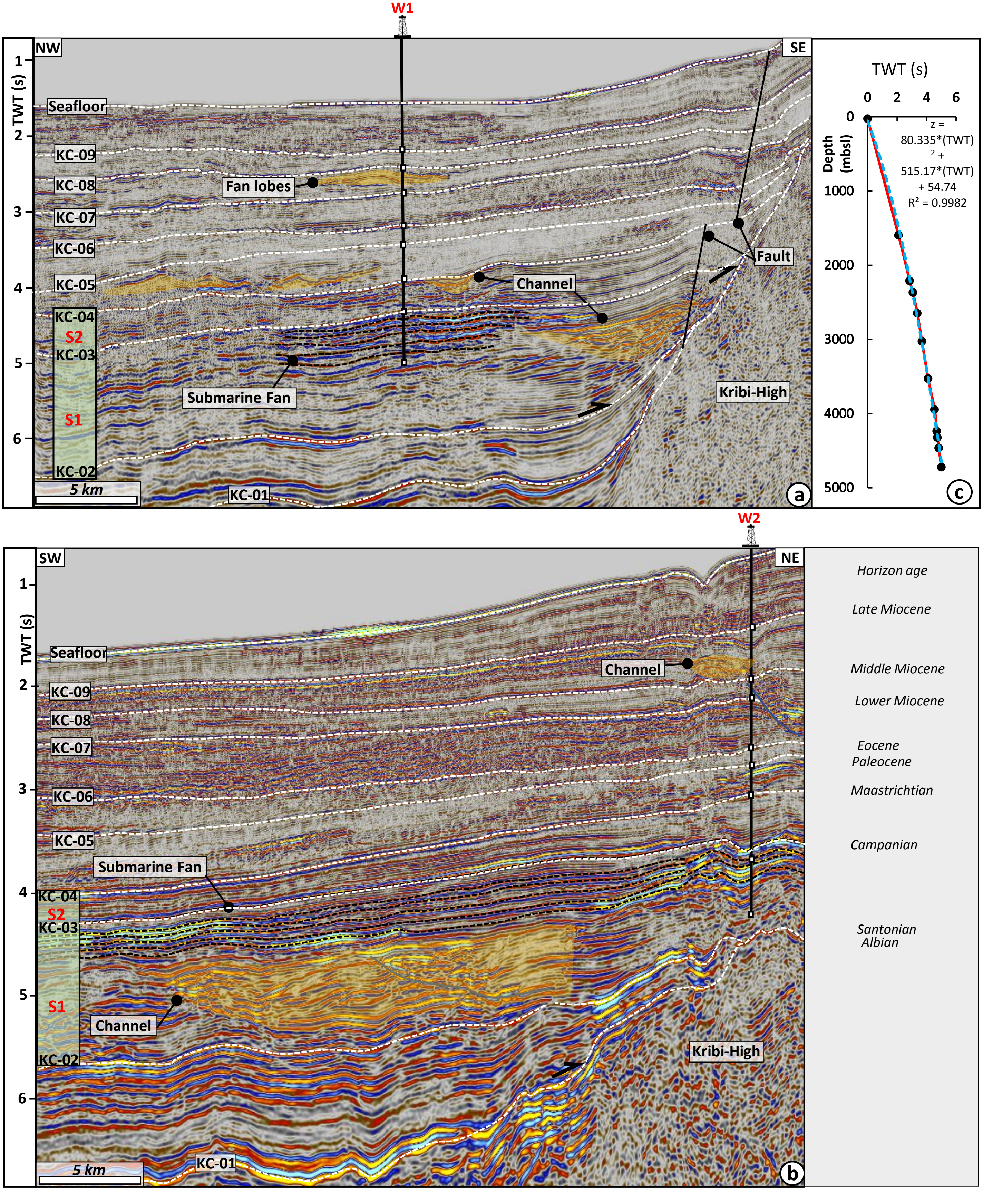
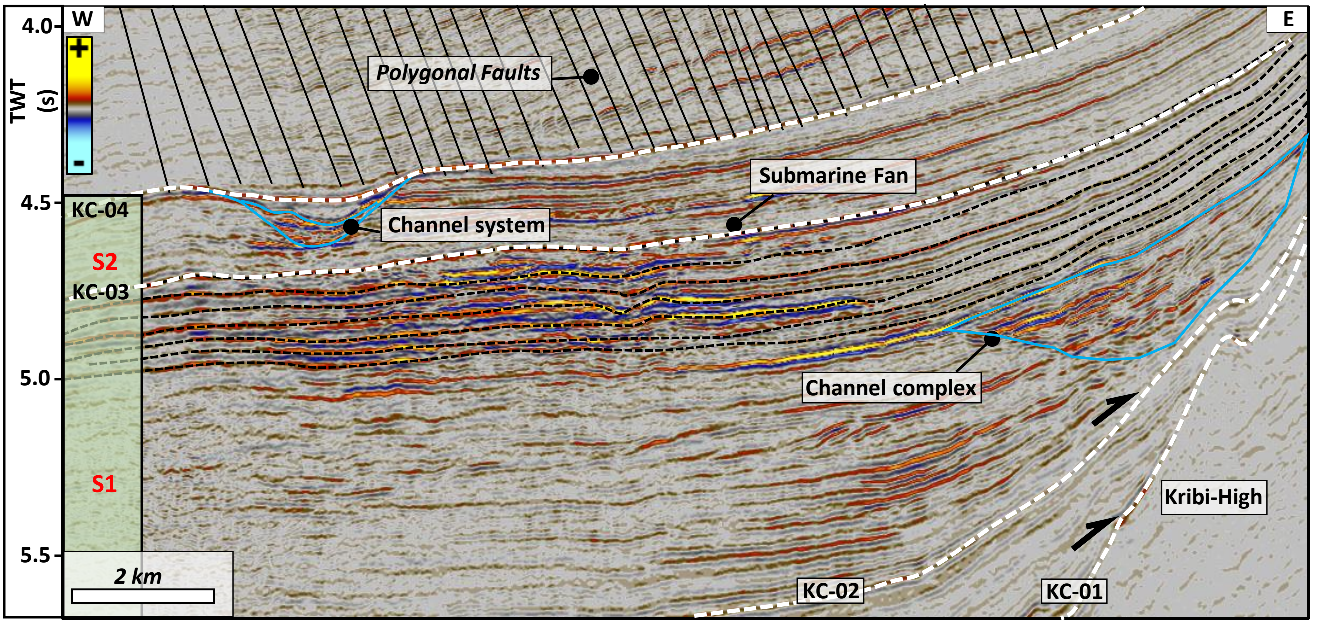

W1
NW
SE
TWT (s)
Seafloor
KC-09
KC-08
KC-07
KC-06
KC-05
KC-04
S2
KC-03
S1
KC-02
KC-01
Fan lobes
Channel
Fault
Submarine Fan
Kribi-High
5 km
a
TWT (s)
Depth (mbsl)
z = 80.335*(TWT)^2 + 515.17*(TWT) + 54.74
R² = 0.9982
c
W2
SW
NE
Channel
Submarine Fan
Kribi-High
b
Horizon age
Late Miocene
Middle Miocene
Lower Miocene
Eocene
Paleocene
Maastrichtian
Campanian
Santonian
Albian

Figure 3



W
E
4.0
4.5
5.0
5.5
TWT (s)
+
-
Polygonal Faults
Submarine Fan
Channel system
KC-04
S2
KC-03
Channel complex
S1
Kribi-High
2 km
KC-02
KC-01

Figure 4

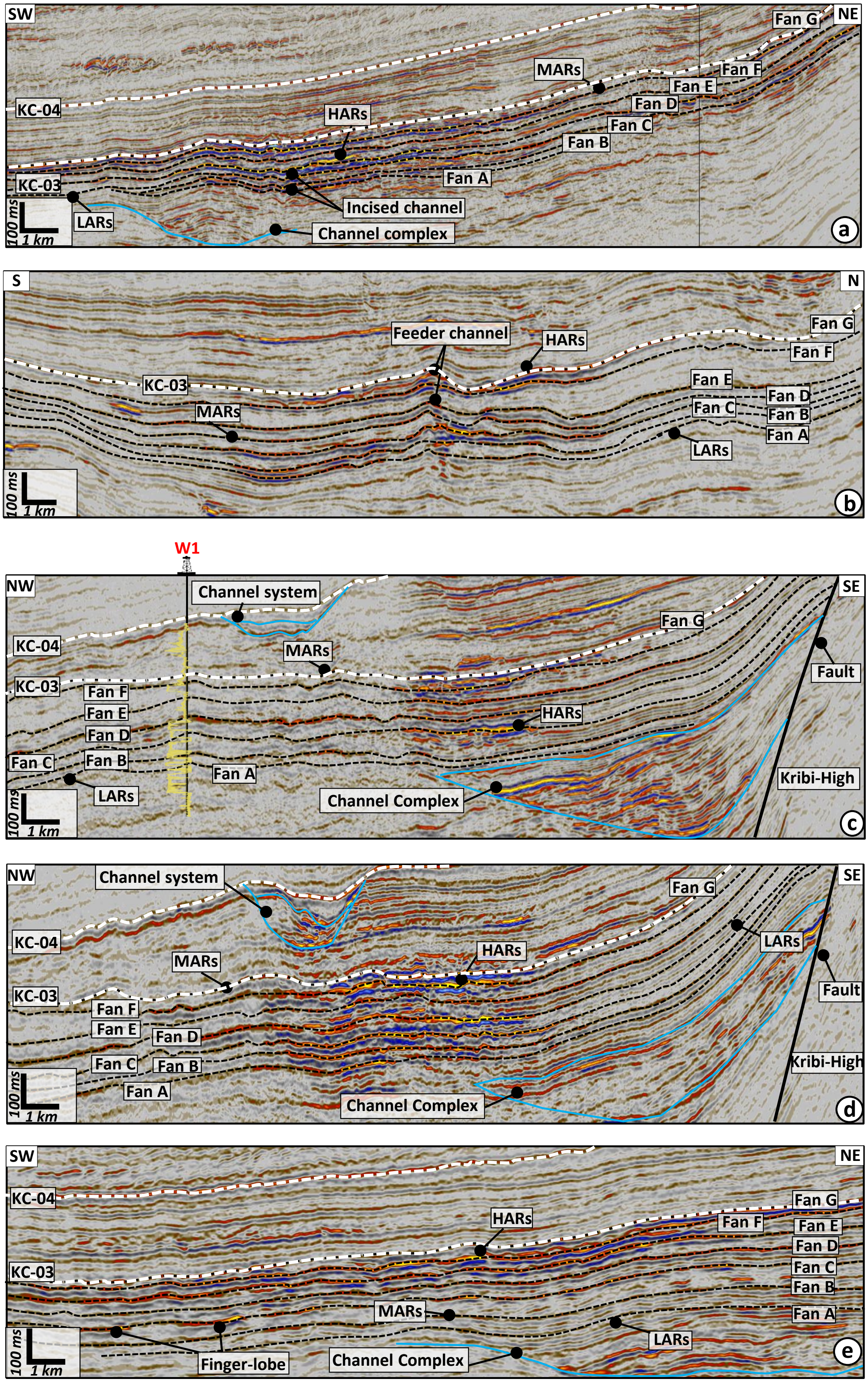

SW
NE
Fan G
MARs
Fan F
Fan E
Fan D
Fan C
Fan B
KC-04
HARs
Fan A
KC-03
Incised channel
LARs
Channel complex
100 ms
1 km
a
S
N
Fan G
Feeder channel
HARs
Fan F
KC-03
Fan E
Fan D
Fan C
Fan B
MARs
Fan A
LARs
b
W1
NW
SE
Channel system
Fan G
KC-04
MARs
Fault
KC-03
Fan F
Fan E
HARs
Fan D
Fan C
Fan B
Fan A
Kribi-High
LARs
Channel Complex
c
Channel system
Fan G
LARs
HARs
Fault
Fan F
Fan E
Fan D
Fan C
Fan B
Kribi-High
Fan A
Channel Complex
d
Finger-lobe
Channel Complex
e

Figure 5

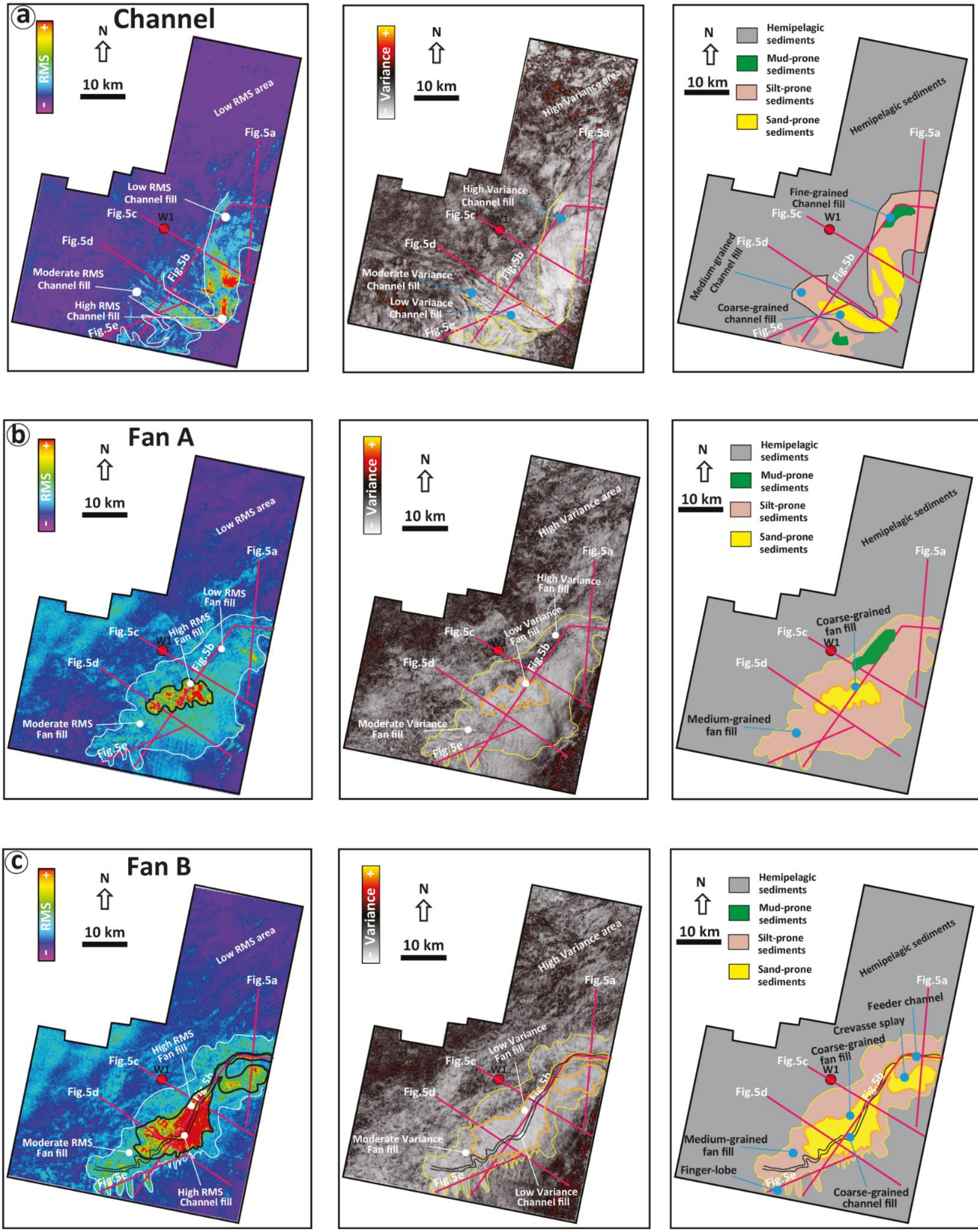
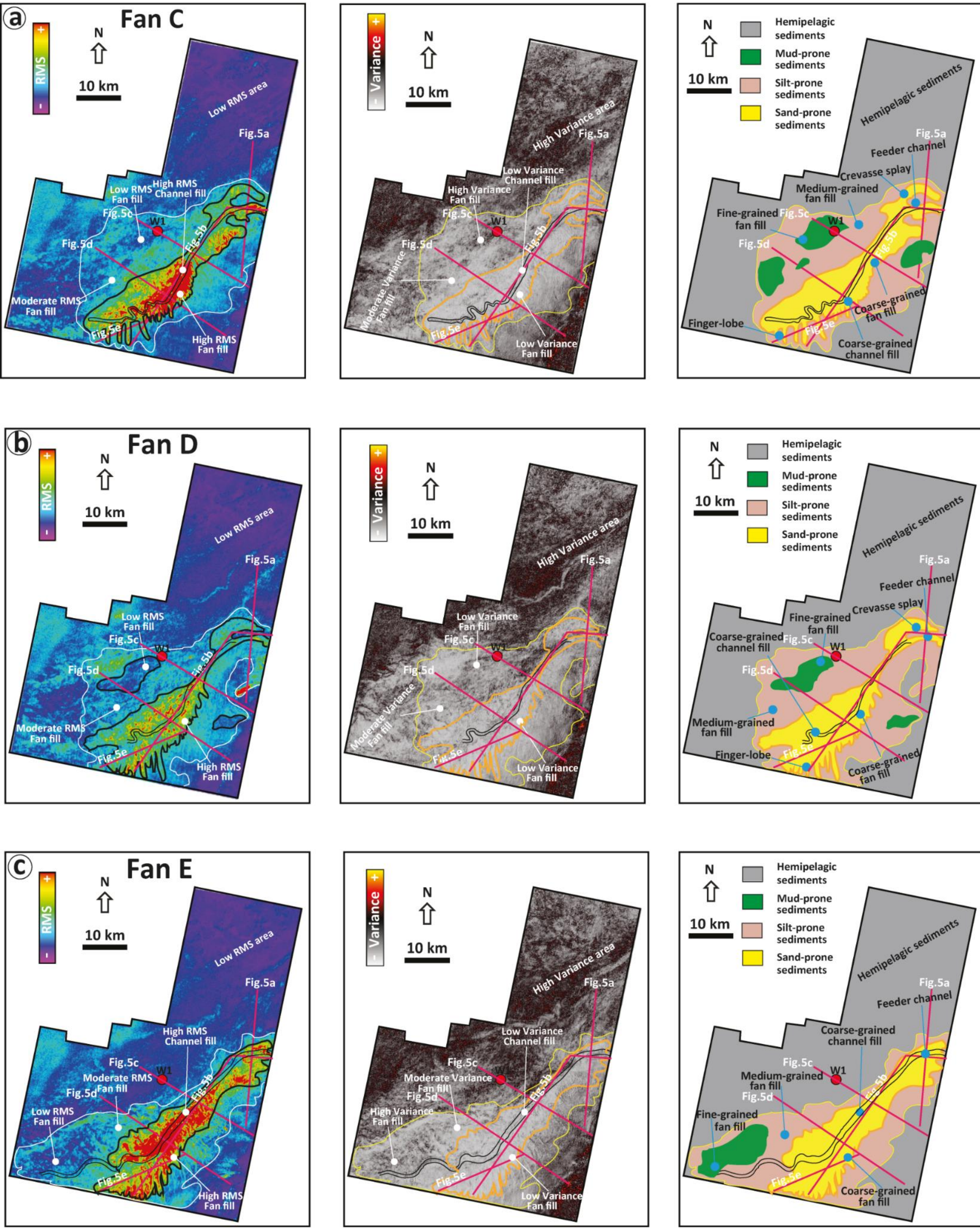

a
Channel
RMS
N
10 km
Low RMS area
Fig.5a
Low RMS Channel fill
Fig.5c
W1
Fig.5d
Fig.5b
Moderate RMS Channel fill
High RMS Channel fill
Fig.5e
Variance
High Variance area
High Variance Channel fill
Moderate Variance Channel fill
Low Variance Channel fill
Hemipelagic sediments
Mud-prone sediments
Silt-prone sediments
Sand-prone sediments
Fine-grained Channel fill
Medium-grained Channel fill
Coarse-grained channel fill
b
Fan A
Low RMS Fan fill
High RMS Fan fill
Moderate RMS Fan fill
High Variance Fan fill
Low Variance Fan fill
Moderate Variance Fan fill
Coarse-grained fan fill
Medium-grained fan fill
c
Fan B
High RMS Fan fill
High RMS Channel fill
Low Variance Fan fill
Low Variance Channel fill
Feeder channel
Crevasse splay
Finger-lobe
Coarse-grained channel fill

Figure 6



a
Fan C
RMS
N
10 km
Low RMS area
Fig.5a
Low RMS Fan fill
High RMS Channel fill
Fig.5c
W1
Fig.5b
Fig.5d
Moderate RMS Fan fill
Fig.5e
High RMS Fan fill
Variance
High Variance area
Low Variance Channel fill
High Variance Fan fill
Moderate Variance Fan fill
Low Variance Fan fill
Hemipelagic sediments
Mud-prone sediments
Silt-prone sediments
Sand-prone sediments
Feeder channel
Crevasse splay
Medium-grained fan fill
Fine-grained fan fill
Coarse-grained fan fill
Finger-lobe
Coarse-grained channel fill
b
Fan D
Low RMS Fan fill
Moderate RMS Fan fill
High RMS Fan fill
Low Variance Fan fill
Moderate Variance Fan fill
Low Variance Fan fill
Fine-grained fan fill
Coarse-grained channel fill
Medium-grained fan fill
Finger-lobe
Coarse-grained fan fill
c
Fan E
High RMS Channel fill
Moderate RMS Fan fill
Low RMS Fan fill
High RMS Fan fill
Low Variance Channel fill
Moderate Variance Fan fill
High Variance Fan fill
Low Variance Fan fill
Coarse-grained channel fill
Medium-grained fan fill
Fine-grained fan fill
Coarse-grained fan fill

Figure 7

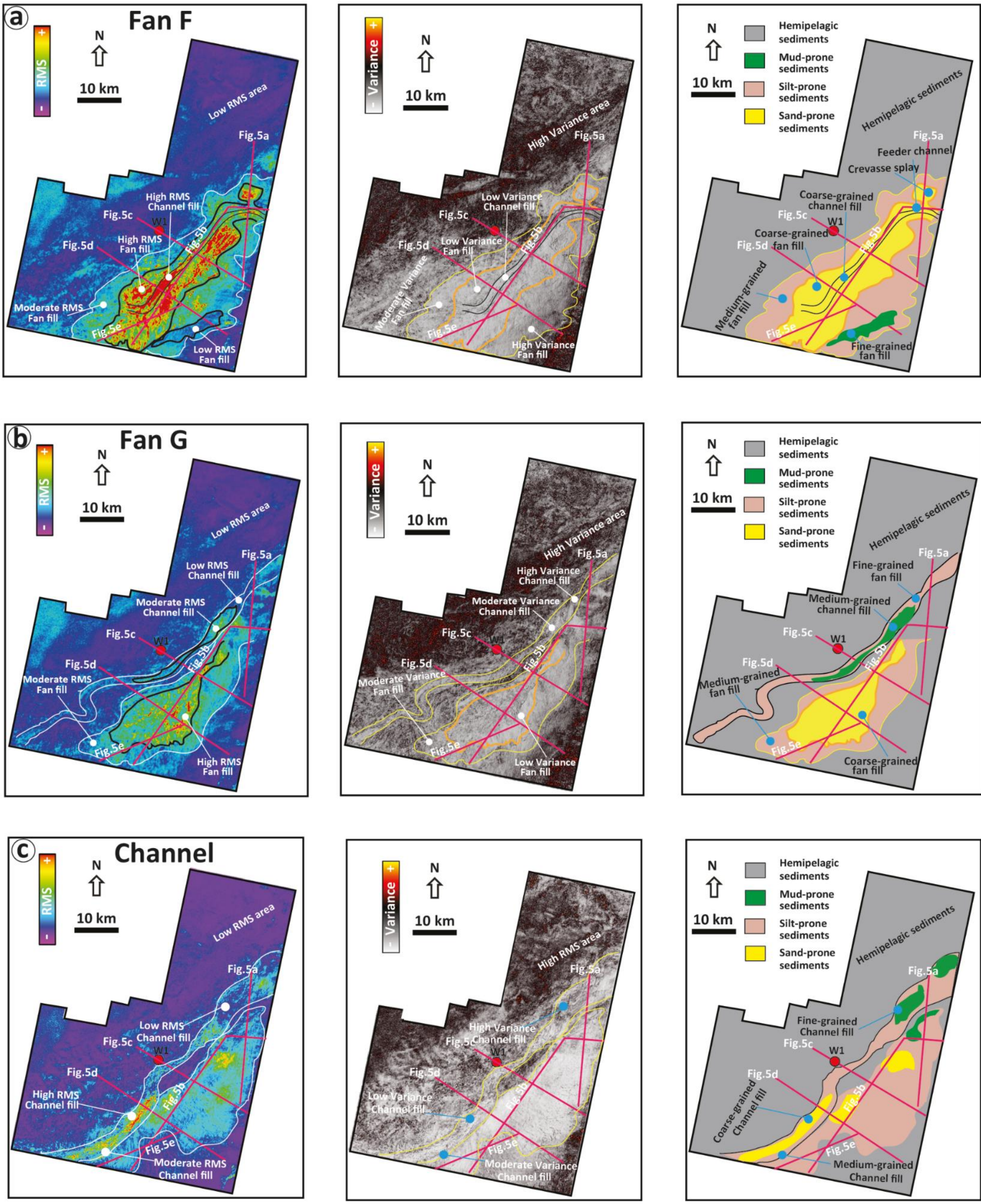
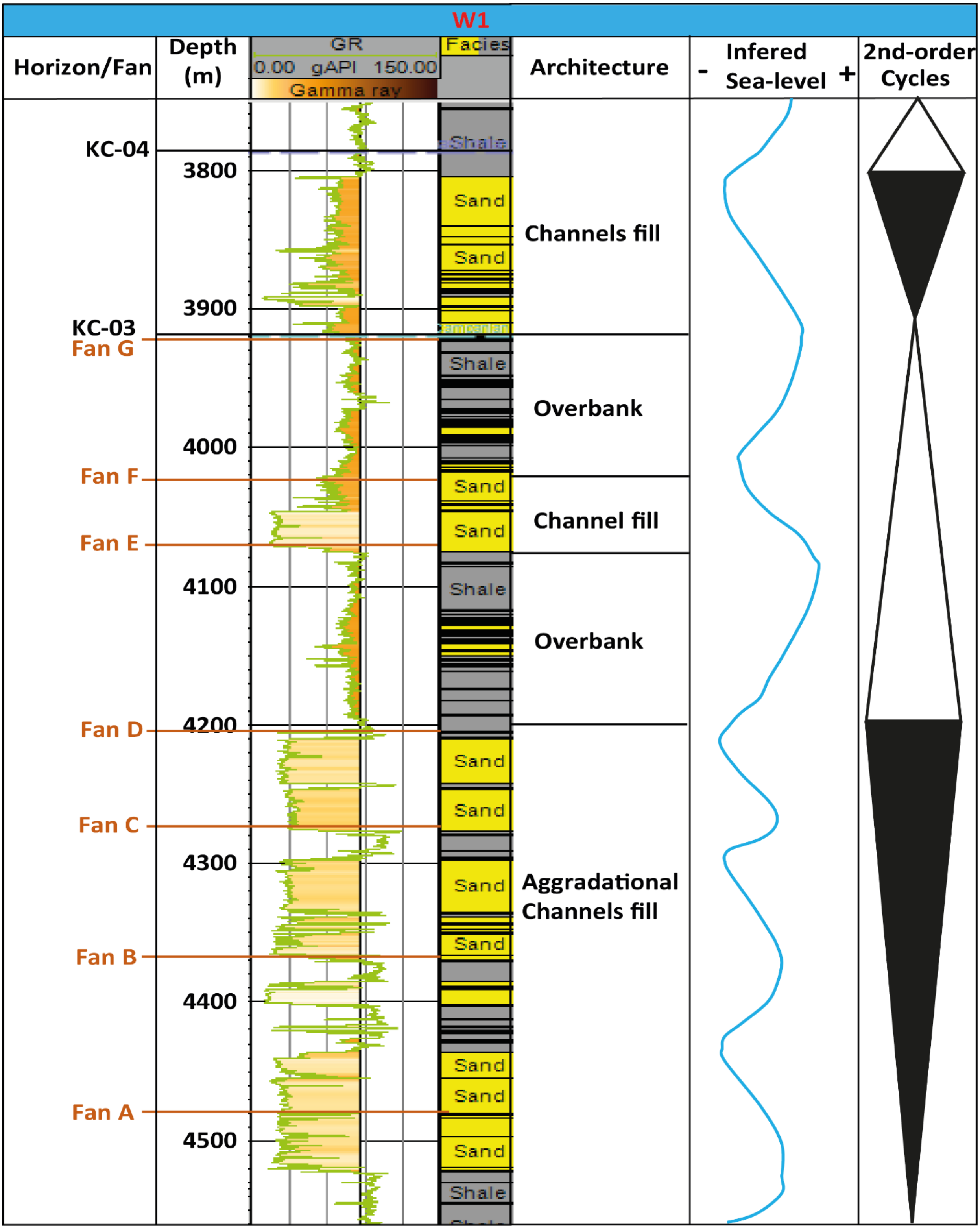

a
Fan F
RMS
N
10 km
Low RMS area
Fig.5a
High RMS
Channel fill
Fig.5c
W1
High RMS
Fan fill
Fig.5d
Fig.5b
Moderate RMS
Fan fill
Fig.5e
Low RMS
Fan fill
Variance
High Variance area
Low Variance
Channel fill
Low Variance
Fan fill
Moderate Variance
Fan fill
High Variance
Fan fill
Hemipelagic sediments
Mud-prone sediments
Silt-prone sediments
Sand-prone sediments
Feeder channel
Crevasse splay
Coarse-grained
channel fill
Coarse-grained
fan fill
Medium-grained
fan fill
Fine-grained
fan fill
b
Fan G
Low RMS
Channel fill
Moderate RMS
Channel fill
Moderate RMS
Fan fill
High RMS
Fan fill
High Variance
Channel fill
Moderate Variance
Channel fill
Moderate Variance
Fan fill
Low Variance
Fan fill
Fine-grained
fan fill
Medium-grained
channel fill
Medium-grained
fan fill
Coarse-grained
fan fill
c
Channel
Low RMS
Channel fill
High RMS
Channel fill
Moderate RMS
Channel fill
High RMS area
High Variance
Channel fill
Low Variance
Channel fill
Moderate Variance
Channel fill
Fine-grained
Channel fill
Coarse-grained
Channel fill
Medium-grained
Channel fill

Figure 8



W1
Horizon/Fan
Depth (m)
GR
0.00 gAPI 150.00
Gamma ray
Facies
Architecture
- Infered Sea-level +
2nd-order Cycles
KC-04
3800
Shale
Sand
Sand
Channels fill
3900
KC-03
Fan G
Shale
Overbank
4000
Fan F
Sand
Channel fill
Sand
Fan E
4100
Shale
Overbank
Fan D
4200
Sand
Sand
Fan C
4300
Sand
Aggradational Channels fill
Sand
Fan B
4400
Sand
Sand
Fan A
4500
Sand
Shale

Figure 9

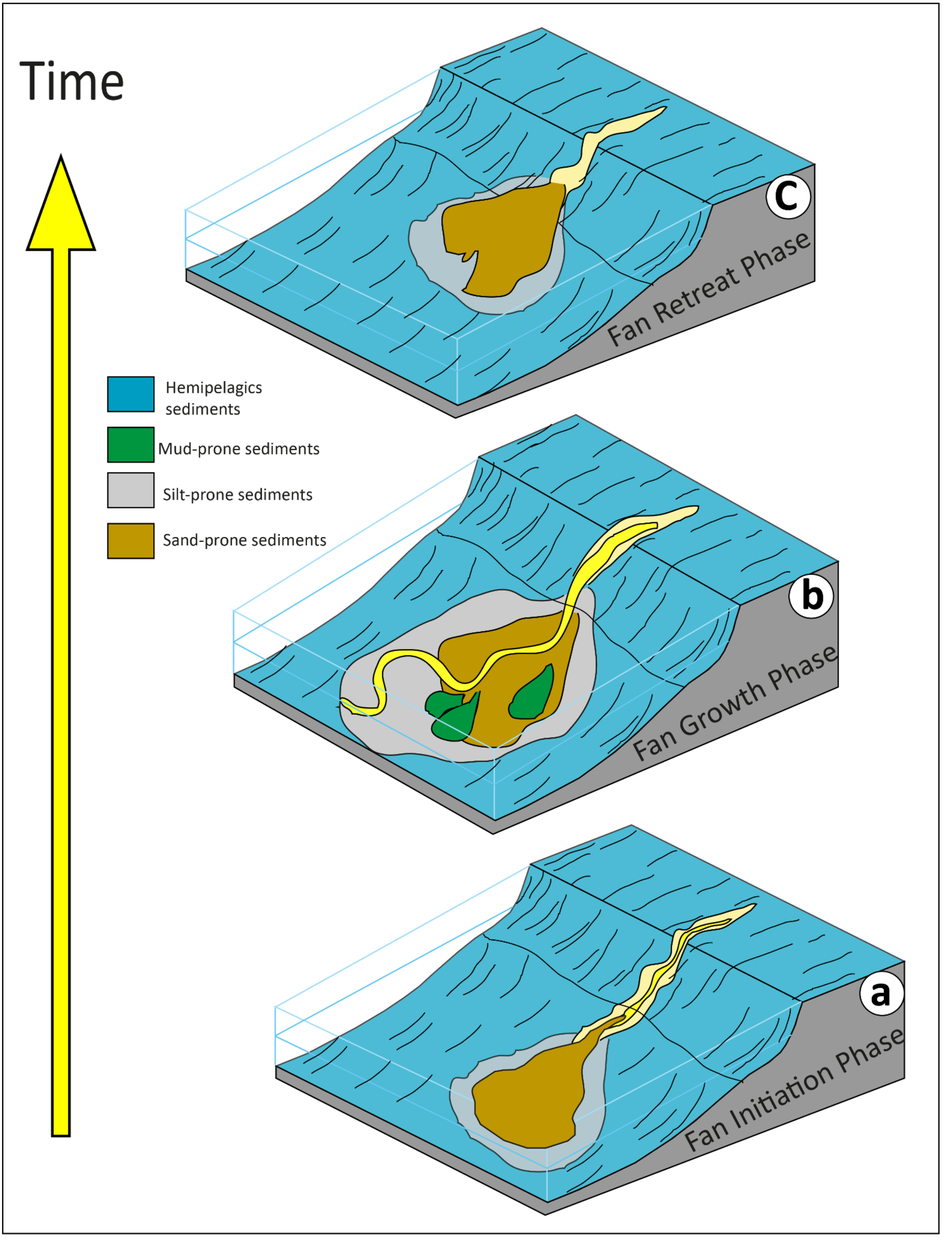
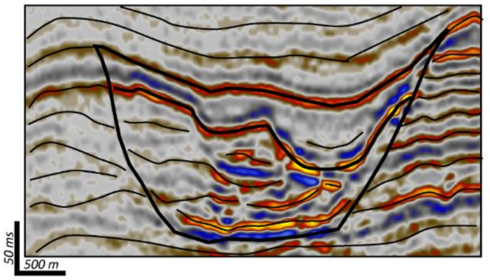
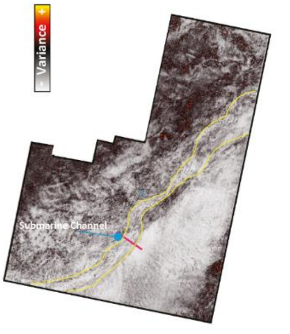
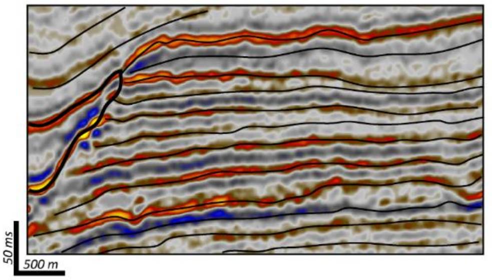
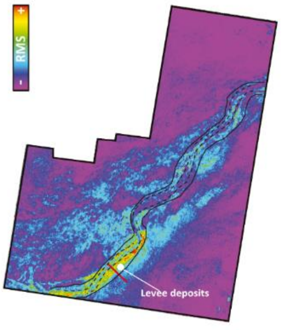
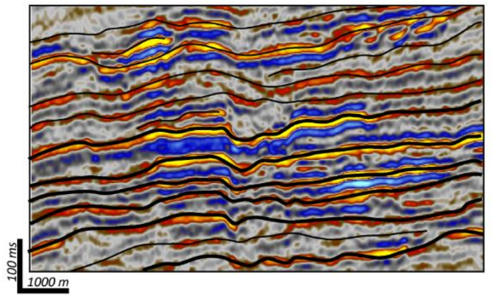
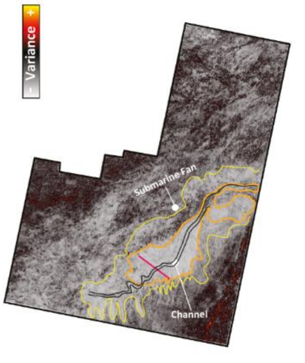
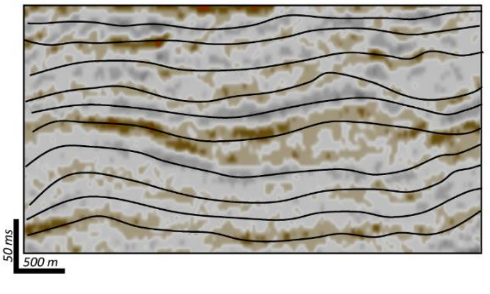

Time
Hemipelagics sediments
Mud-prone sediments
Silt-prone sediments
Sand-prone sediments
C
Fan Retreat Phase
b
Fan Growth Phase
a
Fan Initiation Phase

Table 1

Seismic facies interpretation	Seismic section	Description	Plan/map view
Submarine Channel System		Chaotic, high amplitude, discontinuous reflections, basal lags usually confined within a V- or U- shaped external geometry	
Levees		high- to low-amplitude, continuous, parallel to subparallel reflections	
Submarine Fan		High amplitude seismic facies displaying an aggradational pattern with parallel and good continuity reflectors	
Hemipelagics sediments		Semi transparent, low amplitude, semi-continuous to continuous reflections