

# Three-dimensional modelling of stacked turbidite channels in West Africa: impact on dynamic reservoir simulations

Richard Labourdette<sup>1</sup>, Jérôme Poncet<sup>1</sup>, Julien Seguin<sup>1</sup>, François Temple<sup>1</sup>, JoAnn Hegre<sup>2</sup>  
and Alan Irving<sup>2</sup>

<sup>1</sup>Total, Geoscience Technologies, CSTJF, Avenue Larribau, 64 018 Pau Cedex, France  
(e-mail: richard.labourdette@total.com)

<sup>2</sup>Total E&P UK plc, Geoscience Research Centre, Aberdeen, UK

**ABSTRACT:** The examination of production history from hydrocarbon fields composed of turbidite deposits indicates that fluid flow behaviour is often more complex than expected. The cause is commonly linked to the presence of fine-scale sedimentary heterogeneities, which complicate the reservoir. This is especially true in the case of turbiditic submarine channel complexes with final channel-filling stages composed of lateral migration deposits. These fine-scale heterogeneities are usually below seismic resolution and are rarely represented in initial reservoir models designed for such fields. Thus, it is difficult to match the production history or identify methods to improve production and reduce associated risks.

The various depositional patterns recognized in channel migration and aggradation packages from the Oligocene Malembo Formation of the Congo Basin, offshore Angola, exhibit different dynamic responses when modelled in a reservoir simulator. These dynamic differences are related to the different preservation rates of bank collapse sediments within isolated channel bodies, hereafter referred to as 'elementary channels'. According to these preservation differences, the vertical stacking pattern of channels results in better connectivity than the true lateral migration. This effect has been incorporated into a full-field simulation model by applying petrophysical upscaling methods. The recognition and modelling of detailed sedimentological heterogeneities, and their distribution along full-field models produces a better history match when the inherent uncertainties have been taken into account.

Incorporating all available data and concepts to define reservoir architecture is essential in understanding the impact that fine-scale heterogeneities have on reservoir management. As the lateral extent and areal distribution of heterogeneities is still unknown, our modelling workflow incorporates uncertainty in the form of multiple realizations to identify and measure all uncertainties that might impact dynamic response.

**KEYWORDS:** turbidite channels, heterogeneity, 3D modelling, dynamic impact, West Africa

## INTRODUCTION

Most reservoirs encountered in deep offshore West Africa are large, erosionally confined deep-water channel complexes, displaying a spectrum of architectural styles and channel-fill types (Abreu *et al.* 2003). Many of the reservoir-prone intervals associated with the large, high-quality channel complexes contain significantly sinuous channel elements. With improved technologies (especially better imaging), several researchers have begun to report the presence of deep-water channels with various degrees of sinuosity in modern deep-water fans (e.g. Garrison *et al.* 1982; Damuth *et al.* 1983, 1988). Their relevance in subsurface exploration has been assessed only recently (Stephens *et al.* 1996; Kolla *et al.* 2001), aided by three-dimensional seismic technologies and ever-increasing deep-water exploration.

The highly sinuous channels in the subsurface Tertiary of offshore West Africa range from simple to complex forms resulting from a few to numerous laterally and vertically stacked depositional events (Kolla *et al.* 1998; Posamentier & Kolla 2003), have now been proven to be viable exploration targets (Roberts & Compani 1996; Stephens *et al.* 1996).

Some of the best subsurface examples of confined deep-water channel complexes are located offshore Angola. High resolution (approximately 65 Hz) 3D seismic data have allowed the recognition and detailed mapping of their internal channel architectures that are not clearly imaged in lower-resolution seismic data (35 Hz). Multi-attribute interpretation of seismic facies has led to the definition of architectural elements as constitutive parts of reservoir architecture. They are characterized by a set of consistent sedimentological components

comprising an erosive channel base, channel margin and stacked channels, all of which display varying degrees of aggradation and lateral migration (Kolla *et al.* 2001; Posamentier & Kolla 2003). These architectural elements are defined in wells, characterized by petrophysical measurements and used to populate reservoir models. However, conventional depositional models usually focus on external reservoir architectures, thereby failing to explain reservoir compartmentalization fully as a control on hydrocarbon recovery (Prather *et al.* 2000).

New datasets acquired during the development of confined deep-water channel complex reservoirs (complementary wells, 4D high resolution seismic data and production history) exhibit differences between the initial reservoir models and subsequent observations. The inspection of logs and cores shows that smaller-scale bedding is present within seismically-defined architectural elements (Prather *et al.* 2000). New interpretations have highlighted the importance of sedimentary heterogeneities, such as shale barriers and channel baffles (Kolla *et al.* 2001), that cannot be mapped with conventional seismic data – thereby remaining “sub-seismic”.

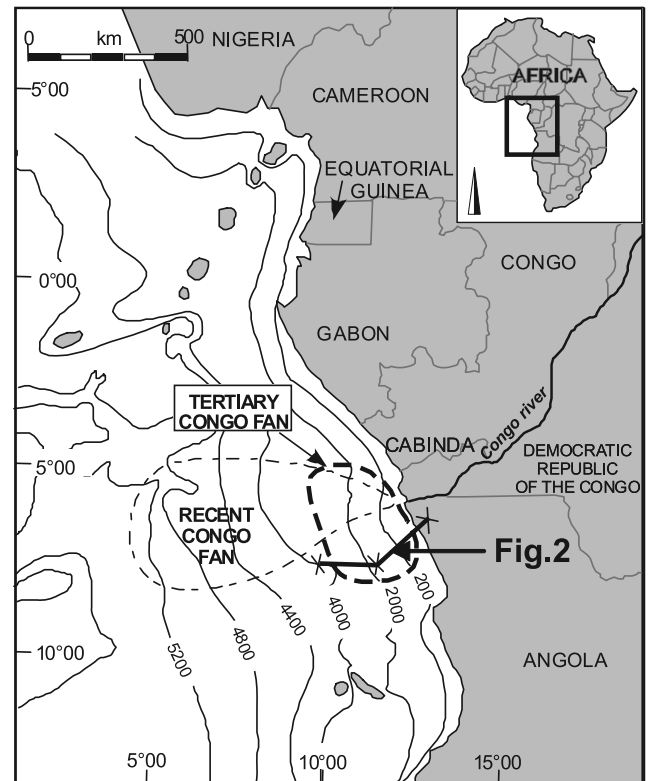
History matching of reservoir model predictions with well test and production data in these Angolan reservoirs has proven to be problematic, with water and gas breakthrough occurring earlier and at a higher ratio than predicted by the models. This demonstrates the importance of reservoir heterogeneity on production geoscience and the need to incorporate it in greater detail in the model. Appropriate geology can now be incorporated effectively in 3D geocellular models at a scale that excludes the statistical downscaling process (Hurst *et al.* 2000), but favours upscaling of petrophysical properties to be included in the final full-field model.

In this contribution we first describe in some detail the morphological and infill characteristics of a relatively simple but sinuous channel form from the Congo Basin (western offshore Angola) to identify the main heterogeneities that are critical for modelling, based on observations and previously published work. This is followed by a methodology used to model these heterogeneities precisely, integrating our observations, concepts and uncertainties to assess their impact on dynamic simulations. These dynamic effects are then introduced in the full-field model which uses upscaled petrophysical distribution laws, to lead to a better and faster history match of the model.

## GEOLOGICAL SETTING

The Lower Congo Basin lies off the west coast of Africa between the Republic of Congo and central Angola (Fig. 1). It covers an area of 115 000 km<sup>2</sup> in water depths exceeding 3500 m. The Lower Congo Basin is in the Congo Basin proper, a sub-basin of the Aptian ‘Salt Basin’ system that occurs along the western coast of Africa (Clifford 1986).

The tectonic, geological and sedimentary evolution of the Congo Basin during the Mesozoic and Cenozoic resulted from the Early Cretaceous rifting of Gondwanaland, the subsequent separation of Africa and South America, and the progressive widening of the South Atlantic Ocean by plate accretion (Lehner & de Ruiter 1977; Stark 1991; Sequeira *et al.* 1998). In the Cenozoic, huge quantities of sediment were delivered to the Congo Basin margin as a consequence of uplift and westward tilting of the African craton, sea-level variations and increased river runoff. The sediment supply, especially from the Congo River during the Tertiary, resulted in the progressive basinward shift of the Angolan margin and the creation of the Tertiary Congo Fan (Amaral *et al.* 1998; Sequeira *et al.* 1998). Structural modifications to this fan resulted from sediment loading, updip extension and downdip compression, as well as mobilization of



**Fig. 1.** Bathymetric map of the Gulf of Guinea, off West Africa (modified after Kolla *et al.* 2001), with the outlines shown of Quaternary (“Recent”) and Tertiary Congo fans. Bathymetric contours are in metres. The location of a schematic geological section across the Angolan continental margin (Fig. 2) is also shown.

the Loeme (Aptian) salt and, to a lesser extent, Albian platform rafting and basement fractures (Fig. 2). All of the many recent giant discoveries off the Angolan margin (e.g. Dalia, Girassol, Hungo, Kuito, Landana fields) have their stratigraphic targets in the Malembo Formation of the Tertiary Congo Fan (Amaral *et al.* 1998; Pettingill 1998).

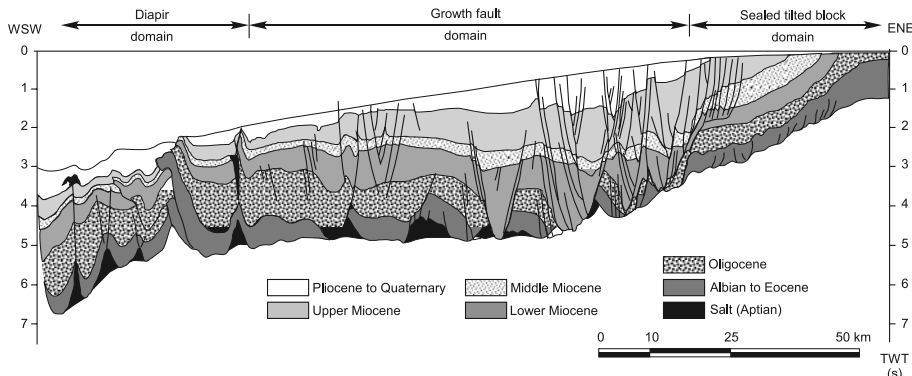
Sand systems were generally deposited at sequence boundaries in cut-and-fill channels which commonly exhibit internal meandering geometries and variable net-to-gross sand ratios, both vertically and laterally (Da Costa *et al.* 2001; Posamentier & Kolla 2003).

The sinuous channels described in this paper are Oligocene in age and are from the Malembo Formation of the Tertiary Congo Fan, which formed seaward of the palaeoshelf margin. This study focuses specifically on the terminal parts of channel complex infills, where the channels are unconfined or only very broadly confined, exhibit the “single cycle” seismic character, and where individual channels can be resolved very clearly (Mayall & Stewart 2000).

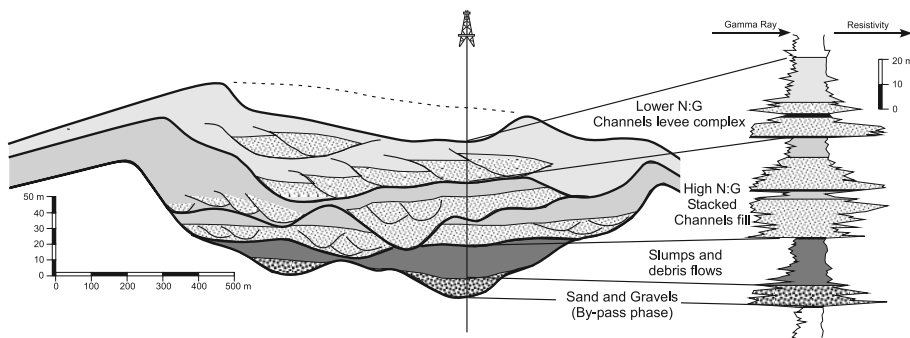
## TURBIDITE CHANNEL MIGRATION

### General description

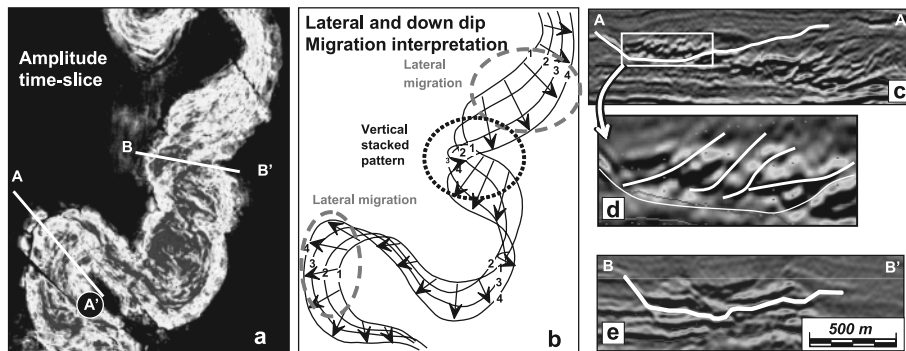
West African confined channel systems are large features up to 200 m thick, 1–5 km wide and at least tens of kilometres long. They are characterized by intricate, inter-cutting, sand-rich turbidite channel complexes. Core data reveal that sandstone reservoirs in these channel complexes are dominated by high-concentration turbidites and traction deposits. Several authors have suggested the presence of both lateral and down-system channel drift (coupled with aggradation), accompanying in-



**Fig. 2.** Regional-scale cross-section interpreted from 2D seismic and well data (modified after Broucke *et al.* 2004).



**Fig. 3.** Schematic idealized fill of an erosionally confined channel complex (modified from Mayall & Stewart 2000).



**Fig. 4.** Seismic characterization of lateral channel migration. (a) Amplitude map of lateral offset stacked channels. (b) Lateral and down dip migration interpretation of the amplitude time-slice, with channel centre-lines distinguishing lateral migration and vertical stacked patterns. (c) Seismic section in the true lateral migration area showing the accretionary organization of shingled beds. (d) Close-up of the morphology of shingled reflections. (e) Seismic section through the vertical stacked pattern.

creased channel sinuosity through time (Stelting *et al.* 1985; Kastens & Shor 1985; Peakall *et al.* 2000; Kolla *et al.* 2001; Sprague *et al.* 2002; Temple & Broucke 2004).

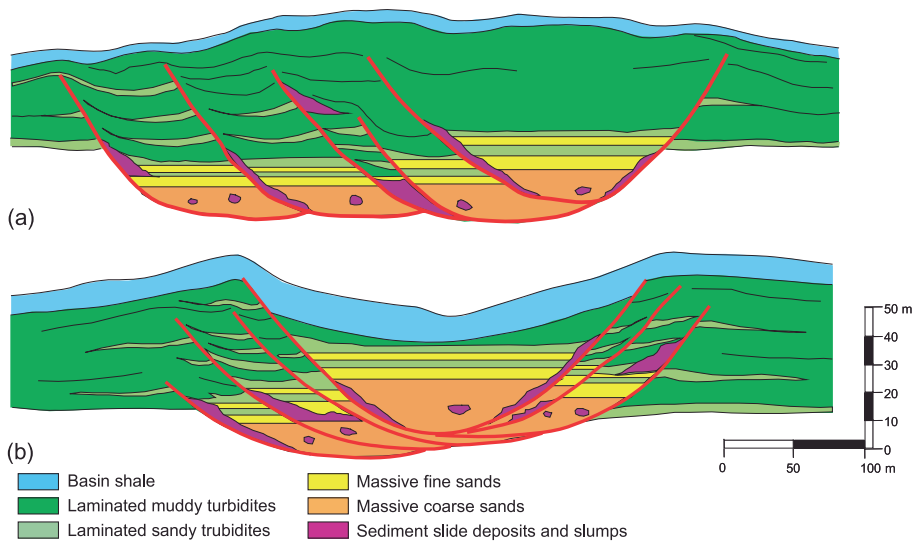
Despite the high variability of channel complex fills (sand content ranging from 20% to 70%), Mayall & Stewart (2000) described a general infill model (Fig. 3). This study focuses on the final part of the channel complex, specifically because it has a higher degree of heterogeneity and thus generates significant problems in the hydrocarbon development of turbidite channel systems (Mayall & Stewart 2000; Mayall & O'Byrne 2002).

### Seismic characterization

The seismic data used in this study are a part of a fifty-four-fold, 3D grid with a bin size of 12.5 m × 12.5 m and cover a surface area of 13 000 km<sup>2</sup>. The methodology used here takes the channel images as seen on the 3D seismic data and divides them into several intervals, which are then displayed as amplitude attribute maps. The following description is based on 3D high resolution seismic data (approximately 65 Hz) calibrated against approximately 60 m of cores from 21 wells.

High resolution 3D seismic data are used for the recognition and detailed mapping of internal channel architectures. Amplitude extractions and horizon slices in the upper erosional channel fill “sequence” of the channel complex (Fig. 4a) display a moderate to high sinuosity map pattern, as described by Abreu *et al.* (2003). Meanders along channels evolve, migrate and are often cut-off over time in a somewhat similar manner to those of subaerial rivers (Damuth *et al.* 1988; Mayall & Stewart 2000) but with aggradational and down dip components (visible on the seismic section shown in Fig. 4b) suggesting that deposition is usually composed of longitudinally migrating sediments (Coterill *et al.* 1999; Kolla *et al.* 2001; Abreu *et al.* 2003; Posamentier & Kolla 2003).

Two typical migration architectures can be distinguished within the same channel complex: one is referred to as a “true lateral migration”, where the channels shift in a constant direction over time; the other is referred to as a “vertical stacked pattern”, in which the direction of channel shifting is less regular (Fig. 4b). Lateral migration is characterized typically by bright amplitudes on the inside of meanders, with a “scroll bar pattern” visible in map view and associated with shingled (inclined parallel) seismic reflections observed on vertical



**Fig. 5.** Conceptual sedimentological model of the architectures formed by successive cycles of erosion/construction of sinuous single channels migrating downdip and perpendicular to the flow direction (around five cycles). (a) The lateral migration pattern: the migration is uni-directional. The overall unit is 500–1000 m wide and 15–25 m thick. (b) The vertical stacked pattern: the sequence results from one or several episodes of back and forth migration. The overall unit is 300–1000 m wide and 25–30 m thick.

seismic profiles (Fig. 4d). In general, the ‘shingled’ reflections are parallel to the inside bend of the last position of the channel-fill (Mayall & Stewart 2000; Abreu *et al.* 2003). The geometry of the shingled reflections forms well-defined patterns (Fig. 4a, d) parallel to the channel margin and dipping towards the channel along which they formed.

The vertical stacked pattern is defined by sub-horizontal seismic reflections in section view (Fig. 4e) and the absence of a “scroll bar” pattern in map view. It is described by Abreu *et al.* (2003) as a “cut and fill pattern”, associated with sharp changes in channel direction during the migration process.

### Sedimentological model

When measured on seismic data, the individual channels that stack up to form the lateral migration pattern are typically 200–300 m wide and 15–25 m thick. The lithological character observed from wireline logs and cored sections and linked and calibrated to seismic data, is fining- and thinning-upward. Each channel is composed of coarse- to very coarse-grained sandstones at its base, fining upward to fine- to very fine-grained sandstones and laminated muddy turbidites at the top. Frequent slumped facies and sediment slides (mass transport complexes of Pickering & Corregidor 2005, types Ia and Ib) can also be found within the lower part of the studied facies tract (Fig. 5). These slumped facies and slide deposits, inducing seismic contrasts, possibly correspond to amplitude changes described by Kolla *et al.* (2001).

The lateral and downdip migration of individual channels through time resulted in two distinct architectures with distinct morphological characteristics that can be observed on seismic data (Fig. 4). Both architectures involve lateral and downdip shifting of channels, but in a consistent direction in the lateral migration case (Fig. 5a). However, the vertical stacked pattern is more varied (Fig. 5b), being associated with the vertical amalgamation of individual channels between two migrating meander loops. The resulting succession of architectures is that of repeated fill and incision, rather than the more continual lateral migration typical of meandering fluvial channels. This filling and cutting is fundamental to the preservation or otherwise of the channel margin facies. For the lateral migration case, most of the channel margin heterogeneities are preserved, whereas there is apparently little or no preservation of channel margin heterogeneities in the vertical stacked pattern due to the repeated effects of internal channel erosion.

These two distinct architectures can be mapped along individual channel fairways using seismic attribute maps. Two different sedimentological end-member models need to be built to reveal potential differences in terms of the preservation of fine-scale heterogeneities and the consequent differences in petrophysical characteristics.

### METHODOLOGY

The modelling workflow adopted herein is based on a small depth-converted extraction of the high resolution seismic data, which focused on a specific area of the final, uppermost part of the channel complex. This final stage of channel filling is well organized and characterized by increasing sinuosity and the development of lateral channel migration. The study area covers 3.2 km<sup>2</sup>; it is calibrated by four wells and is limited vertically by manually picked seismic horizons (base of the massive sands; top of the laminated sandy turbidites).

The modelled area was separated into two distinct parts for which high resolution geological models were constructed: one showing the true lateral migration of single channels; the other showing the vertical stacking of channels (Fig. 6).

Each of the models was based on orthogonal grids, 1250 m × 1250 m × 70 m thick, with a cell size of 10 m × 10 m × 1 m. Initially, an envelope for each individual channel was constructed deterministically according to the interpretation of the seismic section and map observations. The models were then populated deterministically with turbidite facies identified from cored wells and according to sedimentological concepts. The filling of each single elementary channel was simplified by adopting four facies associations whose characteristics and proportions were obtained from sedimentological interpretation of wells data.

The four facies associations are:

- basal channel fills: mass transport complexes and conglomerates to massive coarse sands. They represent up to 60% of the channel fill. Basal lag objects (gravel sands to conglomerates) may also be present at the base of the channels. These may impact production, as they are prone to acting as high permeability fluid drains;
- channel fills: comprising cross-laminated sands and massive to laminated medium to fine-grained high density turbidite sands that generally overlie the basal channel deposits. The sands which represent up to 20% of the channel infill, have a mean thickness of 4 m, and are typically good reservoirs;

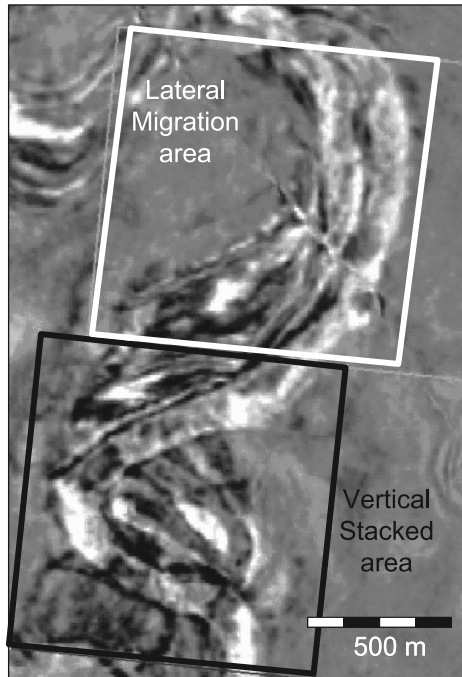


Fig. 6. Selected modelling area for the two sedimentological-architectural patterns. Each model is 1250 m × 1250 m × 70 m.

- abandonment deposits: comprising muddy turbidites with fine-grained ripple-laminated sands that are typically located towards the top of the fining-upward channel fill, and represent waning turbidity current flow. Proportionally they can reach up to 20% of the channel fill;
- collapse margins: comprising a mixture of slide deposits and slumped, laminated sandy to muddy turbidites, which are irregularly distributed along channel bends. These deposits have a maximum thickness of 6 m.

The spatial distribution of the main permeability barriers, which are composed of collapse deposits, remains the major uncertainty in the sedimentological model. The distribution of comparable facies was measured on representative outcrop analogues (Remacha *et al.* 2004) and present-day turbiditic systems (Cronin *et al.* 2005), although a spatial distribution law has not been identified clearly to describe the distribution of these deposits effectively.

Three distribution scenarios were modelled for both areas of interest (lateral migration and vertically stacked). This was done to account for a large range of permeability-barrier distributions inside the ‘high resolution’ models, and to factor in the associated uncertainties. These scenarios represent end-

members of the distribution of channel margin heterogeneities encountered in such a depositional environment. The following scenarios were defined (Fig. 7):

- lateral channel margin collapse: the margin collapse deposits are present on the sides of the elementary channel; margin slide deposits occur more readily;
- draping channel margin collapse: the margin collapse deposits are present along the entire basal surface of the elementary channel, mixing basal mass transport deposits and slide deposits;
- basal channel margin collapse: the margin collapse deposits are present only at the base of the elementary channel. Slide deposits are not preserved as axial mass transport deposits travelling further down the channel occur more readily.

For each sedimentary scenario, the modelled permeability barriers are continuous (by distribution) along the entire length of the channel, even though one would expect them to be represented by pods distributed along the channels (Cronin *et al.* 2005). However, the actual proportion of these pods remains unknown; but it can be approximated and its impact quantified using a ‘multi-scenario workflow’ as described below.

To extend the scenarios describing the distribution of heterogeneities so that they approach true sedimentary reality, a degree of randomness is introduced into each of them. This randomness is generated using geostatistical object-based modelling inside the regions of the channels that are characterized by collapse deposits. An object modelling workflow computes several simulations of collapse pods to distribute the generated heterogeneities over different areas of elementary channel borders.

The outcome of the initial deterministic sedimentological model is used as a framework to build several hundred equiprobable geological models, thus providing different sedimentological and petrophysical realizations of the reservoir and their impact on the dynamic fluid flow response.

A review of the petrophysical data obtained from a selection of validated logs and core plugs was performed. Petrophysical distribution laws, vertical variograms and correlation coefficients between variables were determined for each facies association. Each of the sedimentological scenarios provides a consistent set of facies envelopes within which several possible realizations of petrophysical properties are generated. Within each elementary channel, the petrophysical properties are simulated for the facies associations using Sequential Gaussian Simulation (Deutsch *et al.* 1992). The resulting models can be visualized in 3D, analysed and exported to a flow simulator. For each of the facies, net-to-gross, clay volume ( $V_{\text{clay}}$ ), porosity and permeabilities distributions are defined, based on core data,

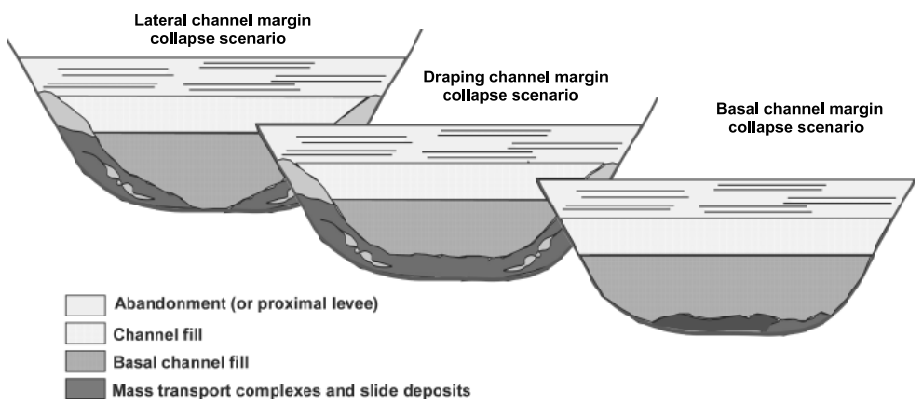


Fig. 7. Schematic representation of the end-members of elementary channel infill. The differences are due to the distribution of channel margin collapse heterogeneities: (a) lateral, (b) draping or (c) basal.

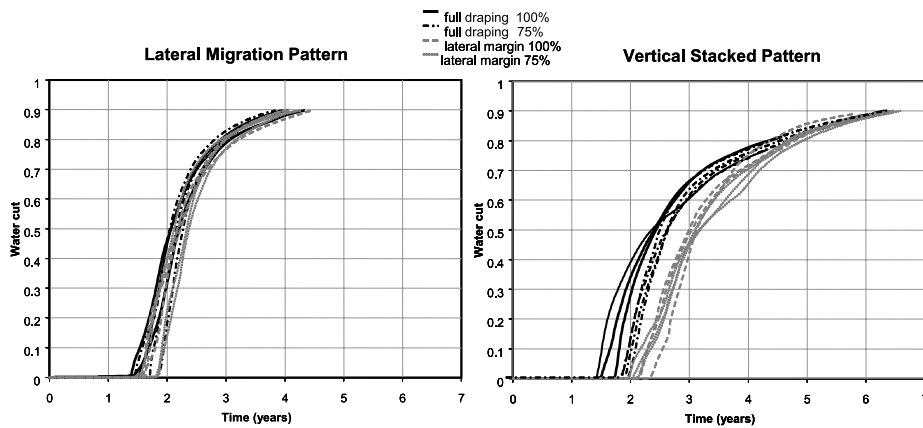


Fig. 8. Water-cut comparison for the lateral migration and vertical stacked patterns. The lateral migration pattern (left) shows an earlier water-cut than the vertical stacked pattern (right).

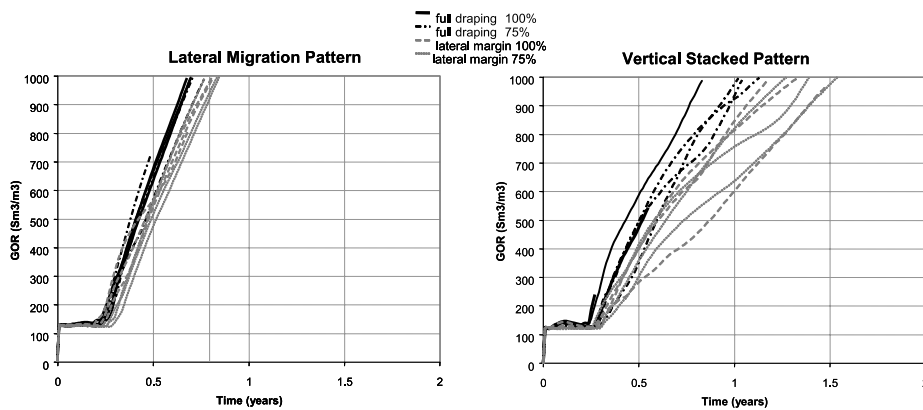


Fig. 9. Gas: oil ratio (GOR) comparison for the lateral migration and vertical stacked patterns. The lateral migration pattern (left) shows a higher GOR than the vertical stacked pattern (right).

well logs and analogues. An uncertainty parameter based on the mean value of the petrophysical parameters is introduced to cover the range of uncertainty defined by the geologist.

The poorer-quality channel margin collapse facies is the main heterogeneity expected to act as a barrier to intra-reservoir fluid flow during production. This facies smears the contact surface between individual elementary channels. The magnitude of the permeability contrast between margin collapse deposits and the better sands of basal channel and channel fills could result in locally poorly drained or totally by-passed areas. The integration of the various deterministic sedimentological scenarios, coupled with simulations of petrophysical properties, enables the definition of the discriminant parameters for dynamic simulations.

### IMPACT ON DYNAMIC RESERVOIR SIMULATION

Only a few selected models were simulated fully using conventional methods because of the long run-times of the two-phase dynamic simulations. A subset of the several hundred models was selected to define a relationship between original oil in place (OOIP) and recoverable reserves, which characterize the impact of previously incorporated static uncertainties (geological and petrophysical) on production. Several methods can be applied to sample the models to be extracted. In this study, the criteria used were regular sampling of the OOIP distribution coupled with representative sampling of the different sedimentological scenarios.

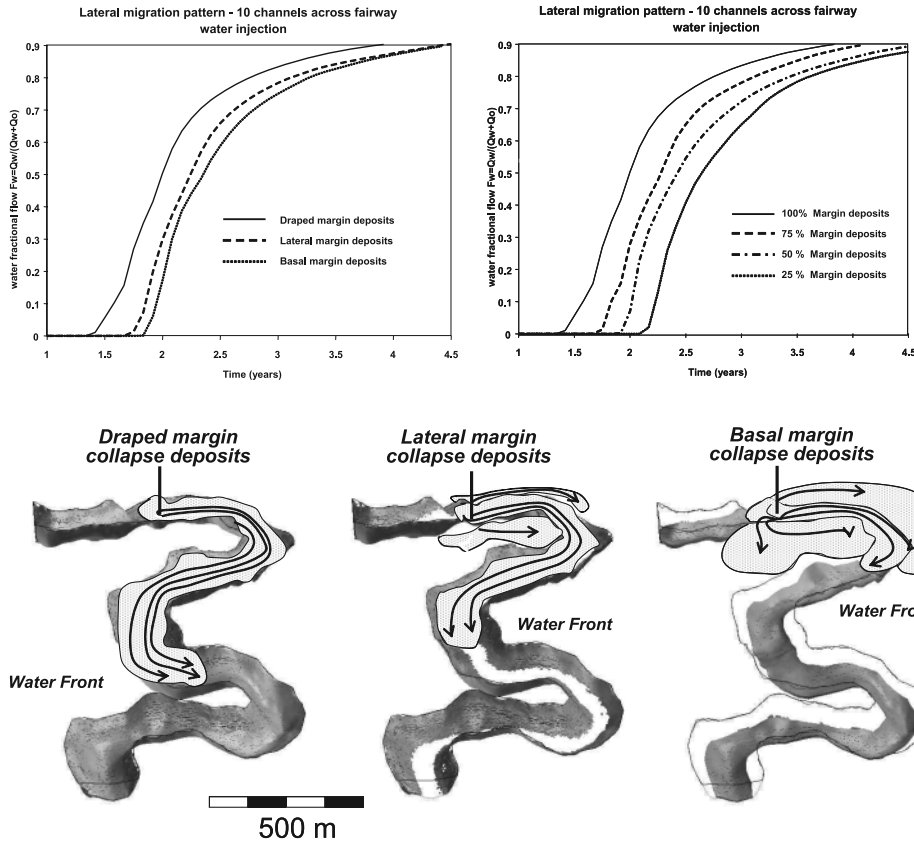
The eighty models resulting from this selection were flow-simulated using a simple development scheme consisting of one injector well and one producer well spaced one kilometre apart along the channel complex. Two types of dynamic simulations were tested: water and gas injection. The initial depletion pressure was 20 bars and input/output rates were set to 1500  $\text{m}^3$  per day (reservoir conditions metres cube per day).

Figures 8 and 9 show an earlier water-cut and higher gas: oil ratio (GOR) for the lateral migration patterns, while the vertical stacked patterns exhibit converging values for both water-cut and GOR.

The dynamic simulation results are similar for each sedimentological scenario (in terms of preservation of margin collapse facies), but differ between them. Water breakthrough occurs earlier in those models with high proportions of margin collapse facies. In the most extreme cases, the low-permeability collapse facies form gutter-like features, which define elongated high-permeability zones (Fig. 10) and may act as preferred conduits for fluid flow.

This comparison clearly distinguishes between the two patterns. The earlier water breakthrough for the lateral migration patterns can be ascribed to the preservation of lateral heterogeneities partitioning the reservoir, whereas these heterogeneities for the vertical stacked patterns tend to be unpreserved due to multiple cross-cutting erosion, resulting in poor partitioning of the reservoir. The margin collapse facies form gutter-like low-permeability features which define elongated conduits for fluid flow (Fig. 11).

As the mobility contrast between injected and produced fluids increases with time, effects due to the continuity of heterogeneities can increase up to ten-fold, leading to a strong reduction in the recovery factor for this realization. In the case of water injection over the entire reservoir thickness, the water front spreads vertically over the whole reservoir section, progressing preferentially through the channel-fill facies associations and then branching out into the basal channel-fill facies associations due to the effects of gravity. High horizontal permeability accelerates breakthrough. In this case, the front is generally stable and piston-like, since the water: oil mobility ratio is close to one.



**Fig. 10.** Impact of the different scenarios on reservoir production history. (a) Relationship between earlier water breakthrough and continuity of heterogeneities for end-member sedimentological scenarios. (b) Relationship between earlier water breakthrough and the increase in collapse margin proportions in the same sedimentological scenario (example shown for draped margin deposits).

**Fig. 11.** Schematic representation of the effect of heterogeneity continuity on drainage of injected fluids (water front spreading through a single channel body). The margin collapse facies form gutter-like low-permeability features which define elongated conduits for fluid flow between the injector and producer wells. In the example shown, the wells are located in the same elementary channel.

In the case of gas injection over the entire reservoir thickness, the front progresses first through channel-fill facies associations and then branches out into abandonment facies associations under the influence of gravity. High horizontal permeability accelerates breakthrough, but the front is unstable and presents significant digitation that by-passes oil pools because of the high mobility ratio between injected gas and produced oil.

## UPSCALING

These detailed, high resolution geological models attempt to capture the heterogeneities in rock properties that can profoundly affect fluid flow within the reservoir and hence oil recovery. Typically these models contain too many grid blocks to be used in full-field flow simulations. Accordingly, a full-field model grid was constructed to produce a model with a reasonable number of cells capable of incorporating the relevant sedimentological heterogeneity. The aim of upscaling is to capture the impact of the heterogeneities in the fine-scale models by simulating flow through them and thereby calculate effective properties for use in the coarse grid cells in the full-field model. Starting from a given grid model, a number of candidate coarse grids are generated using one or more of the various up-gridding algorithms available (Fincham *et al.* 2004). Coarse grids are constructed by amalgamating cells in the fine grid (3 m and 5 m).

Subgrids of the 'high resolution' models are extracted to capture the fine-scale heterogeneity in the dominant facies described in the full-field model. The facies associated with each coarse grid-block are determined by considering the dominant facies in the  $11 \times 11 \times 3$  and  $11 \times 11 \times 5$  subgrids

(equivalent to coarse grid cells). These subgrids are therefore representative of the different proportions of the dominant facies and the different number of channels.

To determine the new upscaled properties distribution to be used in the full-field model, all the various geological models are considered using a volume-weighted arithmetic average for additive properties such as net-to-gross, porosity and water saturation; and applying a pressure solver to upscale non-scalar properties such as the permeability tensor.

At the end of the upscaling process, global statistical distribution laws are extracted to fill the full-field model grid with equivalent parameters (Table 1). Here, the various parameters are expressed using the characteristic parameters describing the output probability distribution laws. Normal distribution (porosity) and log-normal distributions (water saturation and  $k_v/k_h$ ) are characterized using the average and standard deviation parameters derived from probabilistic analysis of the upscaled parameters. Log-horizontal permeability distribution is defined by a Beta distribution (a continuous probability distribution) where Alpha and Beta parameters are the shape parameters estimated from the average and standard deviation of the upscaled values with finite boundaries (0 and maximum = scale parameter).

The upscaled parameter  $k_v/k_h$  is best at discriminating between the lateral migration and vertical stacked patterns. The upscaled  $k_v/k_h$  ratio exhibits a distinct relationship between lateral migration and vertical stacked patterns (Figs 12 and 13). The vertical stacked patterns (Fig. 12) have a  $k_v/k_h$  upscaled distribution closer to the original one (derived from plug and log analysis). On the contrary, the lateral migration pattern (Fig. 13) shows narrow distributions that are clearly expressed and

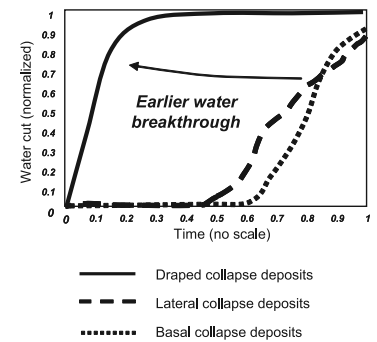
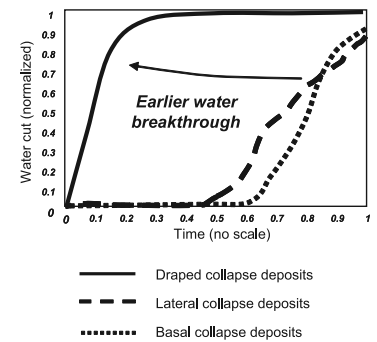
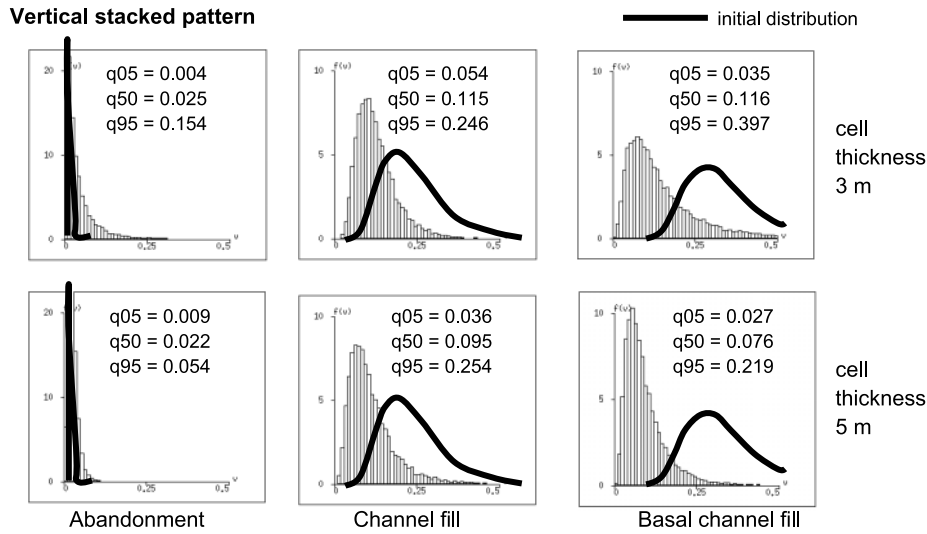
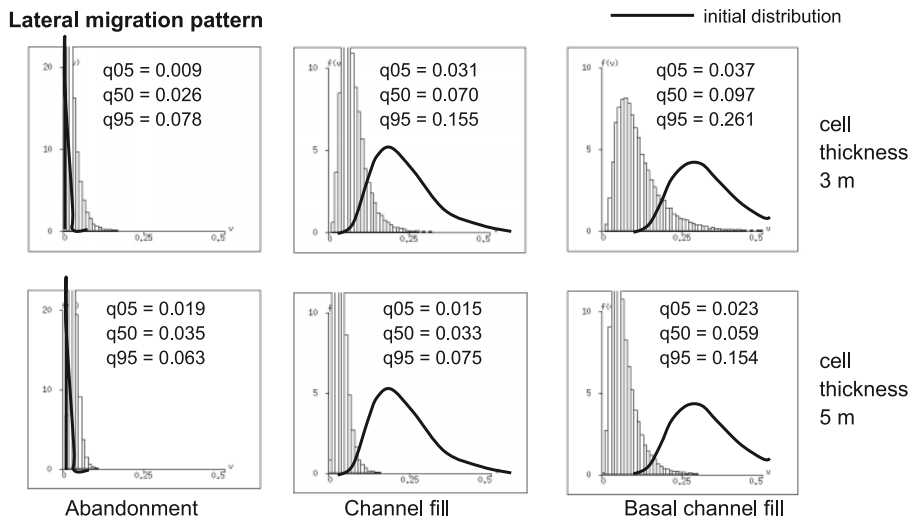


Table 1. Upscaled petrophysical parameter distributions

NTG	User Distribution	Dominant Facies Abandonment						Dominant Facies Channel Fill						Dominant Facies Basal Channel Fill												
		DZ cell = 3 m		DZ cell = 5 m		DZ cell = 3 m		DZ cell = 5 m		DZ cell = 3 m		DZ cell = 5 m		DZ cell = 3 m		DZ cell = 5 m										
		Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked	Lateral Migration	Vertical Stacked									
	Normal distribution																									
Porosity (%)	Average	22.76	23.16	22.40	23.12	22.72	23.07	22.52	23.19	22.32	21.96	21.72	21.93	Average	22.76	23.16	22.40	23.12	22.72	23.07	22.52	23.19	22.32	21.96	21.72	21.93
	Standard deviation	2.03	2.55	1.89	1.99	2.05	2.55	1.99	2.00	2.18	2.50	1.96	2.02		2.03	2.55	1.89	1.99	2.05	2.55	1.99	2.00	2.18	2.50	1.96	2.02
	NTG correlation coef.	0.269	0.208	0.487	0.285	0.258	0.253	0.403	0.356	0.143	0.322	0.476	0.367		0.269	0.208	0.487	0.285	0.258	0.253	0.403	0.356	0.143	0.322	0.476	0.367
	Log-normal distribution																									
Water saturation (%)	Average	16.04	16.55	16.3	16.61	13.68	13.81	13.69	13.59	13.01	12.82	12.74	12.92	Average	16.04	16.55	16.3	16.61	13.68	13.81	13.69	13.59	13.01	12.82	12.74	12.92
	Standard deviation	5.05	6.54	4.18	4.85	3.99	4.78	3.14	3.82	4.31	4.32	3.52	3.52		5.05	6.54	4.18	4.85	3.99	4.78	3.14	3.82	4.31	4.32	3.52	3.52
	Porosity correlation coef.	-0.166	-0.170	-0.244	-0.195	-0.215	-0.147	-0.220	-0.136	-0.042	-0.130	-0.220	-0.136		-0.166	-0.170	-0.244	-0.195	-0.215	-0.147	-0.220	-0.136	-0.042	-0.130	-0.220	-0.136
	Beta distribution																									
Log (horizontal permeability)	Alpha (P)	22.28	17.42	21.74	26.11	25.06	42.55	82.72	24.72	26.51	20.47	44.48	28.35	Alpha (P)	22.28	17.42	21.74	26.11	25.06	42.55	82.72	24.72	26.51	20.47	44.48	28.35
	Beta (Q)	4.68	2.96	4.00	3.69	3.66	6.42	17.80	3.07	4.26	3.59	7.52	4.44		4.68	2.96	4.00	3.69	3.66	6.42	17.80	3.07	4.26	3.59	7.52	4.44
	Scale (max)	3.72	3.86	3.70	3.85	3.92	4.12	4.13	3.96	4.00	4.00	4.01	3.96		3.72	3.86	3.70	3.85	3.92	4.12	4.13	3.96	4.00	4.00	4.01	3.96
	Porosity correlation coef.	0.139	0.068	0.390	0.166	0.232	0.002	0.295	0.028	0.017	0.098	0.187	0.235		0.139	0.068	0.390	0.166	0.232	0.002	0.295	0.028	0.017	0.098	0.187	0.235
	Log-normal distribution																									
kv/kh	Average	0.033	0.047	0.037	0.026	0.079	0.129	0.038	0.115	0.116	0.153	0.070	0.093	Average	0.033	0.047	0.037	0.026	0.079	0.129	0.038	0.115	0.116	0.153	0.070	0.093
	Standard deviation	0.025	0.074	0.014	0.015	0.041	0.063	0.020	0.075	0.076	0.131	0.044	0.066		0.025	0.074	0.014	0.015	0.041	0.063	0.020	0.075	0.076	0.131	0.044	0.066
	Permeability correlation coef.	-0.127	0.089	-0.415	0.115	0.148	0.084	0.233	0.095	-0.167	-0.057	0.198	0.150		-0.127	0.089	-0.415	0.115	0.148	0.084	0.233	0.095	-0.167	-0.057	0.198	0.150



**Fig. 12.** Upscaled  $k_v/k_h$  for the vertical stacked pattern compared with initial distributions derived from plug and log analysis.



**Fig. 13.** Upscaled  $k_v/k_h$  for the lateral migration stacked pattern compared with initial distributions derived from plug and log analysis.

deviate considerably from the original input distributions, when the dominant facies is the channel fill or the basal channel fill. In both depositional patterns, the upscaled  $k_v/k_h$  distribution for dominant abandonment facies does not differ greatly from the input distributions (derived from plug and log analysis).

Analysis of the upscaled parameters shows the impact of internal heterogeneity distributions. In the case of the dominant abandonment facies associations, the upscaled parameters are not affected by margin collapse heterogeneities, due to the similar distribution of petrophysical properties between margin collapse deposits and abandonment facies (low permeability and porosity). By contrast, upscaled parameters for channel fill and basal channel fill facies associations are affected greatly by the extent of preservation of channel margin collapse facies. Internal multi-directional erosional surfaces within vertical stacked pattern areas improve connectivity because of a reduction in the preservation of margin collapse heterogeneities. Within the true lateral migration pattern, uni-directional erosion (parallel to the channel margin) favours the preservation of outer bend margin collapse heterogeneities. According to this observation, the vertical stacked pattern will have better connectivity than the lateral migration pattern.

These upscaled petrophysical properties are the bases for multi-realization simulations at the full-field scale, permitting a

coherent distribution of equivalent petrophysical properties according to geological observations and interpretations. The integration of the upscaled petrophysical properties distributions in the full-field model, taking into account their inherent uncertainties and their layout, defined by seismic interpretation along the channel fairways, enables a faster and more accurate history matching of the full-field model.

## CONCLUSIONS

The evolution of meandering channels over time results in different stacking patterns along channel complexes, ranging from lateral migration, which is best developed in meander loops, to a vertical stacked pattern in the cut-off areas. Seismic map patterns extracted along these channel complexes are clearest in the lateral migration areas, suggesting low-connectivity between individual channels. This low connectivity is usually extrapolated to the entire complex, over-emphasizing the role of mass transport complexes as permeability barriers.

Our 3D modelling indicates that the multiple erosion events observed in vertically stacked areas result in pods of vertical connectivity. This contrasts with areas of lateral migration (meander loops) where more heterogeneities are preserved,

resulting in better reservoir facies connectivity. The degree of connectivity reflects both the original proportion and distribution of the margin collapse facies and their preservation subsequent to channel switching and erosion. The resulting fluid flow pattern is focused much more along individual channels.

An up-scaling process was used to represent this impact in the full-field model. Based on seismic-derived maps, the up-scaled parameter distributions were integrated in the full-field model, to distinguish between the true lateral migration patterns and vertically-stacked patterns. This resulted in a spatial distribution of equivalent petrophysical properties along the channel complex, facilitating faster and more accurate history matching of the full-field model.

The deposits of lateral channel migrations are an under-recognized type of deep-water channel type, but are being described increasingly in subsurface and outcrop examples. High-resolution 3D seismic datasets show that these migrations are a common feature in the late phase of evolution of a channel complex from the Oligocene Malembo Formation of the Congo Fan, offshore Angola. The lateral migration set, which is identified as the last depositional element of the channel complex infill, constitutes the greatest uncertainty in the hydrocarbon development potential of individual channel systems because of the effect that sub-seismic sedimentological heterogeneities can have on production and reservoir management. Understanding the internal heterogeneity distribution and the dynamic impact these heterogeneities have on production is essential to optimize hydrocarbon recovery strategies and well placements, especially in stacked turbidite channel complexes.

The authors thank Eduardo Remacha, Philippe Crumeyrolle, Jean-Loup Rubino and Martine Bez for many discussions on concepts relating to the evolution of sinuous turbidite channels. The *Petroleum Geoscience* reviewers Bryan Cronin, Andy Gardiner and Mohit Khanna and editorial board member Stuart Burley and co-editor Antony T. Buller offered many useful and constructive comments that helped to improve the manuscript. The authors would like to thank Sociedade Nacional de Combustíveis de Angola (SONANGOL), Esso Exploration Angola (Block 17) Ltd, BP Exploration (Angola) Ltd, Statoil Angola Block 17 AS, Norsk Hydro and Total for permission to publish the information contained in this paper.

## REFERENCES

- Abreu, V., Sullivan, M., Pirmez, C. & Mohrig, D. 2003. Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels. *Marine and Petroleum Geology*, **20**, 631–648.
- Amaral, J., Biteau, J.J., Zaroslinska, P. & DeCosta, L. 1998. Angola – the lower Congo Basin Tertiary petroleum systems hydrocarbon distribution in relation with structural and sedimentary evolution (abstract). *AAPG Bulletin*, **82**, 924–925.
- Broucke, O., Temple, F., Rouby, D., Robin, C., Calassou, S., Nalpas, T. & Guillocheau, F. 2004. The role of deformation processes on the geometry of mud-dominated turbiditic systems, Oligocene and Lower–Middle Miocene of the Lower Congo basin (West African Margin). *Marine and Petroleum Geology*, **21**, 327–348.
- Clifford, A.C. 1986. African oil – Past, present, and future. In: Halbouty, M.T. (ed) *Future petroleum provinces of the world*. AAPG Memoir, **40**, 339–372.
- Coterill, K., Dholakia, S.K., Coleman, A. et al. 1999. Sinuous morphologies in submarine channels – Scale and geometries in seismic and outcrop indicating possible mechanisms for deposition. *AAPG Bulletin*, **83**, 136–138.
- Cronin, B.T., Akhmetzhanov, A.M., Mazzini, A., Akhmanov, G., Ivanov, M., Kenyon, N.H. & TTR-10 Shipboard Scientists 2005. Morphology, evolution and fill: implications for sand and mud distribution in filling deep-water canyons and slope channel complexes. *Sedimentary Geology*, **179**, 71–97.
- Da Costa, J.L., Schirmer, T.W. & Laws, B.R. 2001. Lower Congo Basin, deep-water exploration province, offshore West Africa. In: Downey, M.W., Threet, J.C. & Morgan, W.A. (eds) *Petroleum provinces of the twenty-first century*. AAPG Memoir, **74**, 517–530.
- Damuth, J.E., Kolla, V., Flood, R.D. et al. 1983. Distributary channel meandering and bifurcation patterns on the Amazon deep-sea fan as revealed by long-range side-scan sonar (GLORIA). *Geology*, **11**, 94–98.
- Damuth, J.E., Flood, R.D., Kowsmann, R.O., Belderson, R.H. & Gorini, M.A. 1988. Anatomy and growth pattern of Amazon deep-sea fan as revealed by long-range side-scan sonar (GLORIA) and high-resolution seismic studies. *AAPG Bulletin*, **72**, 885–911.
- Deutsch, C.V. & Journel, A.G. 1992. *GSLIB: Geostatistical Software Library and User's Guide*. Oxford University Press, New York.
- Fincham, A.E., Christensen, J.R., Barker, J.W. & Samier, P. 2004. Up-gridding from geological model to simulation model: review, applications and limitations. Paper SPE 90921, presented at the Society of Petroleum Engineers Annual Technical Conference and Exhibition, Houston, Texas, 26–29 September.
- Garrison, L.E., Kenyon, N.H. & Bouma, A.H. 1982. Channel systems and lobe construction in the Mississippi Fan. *Geo-Marine Letters*, **2**, 31–39.
- Hurst, A., Cronin, B. & Hartley, A. 2000. Reservoir modelling sand-rich deep-water clastics: the necessity of down-scaling. *Petroleum Geoscience*, **6**, 67–76.
- Kastens, K.A. & Shor, A.N. 1985. Depositional processes of a meandering channel on Mississippi fan. *AAPG Bulletin*, **69**, 190–202.
- Kolla, V., Bourges, P., Urruty, J.-M., Claude, D., Morice, M., Durand, J. & Kenyon, N.H. 1998. Reservoir architecture in recent and subsurface deep-water meander-channel and related depositional forms (abstract). *European Association of Geoscientists and Engineers/AAPG Third Research Symposium Extended Abstracts*.
- Kolla, V., Bourges, Ph., Urruty, J.M. & Safa, P. 2001. Evolution of deepwater Tertiary sinuous channels offshore Angola (West Africa) and implications for reservoir architecture. *AAPG Bulletin*, **85**, 1371–1405.
- Lehner, P. & de Ruiter, P.A.C. 1977. Structural history of the Atlantic margin of Africa. *AAPG Bulletin*, **61**, 961–981.
- Mayall, M. & O'Byrne, C. 2002. Reservoir prediction and development challenges in turbidite slope channels. Paper OTC 14029, presented at the Offshore Technology Conference, Houston, Texas, 6–9 May.
- Mayall, M. & Stewart, I. 2000. The architecture of turbidite slope channels. *Proceedings of GCSSEPM Foundation 20<sup>th</sup> Annual Research Conference, Deep-water reservoirs of the world, 3–6 December*, 578–586.
- Peakall, J., McCaffrey, W.D., Kneller, B.C., Stelling, C.E., McHargue, T.R. & Schweller, W.J. 2000. A process model for the evolution of submarine fan channels: implications for sedimentary architecture. In: Bouma, A.H. & Stone, C.G. (eds) *Fine-grained turbidite systems*. AAPG Memoir 72/Society for Sedimentary Geology SEPM Special Publication, **68**, 73–88.
- Pettingill, H.S. 1998. Turbidite giants – lessons from the world's 40 largest turbidite discoveries (abstract). *European Association of Geoscientists and Engineers/American Association of Petroleum Geologists Third Research Symposium Extended Abstracts*.
- Pickering, K.T. & Corregidor, J. 2005. Mass-transport complexes (MTCs) and tectonic control on basin-floor submarine fans, Middle Eocene, South Spanish Pyrenees. *Journal of Sedimentary Research*, **75**, 761–783.
- Posamentier, H.W. & Kolla, V. 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research*, **73**, 367–388.
- Prather, B.E., Keller, F.B. & Chapin, M.A. 2000. Hierarchy of deep-water architectural elements with reference to seismic resolution: implications for reservoir prediction and modelling. *Proceedings of GCSSEPM Foundation 20<sup>th</sup> Annual Research Conference, Deep-water reservoirs of the world, 3–6 December*, 817–835.
- Remacha, E., Bolaño, F., Gual, G., Climent, F., Sancho, F.J., & Arcuri, M. 2004. The Morillo turbidite system in the Hecho Group. Total SA Internal Report pp. 30.
- Roberts, M.T. & Compani, B. 1996. Miocene example of a meandering submarine channel-levee system from 3D seismic reflection data, Gulf of Mexico Basin. *Proceedings of Gulf Coast Section SEPM Foundation Seventeenth Annual Research Conference*, 241–254.
- Sequeira, J., Campbell, M. & Smith, P. 1998. Comparison of key play elements of proven and potential petroleum systems of the South Atlantic margin – offshore Brazil and West Africa (abstract). *American Association of Petroleum Geologists International Conference and Exhibition, Extended Abstracts*, 104–105.
- Sprague, A.R., Sullivan, M.D., Campion, K.M. et al. 2002. The physical stratigraphy of deep-water strata: A hierarchical approach to the analysis of genetically-related stratigraphic elements for improved reservoir prediction. *American Association of Petroleum Geologists/Society for Sedimentary Geology SEPM meeting abstracts, Houston, Texas*, 10–13.
- Stark, D.M. (Coordinator) 1991. *Well evaluation conference, Angola, Petroleum geology, Schlumberger Conference Proceedings*, 1–95.
- Stelling, C.E. & DSDP Leg 96 Shipboard Scientists 1985. Migratory characteristics of a mid-fan meander belt, Mississippi Fan. In: Bouma, A.H.,

- Normark, W.R. & Barnes, N.E. (eds) *Submarine fans and related turbidite systems*. Springer-Verlag, New York, 283–290.
- Stephens, A.R., Monson, G.D. & Reilly, J.M. 1996. The relevance of seismic amplitudes in exploring the Niger Delta. *Offshore West Africa Conference Papers*, 54–60.
- Temple, F. & Broucke, O. 2004. Sedimentological models of the Oligocene and Miocene Malembo Formation in offshore Angola (Lower Congo basin). Regional West-African Deepwater Conference and Exhibition, Abuja, Nigeria, 14–18 November. *AAPG Bulletin*, **88**, Program abstracts (Digital).

Received 6 February 2006; revised typescript accepted 6 July 2006.