Uncertainty analysis of fluvial outcrop data for stochastic reservoir modelling

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ABSTRACT: Uncertainty analysis and reduction is a crucial part of stochastic reservoir modelling and fluid flow simulation studies. Outcrop analogue studies are often employed to define reservoir model parameters but the analysis of uncertainties associated with sedimentological information is often neglected. In order to define uncertainty inherent in outcrop data more accurately, this paper presents geometrical and dimensional data from individual point bars and braid bars, from part of the low net:gross outcropping Tortóla fluvial system (Spain) that has been subjected to a quantitative and qualitative assessment. Four types of primary outcrop uncertainties are discussed: (1) the definition of the conceptual depositional model; (2) the number of observations on sandstone body dimensions; (3) the accuracy and representativeness of observed three-dimensional (3D) sandstone body size data; and (4) sandstone body orientation. Uncertainties related to the depositional model are the most difficult to quantify but can be appreciated qualitatively if processes of deposition related to scales of time and the general lack of information are considered. Application of the N_0 measure is suggested to assess quantitatively whether a statistically sufficient number of dimensional observations is obtained to reduce uncertainty to an acceptable level. The third type of uncertainty is evaluated in a qualitative sense and determined by accurate facies analysis. The orientation of sandstone bodies is shown to influence spatial connectivity. As a result, an insufficient number or quality of observations may have important consequences for estimated connected volumes. This study will give improved estimations for reservoir modelling.

KEYWORDS: *uncertainty analysis, fluvial sedimentology, stochastic reservoir modelling*

INTRODUCTION

This paper discusses, on a conceptual basis but using an outcrop dataset as an example, four types of uncertainties associated with the statistical representation and associated quality of outcrop data. The ability to recognize and quantify uncertainty in both hard (measurement) and soft (interpretation) geological data that are used as input to stochastic reservoir modelling studies has increased significantly during the last decade. In subsurface fluvial reservoir modelling, parameter probability distributions (variability) and parameter uncertainties are largely unknown factors. Outcrop analogue information is, therefore, required to obtain basic data and to use as a guideline to derive realistic model input (Bryant & Flint 1993; North, 1996). Nevertheless, many modelling studies, applying outcrop datasets, tend to generate too narrow a range in cases where true natural variability is larger (Brandsæter *et al.* 2005), for example, resulting in the generation of sub-parallel channel bodies or too similar object dimensions. Geological uncertainty assessment through the analysis of a large number of stochastic model realizations for which different input parameter values are used (e.g. Svanes *et al.* 1994; Sandsdalen *et al.* 1996) underestimates, and does not adequately represent, the full range of geological uncertainty because the uncertainties related to the outcrop data are not considered. In addition, the nature and relative importance of uncertainty are related to the nature of the parameter assessed (volumetric or dynamic; Massonnat 2000).

Despite their necessity and importance, attention is rarely paid to uncertainty aspects associated with collecting hard outcrop data. This paper will discuss aspects related to outcrop analogue studies that aim to quantify sedimentological variability at the mesoscopic and macroscopic scale (cf. Tyler & Finley 1991). Such studies have to address both parameter variability and an array of uncertainties associated with the data collected. Previous such studies include Alexander (1993), Bryant & Flint (1993), Bridge & Tye (2000) and references therein that implicitly address uncertainties related to hard outcrop data, in addition to studies focused within the fluvial domain (e.g. Lorenz 1985; Díaz-Molina 1993; Dreyer *et al.* 1993; Willis 1993). Uncertainties related to fluvial outcrop data collected for use in object-based stochastic modelling (e.g. Hirst *et al.* 1993; Holden *et al.* 1998; Journel *et al.* 1998) include uncertainties that are:

1. associated with the preferred depositional model that is defined based on the analysis of preserved facies, i.e. is the

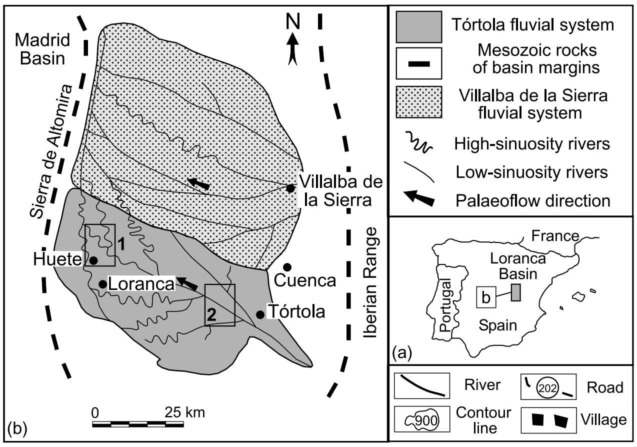

Fig. 1. Location map of the study area. Box 1 depicts the distal study area; box 2 depicts the medial study area.

model correct and is the outcrop the most appropriate analogue for the reservoir under study?;

2. related to the number of observations of, for example, sandstone body dimensions. In this context, the N_0 measure (Hurst & Rosvoll 1991) can be applied to estimate the minimum number of observations required. It is shown here that there are hardly ever enough sandstone body size observations available to quantify dimensional properties and variability sufficiently;
3. related to the true probability distributions of 3D sandstone body size data (if outcrops allow; absolute and relative accuracy and representativeness of deterministic data obtained). Note that if only two-dimensional (2D) cliff faces are available for analysis, quantification is limited to thickness and apparent length in outcrop in association with the palaeoflow directions. All sandstone bodies extending beyond the margins of the outcrop are exposed partially and are truncated. Various methods exist to correct for this effect (Geehan & Underwood 1993; Clark & Good 1997; Visser & Chessa 2000).
4. related to the reliablility of palaeoflow directions measured on a variety of sedimentary structures. For example, to estimate preserved sandstone body orientation and degree of connectivity, measurements taken from mapped channel margins are likely to have a significantly higher reliability than palaeoflow measurements taken from individual dune orientations.

The aim of this study is to analyse the nature of these four uncertainty types using data from the upper Eocene to lower Oligocene Tórtola perennial fluvial system of the Loranca Basin in central Spain (Fig. 1; Díaz-Molina *et al.* 1989; Martinius 2000). This system is characterized as having a labyrinthine architecture (cf. Weber & van Geuns 1990) and a low net: gross (NG) of 0.2. These uncertainties fall under uncertainty levels 1 to 3 of Massonnat (2000; fig. 1). Three-dimensionally exhumed sandstone bodies represent channel deposits formed within channel belts occurring largely isolated and embedded in mudstone and siltstone. This allows for a geometrical and dimensional study of individual point bars and braid bars, *sensu* deposition scale 2 of Bridge & Tye (2000). Uncertainties associated with data on complete channel-belt deposits and the stratigraphic analysis of the Tórtola succession have been addressed by Daams *et al.* (1996).

GEOLOGICAL SETTING OF THE STUDY AREA

The late Oligocene to early Miocene deposits of the Tórtola fluvial system (Díaz-Molina *et al.* 1989; papers in van Veen *et al.* 1994 and Friend & Dabrio 1996; Martinius 2000) are part of the Loranca Basin succession in central Spain, a thrust-sheet-top basin of the Celtiberian Range (Gómez *et al.* 1996). At the time of fluvial activity, the Loranca Basin was located at a palaeolatitude of 30° N (cf. Smith *et al.* 1981) and the system coalesced with the Villalba de la Sierra fluvial system along its northern margin. The apical region of the Tórtola fluvial system was located somewhere near the village of Tórtola, close to the southeastern margin of the Loranca Basin (Díaz-Molina *et al.* 1989). The Loranca Basin was connected to the intracratonic Madrid Basin via a bypass zone located on its northwestern margin. The palaeo-shoreline was located in the Madrid Basin some 360 km away from the bypass zone (Daams *et al.* 1996). It is assumed that glacio-eustatic sea-level fluctuations produced no identifiable effects on the studied intervals (Martinius 2000).

The Tórtola fluvial system was active during a phase of minor tectonic compression which occurred during the early Savian stage of the Alpine orogeny (Alvaro 1986) and ensured sufficient basin subsidence. Mammalian assemblages recovered from the deposits reveal stratigraphic changes in faunal composition which have been interpreted as reflecting a gradual change from cooler and more humid to warmer and drier conditions (Daams *et al.* 1996). The Tórtola fluvial system developed under a weak tectonic regime during the later stages of basin filling, possibly affected by systematic palaeoclimatic changes (Martinius 2000).

Outcrop information was obtained from two sedimentary successions at two localities, hereafter referred to as the medial and distal areas (Fig. 1). Requirements and procedures followed for the acquisition of sandstone body dimensional data and directional (palaeoflow) data have been outlined and discussed in Cuevas Gozalo & Martinius (1993); additionally, cross-sectional panels of the two localities were published and discussed by Martinius (2000). Both successions are orientated transverse to the general palaeoflow directions of the main channel belts, with the distal cross-section at a downstream distance of 45 km from the medial section.

DEPOSITIONAL MODEL

The depositional model for the Tórtola system involves a downstream widening perennial fluvial system characterized by a series of distributary channels and a general downstream progression from gravel-rich low-sinuosity channels to mixed-load high-sinuosity channels that developed in response to changes in bed material size, slope and discharge (Díaz-Molina 1979; Díaz-Molina *et al.* 1989; Daams *et al.* 1996; Martinius 2000). Martinius (2000) defined and illustrated four facies belts, each based on the characteristics and spatial distributions of mudstone, siltstone and sandstone facies. Mudstone and siltstone facies were interpreted to represent widespread overbank flooding of interchannel areas during high-discharge periods. The sandstone bodies were subdivided into seven types, which are interpreted to have formed in rivers with different discharges, sediment yields and channel planform patterns (cf. Schumm 1985). Four facies belts were interpreted to form a continuum along the Tórtola fluvial system profile, each being characterized by specific depositional conditions and, consequently, channel-pattern styles (Fig. 2).

- Gravel-rich braided streams dominated facies belt 1.
- Down gradient, these streams graded into wide, sand-dominated, braided streams of facies belt 2, which contained

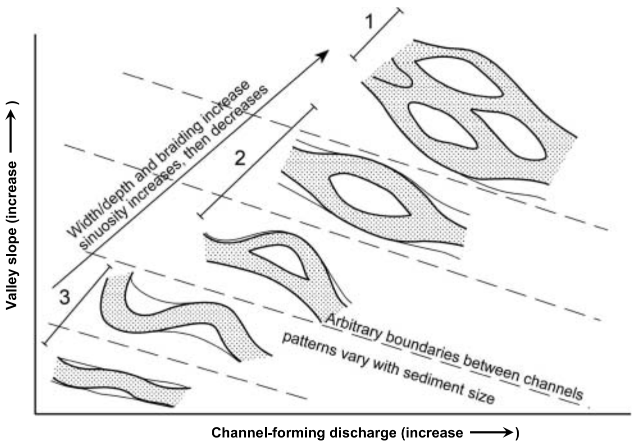

Fig. 2. Gradual variation of equilibrium channel patterns with channel-forming water discharge, valley slope and sediment size (modified after Bridge 2003). The numbered line sections 1–3 refer to the interpreted facies belts on the Tórtola system.

two types of large braid bars (Type 1 and Type 2) and were typified by significant discharge variations.

- Facies belt 3 comprises belts of mixed-load-dominated meandering and low-sinuosity channels containing composite point bar and ribbon sandstone bodies, respectively.
- Facies belt 4 represents distal floodplain areas at the toe of the fluvial system and included non-channelized sheet sandstone bodies.

The facies belts were used to explain both the downstream changes in channel planform style and the cyclic stratigraphic variations.

UNCERTAINTIES ASSOCIATED WITH THE DEPOSITIONAL MODEL

Rationale

How can one reliably define palaeo-environments from preserved deposits that can be typified as being preserved fragments of geological time? Although geological processes operate over long time-scales (>10^5 a), shorter time-scales are generally recorded, because preserved facies, including sandstone bodies, represent a specific and relatively instantaneous moment in time. These deposits contain information about the hydraulic regime and channel-forming discharge that could possibly have been recorded if a hypothetical observer had been present while the channel was still active. The challenge is how to relate the information obtained from instantaneous (<10^{-1} a), short (10^1–10^2 a) or medium (10^3–10^4 a) time-scales with long (>10^5 a, i.e. geological) time-scales.

From a geomorphological point of view, a channel type is characterized by its geometry which can be defined as the 3D form of a channel fashioned over a period of time to accommodate the mean condition of discharge and sediment load (Knighton 1998). Changes in channel geometry can be analysed by looking at, for example, planform pattern and cross-sectional form. At instantaneous to medium time-scales the two most important variables controlling channel-form adjustment, discharge and sediment load, are approximately constant in the mean. Streams will tend to have a range of channel types, indicating different behaviour in the longitudinal direction (Knighton 1998; Bridge & Tye 2000; Bridge 2003). From studies on modern river systems it is clear that no universally accepted set of criteria exists for determining whether all or part of a river system is in equilibrium, and the 'average' character of a stream is uncertain from observation at a specific geographical location (Knighton 1998). It is, therefore, almost impossible to determine whether an ancient stream was in equilibrium, which increases uncertainty related to the preferred depositional model. In fact, it is most likely that the system was not in equilibrium at the point of preservation, as each channel is subject to short-term fluctuations and long-term evolutionery tendencies. Planform pattern and cross-sectional form adjust at different rates so that short-term fluctuations and long-term evolutionery tendencies may be expected to vary from one channel component to another (Knighton 1998; Bridge 2003).

At long time-scales, it is desirable that a conceptual depositional model used as a basis for stochastic modelling describes the system when it is in equilibrium; a task with which a significant degree of uncertainty is associated. In the Tórtola system, different sandstone body types occur in close association within the same stratigraphic interval. In the distal area, ribbon sandstone bodies, interpreted to have been formed in mixed-load straight channels, co-occur with single point bars, interpreted to have formed in mixed-load meandering channels (Martinius 2000; fig. 9) and with (mid-channel) braid bars, interpreted to have formed in sand-dominated braided rivers, as well as single and composite point bars in the medial area (Martinius 2000; fig. 10). The co-ocurrence of these different sandstone body types in specific stratigraphic intervals could point to a state of disequilibrium or non-equilibrium of streams in these two particular areas at medium to long time-scales. Some of the braid bars, however, are fully preserved, including topsets. Assuming that bankful discharge is dominant and thus is most effective in shaping bars (cf. Knighton 1998; Bridge 2003), the associated braided channels would have been in a state of (graded) equilibrium at the short to medium scale, and possibly not at the long time-scale, which is in contrast to the suggestion above. Consequently, a significant degree of uncertainty is associated with the interpretation of an observed sandstone body (i.e. channel) geometry as defined by cross-sectional form and planimetric pattern. Also, similarity of form is no guarantee of similarity of process (cf. Knighton 1998, p. 225).

Uncertainty definition

Martinius (2000) found that different sandstone facies types appear and disappear at distinctive stratigraphic levels, and exhibit both a vertical and lateral organization. Sandstone bodies with different geometries (ribbons, composite point bars, mid-channel bars) occur in association, particularly in the medial area. In addition, channels join at the bypass zone connecting the Loranca Basin with the Madrid Basin. Although the model of a downstream-widening perennial system with distributary channels and general downstream changing channel planform style is preferred, these charactersitics could be explained alternatively by using an anastomosing river model. The reader is refered to Makaske (2001) for clarification of the characteristics of an anastomosing system.

The fact that concurrent ribbon sandstone bodies, point bars and mid-channel bars are a common feature of the Tórtola system (Figs. 3a, c) argues against a wider definition of an anastomosing system. A facies model for the vertical sedimentary succession of an anastomosing channel deposit does not exist because of the many modes of lateral and vertical accretion which make it difficult to asses the validity of such a facies model. In addition, the reconstruction of a multichannel palaeoriver based on individual fossil channel deposits in a 2D exposure is assumed to be difficult. Therefore, no conclusive statement can be made with respect to the depositional

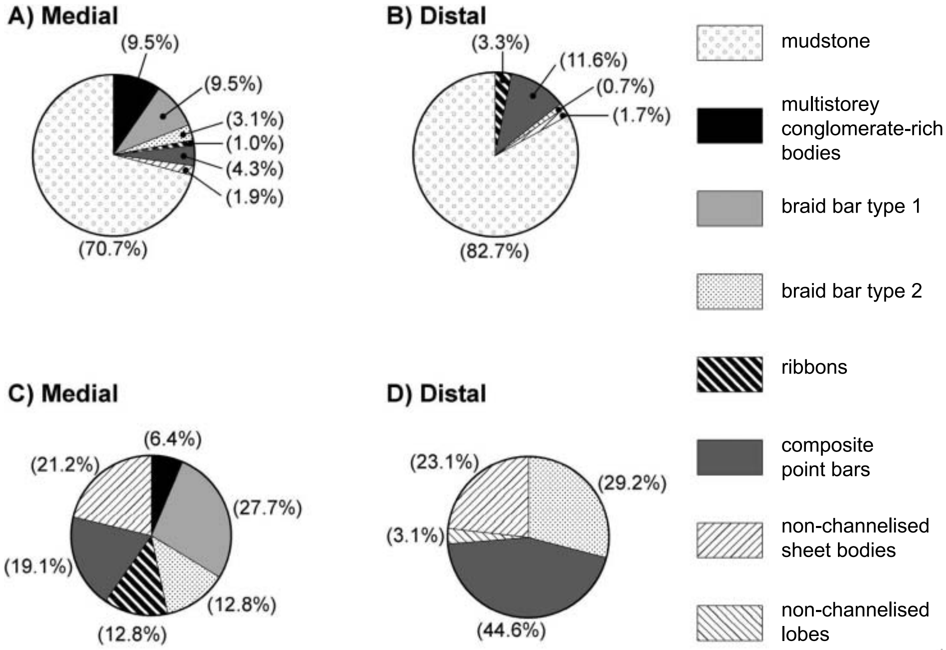

Fig. 3. (**a**, **b**) Relative ratios of the fine- and coarse-grained lithofacies of the total stratigraphic succession of the Tórtola fluvial system: (**a**) medial area; (**b**) distal area. (**c**, **d**) Relative ratios of genetic types of (**c**) the medial area and (**d**) the distal area of the Tórtola fluvial system.

environment and arguments can only point to the most likely setting associated with a relatively high degree of argument uncertainty.

The preferred depositional model for the Tortola Fm. proposes longitudinal changes in channel pattern (Martinius 2000). This model is uncertain since continuous downstream exposures of individual channel deposits of more than 500 m do not exist. Commonly, only relicts of ancient channels are preserved and furthermore, outcrops where stratigraphic successions of some thickness are exposed cannot generally be traced downstream for more than 5 km. The facies belts of the fluvial system are assumed to have been contemporaneous. Also, a sample bias and, hence, uncertainty has been introduced into the dataset by the fact that the two small sampling areas are supposed to be representative of the entire system. Yet another bias is introduced because the observations come from four different stratigraphic intervals that were controlled by different magnitudes of auto- and allocyclic factors (Daams *et al.* 1996; Martinius 2000).

In conclusion, the main aspect of depositional model uncertainty is the relationship of short- to medium- with long time-scales, and degree of system equilibrium. In subsurface modelling projects a commonly applied method to represent uncertainties associated with the interpretation of the depositional model is to build two or more alternative models (scenarios). Scenarios may be defined by applying separate parameter definitions or by defining alternative stochastic models for representing subsurface heterogeneity. Volumes and flow properties are assessed and compared in each case.

UNCERTAINTIES RELATED TO THE NUMBER OF SANDSTONE BODY SIZE OBSERVATIONS

Rationale

Hurst & Rosvoll (1991) proposed a simple measure of sample sufficiency valid for normal distributions, defined as $N_0 = (10CV)^2$, where N_0 is the number of data points needed to estimate the mean to within 20%; and CV is the coefficient of variation, defined as (Lake & Jensen 1991) CV= standard deviation/arithmetic average.

Applying this estimate to sandstone body size observation is a useful tool in assessing the outcrop quality in terms of its usefulness for deriving quantitative analogue data. Corbett & Jensen (1992) proposed three classes of CV (very heterogeneous, heterogeneous, homogeneous) to classify permeability heterogeneity qualitatively. This classification is applied here to the level of sandstone body size heterogeneity. The following discussion assumes that the frequencies of observed sandstone body sizes are distributed normally.

Uncertainty definition and consequences

Application of the N_0 measure reveals that:

- in the medial area, thickness, width and length data of Type 2 braid bar sandstone bodies have been collected in sufficient quantities (Tables 1 and 2) to obtain an indication of the variability of body size;
- in the distal area only ribbon thickness variability data are sufficient. The uncertainty associated with ribbon thickness is, therefore, significantly lower than that associated with ribbon width;
- similarly, composite point-bar body thickness (distal area) conforms to the N_0 measure;
- the relationship between the estimated width and length of composite point-bar sandstone bodies (distal area) indicates that a sufficient amount of data has been obtained. Therefore, the utilization of the W/L ratio of composite point-bar sandstone bodies for stochastic modelling procedures is justified statistically. Given an observed value of either W or L, the conditional probability distribution of the unknown parameter can be determined from the bivariate probability distribution, as outlined in Cuevas Gozalo & Martinius (1993). The conditional probability distribution indicates the range of parameter values which has a certain occurrence probability. This knowledge is of importance for reservoir characterization and modelling when predicting sandstone body parameters from a limited dataset.

All other size parameters have been sampled insufficiently in the field to decrease associated uncertainty to a level below

Table 1. *Data sufficiency with respect to dimensional properties of sandstone bodies*

Sandstone body type	Thickness		Width (W)		Length (L)		W/L	
	Medial	Distal	Medial	Distal	Medial	Distal	Medial	Distal
Braid bar Type 1	I	—		—		—		—
Braid bar Type 2	S	—	S	—	S	—	S	—
Ribbon	I	S	I	I	I	I	I	I
Composite point bar	I	S	I	I	I	I	I	S
Non-channelized sheet	I	I	I	I	I	I	I	I

S, sufficient; I, insuficient; —, not present

Table 2. *Descriptive statistics of sandstone bodies of the medial area*

	Thickness					Width (W)				Length (L)		W/L	
	I	II	III	IV	V	I	II	III	IV	II	IV	II	IV
n	15	6	5	5	9	15	6	5	5	6	5	6	5
μ (m)	4.9	9.6	5.9	6.9	1.1	56	30.8	32	62	44.2	86	0.7	0.7
s^2	5.1	5.7	7.0	15.9	1.1	1076	34.2	70	470	74.2	880	0.0	0.0
s	2.3	2.4	2.7	4.0	1.0	32.8	5.8	8.4	21.7	8.6	29.7	0.1	0.0
CV (%)	45.8	24.9	44.7	57.7	96.2	58.6	19.0	26.1	35.0	19.5	34.5	12.7	5.1
Skewness	0.7	−0.5	−0.2	0.1	1.9	1.3	0.5	−0.3	−0.3	1.0	−0.6	1.5	−0.6
Kurtosis	2.6	2.0	1.6	2.0	5.3	3.9	2.0	1.8	2.4	3.1	2.4	3.7	1.7
Minimum (m)	2.1	5.8	2.5	1.7	0.2	15	25	20	30	35	40	0.6	0.7
Median (m)	4.6	10.1	6.4	6.4	0.8	45	30	30	60	42.5	90	0.7	0.8
Maximum (m)	9.8	12.3	9.1	12.3	3.6	140	40	40	90	60	120	0.9	0.8

Sandstone bodies: braid bar type 1 (I); braid bar type 2 (II); ribbon (III); composite point bar (IV); and non-channelized sheet (V). n, number of observations; μ, mean; s, standard deviation;? s^2, variance; CV, coefficient of variation.

20%. Therefore, their variability cannot be assessed with sufficient reliability.

In conclusion, the main aspect of uncertainty related to the number of sandstone body size observations is the relation between variation in observed dataset of dimensional property and the absolute number of observations (n). A proposed method to represent these uncertainties in stochastic modelling is to estimate n from the number of wells available when constraining the stochastic model with the number of objects. Apply N_0 measure and reject hard data if necessary.

UNCERTAINTIES RELATED TO THE ACCURACY OF SANDSTONE BODY DIMENSIONS

Many studies of fluvial deposits in outcrop or in the subsurface are devoted to the analysis and quantification of lithofacies variability at sandstone body scale and pay little or no attention to uncertainty aspects of the data presented (but see Budding *et al.* 1992; Bridge & Tye 2000). Outcrop-derived datasets that record size variability of fluvial sandstone bodies are comparatively uncommon and moreover are derived from widely different fluvial settings (e.g. Nami & Leeder 1978; Fielding & Crane 1987; Dreyer *et al.* 1993). Additionally, most of these data are limited to deltaic lower coastal plain environments. Sandstone body size is controlled by a large number of factors, such as channel-forming discharge, sediment load characteristics and avulsion periodicity; however, uncertainties related to the analysis of these controlling factors are not covered in the scope of this study.

For this study, 3D data were measured from plan-view reconstructions of well-exhumed sandstone bodies (Fig. 4), together with their palaeoflow directions (Fig. 5), exposed in an area described in Cuevas Gozalo & Martinius (1993) and an area laterally adjacent to that. Additional findings for the medial area are presented here and important features are summarized by descriptive statistics (Tables 2 and 3; Fig. 6). The procedure used here for reconstructing sandstone body dimensions is described in Cuevas Gozalo & Martinius (1993).

Measurement errors (random and systematic) are introduced when obtaining hard data, such as sandstone body thickness, width and length if applicable. The latter two types of data can be measured directly in outcrop if the sandstone bodies are well enough exhumed, as is regularly the case in the Tórtola example, or on paper from reconstructed sandstone body shapes using strike directions of key (bounding) surfaces and palaeoflow measurements. Reconstructions on paper (as in Cuevas Gozalo & Martinius 1993) introduce a new random and systematic set of errors and increase uncertainty.

The dimensional dataset of the distal area (Fig. 6) contains data on both single and composite point-bar bodies without distinguishing between the two. Unlike single point-bar bodies, composite point-bar bodies show internal erosional and non-erosional reactivation surfaces between large-scale inclined strata. These are formed by the relocation of the channel associated with a change in bend curvature possibly related to discharge fluctuations. An overview of theory and models for simple versus composite meander bends is covered by Bridge (2003). Superimposed composite point-bar bodies have been taken apart into individual composite point-bar bodies to estimate their dimensions. Several sedimentological criteria have been applied, namely (i) occurrence of large-scale erosional surfaces, (ii) extensive lag deposits, (iii) sharp changes in bedding pattern and (iv) abrupt petrological changes. The correct application of these criteria, however, can be a matter of debate (see the examples in Bridge & Tye 2000) and introduces uncertainty in the dimensional dataset which devaluates the understanding of size variability. For this study, composite and single point-bar bodies have been treated similarly.

An additional source of uncertainty is related to the fact that outcrop sections are often limited and only allow for a partial view of the sandstone body. Two methods have been

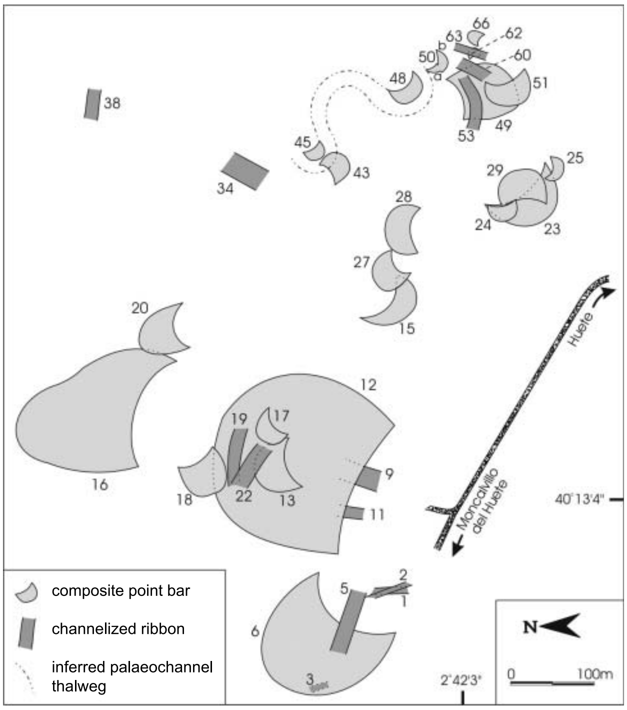

Fig. 4. Representation of the position and size of sandstone bodies of the distal area of the Tórtola fluvial system relative to each other. The figure shows a projection of sandstone bodies occurring at various stratigraphic levels in the distal succession on a horizontal plane. Sandstone bodies are numbered according to their order of stratigraphic appearance. Plan-view reconstructions were based on lateral lithofacies changes, field measurements of the length of the outcrop contour of each sandstone body and aerial photographs on a scale of 1: 2100. First, the outcrop contour is delineated from the aerial photographs supplemented by field measurements. The margins of each sandstone body are indicated on the outcrop contour as often as these cut the outcrop. The position and orientation of lateral accretion units, when present, are delineated; local palaeocurrent directions are indicated. The general trend of the palaeochannel deposit can be drawn from these data. Sandstone body thickness variations help to determine the proximity of the margins. General palaeoflow directions and accurate measurements of sandstone body width can be obtained from the reconstructed plan-view geometry. For ribbon sandstone bodies, the body indicates the position of the palaeochannel. In the case of composite point-bar bodies, the last position of the palaeochannel will be adjacent to the body.

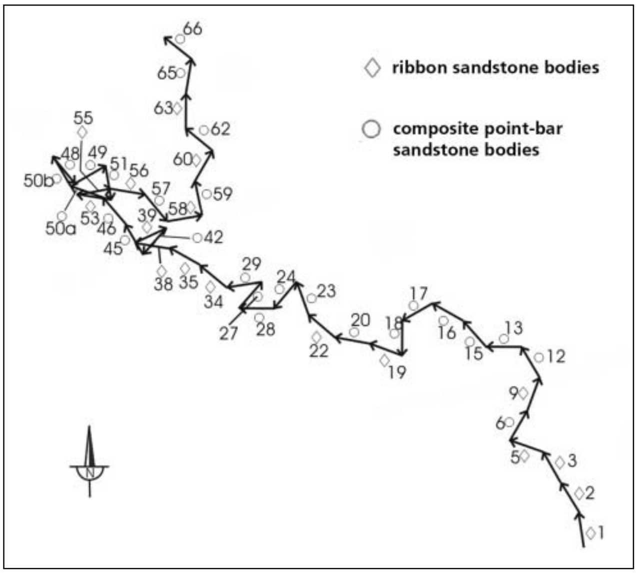

Fig. 5. Schematic illustration of the reconstructed and ranked palaeoflow directions through time (measured cf. Allen 1966; Miall 1974) of the sandstone bodies of the distal area plotted in stratigraphic order one after the other by means of an arrow with fixed and arbitrary length.

Table 3. *Descriptive statistics of ribbon (III) and composite point-bar sandstone bodies (IV) of the distal area*

	Thickness		Width (*W*)		Length (*L*)	*W/L*
	III	IV	III	IV	IV	IV
n	18	26	18	26	23	23
μ (m)	4.1	4.5	29.9	45.6	66.1	0.7
*s*2	3.1	3.9	549.0	1241.9	3453.6	0.1
s	1.8	2.0	23.4	35.3	58.8	0.2
CV (%)	43.3	43.5	78.3	77.4	88.9	32.7
Skewness	0.4	0.3	1.9	1.6	2.4	1.6
Kurtosis	2.6	2.3	5.8	4.8	8.9	5.5
Minimum (m)	1.1	1.6	10.0	10.0	14.0	0.5
Median (m)	3.9	4.8	22.0	34.0	58.0	0.6
Maximum (m)	8.0	8.8	100.0	140.0	280.0	1.4

n, number of observations; μ, mean; *s*, standard deviation; s^2, variance; *CV*, coefficient of variation.

developed to correct for truncated length observations in 2D outcrops (Geehan & Underwood 1993; Visser & Chessa 2000). Most often, a component of, for example, a braid bar is visible and measurable, of which the nature can be established by regular facies analysis. Facies analysis by itself, however, is not able to shed light on sandstone body dimensions since it only supplies information on channel-forming discharge and sediment load characteristics (cf. Alexander 1993; Bridge 2003). Reliable data on sandstone body length are affected most severly by incomplete initial preservation, post-depositional erosion and/or outcrop limitations. In virtually all cases, these processes have increased the associated uncertainty to a high level, even in cases where preserved sections of Pleistocene or Holocene channel sandstones in subcrop can be traced over large geographical areas (Friend *et al.* 1986; Wu *et al.* 1996; Berendsen & Stouthammer 2001). It is essential to establish whether one or more units of the braid bar are exposed and which units, i.e. bar head and/or bar tail, cross-bar channel, tributary mouth bar (cf. Bridge 2003; Figs 7a, b) and what are their relative proportions. Braid-bar Type 2 might, in reality, represent either an alternate (unit) bar (considered most likely) or only a particular unit of a unit bar, for example, a bar-head unit or a tributary mouth bar (Bridge & Tye 2000). Therefore, a significant degree of uncertainty is associated with estimated braid-bar dimensions if the full bar is not exposed and/or if its depositional nature is not recognized.

The dimensional characteristics of point bars and braid bars are influenced by both intrinsic changes (i.e. thresholds that are exceeded during the natural cyclic progression of events in a fluvial system) and extrinsic changes (i.e. thresholds that are exceeded by external (or allocyclic) factors operating outside the alluvial depositional environment (Schumm 1985)). These are part of a continuum and there is a larger tendency for intrinsic changes to keep relationships similar. Extrinsic changes affect relationships either gradually, to restore equilibrium, or suddenly (for example, floods). If the effects of both intrinsic and extrinsic changes are present in a dimensional dataset, uncertainty is increased, for example, by which origin of change is a particular observation most influenced, and a larger dataset may be needed to capture these effects appropriately.

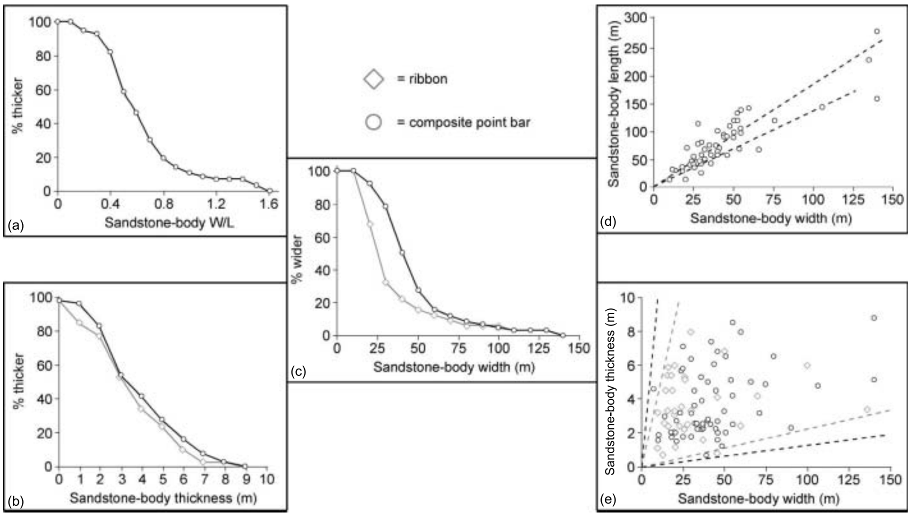

Fig. 6. Scatterplots and curves of cumulative distribution functions (CDF) of width (*W*), thickness (*T*) and length (*L*) of sandstone body types of the distal area of the Tórtola fluvial system. (**a**) CDF curve of *W/L* of composite point-bar sandstone bodies. CDF curves of sandstone body (**b**) thickness and (**c**) width of ribbon and composite point-bar sandstone bodies. (**d**) Scatterplot of *W/L* of composite point-bar bodies. (**e**) Scatterplot of *W/T* of ribbon and composite point-bar sandstone bodies. No relation is found.

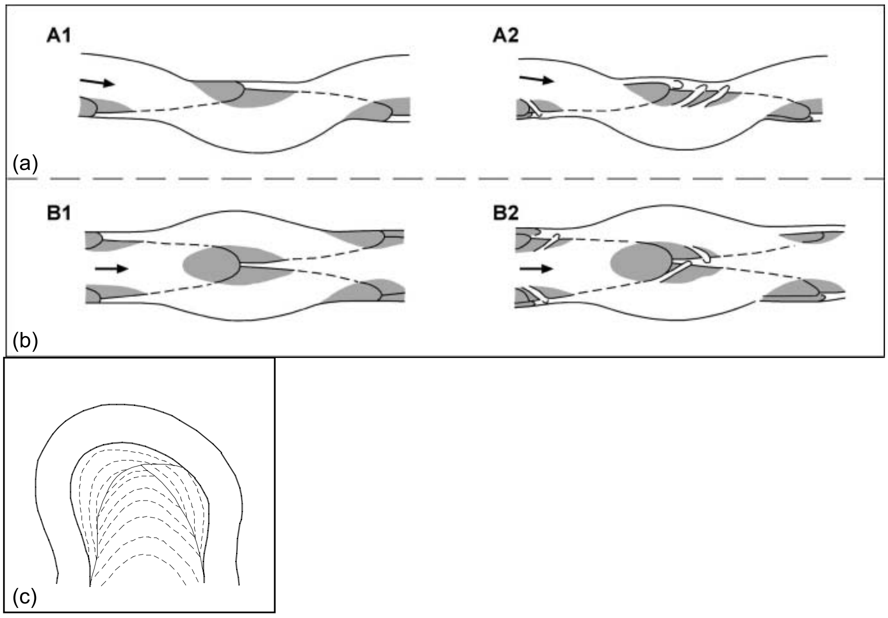

Fig. 7. (**a**, **b**) Examples of braid bars (modified after Bridge 2003). Solid or dashed line represents the crest line of the bar, arrow depicts flow direction. Stippled areas are topographic highs. **A1**, a single row of alternate bars in a straight channel; **A2**, as A1 but with cross-bar channels and associated channel-mouth bars. **B1**, a double row of braid bars and side bars in a straight channel; **B2**, as B1 but with cross-bar channels and associated channel-mouth bars. (**c**) Plan view sketch of a composite point bar (after Díaz-Molina *et al.* 1989).

In conclusion, the main aspect of uncertainty related to the accuracy of sandstone body dimensions is the incomplete preservation and/or exposure of modelling objects. A proposed method to represent these uncertainties in stochastic modelling is to change the mean of single or combined object parameter(s) and, secondly, to vary the variance to generate multiple model realizations.

UNCERTAINTIES RELATED TO PALAEOFLOW DIRECTIONS

Rationale

A stochastic, object-based modelling tool was applied to investigate the effect of uncertainty related to channel palaeoflow directions by investigating palaeoflow variability. Object-based modelling techniques are characterized by the fact that they:

- are capable of utilizing all available data (core, well log, seismic and pressure data);
- are completely deterministic only at well locations;
- create realistic reservoir body geometries, albeit based on uncertain input data;
- represent statistical variability in an attempt to replicate natural variability or uncertainty of the spatial arrangement of geological objects (e.g. sandstones bodies, cemented surfaces, shale drapes).

Objects (i.e. sandstone bodies) are generated based on predefined size parameter distributions and accepted or rejected based on well conditioning.

A cross-section through the distal area of the Tórtola system was chosen as study target and was treated as if composed of two lithologies: sandstone (ribbons and composite point bars) and mudstone. Based on the fully deterministic 2D cross-section and calculated proportion curves (Fig. 8), 62 artificial wells were created each with a spacing of 15 m (Fig. 9) to capture all information adequately and such that each sandstone body is penetrated at least once.

Non-channelized sheet sandstone bodies were excluded because of their low volume fraction (1.7% of total sediment volume; Fig. 3b) and generally indistinct orientation. Ribbons, interpreted as short-lived, and straight channel fill deposits, were modelled as continuous channels, and composite point bars were modelled as individual crescent-shaped objects as insufficient information was obtained to characterize associated

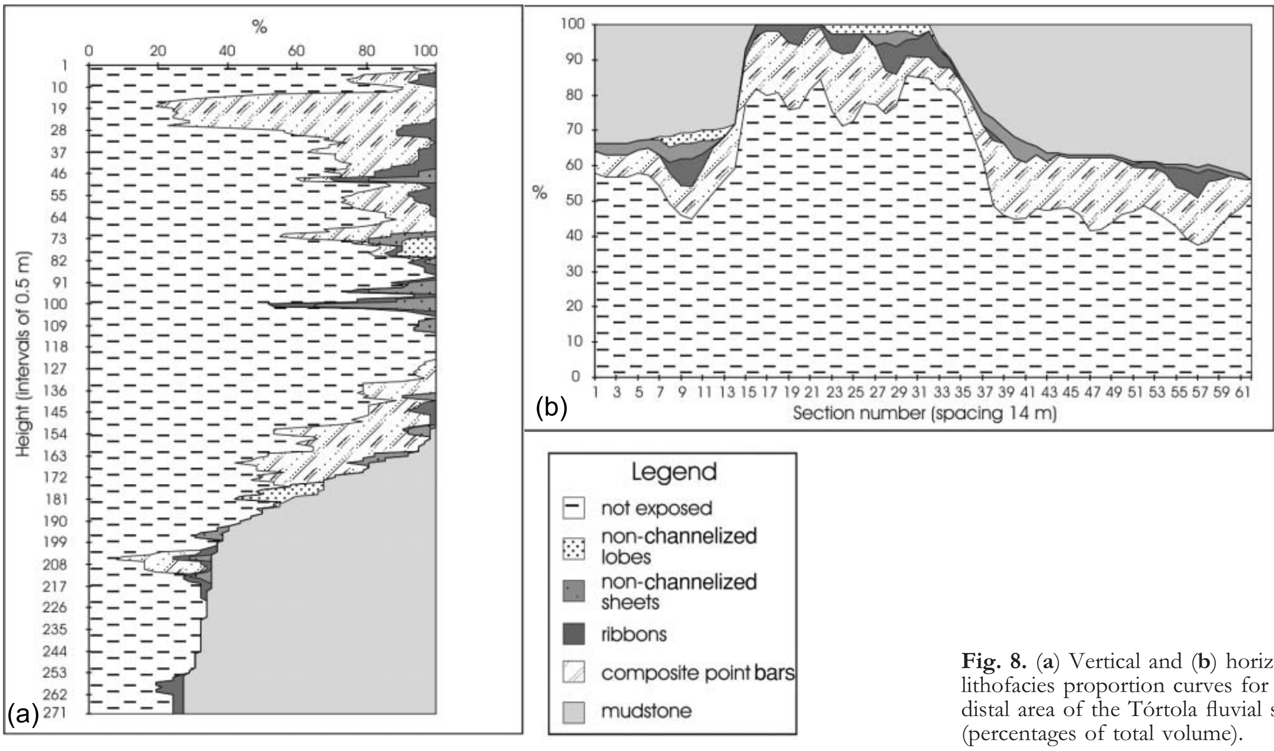

Fig. 8. (**a**) Vertical and (**b**) horizontal lithofacies proportion curves for the distal area of the Tórtola fluvial system (percentages of total volume).

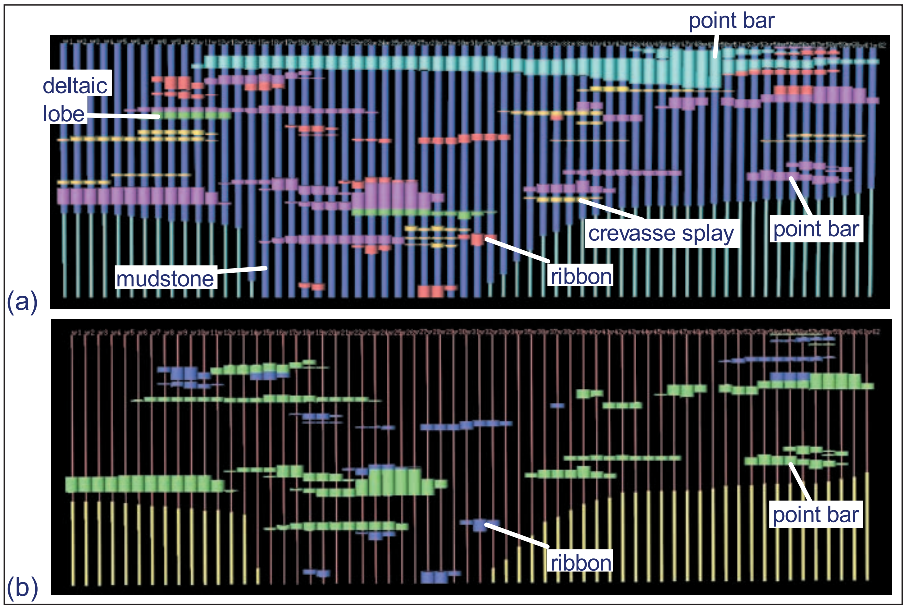

Fig. 9. Stochastic model realization of the distal succession: (**a**) all lithofacies represented; (**b**) ribbon and composite point-bar sandstone bodies only.

channel shapes in more detail. Each ribbon and composite point-bar body was described as an individual object. The large-scale distribution and orientation of both object types are described by a fibre-process model in the case of ribbons, while a general marked-point process is used for composite point bars. The dimensions of ribbon objects and the sinuosity of each object are described by four one-dimensional Gaussian functions, whereas composite point bars are described by 'marked points'.

Generation of the model realizations is achieved by an iterative, simulated annealing technique. The algorithm starts with a reservoir volume comprising only mudstone (background) lithology. For each iteration, a choice is made to either keep, reject, or swap the newly created object according to whether it satisfies the input conditioning data, which generates a new object configuration. Subsequently, the probability for the new configuration is calculated by an objective function. If the probability increases, the new configuration is accepted and the process continues. However, if the probability decreases, the old configuration is restored and the iteration process resumes. A simulated annealing algorithm (a 'temperature' term) is used to drive the simulation towards the desired input object volume fractions.

Uncertainty definition and consequences

Figure 10 shows one realization of ribbon and composite point-bar distributions valid for a specific input volume fraction value. For each volume fraction value all model simulation results are equiprobable. Therefore, a large number of realiza-

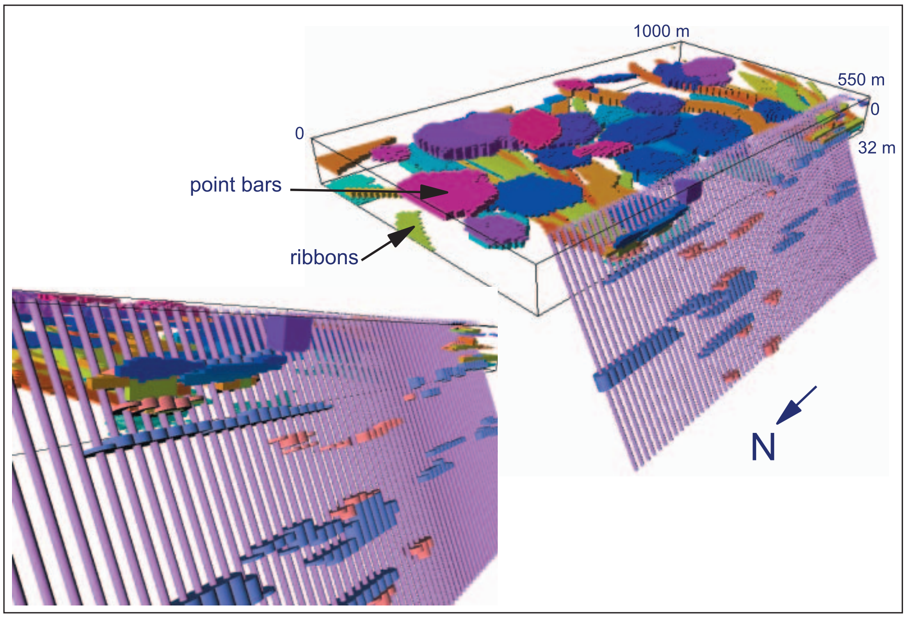

Fig. 10. Merged stochastic model realization of simulated ribbon and point-bar sandstone body distributions.

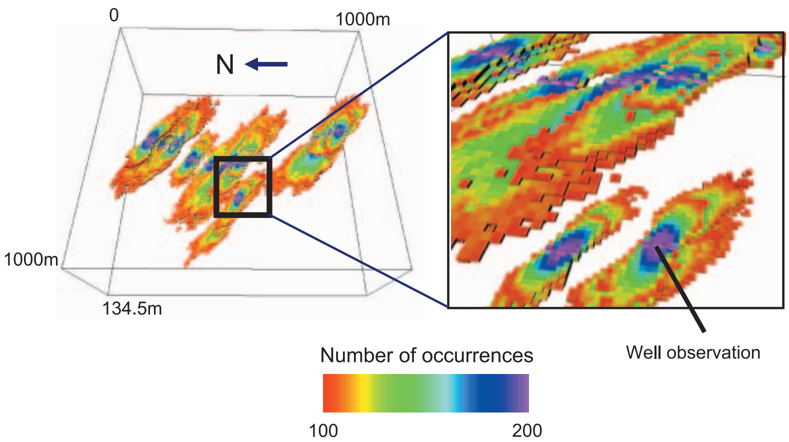

Fig. 11. Average of 200 ribbon and composite point-bar realizations.

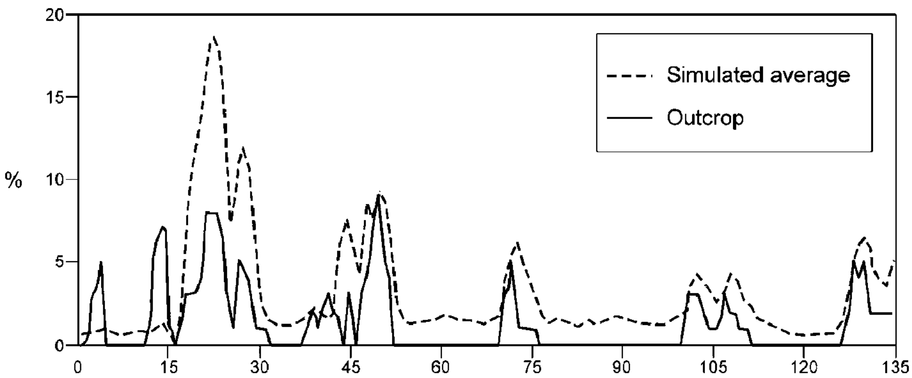

Fig. 12. Vertical lithofacies proportion curves constructed based on outcrop data from the distal area of the Tórtola fluvial system (solid line) and on averaging of 200 stochastic modelling realizations (dashed line).

tions have to be produced to be able to reproduce the input statistics (Fig. 11).

Comparison of the vertical facies proportions curve constructed from the outcrop data with that based on average model results (Fig. 12) shows that trends in ribbon distribution present in the cross-section are honoured. However, between 0 m and 15 m depth (top slice of outcrop) the trend is not honoured due to edge effects. Analysing edge effects is an efficient tool in tuning stochastic parameter estimations. Generally, edge effects should be avoided or alternatively they may be interpreted as an indication of the need for choosing an alternative stochastic realization.

Figure 13 illustrates the effect of varying the range of orientation of ribbon sandstone bodies. A low palaeoflow variability produces model results which predict a large connected volume around a wellbore where the probability of finding connected ribbon sandstone bodies is present, although this probability is decreasing away from the wellbore.

The model with high palaeoflow variability produces results that predict a significantly smaller connected volume around

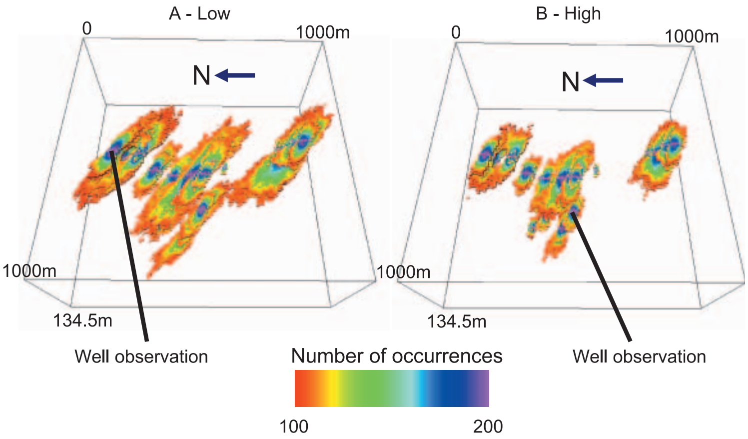

Fig. 13. Illustration of the effect of the variability of ribbon orientation.

Table 4. *Summary of main aspects of the four discussed uncertainties, with proposed methods to represent these in stochastic modelling*

Summary of main aspect of four uncertainty sources	Method to represent uncertainty in stochastic model
(1) Depositional model: Relationship of short- to medium- with long time-scales, and degree of system equilibrium.	Build two or more alternative scenarios with separate parameter definitions, or apply alternative stochastic models. Assess consequences for volumes and flow. Keep the alternative models until they are justifiably rejected.
(2) Sample completeness: Relation between variation in observed dataset of dimensional property and the absolute number of observations (statistical validity).	When constraining the stochastic model with the number of objects, estimate n from the number of wells available. Apply N_0 measure and reject hard data if necessary.
(3) Dimensions: Sample bias (incomplete preservation and/or exposure of modelling objects).	Change mean of single or combined object parameter(s) and/or vary variance to generate multiple model realizations.
(4) Orientation: The mean direction and degree of variation of palaeoflow and its effect on connectivity.	Change mean and/or vary variance to generate multiple model realizations.

the wellbore where the probability of finding connected ribbon bodies is present.

These findings illustrate the sensitivity of sandstone body connectivity to the degree of variation, or in this case, uniformity, of palaeoflow directions as measured from sandstone body orientation. Consequently, the many uncertainties regarding collecting palaeoflow data can have important consequences when calculating connected volumes. The latter is based on stochastic model results and is used as input to fluid-flow simulation studies. Accurately specifying the descriptive summary statistics of palaeoflow measurements, whether they are related to direct measurements of sandstone body orientations or measured from cross-bedding obtained from outcrop work, and addressing these uncertainties is, therefore, important.

In conclusion, the main aspect of uncertainty related to palaeoflow observations is the mean direction and the degree of variation and its subsequent effect on modelled connectivity. A proposed method to represent these uncertainties in stochastic modelling is to change the mean and/or to vary the variance to generate multiple model scenarios with multiple realizations.

Uncertainties related to data used as input for object-based stochastic modelling can alternatively be reduced by applying physical (scale) modelling (e.g. van Heijst & Postma 2001; Moreton *et al.* 2002) or 3D, process-based modelling techniques (e.g. Mackey & Bridge 1995; Karssenberg *et al.* 2001). These two techniques could be used potentially to generate more realistic sedimentological models and qualitative and quantitative data that can be used to constrain modelling input parameters better, but results have to be scaled to match reservoir dimensions. With respect to the topics discussed in this paper, physical scale models in, for example, flume tanks, with their high spatial resolution of data, (1) supply an order of magnitude more data on alluvial architecture than existing outcrop datasets, (2) are typified by the availability of 3D geometric data, (3) enable the identification of 'true' palaeoflow direction and hence correction of depositional geometries, (4) supply data that need no correction for outcrop orientation, topographic distortion or partial or complete lengths of sedimentary bodies and (5) can be linked to permeability distribution (Moreton *et al.* 2002), the last factor being a critical parameter for fluid-flow simulations. However, uncertainties related to the modelling of geological time (Ashworth *et al.* 1999; Moreton *et al.* 2002) should be addressed. A disadvantage of process-based models is that they generally cannot be conditioned to subsurface observations (i.e. well obervations, seismic data or dynamic production data). In addition, it is unlikely that a specific observed alluvial architecture can be explained by a unique combination of controlling variables. It is, therefore, very difficult to define the input parameters of process-based models (North 1996; Bridge 2003) and unlikely that process-based models can generate realistic reservoir architecture. Recent developments, however, indicate that conditioning to well data should be possible, in principle (Karssenberg *et al.* 2001). The data obtained from physical and/or process-based models could subsequently be applied as input to stochastic modelling techniques to create hybrid models (North 1996; Bridge 2003). Given the correct use of these models, input data uncertainty could be reduced significantly.

CONCLUDING REMARKS

Traditionally, uncertainty analysis of outcrop data used as input for stochastic reservoir models has been neglected. Table 4 summarizes the main aspects of the four uncertainties discussed and proposes methods to represent these in stochastic modelling. In the subsurface, however, uncertainty analysis is an important and a routinely applied evaluation technique for stochastic reservoir modelling. Stochastic modelling of fluvial successions is used for calculations of, for example, in-place volumes, reserves and recoverables (Svanes *et al.* 1994; Sandsdalen *et al.* 1996) and for field development planning (e.g. Svanes *et al.* 2004). The aim is to define, quantify and reduce subsurface uncertainty. Generating alternative, scenario-based stochastic models can represent the uncertainty range better, but will, however, generate many realizations. The final number of scenarios and realizations can be reduced using experimental design techniques and the uncertainty distribution can be estimated from these outcomes. To analyse the impact of uncertainties related to sedimentalogical or structural heterogeneities on fluid flow the realizations can subsequently be subjected to, for example, waterflood simulation (Kjønsvik *et al.* 1994; Jones *et al.* 1995) or streamline simulation techniques (Brandsæter *et al.* 2001; Ottesen & Townsend 2002). Uncertainty analysis is important because uncertainties in data associated with defining model input have the potential to affect both volume calculations and reservoir engineering decisions in a negative manner. These decisions can only be reliably made if uncertainty is reduced to an acceptable level. The effort put into estimation of uncertainty should be balanced with the importance and correct representation of the data type of interest. For each specific goal, key factors contributing to uncertainty estimates need to be identified. Furthermore, in addition to defining parameter variability, the sedimentologist should routinely quantify uncertainties associated with all reservoir modelling input parameters. This requires an in-depth understanding and knowledge of sedimentary and stratigraphic processes and products. Modelling strategies should be based upon an assessment and ranking of these uncertainties.

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