The Deep-Water Architecture Knowledge Base: towards an objective comparison of deep-marine sedimentary systems

Jaco H. Baas[1], **William D. McCaffrey**[1] **and Robert J. Knipe**[2]
[1] *Turbidite Research Group, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*
(e-mail: j.baas@earth.leeds.ac.uk)
[2]*Rock Deformation Research, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK*

ABSTRACT: A quantitative method is proposed for the comparison of deep-marine clastic depositional systems and the analysis of their architectural properties. The method comprises a knowledge base of quantitative, literature-derived information from modern and ancient, surface and subsurface deep-water systems, implemented as a relational database management system and referred to as the Deep-Water Architecture Knowledge Base (DWAKB). The types of information contained within the knowledge base include: (1) internal and external parameters controlling system architecture, such as tectonic setting, grain size of available sediment, degree of basin confinement and number and distribution of sediment input points; (2) the dimensions of architectural elements, such as channels, levees, lobes, open slope and basin plain; (3) the spatial organization of the architectural elements; and (4) the bed thickness distribution and proportion of different lithologies within the architectural elements. The potential value of the DWAKB for comparative studies of deep-marine clastic systems is considerably higher than that of classification schemes and system analogue concepts presently available. Thus, in contrast to classification schemes, the knowledge base is not limited in the number of controlling parameters and it does not have a limited time span because of the flexibility to update existing records and add new datasets. Moreover, system analogues can be selected more objectively through the use of statistical methods, and the knowledge base allows unsurpassed integration of large-scale architectural data with bed- and facies-scale data. The expected value of the DWAKB is illustrated with several examples of quantitative data analysis. These include the determination of the frequency of occurrence of levees in systems of different grain size, the calculation of the dimensions of submarine channels as a function of grain size and proximity to the source area, and the construction of idealized models for sand-rich and mixed mud–sand systems based on probabilities of spatial transitions between architectural elements.

KEYWORDS: *clastic sediments, submarine environment, turbidite, knowledge-based systems*

INTRODUCTION

At present, deep-marine clastic depositional systems are one of the most intensively studied systems in sedimentary geology. This largely reflects the increased activities of the hydrocarbon industry in modern and ancient slope and deep basinal settings. The analysis of a deep-marine system relies heavily on the identification of type and distribution of architectural elements (e.g. channels, levees and lobes) within the system as well as on comparison with other systems of similar character. Classification schemes have been developed since the 1970s to facilitate comparative studies. Early schemes generalized data on modern systems (Normark 1970, 1978), ancient rock records (Mutti & Ricci Lucchi 1972) or both (Walker & Mutti 1973; Walker 1978, 1980) into single fan models. Although such models remained popular until the end of the 1980s, there was a simultaneous slow but steady evolution towards more advanced models that incorporate the many variables now believed to control the architecture of deep-marine depositional systems. These variables include climate, tectonics, sea-level, type and source of sediment and rate of sediment supply (Fig. 1). In particular, it was recognized that the shape and internal organization of deep-water systems vary as a function of grain size (Mutti 1979; Stow *et al.* 1985), sea-level (Mutti 1985; Posamentier *et al.* 1991), basin configuration and degree of basin confinement (e.g. MacDonald 1986; Sinclair 1992, 2000), number and distribution of sediment input points (Chan & Dott 1983; Heller & Dickinson 1985; Surlyk 1987; Reading 1991) and tectonic setting (Shanmugam & Moiola 1988). Mutti (1985) proposed a classification scheme of submarine fans inspired by sequence stratigraphy in general and sea-level change in particular. Another classification scheme used the concept of flow efficiency, i.e. the ability of a flow to carry its sediment load

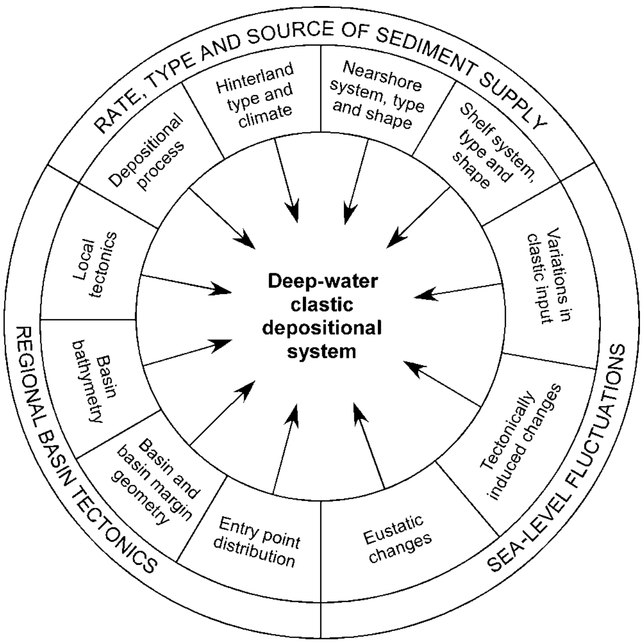

Fig. 1. Major parameters controlling the morphology of deep-water clastic depositional systems (after Stow *et al.* 1996).

basinward (Mutti 1979; Pickering *et al.* 1989; Mutti *et al.* 1999). More recently, a new classification scheme was introduced, comprising 12 deep-marine systems in unconfined depositional settings, differentiated using grain size of available sediment (i.e. mud-rich, mixed mud–sand, sand-rich and gravel-rich) and feeder type (i.e. single point-sourced ‘fan’, multiple point-sourced ‘ramp’ and line-sourced ‘apron’) (Reading 1991; Reading & Richards 1994; Richards & Bowman 1998; Richards *et al.* 1998). Hurst *et al.* (1999, 2000) extended this classification scheme to account for confined deep-marine basins.

Classifications have undoubtedly proven their usefulness. In accordance with the **facies model** concept (Walker 1984), which lies at the root of most fan models, classification schemes are helpful as a norm, for purposes of comparison, as a framework for future observations and as a predictive tool for new discoveries. They also act as a basis for interpretation of (sub)environment and depositional process. Yet, the disadvantages of classification schemes have become increasingly evident in recent years. Perhaps their most serious drawback is that they can describe only a limited subset of depositional systems, thus hampering comparative studies. Extending, for example, Reading & Richards’s (1994) scheme to more than two controlling parameters multiplies the number of end-member systems, making the revised scheme impractical. The dilemma is that a classification scheme needs to cover as many controlling parameters as possible to capture the natural variability of deep-water systems sufficiently well whilst remaining useable. There are a number of further disadvantages.

1. Classification schemes are typically based on the state-of-the-art knowledge at the time of their erection. In order to remain useful for a long time in any rapidly evolving field, such as in deep-water geology, there should be ample room for incorporating new discoveries.
2. The uncritical use of classifications may lead to biased interpretations.
3. Classifications emphasize the large-scale architecture of deep-marine systems. Variations on the scale of individual beds or sedimentary facies are often undervalued, yet are important in outcrop and for petrophysical studies.
4. Classifications generally lack quantitative data with regard to, for example, size and spatial organization of architectural elements, and thickness distribution and horizontal extension of constituent facies.

Perhaps driven by frustration with existing schemes, recent literature shows a tendency to move away from classifications and adopt the **analogy concept** instead (e.g. Schuppers 1993; Cronin & Kidd 1998; Wynn *et al.* 2000; Robertson *et al.* 2002; Martinsen *et al.* 2003). The analogy concept involves the search for a deep-marine depositional system formed under environmental conditions that match the properties of a system under investigation as closely as possible, with the principal aim to aid in the interpretation of the case study data. Although the use of thoroughly studied analogues to advance the knowledge of less well-known deep-marine systems is appealing, particularly when applied carefully (e.g. Smith & Møller 2003), the analogy method suffers from some disadvantages of its own. First, systems at outcrop rarely serve as good analogues to each other, suggesting they may not necessarily serve as appropriate analogues for subsurface systems. Secondly, it is vital that the reference system is established as a proper analogue for the case study at an early stage, in order to minimize the danger of biased interpretations. In other words, the systems should be similar in terms of at least part of the controlling parameters given in Figure 1. Unfortunately, the choice of reference system is often poorly justified, which strongly devalues the application of the analogy concept in its present form.

There is an urgent need for a method of describing and classifying deep-marine depositional systems that integrates existing knowledge into present and future case studies in a reliable and well-founded manner, whilst retaining the advantages of classification schemes and analogy concepts. The present paper proposes such a method through the application of a knowledge base of deep-marine clastic depositional systems. The knowledge base, referred to as the Deep-Water Architecture Knowledge Base (DWAKB), consists of a large compilation of sedimentological records from peer-reviewed literature sources, which can be used to compare the properties of natural depositional systems and to construct architectural models based on any chosen set of controlling parameters. Statistical methods can be applied at any stage to analyse both input and output parameters. Below, the rationale for building the DWAKB, the type of data it contains and the way in which data storage is structured, is described. Thereafter, examples demonstrating the potential value of the knowledge base for the study of deep-marine sedimentary systems are provided.

DEEP-WATER ARCHITECTURE KNOWLEDGE BASE

Basics

The DWAKB is primarily a structured set of architectural and environmental information derived from peer-reviewed publications of modern and ancient, surface and subsurface, deep-marine clastic depositional systems. In addition to the number and basic dimensions of architectural elements, the DWAKB stores information on spatial transitions between architectural elements, distribution of bed thickness within the elements, and the relative percentages of mud, silt, sand and gravel (Table 1). The strengths of the knowledge base are the wide range of depositional systems it captures, the comprehensive number of data records for each depositional system, the organization of the records which allows for easy comparison and detailed quantitative analysis, and the flexibility it offers to update existing records and add new datasets. In the present version,

Table 1. *Data categories included in the Deep-Water Architecture Knowledge Base*

Data category	Form	Predefined classes	Description
Citation	SI,AE,AD, VT,DT,LT		Unique citation of research paper (primary key)
Reference	SI		Full reference to research paper
Year	SI		Year of publication
Basin	SI		Name of basin
Formation	SI		Name of formation or depositional system
Location	SI		Geographical location
Age	SI		Age (or age range) of depositional system
Basin Type	SI		Type of sedimentary basin and degree of confinement
Sediment	SI	mud-rich, mixed mud–sand, sand-rich, mixed sand–gravel, gravel-rich, other	Grain size of available sediment (cf. Reading & Richards 1994)
Supply System	SI	single point source, multiple point source, line source, other	Type of feeder system (after Reading & Richards 1994)
Method	SI	Lithology, Gamma Ray, V_{shale}, Seismic, Acoustic, Other	Method(s) used to obtain data described in paper
Status	SI	Read, Copy, Scanned, Digitized	Administrative information
Comments	SI,AE,AD, VT,DT,LT		Memo field for additional information
Type of architectural element	AE,VT, LT,DT	See text	Most common architectural elements (predefined)
Other – Type	AE		Up to ten additional architectural elements
Nr.	AE		Number of architectural elements. 0=architectural element not present (explicitly mentioned in paper)
DQI	AE	0,1,2,3	Data Quality Index. 0=no index value defined (default); 1=low quality; 2=moderate quality; 3=high quality
Type of architectural element	AD	See text	Predefined and new architectural elements
Architectural Element Size – X	AD	Mean, Minimum (=Min), Maximum (=Max)	Size of architectural element measured parallel to main flow direction (in metres)
Architectural Element Size – Y	AD	Mean, Minimum (=Min), Maximum (=Max)	Size of architectural element measured perpendicular to main flow direction (in metres)
Architectural Element Size – Z	AD	Mean, Minimum (=Min), Maximum (=Max)	Thickness of architectural element (in metres)
Sand/Gravel Bed Thickness – Unspecified	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Relative percentage and thickness distribution (in metres) of sand/gravel beds with unknown clay content
Sand/Gravel Bed Thickness – <15% Clay	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Relative percentage and thickness distribution (in metres) of sand/gravel beds with <15% clay ('clean' sand)
Sand/Gravel Bed Thickness – 15–40% Clay	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Relative percentage and thickness distribution (in metres) of sand/gravel beds with 15–40% clay ('impure' sand)
Fines/Other Bed Thickness – Silt	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Relative percentage and thickness distribution (in metres) of silt beds
Fines/Other Bed Thickness – Clay	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Relative percentage and thickness distribution (in metres) of clay and mud beds
Fines/Other Bed Thickness – Other	AD	%, Mean, Minimum (=Min), Maximum (=Max), Standard deviation (St-Dev)	Type, relative percentage and thickness distribution (in metres) of other lithologies
Net:Gross	AD	Mean, Minimum (=Min), Maximum (=Max)	Ratio of net sand to gross lithology
Further work?	AD		Administrative information
Up/Down input fields	VT		Number of vertical transitions between predefined and additional architectural elements
Left/Right input fields	LT		Number of left- and right-lateral transitions (looking downdip) between predefined and additional architectural elements
Updip/Downdip input fields	DT		Number of updip and downdip transitions between predefined and additional architectural elements

SI, Source Information; AE, Architectural Elements; AD, Architectural Dimensions; VT,LT,DT, Vertical, Lateral, Dip Transitions

the DWAKB contained information on almost 100 depositional systems and more than 500 architectural elements within these systems. The depositional systems cover, amongst others, passive and active margin settings, recent and ancient submarine fans, ramps and aprons, and a wide range of sediment sizes. The DWAKB is implemented as a relational database management system, enabling a user readily to filter out datasets relevant to a particular case study, as shown schematically in Figure 2. In addition, this structure allows for straightforward updating and expansion of the knowledge base.

Rationale

The main rationale for building the DWAKB was to provide a data resource for the scientific community and the hydrocarbon industry that uses the wealth of existing knowledge on deep-marine clastic depositional systems more effectively than classification schemes and the analogy concept, thus overcoming the drawbacks of those methods described above. In contrast to classification schemes, the DWAKB is not limited in the number of recognized controlling parameters, because it does not predefine 'standard' models of deep-marine systems. In

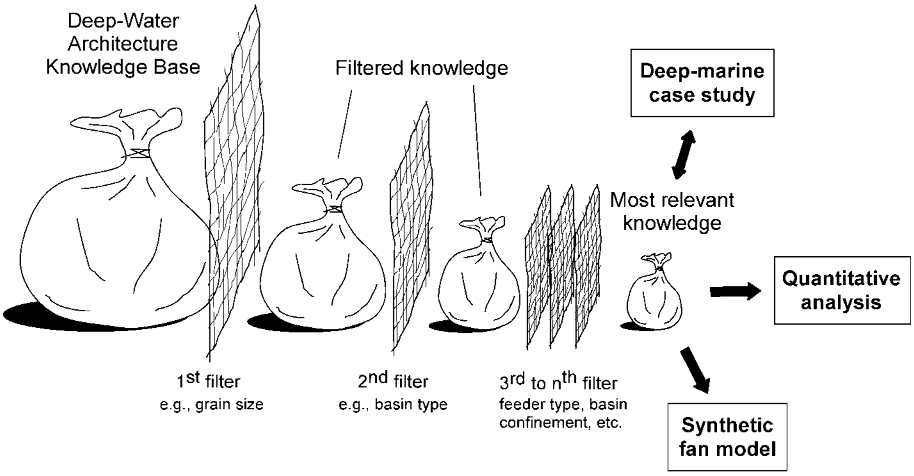

Fig. 2. Cartoon exemplifying how the Deep-Water Architecture Knowledge Base can be used in the analysis of deep-water clastic depositional systems. Multiple data filters permit the most relevant knowledge to be extracted. This knowledge may then be used in comparative studies of deep-water systems (as alternative to 'analogue concepts'), in building synthetic fan models (as alternative to classification schemes) and in conducting various kinds of quantitative analyses.

fact, a model built with knowledge base data should be based on as many controlling parameters as possible, tailored, of course, to the knowledge available for the system to which the model is considered analogous. This approach should also reduce the risk of biased interpretations. Moreover, the DWAKB does not have a limited life span, provided that it is updated regularly. Analogues can be selected more objectively than with existing methods, not only because information is conveniently available at a single location, but also because statistical information can be used to warrant the particular choice. Finally, the DWAKB permits integration of large-scale architectural data with bed-scale and facies-scale data.

Implementation

The DWAKB uses a Microsoft® Access relational database to store all the literature data. The data are organized in different subject areas, implemented as *tables* and *forms* in Microsoft® Access. Each subject area (or table, or form) contains a pre-defined set of data categories, called *fields* in database terminology. Each field corresponds to a unique type of data, e.g. the type of basin in which the deep-marine system occurs or the mean thickness of levees in that system. Tables are related by means of citation fields, each of which identifies one unique literature source or several closely related sources, usually by the same author(s). In order to maintain objectivity, the DWAKB merely contains data and interpretations provided by the author(s) of the publications. Thus, data are not changed in any way during population of the database. However, it is possible to evaluate the quality of the data from within the knowledge base, and so increase its longevity, through assignment of data quality indices, ranging from 0 to 3 (see below).

The DWAKB has six main forms, which represent the following subject areas:

- SOURCE INFORMATION. This form summarizes basic information on the literature source, the name, location and age of the depositional system, basin type, grain size of available sediment, sediment feeder type and data collection method.
- ARCHITECTURAL ELEMENTS. This form provides an overview of the type and number of architectural elements found in a depositional system. Input fields for the most common architectural elements are provided, but it is also possible to define up to ten additional element types. A data quality index value can be assigned to each architectural element to specify how accurately it has been recognized.
- ARCHITECTURAL DIMENSIONS. Quantitative information on the size of architectural elements, and the thickness and relative percentage of beds of various lithology within those elements are shown on this form.
- VERTICAL TRANSITIONS. In order to describe the internal architecture of a deep-marine system, it is necessary to know how the architectural elements are organized in space. This form provides a matrix of the number of transitions between architectural elements in stratigraphically upward and downward directions.
- DIP TRANSITIONS. This form provides information on the number of transitions between architectural elements in a direction parallel to the main sediment transport path.
- LATERAL TRANSITIONS. This form comprises a matrix for right- and left-lateral transitions between architectural elements.

Data categories

Table 1 shows the data categories available in the latest version of the DWAKB. Each data category is accompanied by the form(s) it appears on, the data format (predominantly text or numeric) and a short description of the type of information it represents. Several data categories have pre-selected classes, which are listed in Table 1 as well. The pre-selected classes of the SEDIMENT and SUPPLY SYSTEM fields are essentially identical to those defined by Reading & Richards (1994). On the ARCHITECTURAL DIMENSIONS form, the size distribution of architectural elements and the thickness distribution of sediment beds within these elements are characterized by descriptive statistics, i.e. minimum, maximum, mean and standard deviation. More detailed statistical information can be obtained from the papers that provide sedimentary logs or correlation panels with sufficiently high resolution to recognize individual sediment beds. Well logs provide an additional wealth of input data for constraining the statistics. A selected number of logs and panels have been digitized as part of the present project.

In order to facilitate data analysis, the most common architectural elements within deep-water clastic systems are provided on the ARCHITECTURAL ELEMENTS form and the various TRANSITIONS forms. The first-order subdivision of architectural elements includes channels, lobes, levees, background and mass flows. The second-order subdivision was inspired by the classification scheme for architectural elements proposed by Stow (1985). In the DWAKB, the channel class is divided into proximal channels, mid-fan channels and distal distributary channels. The distinction between proximal and mid-fan channels is based on their position along the main transport path of the sediment gravity flows that formed the depositional system. Proximal channels and canyons are most frequent on continental slopes, hence at relatively steep slope gradients, while mid-fan channels extend from the base of slope basinward. Many submarine fans comprise distributary channel patterns in distal locations, often closely associated with depositional lobes. This subclass includes small, metre-scale distributary channels or gullies. Levees are subdivided into proximal and distal levees, according to their distance laterally away from the channel. The lobe subclasses are main lobe and lobe fringe. Lobe fringes cover both distal and lateral fringes. The background class denotes relatively fine-grained deposits, subdivided into interchannel and interlobe deposits, and open slope and basin plain deposits. Each class of architectural elements has an 'Unspecified' subclass, to allow for literature records without subdivison into subclasses. The mass flow class covers predominantly debris flow complexes, slumps and slides.

Apart from the pre-selected architectural elements, there are up to ten input fields for additional architectural elements. The prevailing additional architectural elements in the DWAKB are sheet deposits and associated intersheet deposits (i.e. equivalent to interlobes and interchannels). Occasionally, sheets have been subdivided into muddy and sandy sheets or proximal and distal sheets. They may occur at the mouth of channels, form extensive channel overbank deposits, or be unrelated to other architectural elements, such as in ponded basins.

The correct identification of architectural elements is crucial to the analysis of deep-water depositional systems. Diagnostic criteria have been available since the early recognition of submarine fans, and new criteria are developed in conjunction with the ever-advancing knowledge base of deep-marine systems. Certain architectural reconstructions, however, are based on more evidence than others, and are therefore more reliable. Moreover, criteria that are considered diagnostic at one time may prove controversial later. For example, the idea that thickening-upward sequences are typical of lobe deposits was popular some decades ago, but is now considered too simplistic. Provisions have been made in the DWAKB to evaluate the varying quality and timeliness of architectural interpretations. Each architectural element on the ARCHITECTURAL ELEMENTS form is assigned a Data Quality Index (DQI) value, ranging from 0 to 3. The default is DQI=0, which means that no index value has been given. A value of 1 refers to an architectural element that was defined using weakly founded criteria or no criteria at all. Data records that support the architectural interpretation moderately well are given an index value of 2. Architectural elements are assigned DQI=3, if the data fully support the interpretation, and are thus based on a reliable set of diagnostic criteria. The allocation of index values is based on present-day knowledge of the shape and internal organization of architectural elements. Because this knowledge is changing continuously, the DQI category should be considered flexible, i.e. regular tuning of the DQI values to new architectural information should be undertaken. Allocation and tuning of DQI values is a specialist sedimentological task, so it is the only data category that may have some inherent subjectivity. The structure of the knowledge base allows each user to decide whether to use the existing DQI values, modify them or discard them altogether. Importantly, all other data categories should remain unchanged in order to ascertain that the knowledge base is an objective representation of the literature.

KNOWLEDGE BASE APPLICATIONS

The DWAKB data can be analysed in various ways. Synthetic deep-water systems can be constructed based on predefined sets of controlling parameters. In a similar way, analogue systems may be chosen directly from the natural systems included in the knowledge base. Such choices should rely at least in part on quantitative information and they should be justified statistically. Mathematical methods can also be used to analyse the size and internal organization of architectural elements and to conduct risk analysis of spatial transitions between architectural elements. It is possible, for instance, to predict which architectural elements are most likely to border a known element in downdip and lateral directions, which is particularly important in determining quality variation of hydrocarbon reservoirs. Further examples of DWAKB applications include investigating the reliability of existing classification schemes, contrasting unconfined basins with partially confined and ponded basins, and determining if modern fans are good proxies for ancient fans. There is also scope to identify topics that need more attention in future deep-water research. DWAKB applications need not be restricted to sedimentological problems. Indeed, the initial objective in building the knowledge base was to generate submarine fan models for fault seal analysis in deep-marine reservoir modelling.

The value of the DWAKB in the analysis of deep-marine clastic depositional systems is demonstrated below by means of three examples. In the first example, the frequency of occurrence of levees is compared for depositional systems of contrasting grain size. In the second example, submarine channel depth and width are analysed as a function of grain size and channel subclass. In the third example, synthetic, idealized models for sand-rich and mixed mud–sand systems are constructed and probabilities of spatial transitions between architectural elements within those systems are investigated.

Channel levees versus grain size

Submarine channels are often separated from interchannel deposits and other background facies by levees. The levees may attain considerable positive relief, particularly in depositional channels (e.g. Clark & Pickering 1996). Yet, there is also some evidence that levees are more common and larger in muddy systems than in sandy systems (e.g. Galloway 1998, fig. 1). This is explained by differences in settling velocity, which render muddy turbidity currents more likely to flow overbank than sandy equivalents. However, detailed studies focusing on the relationship between the occurrence of levees and grain size of deep-water clastic systems are lacking. The DWAKB is well suited for helping to define this relationship, if it is assumed that the depositional systems contained within the knowledge base are a statistically significant sample of the total population of natural systems. Figure 3a shows the number of deep-water systems in the knowledge base that contain levees relative to the total number of systems in mud-rich, mixed mud–sand, sand-rich and gravel-rich environments. The average number of levees for each type of system is shown in Figure 3b. The following procedure was used to extract the data:

1. depositional systems without channels were discarded. This filter reduced the number of systems from 70 to 59;
2. these systems were then subdivided into four groups according to grain size of available sediment (i.e. following the SEDIMENT data category in Table 1);
3. for each group of systems the relative percentage of systems that contain leveed channels was determined. These data are represented by the dashed line in Figure 3a;
4. subsequently, levee percentages were recalculated using only DQI-values greater than 1, so as to filter out controversial data. This reduced the number of systems to 51. The results are given by the continuous curve in Figure 3a;

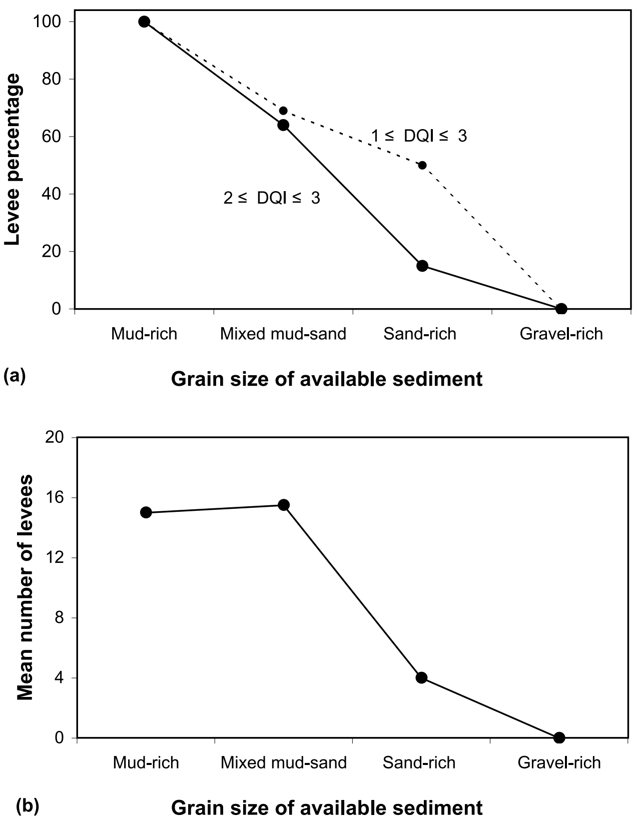

Fig. 3. (**a**) Levee percentage as a function of grain size of available sediment for different DQI ranges. (**b**) Mean number of levees as a function of grain size.

5. finally, the average number of levees per group of systems was calculated from the filtered data and plotted in Figure 3b.

The data shown in Figure 3 confirm that levees are more frequent in fine-grained than in coarse-grained deep-water systems. All the mud-rich systems contain leveed channels. In progressively coarser-grained systems, the percentage of systems with levees gradually decreases until it reaches zero in the gravel-rich systems. Possible misinterpreted levees are most abundant in the sand-rich systems, as shown by the reduction of levee percentage from 50% for $1 \leq \mathrm{DQI} \leq 3$ to 19% for $2 \leq \mathrm{DQI} \leq 3$. Mixed mud–sand systems appear halfway between their end-member systems in terms of levee frequency (Fig. 3a). However, the average number of levees in the mixed mud–sand systems is more typical of mud-rich than of sand-rich end-member systems (Fig. 3b). It is therefore tempting to conclude that levees, when present, are as common in mixed systems as in mud-rich systems. Caution is required, however, because available literature on mud-rich and mixed mud–sand systems is skewed towards marine geological studies of (sub-)recent systems, which usually yield a greater number of architectural elements than outcrop studies of ancient, mostly sand-rich systems. This illustrates the potential of the DWAKB to aid the recognition of the limits of our knowledge of deep-water clastic systems, and thus the identification of important areas of future research.

Channel size versus channel subclass and grain size

Intuitively, the size of channels should be thought to decrease along the transport path of sediment gravity flows in clastic deep-water systems. Furthermore, since fine-grained systems generally are considered to be larger in size than coarse-grained systems (e.g. Reading & Richards 1994), it may be assumed that the size of channels follows the same trend. Figure 4 plots dimensional information from the DWAKB that permits these hypotheses to be examined quantitatively. Minimum, mean and maximum channel widths and depths are plotted as a function of grain size of available sediment (see SEDIMENT data category in Table 1) and channel subclass (i.e. proximal, mid-fan and distributary channels) in Figures 4a and b, respectively. There was no need to filter out low quality data, because practically all channels for which dimensions are available have DQI values larger than one.

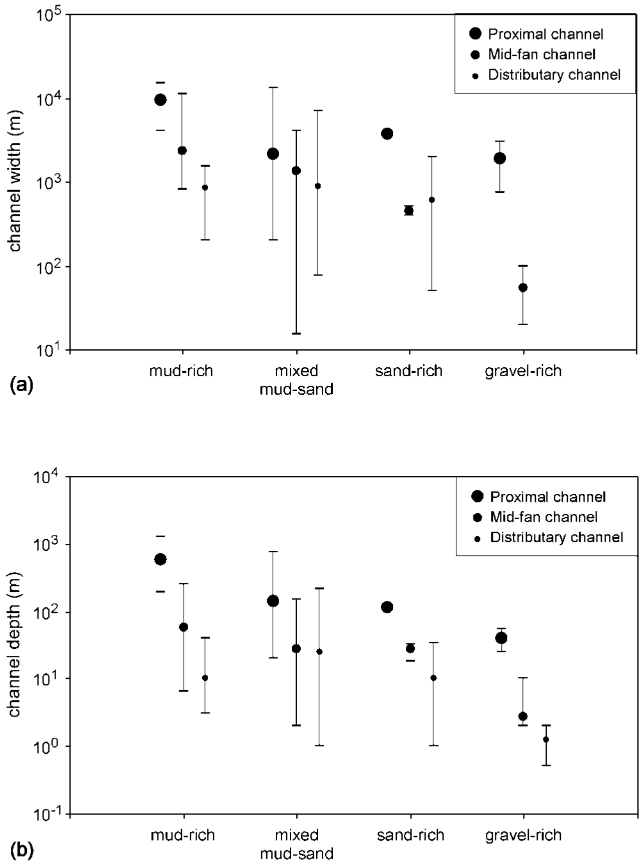

Fig. 4. (**a**) Channel width and (**b**) channel depth as a function of grain size of available sediment and channel subtype. Dots denote mean values, vertical lines connect minimum and maximum widths and depths. Note logarithmic scale of vertical axes.

It is immediately evident from Figure 4 that channel widths and depths are highly variable, both amongst and within data categories. Differences of several orders of magnitude within a single channel subclass are no exception, which is probably due to diffusion by controlling parameters not incorporated in this example, such as size and proximity of the source area and sediment supply rate. Despite the variability, there is a clear tendency for mean channel width and depth to decrease with increasing distance from the source area. A similar trend, although less pronounced, is apparent for grain size, with channels in mud-rich systems being up to 40 times wider and up to 20 times deeper than in gravel-rich systems. The fact that more data are available for channel depth (or channel fill thickness in ancient systems) than for channel width may at least partly explain why the above trends are better constrained for channel depth than for channel width. Alternatively, there may be yet unknown sedimentological reasons why channel width is more variable than channel depth. Also worthy of note

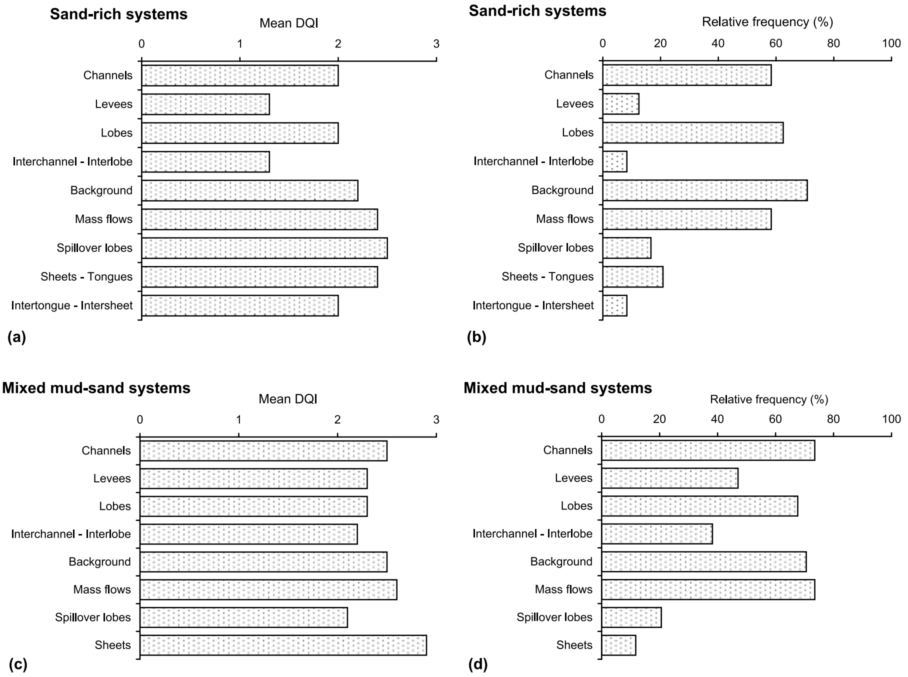

Fig. 5. Bar graphs showing mean DQI values and relative frequencies of different types of architectural elements in (**a**, **b**) sand-rich systems and (**c**, **d**) mixed mud–sand systems. Relative frequency denotes the ratio of the number of depositional systems that contain a particular architectural element to the total number of systems at the given grain size.

is the observation that the variations in channel size are largest for the mixed mud–sand systems, with the range in channel width and depth roughly overlapping that of both the mud-rich and sand-rich systems. This suggests, together with the levee frequency data presented earlier, that the mixed systems have properties in common with both the sand-rich and mud-rich systems, rather than comprising a unique type of system, as proposed by Reading & Richards (1994). Further conclusive evidence is needed, however. Although part of this can be extracted from the DWAKB, such a study is beyond the scope of the present paper.

Synthetic sand-rich and mixed mud–sand depositional systems

In this final example, the DWAKB is used to construct synthetic, idealized sand-rich and mixed mud–sand depositional systems, based on investigations of the most common architectural elements and their spatial transitions in those systems. The main objective is to describe a method that makes more effective use of existing knowledge of deep-marine clastic systems than hitherto. Figures 5 to 9 show the results, derived by means of a number of steps.

1. The initial step was to filter the DWAKB for sand-rich and mixed mud–sand systems. Sand-rich systems have overall net:gross ratios of 70% or greater, while net:gross ratios of mixed mud–sand system are between 30% and 70% (*sensu*-Reading & Richards 1994). Grain size is the only filter in this example. This effectively means that grain size control on the morphology and internal organization of the submarine systems is separated from that of all other controlling parameters. Hence, it is possible to verify how great the influence of grain size on system architecture variability really is (cf. Mutti 1979; Stow *et al.* 1985).
2. Subsequently, mean DQI values were calculated for each type of architectural element and for each grain size in order to assess data quality (Figs 5a, c).
3. After discarding all architectural elements with DQI=0 and DQI=1, the number of systems from which a particular type of architectural element has been reported is divided by the total number of systems in the same grain-size class. This is repeated for all architectural elements, eventually providing a reasonable measure of the relative frequency of each type of architectural element in the sand-rich and mixed mud–sand systems (Figs 5b, d). Yet, it should be noted that the calculated frequencies for, in particular, fine-grained architectural elements (e.g. background facies) may be slightly too low, because coarse-grained architectural elements (e.g. channels and lobes) tend to attract more attention in the literature. Moreover, relatively new architectural elements, such as spillover lobes and sheets, have lower frequency, simply because they have not yet been described many times.
4. The next step was to find the most common spatial transitions between architectural elements from the TRANSITIONS forms. This was done by first determining for each architectural element the relative frequency of transitions to other architectural elements in all six principal directions, then extracting the transitions with highest frequency. For example, distributary channels in sand-rich systems were found stratigraphically above other architectural elements in 23 cases. In three cases the channels overlie lobe fringe, basin plain, interchannel/lobe or other distributary channel deposits. In eight cases they overlie main lobe deposits. The upward transition from main lobe to distributary channel is therefore classified as most common (with 35% probability), while transitions to the other elements are considered subordinate (with 13% probability).
5. Finally, the transitions with highest probability were used to build the architectural frameworks shown in Figures 6 and 7 for sand-rich systems and in Figures 8 and 9 for mixed mud–sand systems, thus assuming that these transitions jointly determine the dominant three-dimensional architecture of these systems. The figures include numerical information on transition probabilities next to the lines that connect the architectural elements.

Description of sand-rich systems The synthetic sand-rich systems are dominated by channels, lobes, background deposits and mass flows (Fig. 5b), all with mean DQI values of 2 or greater (Fig. 5a). The channel class comprises proximal channels, mid-fan

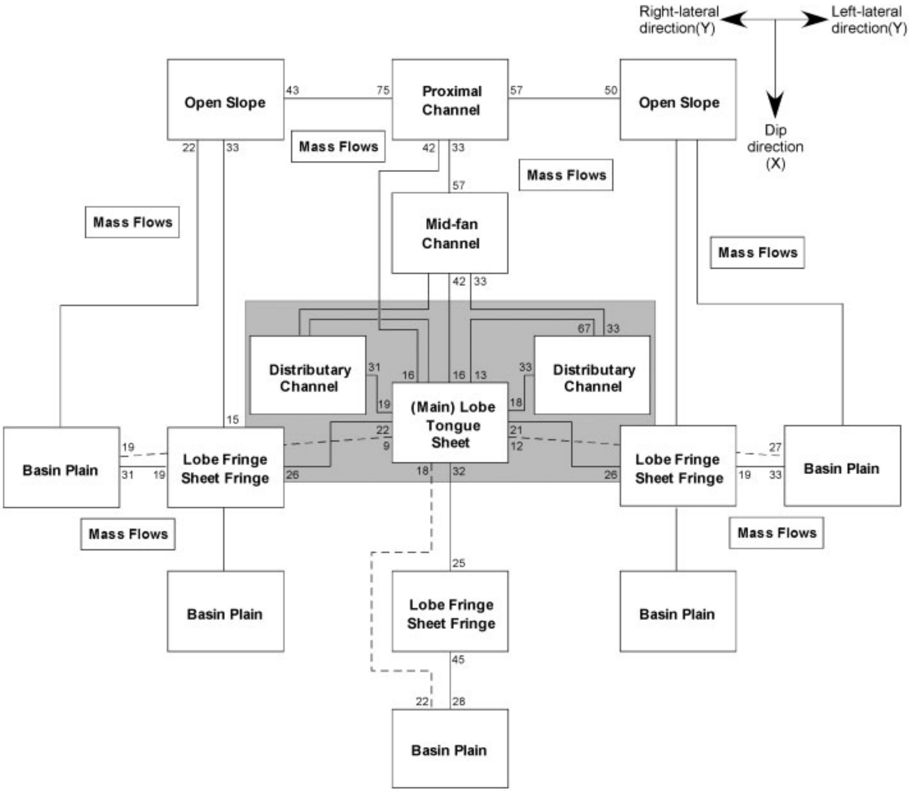

Fig. 6. Most common transitions between architectural elements in lateral and dip directions in a synthetic, idealized sand-rich depositional system. Numbers indicate probabilities of transitions in percentages. For example, the probability of finding a proximal channel updip from a known mid-fan channel is 57% and, conversely, there is a 33% chance of finding a mid-fan channel downdip from a known proximal channel. Dashed lines denote subordinate transitions. Each architectural transition is labelled only once, hence transitions without number are the same as identical transitions elsewhere in the diagram. The grey box signifies channellized lobes, with complex horizontal transitions between lobes and distributary channels. Note the general absence of levees and interchannel and interlobe deposits.

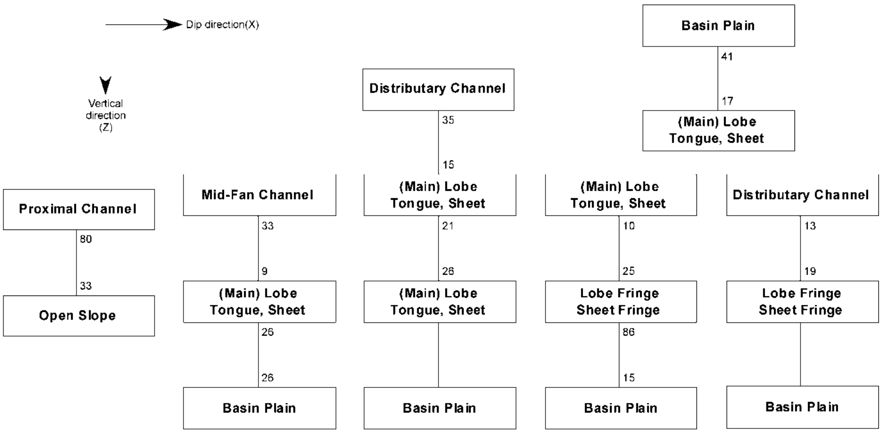

Fig. 7. Most common transitions between architectural elements in vertical and dip directions in a synthetic, idealized sand-rich depositional system. See Figure 6 for explanation of numbers.

channels and distributary channels, but distributary channels are most common. The background class includes open slope and basin plain facies. Relative frequencies of levee, interchannel and interlobe deposits are low (Fig. 5b). This is due to the high number of controversial interpretations, as shown by the low mean DQI values (Fig. 5a). Channel spillover lobes (e.g. Grecula *et al.* 2003; Lien *et al.* 2003), sheets (e.g. Sinclair 2000; Johnson *et al.* 2001), tongues (Satur *et al.* 2000) and associated intersheets and intertongues are the latest architectural elements reported from sand-rich clastic systems. The detailed descriptions of these elements from well-exposed sedimentary successions warrant high mean DQI values (Fig. 5a). At present, however, the number of studies is insufficient to determine if spillover and sheet facies are more characteristic of sand-rich depositional systems than levee and lobe facies.

Figures 6 and 7 show the idealized sand-rich depositional system in plan view (i.e. XY-plane) and in vertical cross-section parallel to the dip direction (i.e. XZ-plane), respectively. In both figures, lobe deposits form a group together with sheets and tongues, and fringe facies include both lobe and sheet fringes. The most common transitions in the dip direction are open slope deposits to lobe fringe and basin plain deposits, and proximal channels to an area with complex planar organization of distributary channel and main lobe facies (grey box in Fig. 6), either directly or via mid-fan channels. The interspersed distributary channels and lobes mostly represent channellized lobes. This is confirmed by the characteristic vertical stacking pattern of these architectural elements (Fig. 7). Main lobe deposits grade primarily into basin plain deposits via lobe fringe deposits, both downcurrent and towards the lateral fringes. Direct transitions from main lobe to basin plain are of secondary importance (dashed line in Fig. 6). Further lateral transitions are between proximal channels and open slope deposits, and between distributary channels and main lobe facies. Both these transitions confirm the above DWAKB-derived observation that levees are rare in sand-rich systems. Mass flows occur everywhere in the system, constituting on average 20% of the total number of transitions. Yet, mass flow

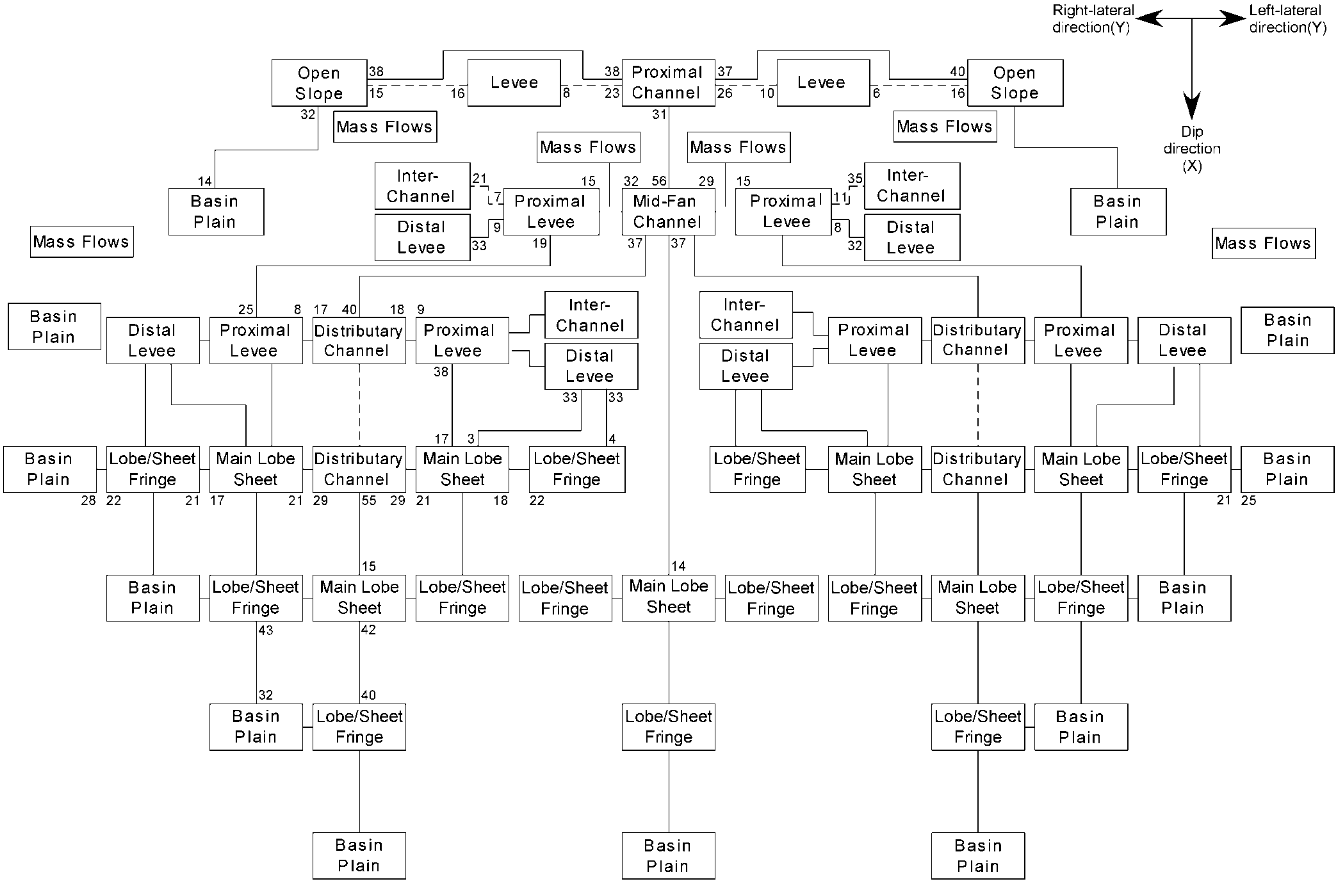

Fig. 8. Most common transitions between architectural elements in lateral and dip directions in a synthetic, idealized mixed mud–sand depositional system. Note the greater complexity in comparison with the synthetic sand-rich system (Fig. 6). See Figure 6 and text for further explanation.

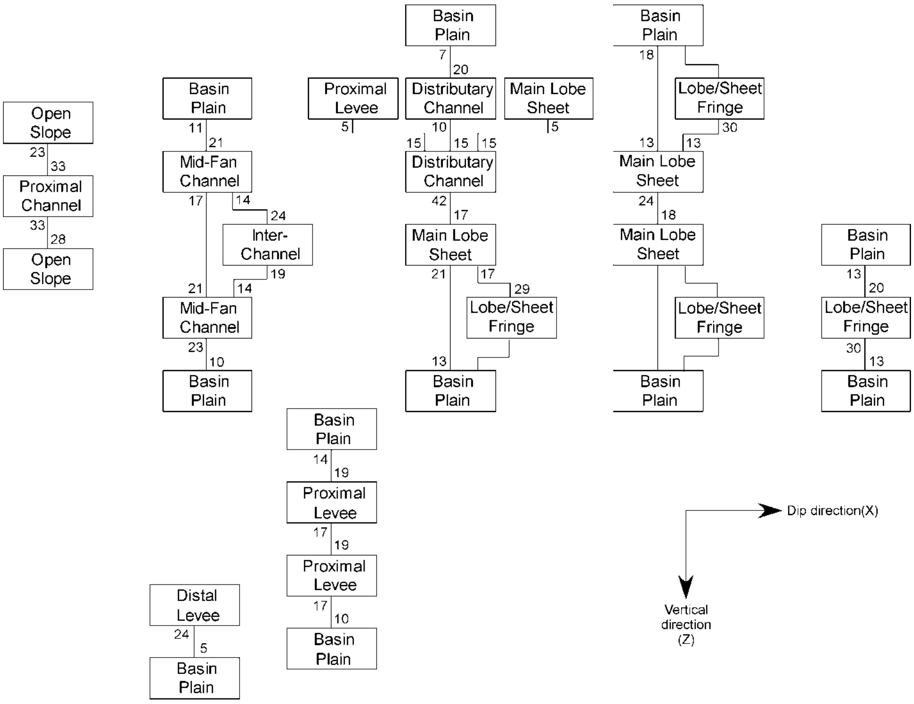

Fig. 9. Most common transitions between architectural elements in vertical and dip directions in a synthetic, idealized mixed mud–sand depositional system. See Figure 6 and text for further explanation.

facies border proximal architectural elements more frequently than distal architectural elements. The assemblage of vertical transitions shown in Figure 7 has some characteristics of a submarine fan prograding over basin plain deposits. Most commonly, mid-fan channels overlie main lobe deposits, and lobe fringe deposits are found below main lobe and distributary channel deposits. Moreover, proximal channels dominantly overlie open slope facies and most basin plain deposits form on top of main lobe deposits.

Generally speaking, the transitions between architectural elements in the synthetic sand-rich system are accurate to around 20% or more. Some exceptionally low probabilities are present in the channellized lobe region (Fig. 6) and in some vertical successions (Fig. 7). Nevertheless, the overall mean probability is about 30%. This effectively means that the chance of correctly predicting the most common transition between two architectural elements is about one in three, on average.

Description of mixed mud–sand systems In common with the sand-rich system, the synthetic mixed mud–sand deep-water system is dominated by channels, lobes, background deposits and mass flow deposits (Figs 5c, d). In contrast with that system, however, interchannel and interlobe deposits and, in particular, levees play a significant architectural role, with DQI>2 (Fig. 5c) and relative frequencies of around 40% (Fig. 5d). Spillover lobes (e.g. Normark *et al.* 1998; Posamentier & Kolla 2003) and sheets (Kneller & McCaffrey 1999; Haughton 2001; Felletti 2002) have been recognized in mixed systems as well, but again their relative frequency may be anomalously low due to lack of data.

Figures 8 and 9 show a synthetic mixed mud–sand system in plan view and in longitudinal cross-section, respectively. The larger number of architectural elements renders the mixed system more complex than the sand-rich system. The most common downdip transitions through the centre of the system comprise proximal channel via mid-fan channel to multiple distributary channels, two of which are shown in Figure 8, or directly from mid-fan channel to lobe facies. Mid-fan channels and relatively proximal distributary channels are bounded by levees, divisible into proximal and distal levees. Interchannel deposits regularly separate the leveed distributary channels. Levees may be present adjacent to proximal channels, but lateral transitions to open slope deposits are more common. The middle part of the mixed system comprising distributary channels and lobes is less compact than in the sand-rich system. Leveed distributary channels evolve downdip into distributary channels without levees (thus directly bordering main lobes), which in turn give way to terminal lobe deposits. Main lobes are transitional laterally and downdip to lobe fringe deposits, then to basin plain deposits. Off centre, proximal levees adjoin main lobe deposits and distal levees border either main lobe or lobe fringe deposits in a downdip direction (Fig. 8). Mass flow deposits mainly occur in proximal regions, in particular on the open slope, the base of slope and near the edges of mid-fan and proximal channels. Their mean contribution to the total population of architectural transitions is about 17%.

Vertical transitions in mixed mud–sand systems are highly variable (Fig. 9). Yet, several dominant trends can be recognized. Open slope and basin plain deposits most commonly surround proximal and mid-fan channels, respectively. Mid-fan channels can also be stacked on top of each other or they can be separated by interchannel deposits. In the middle part of the mixed system, distributary channels frequently cut into main lobe deposits and they are preferably overlain by basin plain deposits or other distributary channels. Proximal and distal levees are most often associated with basin plain deposits, while main lobe deposits are intercalated with various types of architectural elements, including basin plain, distributary channel and lobe fringe facies. Finally, lobe fringe deposits are most commonly found between main lobe or basin plain facies.

The bulk mean transition probability in the synthetic mixed mud–sand system is about 20%, and maximum probability rarely exceeds 40%. This confirms the high architectural complexity in comparison with the sand-rich system. Horizontal transitions tend to have higher probabilities than vertical transitions. The chance of correctly predicting the most common transition between two architectural elements in the mixed mud–sand system is thus about one in five on average.

Discussion The method of building synthetic deep-marine clastic systems presented above is objective and well founded, because it integrates a comprehensive set of literature-derived architectural information of natural systems. Hence, the method illustrates clearly how the DWAKB may benefit both academic- and hydrocarbon industry-related analysis of deep-marine sedimentary environments. From an industrial point of view, the synthetic systems, and the transition probabilities on which their architecture is based, may prove particularly useful in the development of 3D reservoir modelling software. The merit of the DWAKB relies heavily on the amount of architectural data it contains. Evidently, the present version of the knowledge base contains sufficient information to construct realistic synthetic submarine fans at one level. However, continuous addition of new architectural data, including comprehensive 3D datasets available to the hydrocarbon industry, will increase the value of the DWAKB even further.

The synthetic sand-rich and mixed mud–sand systems presented in Figures 6–9 should be regarded as 'common denominator' natural system types within the same grain-size range. Although very useful for showing capabilities of the DWAKB, it should be borne in mind that grain size is just one of many controlling parameters. In other words, the 'average' set of architectural properties derived from the DWAKB-data and depicted in Figures 6–9 is likely to be representative of only few natural systems. For example, the synthetic models presented make no distinction between unconfined, partly confined and ponded basins. Therefore, DWAKB-derived information demonstrating that lobes and sheets are particularly abundant in partly confined and ponded basins is not reflected in the synthetic models. The exclusion of degree of basin confinement as control on system architecture, in addition to many other parameters (Fig. 1), may at least in part explain the low probabilities of architectural transitions in these particular synthetic sand-rich and mixed mud–sand systems. Transition probabilities are expected to increase through the application of additional data filters, provided that a statistically significant number of reference systems remains after filtering. This is the subject of ongoing work by the authors.

Despite the above limitations, the objective, statistics-driven approach used to construct the sand-rich and mixed mud–sand systems yields realistic results. Both systems have predictable arrangement of most architectural elements. In general agreement with existing models, the synthetic sand-rich system lacks levees. Furthermore, mid-fan channels are absent or confined in length (i.e. of the order of 5 km for sand-rich systems versus 30 km for mixed mud–sand systems), implying rapid deposition near the base of slope, and distributary channels are intimately linked to depositional lobes, suggesting rapid channel switching on a 'suprafan'-type lobe (Normark 1970, 1978). The properties of the synthetic mixed mud–sand system differ from those of the sand-rich system, but along the lines of existing models as well. As expected, the mixed system has abundant levees, especially in proximal and middle regions, discrete separation of architectural elements along the entire length of the system, implying a predominance of efficient flow types, and mass flow deposits mainly in areas with high bed slope gradients.

The fact that the above modelling exercise yields viable results, in spite of its simple approach, not only inspires confidence that the information contained within DWAKB is a proper representation of natural deep-water depositional systems, but also shows that grain size plays a major part in controlling the morphology and internal organization of such systems. The importance of sediment type has been recognized before, and it is reflected in existing classification schemes (e.g. Mutti 1979; Stow *et al.* 1985; Reading 1991), but the innovative character of the present work should be sought in its quantitative approach and statistical justification. Further synthetic modelling with the knowledge base data could be used to isolate other control parameters, such as degree of basin confinement, number and distribution of sediment input points, tectonic setting and hinterland climate. In this way, the relative importance of each parameter in controlling architectural variability can be determined. The parameters that impose the greatest influence on system architecture may then be used to revise classification schemes. Alternatively, classification schemes may be abandoned altogether to make way for architectural analysis of deep-water systems using analogues derived through the use of DWAKB filters, thus based on objectively justifiable criteria.

CONCLUSIONS

The collation of information on deep-marine clastic systems and its classification within a relational database management system represents a new approach in the study of such systems. The approach allows the relative importance of a range of controlling parameters on system architecture to be evaluated objectively. Conversely, given increasing knowledge of the nature of the controls and the depositional setting, the nature and significance of architectural elements together with the spatial transition probabilities between elements within a system can be predicted with increasing accuracy. The DWAKB should therefore find application in elucidating the controls on deep-marine clastic system architecture, in highlighting areas that warrant further research and in building stochastic or combined deterministic-stochastic reservoir models of such systems. The knowledge base is designed to accommodate further information as it becomes available. Therefore, it is anticipated that the application of the DWAKB will become more sophisticated as it expands, to provide an increasingly viable, well-founded alternative to existing classification schemes or analogue system-based approaches to the study of deep-marine clastic systems.

This work is part of the LINK project 'Fault Seal Processes and Trap Development in Deep Marine Reservoirs', jointly sponsored by Chevron-Texaco and the National Environment Research Council of the United Kingdom (grant number: NER/T/S/2000/01009). The authors are grateful to Bruce Levell, Joe MacQuaker, Ru Smith and journal Editor, John Parker, for constructive comments on an earlier version of this paper. The DWAKB is available from http://earth.leeds.ac.uk/~jhbaas.

REFERENCES

Chan, M.A., Dott, Jr. & R, H. 1983. Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon – fan or non-fan?. *AAPG Bulletin,* **67**, 2100–2116.

Clark, J.D. & Pickering, K.T. 1996. *Submarine Channels: Processes & Architecture.* Vallis Press, London.

Cronin, B.T. & Kidd, R.B. 1998. Heterogeneity and lithotype distribution in ancient deep-sea canyons; Point Lobos deep-sea canyon as a reservoir analogue. *Sedimentary Geology,* **115**, 315–349.

Felletti, F. 2002. Complex bedding geometries and facies associations of the turbiditic fill of a confined basin in a transpressive setting (Castagnola Fm, Tertiary Piedmont Basin, Italy). *Sedimentology,* **49**, 645–667.

Galloway, W.E. 1998. Siliciclastic slope and base-of-slope depositional systems: component facies, stratigraphic architecture, and classification. *AAPG Bulletin,* **82**, 569–595.

Grecula, M., Flint, S., Potts, G., Wickens, D. & Johnson, S. 2003. Partial ponding of turbidite systems in a basin with subtle growth-fold topography: Laingsburg-Karoo, South Africa. *Journal of Sedimentary Research,* **73**, 603–620.

Haughton, P. 2001. Contained turbidites used to track sea bed deformation and basin migration, Sorbas Basin, south east Spain. *Basin Research,* **13**, 117–139.

Heller, P.L. & Dickinson, W.R. 1985. Submarine ramp facies model for delta-fed, sand-rich turbidite systems. *AAPG Bulletin,* **69**, 960–976.

Hurst, A., Verstralen, I., Cronin, B. & Hartley, A. 1999. Sand-rich fairways in deep-water clastic reservoirs: genetic units, capturing uncertainty, and, a new approach to reservoir. *AAPG Bulletin,* **83**, 1096–1118.

Hurst, A., Cronin, B. & Hartley, A. 2000. Reservoir modelling sand-rich deep-water clastics: the necessity of down-scaling. *Petroleum Geoscience,* **6**, 67–76.

Johnson, S.D., Flint, S., Hinds, D. & De Ville Wickens, H. 2001. Anatomy, geometry and sequence stratigraphy of basin floor to slope turbidite systems, Tanqua Karoo, South Africa. *Sedimentology,* **48**, 987–1023.

Kneller, B. & McCaffrey, W. 1999. Depositional effects of flow nonuniformity and stratification within turbidity currents approaching a bounding slope: deflection, reflection, and facies variation. *Journal of Sedimentary Research,* **69**, 980–991.

Lien, T., Walker, R.G. & Martinsen, O.J. 2003. Turbidites in the Upper Carboniferous Ross Formation, western Ireland: reconstruction of a channel and spillover system. *Sedimentology,* **50**, 113–148.

MacDonald, D.I.M. 1986. Proximal to distal sedimentological variation in a linear turbidite trough: implications for the fan model. *Sedimentology,* **33**, 243–259.

Martinsen, O.J., Lien, T., Gjelberg, J., Loseth, T.M. & Soegaard, K. 2003. Deep-water sedimentation in some circum-Atlantic basins: controls and comparisons. *AAPG Annual Meeting, Salt Lake City, Utah.* AAPG, Tulsa, OK, A114.

Mutti, E. 1979. Turbidites et cones sous-marins profonds. *In:* Homewood, P. (ed.) *Sedimentation Détritiques (Fluviatile, Littoral et Marine).* Institut de Géologie, Université de Fribourg, Switzerland, 353–419.

Mutti, E. 1985. Turbidite systems and their relations to depositional sequences. *In:* Zuffa, G.G. (ed.) *Provenance of Arenites.* NATO-ASI Series. Reidel Publishing Company, Dordrecht, 65–93.

Mutti, E. & Ricci Lucchi, F. 1972. Le torbiditi dell'Appennino settentrionale: introduzione all'analisi di facies. *Memorie della Societa Geologia Italiana,* **11**, 161–199.

Mutti, E., Tinterri, R., Remacha, E., Mavilla, N., Angella, S. & Fava, L. 1999. *An Introduction to the Analysis of Ancient Turbidite Basins from an Outcrop Perspective.* AAPG Continuing Education Course Note Series, **39**.

Normark, W.R. 1970. Growth patterns of deeps-sea fans. *AAPG Bulletin,* **54**, 2170–2195.

Normark, W.R. 1978. Fan valleys, channels, and depositional lobs on modern submarine fans: characters for recognition of sandy turbidite environments. *AAPG Bulletin,* **62**, 912–931.

Normark, W.R., Piper, D.J.W. & Hiscott, R.N. 1998. Sea level controls on the textural characteristics and depositional architecture of the Hueneme and associated submarine fan systems, Santa Monica Basin, California. *Sedimentology,* **45**, 53–70.

Pickering, K.T., Hiscott, R.N. & Hein, F.J. 1989. *Deep Marine Environments: Clastic Sedimentation and Tectonics.* Unwin Hyman, London.

Posamentier, H.W. & Kolla, V. 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research,* **73**, 367–388.

Posamentier, H.W., Erskine, R.D. & Mitchum, R.M. 1991. Models for submarine fan deposition within a sequence stratigraphic framework. *In:* Weimer, P. & Link, M.H. (eds) *Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems.* Springer-Verlag, Berlin, 127–136.

Reading, H.G. 1991. The classification of deep-sea depositional systems by sediment calibre and feeder system. *Journal of the Geological Society, London,* **148**, 427–430.

Reading, H.G. & Richards, M. 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *AAPG Bulletin,* **78**, 792–822.

Richards, M. & Bowman, M. 1998. Submarine-fan systems II: variability in reservoir architecture and wireline log character. *Marine & Petroleum Geology,* **15**, 821–839.

Richards, M., Bowman, M. & Reading, H. 1998. Submarine-fan systems I: characterization and stratigraphic prediction. *Marine & Petroleum Geology,* **15**, 689–717.

Robertson, E., Corbett, P.W.M., Hurst, A., Satur, N. & Cronin, B.T. 2002. Synthetic well test modelling in a high net-to-gross outcrop system for turbidite reservoir description. *Petroleum Geoscience,* **8**, 19–30.

Satur, N., Hurst, A., Cronin, B.T., Kelling, G. & Gürbüz, K. 2000. Sand body geometry in a sand-rich, deep-water clastic system, Miocene Cingöz Formation of southern Turkey. *Marine & Petroleum Geology,* **17**, 239–252.

Schuppers, J.D. 1993. Quantification of turbidite facies in a reservoir-analogous submarine-fan channel sandbody, south-central Pyrenees, Spain. *In:* Flint, S.S. & Bryant, I.D. (eds) *The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues.* International Association of Sedimentologists, Special Publications, **15**, 99–111.

Shanmugam, G. & Moiola, R.J. 1988. Submarine fans: characteristics, models, classification, and reservoir potential. *Earth-Science Reviews,* **24**, 383–428.

Sinclair, H.D. 1992. Turbidite sedimentation during Alpine thrusting: the Taveyannaz sandstones of eastern Switzerland. *Sedimentology,* **39**, 837–856.

Sinclair, H.D. 2000. Delta-fed turbidites infilling topographically complex basins: a new depositional model for the Annot Sandstones, SE France. *Journal of Sedimentary Research,* **70**, 504–519.

Smith, R. & Møller, N. 2003. Sedimentology and reservoir modelling of the Ormen Lange field, mid Norway. *Marine and Petroleum Geology,* **20**, 601–613.

Stow, D.A.V. 1985. Deep-sea clastics: where are we and where are we going? *In:* Brenchley, P.J. & Williams, B.J.P. (eds) *Sedimentology: Recent Developments and Applied Aspects.* Geological Society, London, Special Publications, **18**, 67–93.

Stow, D.A.V., Howell, D.G. & Nelson, C.H. 1985. Sedimentary, tectonic, and sea-level controls. *In:* Bouma, A.H., Normark, W.R. & Barnes, N.E. (eds) *Submarine Fans and Related Turbidite Systems.* Frontiers in Sedimentary Geology. Springer-Verlag, New York, 15–22.

Stow, D.A.V., Reading, H.G. & Collinson, J.D. 1996. Deep seas. *In:* Reading, H.G. (ed.) *Sedimentary Environments: Processes, Facies and Stratigraphy* 3rd edn. Blackwell Science, Oxford, 395–453.

Surlyk, F. 1987. Slope and deep shelf gully sandstones, Upper Jurassic, East Greenland. *AAPG Bulletin,* **71**, 464–475.

Walker, R.G. 1978. Deep-water sandstone facies and ancient submarine fans: models for exploration for stratigraphic traps. *AAPG Bulletin,* **62**, 932–966.

Walker, R.G. 1980. Modern and ancient submarine fans: reply. *AAPG Bulletin,* **64**, 1101–1108.

Walker, R.G. 1984. *Facies Models.* Geoscience Canada Reprint Series, **1**.

Walker, R.G. & Mutti, E. 1973. Turbidite facies and facies associations. *In:* Middleton, G.V. & Bouma, A.H. (eds) *Turbidites and Deep-Water Sedimentation.* SEPM Pacific Section Short Course Notes, 119–157.

Wynn, R.B., Masson, D.G., Stow, D.A.V. & Weaver, P.P.E. 2000. The Northwest African slope apron; a modern analogue for deep-water systems with complex seafloor topography. *Marine & Petroleum Geology,* **17**, 253–265.

Received 3 November 2004; revised typescript accepted 21 February 2005.