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Deep-water sedimentary systems: New models for the 21st century

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Abstract

One of the principal scientific, technical and environmental challenges for the next century is undoubtedly the exploration and understanding of the deep oceans. Close collaboration between the hydrocarbon industry and scientific community is allowing us to push back this frontier and so to develop new models for deep-water sedimentary systems. The turbidity current paradigm is under scrutiny and refinements proposed for massive sands, megabeds and immature turbidites. Source area and sediment type are key controls. Bottom currents play an important part in the shaping of margins, the generation of hiatuses and bounding surfaces, the winnowing of sands and ventilation of ocean basins. It is at the level of architectural elements and their three-dimensional geometry that much activity is currently focused. Most advance has so far been made in terms of channel types, dimensions, aspect ratios, stacking patterns and hierarchies; to a lesser extent this is true for lobes, levee complexes, contourite drifts and sheet sands. It is only after this phase of study that we will be able to significantly improve our models for the larger-scale systems—fans, ramps, slope-aprons, basin plains and drifts. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

This paper is intended as a short introduction to an important thematic set published in *Marine and Petroleum Geology* (Vol. 17, 2000) that arose from a special symposium at the biennial Geological Society (London) conference, *Geoscience 98*, held in Keele (UK) in April 1998. Rather than simply list the papers with brief commentaries on each, we attempt to highlight what we consider some of the most significant developments in deep-water research today. In so doing, we draw extensively on the papers published in this volume, as well as those presented at the meeting but not published herein (abstracts and/or other publications are listed as appropriate).

We also provide a selective and eclectic overview of some of the most important models and concepts that will guide research and its application to deep-water oil exploration and production as we move into the next century. Clearly, this is in the view of the authors, who fully acknowledge that the deep water is a fast-moving field and one still full of differences in opinion and controversy. However, the past two or three years have seen a number of such meetings and symposia devoted to deep-water research and exploration (for example, in Leeds, Aberdeen, Houston, Almeria, Trondheim, Birmingham), and at many of these the same key topics and models have been expounded. As far as possible, we have restricted referencing to those papers published herein (2000) or in the abstract volume for *Geoscience 98* (1998). More extensive reference to relevant work can be found in those papers.

2. Oil in deep water: state of play

An estimated 1200 to 1300 oil and gas fields, including discoveries and producing fields, are known from deep-water turbidite and related systems (Fig. 1). The uncertainty in this figure derives from a relative lack

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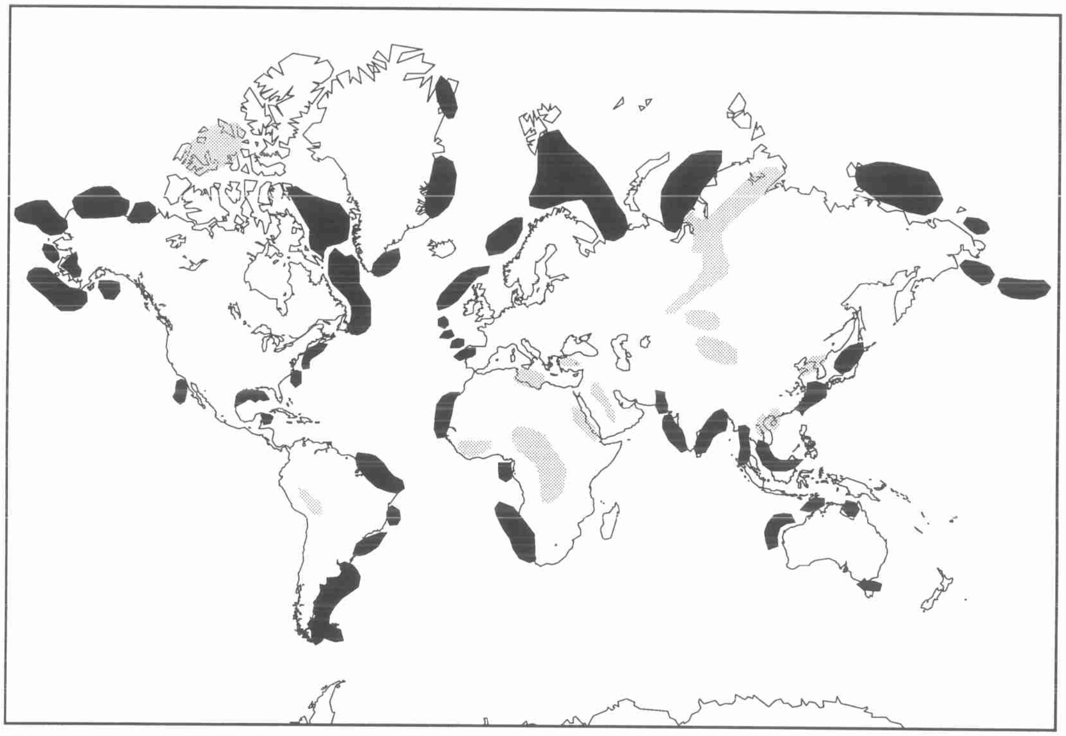

Fig. 1. World map showing principal frontier areas for hydrocarbon exploration, including the main deep-water provinces (in black).

of publicly available data from Russia, the former USSR and China. Pettingill (1998) documented 925 of these fields (excluding carbonate plays) from 54 basins, of which 43 could be classified as giants (>500 million barrels oil equivalent). Many of these turbidite fields are from well-established provinces such as California, the North Sea and Gulf of Bohai, that presently lie beneath the continent or below shallow shelf waters. The early giants were almost all from convergent/obliquely convergent margin basins, whereas the later ones are dominantly from divergent margins, including the Gulf of Mexico, Campos, Niger Delta, Lower Congo/Angola, and west of Shetlands. Currently undeveloped giants lie in remote areas of the MacKenzie Delta, the Margarita Basin off Venezuela and on the NW Shelf of Australia.

The discovery and development of all sizes of turbidite fields has shown a sharp increase over the past 20–30 years and the trend looks set to continue. Established provinces with known good source rock capacity are the most favoured basins for future exploration.

3. Facies and processes: new models, new directions

3.1. Turbidites, debrites and megabeds

The turbidite paradigm is still dominant and turbidites are undoubtedly very common deep-water deposits. However, the paradigm is now 50 years old and everything from a 1 cm thick silt-laminated mudstone to a 50 m thick boulder–pebble–sand graded megabed has been called a turbidite. It is now well known that other processes and process combinations are important and, in some cases dominant, in the accumulation of sediments in deep water (Shanmugam, 2000). In particular, muddy and sandy debrites, as well as composite megabeds (slump-debrite-turbidite bipartite and tripartite units), are very common components of slope-apron systems (e.g. Armishaw, Stow & Holmes, 1989; Armishaw, Holmes & Stow, 2000; Reeder, Rothwell & Stow, 2000). The passage of large turbidity currents through channels or around local intra-basinal topography can destabilise flanking sediment and lead to debris flow emplacement within channel deposits (McCaffrey & Kneller, 1998). The interaction of turbidity currents with topography can also lead to flow reflection, deflection and separation and hence to complex sequences within the turbidite deposited (e.g. Al-Ja'aidi, McCaffrey & Kneller, 1998; Buckee, Kneller, Rothwell & Milana, 1998).

It is also important to acknowledge that the turbidity current which deposited the >20 m thick megaturbidite, with a total volume of around 400 km^3, across the entire Herodotus Basin plain in the SE Mediterranean (Reeder et al., 2000), is likely to have been very different from the flows that deposit thin-bedded fine-grained turbidites on, for example, the NW African

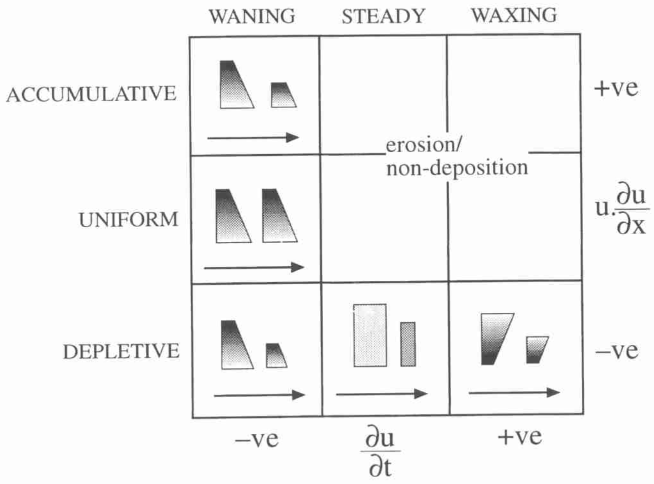

Fig. 2. Time-space (acceleration) matrix for turbidity currents. Changes in time are plotted horizontally and changes in space vertically. Theoretical grading of beds shown under different flow conditions, with downstream evolution of beds indicated by arrows. (From Kneller, 1995.)

margin (Wynn, Masson, Stow & Weaver, 2000) or the Amazon Fan channel levees (Damuth, 1998; Rimington, Cramp & Morton, 2000). However, these all appear to have been far travelled flows that had ignited into 'uniform' turbidity currents. Their distinction from short-lived surge-type flows that deposit immature turbidites and from longer-lived hyperpycnal flows is important for understanding both the process and geometry of the deposits.

Although significant advances have been made recently, improving our knowledge of flow properties and behaviour is still a lively research area. The Kneller (1995) time-space matrix for turbidity currents and their deposits is an important step forward for the paradigm, explaining many of the variations observed in turbidite deposits (Fig. 2).

3.2. Deep-water massive sands

Very thick bedded (> 1 m), essentially structureless sands are commonly important as a deep-water reservoir facies. Their origin has been a matter of much controversy over the past few years. In this volume, Shanmugam (2000) argues that they result almost entirely from sandy debris flows; Amy, Kneller and

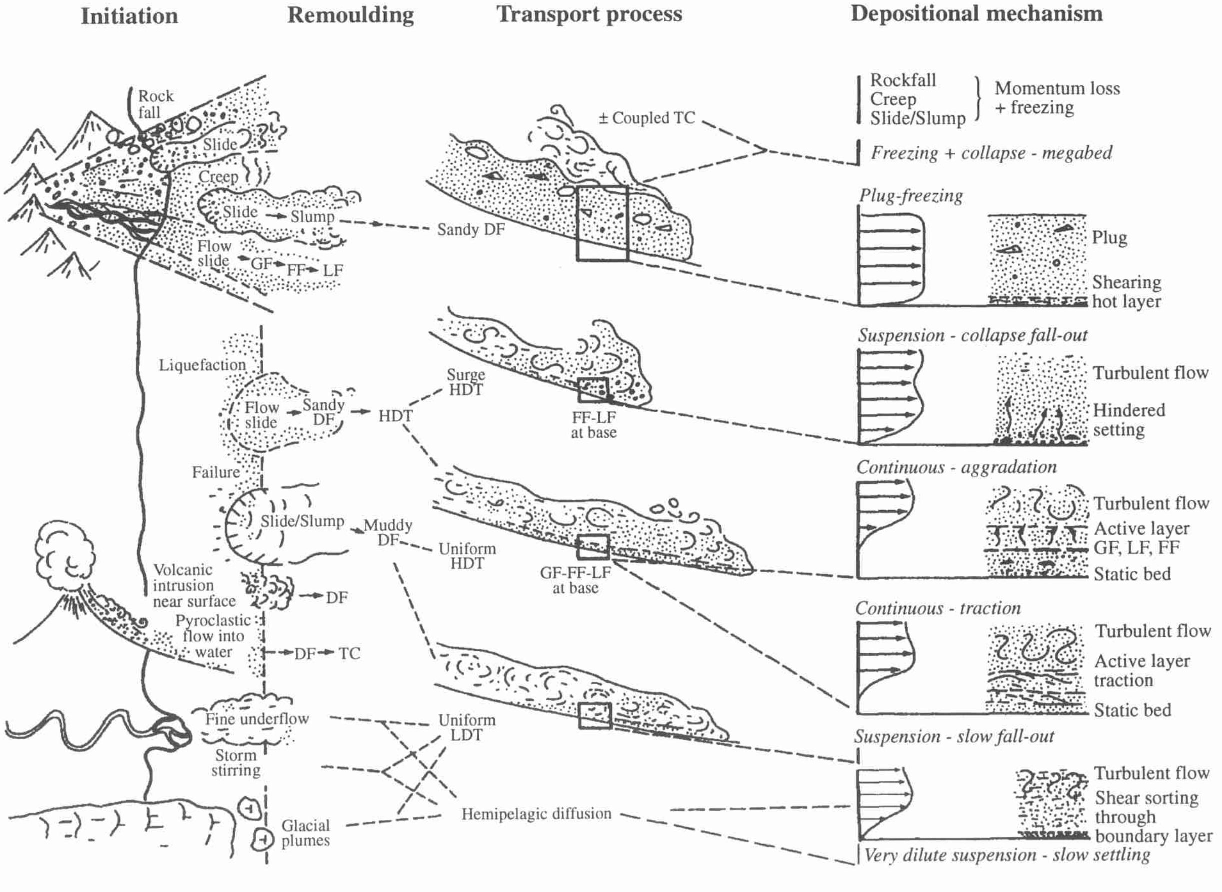

Fig. 3. Composite model for the initiation, remoulding, transport by and deposition from downslope gravity processes. (From Stow et al., 1996; Stow & Johansson, this issue.)

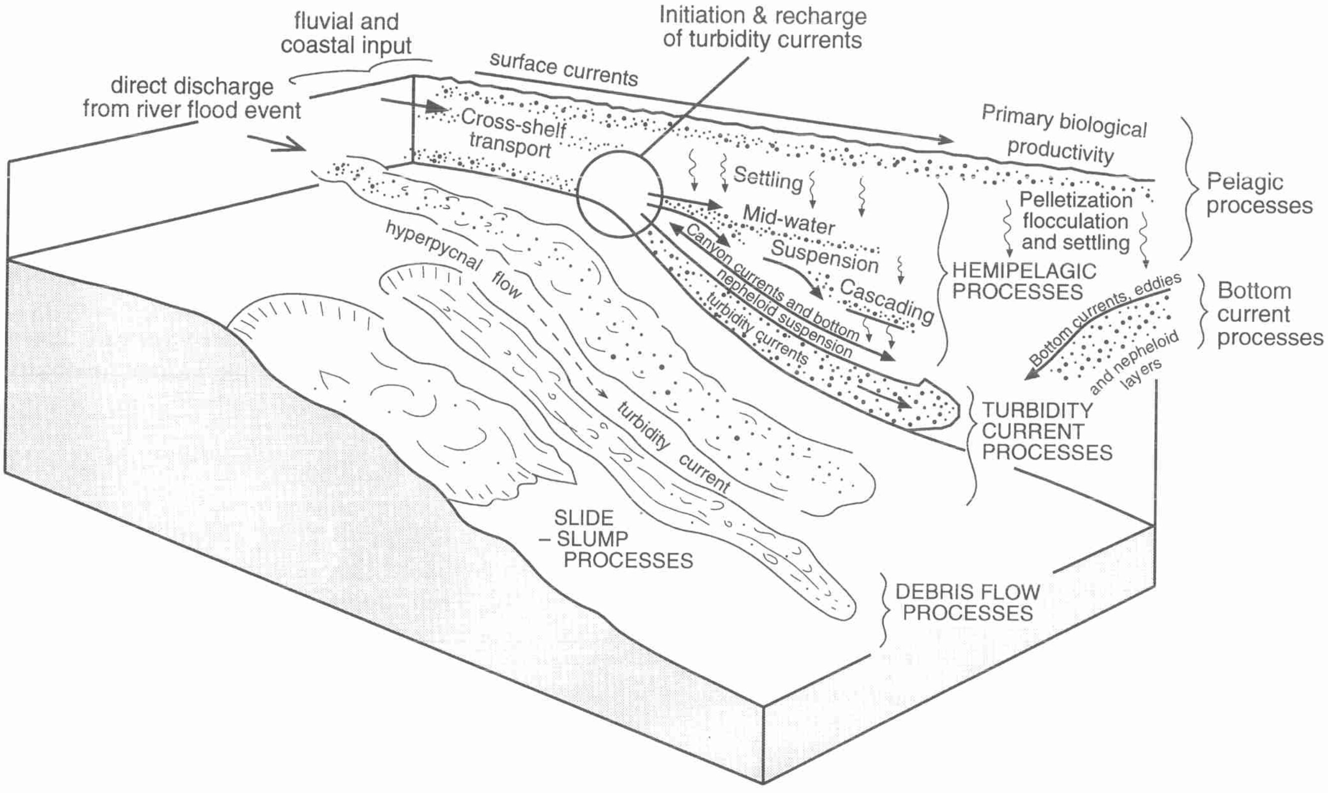

Fig. 4. Composite diagram illustrating the range of processes and their interaction that influence the transport and deposition of fine-grained sediments, in particular, in deep water.

McCaffrey (1998) believe that the 30 m thick sheet sands of the Tertiary Annot system at Peira Cava were deposited by surge-type turbidity currents; whereas Surlyk and Noe-Nygaard (1998) emphasise the importance of post-depositional diapirism and intrusion on such deposits in the Upper Jurassic Hareelv Formation of East Greenland, as well as in a number of equivalent North Sea reservoirs.

In their careful review of the deep-water massive sand problem, Stow and Johansson (2000) document results from some 70 examples worldwide, and conclude that the processes of flow initiation, transport and deposition are varied and complex (see Fig. 3). The massive sand bodies occur in four main geometries, including chutes/flow slides, channel ribbons, lobes/lenses and basin fill sheets. These occur at a variety of scales in fan deltas, slope and fan channels and lobes, and in restricted troughs or basins. The key controls on their occurrence are tectonic activity and clean sand supply, whereas sea-level is less critical (Johansson & Stow, 1998). Recent drilling on the Amazon Fan (Damuth, 1998) recovered probably modern analogues of such sands (in some cases in beds >10 m thick), as well as demonstrating the seismic facies of confined channel (High-Amplitude Reflectors) and laterally extensive interchannel sands (High-Amplitude Reflector Packages).

3.3. Contourites and bottom currents

The contourite paradigm is some 35 years old and it is now abundantly clear that bottom currents are very influential in shaping some continental margins, and that contourites are commonly found interbedded with turbidites. The range of processes that deposit and rework fine-grained sediments, in particular, are closely inter-related (Fig. 4). Based on data from numerous drill and core sites through distinct contourite drifts, the cyclic facies model from muddy to silty to sandy contourites and back, is well established (Stow, Reading & Collinson, 1996). This fluctuation in grain size, or in its various proxies, can be used to decode past changes in deep paleocirculation and hence paleoclimate. Current research is beginning to focus on sedimentation in oceanic gateways as a sensitive record of past bottom currents (e.g. Reeder, Stow & Rothwell, 1998; Howe & Pudsey, 1998).

Significant advances are now being made in the still controversial areas of: identifying fossil contourites in the ancient record on land (Stow, Faugeres, Viana &

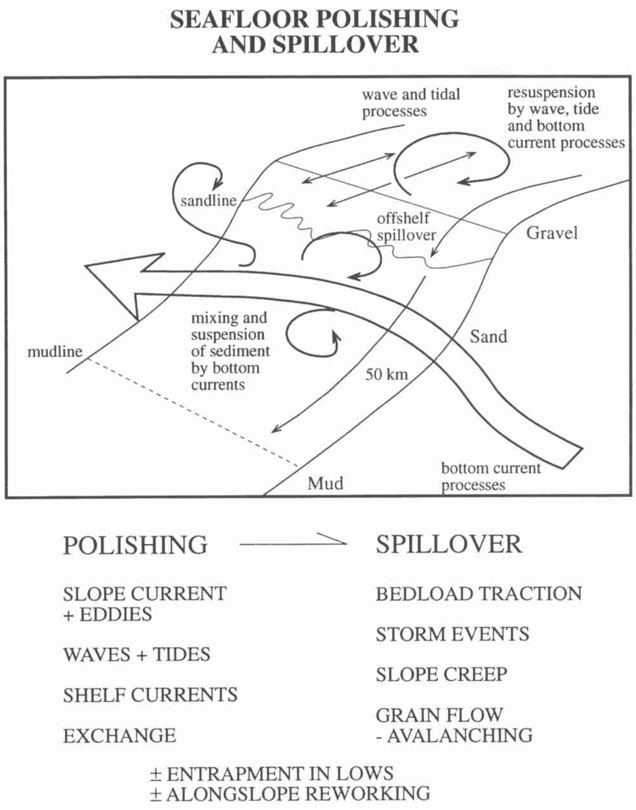

Fig. 5. Model for seafloor polishing and offshelf sand spillover under the influence of a variety of bottom current and downslope gravity processes. (From Stow, 1998; Armishaw et al., 1999.)

Gonthier, 1998); documenting the specific seismic characteristics that distinguish contourite from turbidite systems, particularly where they may have a similar mounded form and size in the subsurface (Faugeres, Stow, Imbert & Viana, 1998; Faugeres, Stow, Imbert, Viana & Wynn, 1999); and understanding the nature and occurrence of bottom-current reworked sands and sandy contourites, and their potential as reservoir targets (Armishaw et al., 2000). Stow (1998) shows that seafloor polishing in the outer shelf zone by a combination of tidal, wave, shelfal and slope currents can yield a clean sand source for supply into deeper water (Fig. 5). Offshelf spillover processes, topographic entrapment on the upper slope, and the alongslope reworking of sandy contourites can all yield potential non-turbidite reservoirs in slope settings (e.g. Viana, Faugeres & Stow, 1998).

3.4. Deep-water source rocks

Pelagic and hemipelagic sedimentation, and the enrichment of such background sediments in organic carbon, were topics not specifically addressed at the Keele meeting (apart from one paper by Bigg, Handoh, Inoue & Jones, 1998) and so not included in this thematic set. However, they are important areas of active research at present, and the occurrence of deep-water black shales is a crucial element in the search for turbidite plays. Some of the current thinking was summarised in a series of papers at the *Marges* meeting in Paris earlier this year (Huc, Bertrand, Stow, Gayet & Vandenbrencke, 2000; Stow, Huc & Bertrand, 2000) (see Fig. 6).

4. Architectural elements, hierarchies and geometries

4.1. Architectural elements

Some disillusionment with broad-brush environmental models of deep-water systems, coupled with ever more detailed seafloor mapping and subsurface seismic resolution, has led to recent attempts at characterising fundamental building blocks or architectural elements in the deep sea. Paradoxically, this has created more confusion, at least in the short term, as we struggle to agree on which elements are fundamental and what scale and hierarchy are most appropriate for their description (see Stow et al., 1996). The elements range from turbidite bed to turbidite complex (basin-fill scale), with the first-order element being either the largest or smallest, depending on which system is used. Some systems have used map-type features as elements, whereas others concentrate on packets of beds that might be logged in the field or in a borehole section.

However, for both outcrop studies and reservoir characterisation, it is clear that the element approach is the important one to follow, being ever mindful of the scale and stacking pattern of individual elements. Most of the papers in this volume exemplify such an approach. From the subsurface, Prather (1998) provides a careful analysis of ponded basin elements in Gulf of Mexico reservoirs; Wonham et al. (2000) present a detailed study of stacked channel-levee-sheet elements in erosional 'troughs' offshore West Africa; and Chapin (1998) demonstrates the application of element data from outcrop analogues to solving reservoir problems. The identification of turbidite elements and element complexes within modern systems is treated by Damuth (1998) for the Amazon fan, Talling, Lee and Ernst (1998) using quantitative geomorphic analysis of canyons, Wynn et al. (1998, 2000) for the NW African slope-apron, and Armishaw et al. (1998) for the elements of margin instability on the Rockall margin. Contourite systems and their elements are dealt with by Stoker and Stow (1998, Rockall), Howe and Pudsey (1998, Scotia Sea), Reeder et al. (1998, Sicily Gateway), and Faugeres et al. (1998, seismic elements). Finally, outcrop studies include those by Satur, Hurst, Cronin, Kelling and Gurbuz (2000) on

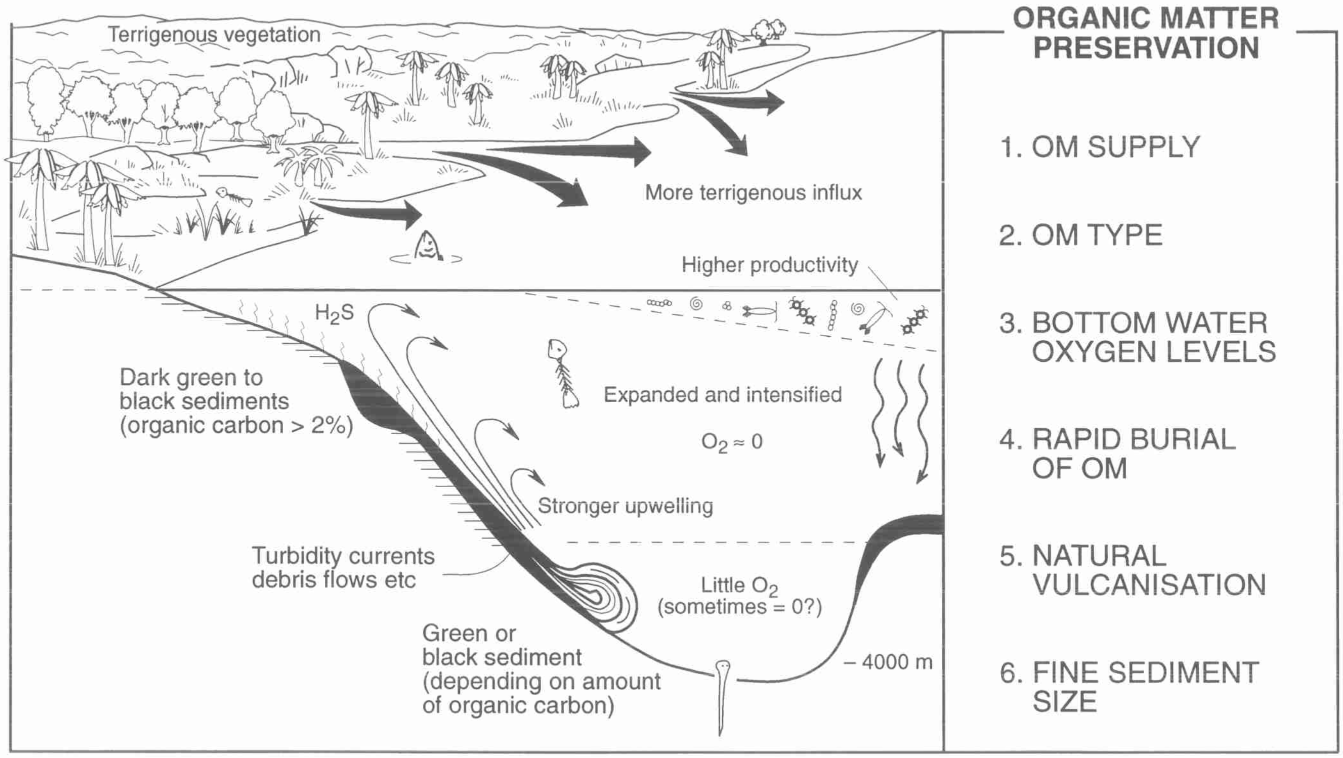

Fig. 6. Model for the interplay between organic matter (OM) supply — terrigenous, pelagic, resedimented — and its preservation in deep-water sediments. The factors that aid preservation (as listed) are influenced by climate, sea-level, oceanic circulation and basin physiography.

fan elements from southern Turkey, and Dade and Woodcock (1998) on vertical sequences in turbidite systems from the Welsh Silurian.

The architectural elements presently recognised include:

- Hiatuses, erosional plains, and other bounding surfaces.
- Erosional slide and slump scours.
- Canyons, troughs, channels and gullies.
- Channel levees and overbank deposits.
- Depositional lobes (isolated, clustered, splay).
- Irregular mounds (slide, slump and debrite masses).
- Contourite drifts (elongate mounded, irregular patch, contourite-fan).
- Sheets and drapes on slopes, basins, fans and drifts.
- Megaturbidites and other megabeds.
- Tectonic features (growth faults, diapirs, compressional fault mounds).

These elements are commonly a few hundred metres to several kilometres in width, a few metres to a few hundred metres in relief or thickness and may be irregular in outline, approximately equidimensional or markedly elongate. Each element may occur at a range of scales and within a hierarchy of similar features. The sedimentary composition, including facies associations and vertical sequences, that make up any one element, can vary, typically within a limited range. We summarise a working classification in Fig. 7. Key research at present is to better map these elements in present-day deep water, and to compare the images with those obtained from careful 3-D seismic analysis (e.g. seismic attribute mapping).

Table 1
Principal attributes of deep-water channels

Attribute	Typical range
Depth (m)	10–1000
Width (km)	0.1–50
Length (km)	10–3000
Depth/width (ratio)	1:4–1:50
Gradient (m/m)	< 1/1000–500/1000
Profile (longitudinal)	Smooth, abrupt, stepped
Cross-section	V-shape, u-shape, saucer-shape
Sinuosity	Straight, low–high sinuosity, meandering
Erosion/deposition	Erosive, mixed, depositional
Migration	Horizontal, oblique, vertical
Channel fill	
Sediment	Mud, sand, gravel
Process	Hemipelgite, turbidite, debrite, slump-slide
Geometry	Sheet (thin–thick), lens, ribbon, mound
Bedforms	
Erosive	Chevrons, flutes, steps, flat scour, thalweg
Depositional	Dunes, waves (regular–irregular)

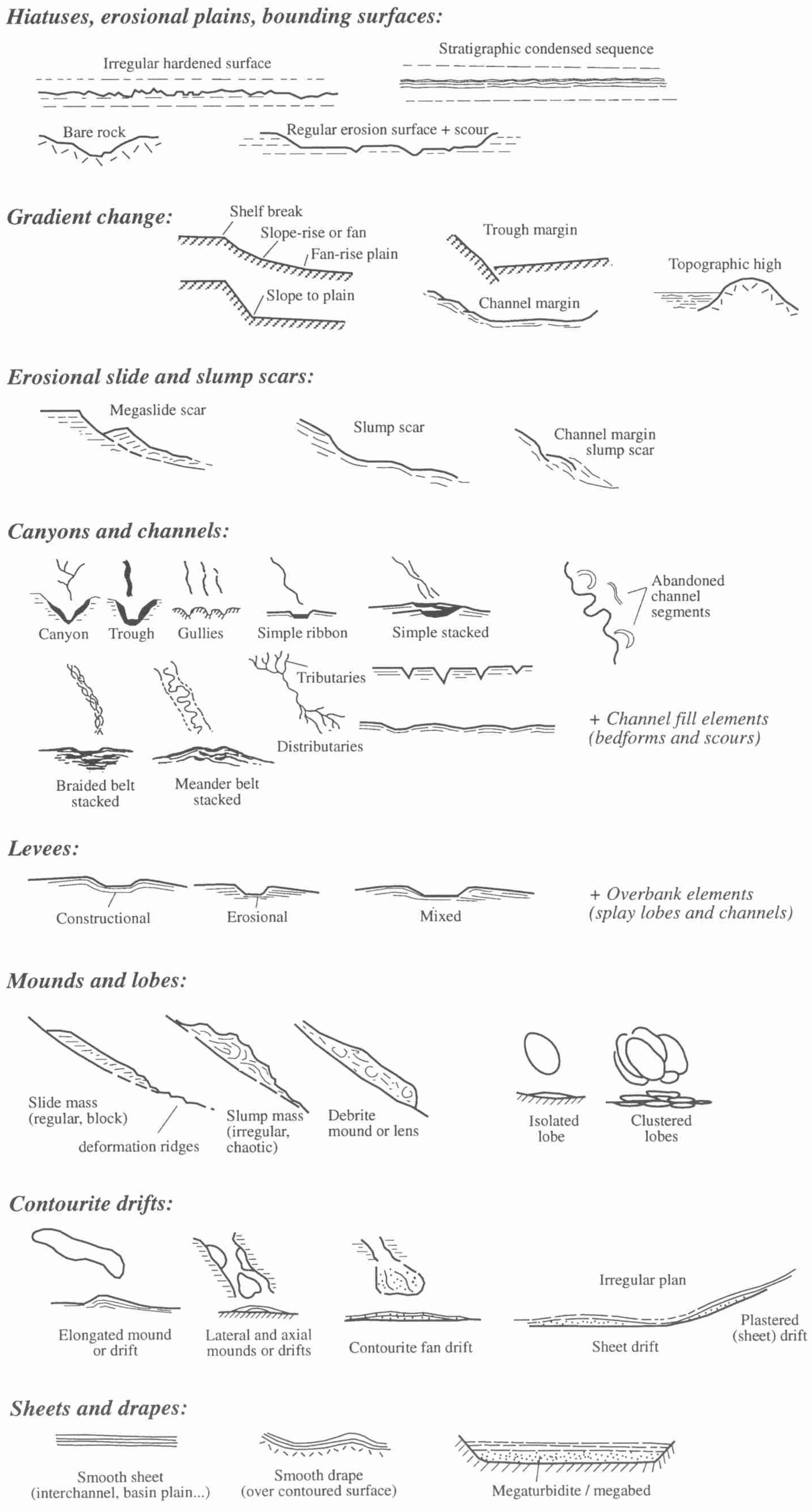

Fig. 7. The principal architectural elements in deep-water sedimentary systems.

4.2. Geometry and stacking

Critical to the full characterisation of architectural elements is documentation of both geometry and stacking patterns. Much work is still needed in this area but, because of their great importance as deep-water reservoir plays, our knowledge of channel systems is probably the most advanced — and so is used here by way of illustration.

The natural variability of channels (*sensu lato*) is enormous: they include steep-sided v-shaped canyons, deeply incised u-shaped delta-front troughs, simple straight to slightly sinuous slope gullies, braided to meandering channel complexes, shallow ephemeral high-gradient fan-delta channels, extremely low-gradient ocean basin channels, and so on. The key attributes that are important in characterising these different types of channel are shown in Table 1, together with the typical ranges for each attribute. Fig. 8 illustrates a simple cross-plot of channel width versus depth, and also some of the variety of channel types that populate this.

Important channel attributes that still need to be better defined include: lateral and vertical connectivity of specific fill elements, as well as between successive channel elements; proximal to distal evolution or variation of channel attributes; vertical sequences and stacking patterns of channel fill; and the nature of channel transition features (e.g. channel-levee, channel-lobe).

In fact, all data on channel attributes needs significant update and refinement so that we can define with greater rigour channel types and their variability, significant attribute ratios, and likely error bars. Several

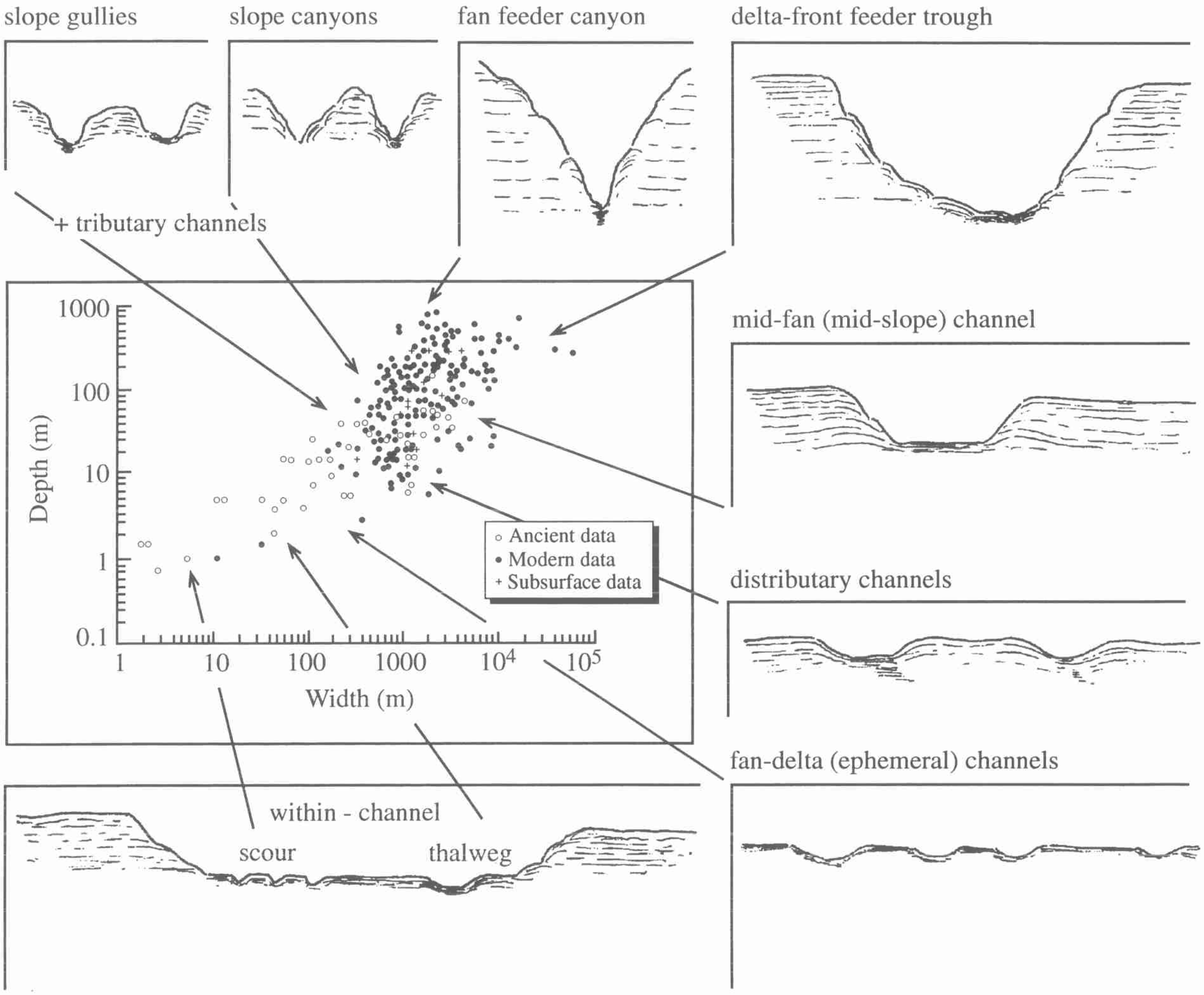

Fig. 8. Plot of depth vs width for a number of deep-water channels (from Pickering & Clark, 1996), with schematic representation of the types of channels that best fit different dimension fields on the depth/width plot.

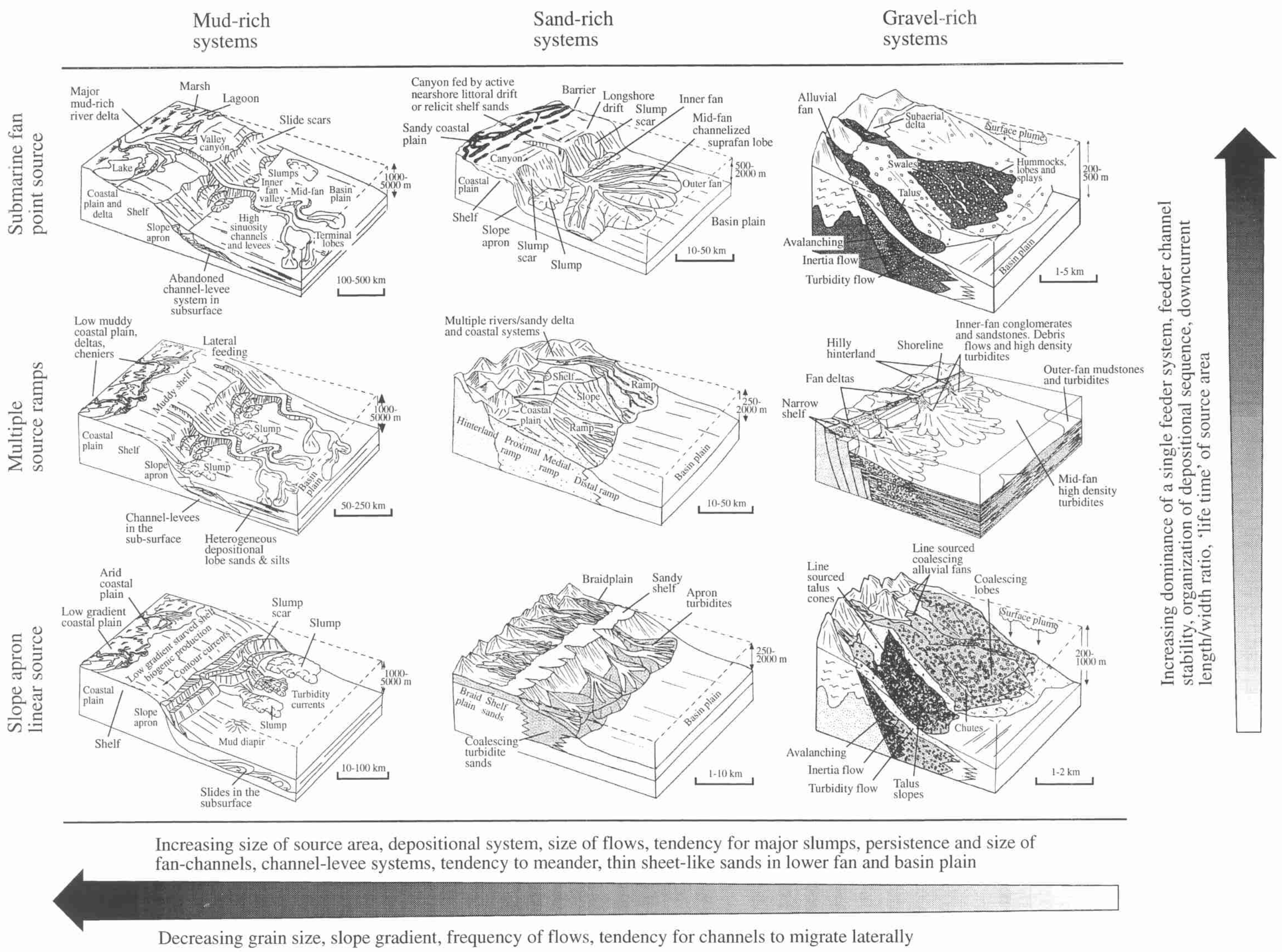

Fig. 9. Summary environmental models for submarine fans, ramps and slope-apron systems, classified on the basis of (i) volume and grain size of available sediment, and (ii) nature of the supply system (number of input points) (from Reading & Richards, 1994; Stow et al., 1996).

papers in this volume illustrate such data acquisition from modern fan channels (Damuth, 1998; Talling et al., 1998), from ancient systems (Satur et al., 2000), and from the subsurface (Wonham et al., 2000). This last contribution, in particular, demonstrates the detailed data on element geometry that can be derived from 3-D seismic attribute mapping. Significant research advance will be made by cross matching such seismic attribute analysis with high-resolution seafloor mapping of modern analogues.

Similar attribute databases are currently being developed for all deep-water elements.

5. Environmental models

Larger-scale environmental studies are used for the first order characterisation and classification of deep-water systems. Bouma (2000), for example, argues that fine-grained submarine fans are significantly different from their coarser-grained counterparts and have a very different association and distribution of architectural elements. They therefore require a distinct environmental model. Damuth (1998) describes the Amazon fan as a typical mud-rich fan, but also illustrates the occurrence of periods of dominant sandy deposition. Several different types of slope apron system are addressed in papers by Prather (1998), Wynn et al. (2000) and Armishaw et al. (2000).

The environmental classification of margin turbidite systems (including fans, ramps and slope aprons) is now relatively well established (Reading & Richards, 1994; Stow et al., 1996). This is based on (i) the volume and grain size of available sediment, and (ii) the nature of the supply system — point source, multiple source or linear source. We illustrate some of the possible environmental models in Fig. 9, but stress that there is a gradational continuum between the systems differentiated.

Current research is now focused on the various types of slope apron system and their controls, as well as on improved models for basin plains and contourite drifts (e.g. Stow et al., 1996). Such research needs to integrate subsurface seismic and borehole data with the results of modern seafloor mapping/sampling and detailed analysis of ancient analogues. Further work is needed on the seismic/sequence stratigraphic models, their application to deep-water systems and their different influence by sea-level and tectonic factors.

6. Conclusion

The buzz of research activity surrounding deep-water sedimentary systems derives in part from the economic importance of this new frontier and in part from its scientific challenge. The collection of papers in this volume, together with those presented at *Geoscience 98* in Keele, and at a series of similar meetings over the past three years, clearly demonstrate that interest, as well as elucidate a number of the key findings and research directions that we are set to take into the 21st century. These can be summarised as follows:

- Deep-water turbidite and related reservoirs will be at the forefront of oil and gas exploration and production for at least the next 25 years. The principal targets will be deep passive margin basins, but also any deep-water system with adequate source-rock recharge potential. Further work on deep-water source rocks is essential.
- The downslope processes that operate to deliver sediment into deep water are varied and complex. Single resedimentation events typically have multiple stages and evolve from one fluid state to another. Simplistic process models are fast being refined and replaced.
- Sediment supply (volume, source, nature and grade) are more important than process in determining the nature of the ultimate deposit. Glaciated margins, large river/delta systems, carbonate shelves, etc., will each give rise to very different deep-water facies and associations. The seafloor polishing effect is capable of providing a clean sand source in the outer shelf/upper slope region.
- A key research focus now is to examine deep-water systems at the level of architectural elements: the definition of these building blocks, their stacking patterns, geometries and physical attributes. Quantification of these attributes and their error bars needs significant work.
- At the larger scale, research must be directed towards slope aprons, basins and drifts, as well as seismic/sequence stratigraphy and the interplay of fundamental controls in determining deep-water facies and architecture.

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