Bottom currents, contourites and deep-sea sediment drifts: current state-of-the-art

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Abstract: This paper provides both an introduction to and summary for the Atlas of Contourite Systems that has been compiled as part of the International Geological Correlation Project – IGCP 432. Following the seminal works of George Wust on the physical oceanography of bottom currents, and Charley Hollister on contourite sediments, a series of significant advances have been made over the past few decades. While accepting that ideas and terms must remain flexible as our knowledge base continues to increase, we present a consensus view on terminology and definitions of bottom currents, contourites and drifts. Both thermohaline and wind-driven circulation, influenced by Coriolis Force and molded by topography, contribute to the oceanic system of bottom currents. These semi-permanent currents show significant variability in time and space, marked by periodic benthic storm events in areas of high surface kinetic energy.

Six different drift types are recognized in the ocean basins and margins at depths greater than about 300 m: (i) contourite sheet drifts; (ii) elongate mounded drifts; (iii) channel related drifts; (iv) confined drifts; (v) infill drifts; and (vi) modified drift-turbidite systems. In addition to this overall geometry, their chief seismic characteristics include: a uniform reflector pattern that reflects long-term stability, drift-wide erosional discontinuities caused by periodic changes in bottom current regime, and stacked broadly lenticular seismic depositional units showing oblique to downcurrent migration. At a smaller scale, a variety of seismic facies can be recognized that are here related to bottom current intensity. A model for seismic facies cyclicity (alternating transparent/reflector zones) is further elaborated, and linked to bottom current/climate change. Both erosional features and depositional bedforms are diagnostic of bottom current systems and velocities.

Many different contourite facies are now known to exist, encompassing all compositional types. We propose here a C1–5 notation for the standard contourite facies sequence, which can be interpreted in terms of fluctuation in bottom current velocity and/or sediment supply. Several proxies can be utilized to decode contourite successions in terms of current fluctuation. Gravel lag and shale chip contourites, as well as erosional discontinuities are indicative of still greater velocities. There are a small but growing number of land-based examples of fossil contourites, based on careful analysis using the recommended three-stage approach to interpretation. Debate still surrounds the recognition and interpretation of bottom current reworked turbidites.

Contourites are an extremely important but still relatively little known group of sediments, that have been surrounded by controversy since they were first recognized in the early 1960s. They are one of the keys to our further understanding of bottom-water circulation and the ocean-climate link, and play an increasingly critical role in palaeoceanographic studies. They are an important part of the spectrum of deposits that confront the oil industry as exploration moves into progressively greater water depths.

In order to foster greater international dialogue on these issues, as well as to stimulate more focussed research, an International Geological Correlation Programme initiative (Project 432) was launched in 1998. One of the early aims of this project was to publish a compendium of examples of contourite systems, both modern and ancient, and this volume is the result. This introductory paper provides an opportunity for the volume editors to summarise current knowledge and understanding of these systems, to highlight key areas of study, to document a consensus view on terminology, and to lay some pointers towards the direction of future research. This overview derives from many sources, including: our individual research experience and publications; discussions with many other scientists, facilitated by various IGCP432 workshop meetings; informal research reports in the IGCP432 Newsletter series; and a recent synthesis written by the senior author for the *Encyclopedia of the Oceans* (Stow 2001, in part based on Stow 1994). In such a concise synthesis, it has not always been possible to fully reference the many ideas and data that are included. Instead we provide below a summary of some of the key publications used. We also refer, as appropriate, to the 35 other contributions in this volume.

Historical perspective

At about the same time that marine geologists first began to recognize the significance of turbidity (density) currents in the erosion and deposition of sediments, the German physical oceanographer George Wust initially proposed that bottom currents driven by thermohaline circulation might be sufficiently strong to influence sediment flux in the deep ocean basins. But at that time, in 1936, his contention was loudly decried by other physical oceanographers and thus went largely unheard by geologists. It was not until the 1960s, following pioneering work by the American team of Bruce Heezen and Charlie Hollister, that the concept was forced centre-stage in marine science, with combined geological and oceanographic evidence that was irrefutable.

In their seminal paper of 1966, Heezen *et al.* demonstrated the very significant effects of contour following bottom currents (also known as contour currents) in shaping sedimentation on the deep continental rise off eastern North America. The deposits of these semi-permanent alongslope currents soon became known as contourites, clearly distinguishing them from the deposits of downslope event processes known as turbidites. The ensuing decade saw a profusion of research on contourites and bottom currents in and beneath the present-day oceans, and the

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demarcation of slope-parallel, elongate, mounded sediment bodies made up largely of contourites that became known as drifts. Their early identification in ancient rocks exposed on land, however, proved mostly inaccurate, as this was based on comparisons with the North American rise sediments. Subsequent work has demonstrated a much more complex interbedding of fine-grained turbidites, bottom current reworked turbidites, and contourites on the eastern North American rise (Stow 1979; Hollister 1993).

Other significant stepping stones that have helped to direct contourite research through the 1980s and 1990s are highlighted below, with example references only. A more accurate view was developed of contourite sediments from coring of drift deposits, and standard facies models were developed (Stow 1979, 1982; Faugères *et al.* 1984; Gonthier *et al.* 1984). The direct link between bottom current strength and nature of the contourite facies, especially grain size, was demonstrated (Ellwood & Ledbetter 1977; Stow *et al.* 1986). This has been taken forward through the work by Nick McCave and associates (Robinson & McCave 1994; McCave *et al.* 1995) in decoding the often very subtle signatures captured in contourites in terms of variation in deep-sea palaeocirculation. Discrimination was made between contourites and other deep-sea facies, such as turbidites deposited by catastrophic downslope flows and hemipelagites that result from continuous vertical settling in the open ocean (Stow & Lovell 1979; Stow & Tabrez 1998). Much progress has been made on the types and distribution of sediment drifts (McCave *et al.* 1988; Faugères & Stow 1993; Howe *et al.* 1994; Stoker *et al.* 1998*a*), as well as on their seismic characteristics (Faugères *et al.* 1999).

For the most part, physical oceanographers have worked independently of geologists on the nature and variability of bottom currents, so that much integration is still required between these disciplines. Important contributions that to some extent bridge this divide have come from the HEBBLE project on the Nova Scotian Rise (Nowell & Hollister 1985; McCave *et al.* 1988), extensive work around the Antarctic margin (Pudsey *et al.* 1988; Gilbert *et al.* 1998), and recent work along the Brazilian continental margin (Viana *et al.* 1998*a*, *b*). The international deep-sea drilling programme in its various guises (DSDP, IPOD, ODP) has contributed enormously to contourite research; the palaeoceanographic context and study of oceanic gateways remain primary targets at present (see review in Stow *et al.* 1998). Although much effort also has been made to correctly identify fossil contourites in ancient series on land, much confusion and controversy still abounds (Stow *et al.* 1998*a*; Shanmugam 2000). Their recognition in oil company boreholes, therefore, and the contribution of contourite facies to hydrocarbon reservoir intervals remains a target for further study (Shanmugam *et al.* 1993, 1995).

Several edited volumes of papers dealing in part or wholly with contourite systems have been published or are in press at the time of writing, emphasising the current level of interest and research. These include Nowell & Hollister 1985; McCave *et al.* 1988; Stow & Faugères 1993, 1998; Gao *et al.* 1998; Mienert 1998; Stoker *et al.* 1998*b*; Maldonado & Nelson 1999; Stow & Mayall 2000; Wynn & Stow in press; Rebesco & Stow in press; as well as the present publication.

Consensus on terminology

While recognizing the need to retain a certain fluidity in our use of terms to allow for developments in understanding, most workers would currently agree on the following broad definitions and usage. As far as possible, contributions to this volume conform with this view.

Bottom currents is the generally accepted term for those currents that operate in deep-water and that are part either of the normal thermohaline or of the major wind-driven circulation pattern of the oceans and their marginal seas. In general they are semi-permanent in nature with a net flow alongslope. In detail, they are extremely variable in direction and velocity, typically exhibiting giant eddies, and local downslope or oblique-to-slope flow, especially at the exit of narrow gateways. They do not hug rigidly to the contours, although the term *contour current* is still widely used synonymous with bottom current. Other types of current that operate in deep water include: internal tidal and internal wave-related currents, downwelling slope currents, upwelling slope currents, and clear-water up and down canyon currents. It is not necessarily possible to distinguish the seismic features or sediment facies that result from these currents from those of bottom currents. Where a distinction can be made (especially in modern or sub-recent) systems, then a modifying term should be applied.

Contourites are the sediments deposited by or significantly affected by the action of bottom currents. A wide range of contourite facies can be recognized from muddy to gravel-lag facies, and of all different compositions depending on the sediment supply system. Because of process interaction and process continuums in the deep sea, many transitional facies can occur. Where distinction can be made, then terms such as *bottom current moulded hemipelagite* or *bottom current reworked turbidite* should be used. The term *fossil contourite* is now widely applied to ancient contourites exposed on land, as well as to those interpreted as contourites in deep boreholes.

There has always been a problem surrounding the appropriate water depth at which to call a bottom current deposit, a contourite, recognizing that many different currents will act upon the seafloor everywhere from the shoreline outwards, as well as in lacustrine settings. It makes little sense to be too rigid in defining an upper depth limit for contourites *sensu stricto*, as the precise water depth at which sub-recent and older contourites accumulated is generally unknown. This is even more true of fossil contourites. We therefore favour retaining, as a guideline, a water depth of around 300 m as the upper limit for contourite deposition. Clearly, if a mid to upper slope current system straddles this depth limit, perhaps on a seasonal basis, then the whole deposit should be given the same name. A qualifying term, such as *shallow water contourite* is recommended in this case, and the same should be used for drift deposits in relatively shallow gateways.

Sediment drift is a general term for a sediment accumulation, of no definitive or unique geometry, that has experienced some current control on deposition. It is not restricted to bottom current deposits. *Contourite drift* is the specific term for a sediment drift that has been formed principally (though not necessarily exclusively) by bottom currents. Various types of contourite drifts are recognized (see below), including mixed drift systems for those where there has been significant process interaction, e.g. bottom current modified turbidite drift, etc.

The terms *mound*, *lobe*, *fan*, *channel*, *levee* are all also associated closely with turbidite and associated downslope systems. When applying these terms to contourite systems it is therefore important to modify with the contourite prefix.

Bottom currents

At the present day, deep-ocean bottom water is formed by the cooling and sinking of surface water at high latitudes, followed by the deep slow thermohaline circulation of these polar water masses throughout the world's ocean (Figs 1 and 2). Antarctic Bottom Water (AABW) is the coldest, densest and hence deepest water in the oceans, forming close to and beneath floating ice shelves around Antarctica, with localized areas of major generation such as the Weddell Sea. Once formed at the surface, partly by cooling and partly as freezing seawater leaves behind water of greater salinity, AABW rapidly descends the continental slope, circulates eastwards around the continent and then flows northwards through deep-ocean gateways into the Pacific, Atlantic and

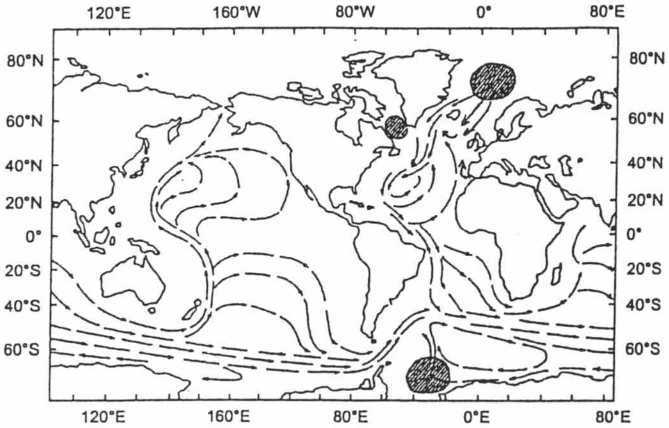

Fig. 1. Global pattern of abyssal circulation. Shaded areas are regions of production of bottom waters (after Stow *et al.* 1996).

ndian Oceans (**Pudsey *et al.***, **Pudsey & Howe**, **Carter & McCave**). Here it is further compartmentalized by topographic barriers, such as the mid-ocean ridges and aseismic ridge systems, either circulating within the sub-basin or escaping to an adjacent sub-basin where the gateway sill is sufficiently deep.

Arctic Bottom Water (ABW) forms in the vicinity of the subpolar surface water gyre in the Norwegian and Greenland Seas and then overflows intermittently to the south through narrow gateways across the Scotland–Iceland–Geenland topographic barrier, into the Rockall, Iceland and Greenland basins (**Howe *et al.*** and **Akhurst *et al.***). It mixes with cold deep Labrador Sea Water as it flows south along the Greenland–North American continental margin, and with recirculated North Atlantic Bottom Water in the Rockall Basin. Above these bottom waters, the ocean basins are further stratified into water masses of different temperature, salinity and density characteristics, each of which has its own circulatory pattern and shows slow mixing with adjacent water masses.

Bottom waters generally move very slowly throughout the ocean basins, at velocities no greater than 1–2 cm s^{-1}. However, hey are significantly affected as they flow by the Coriolis Force, which results from the Earth's spin, and by basin or gateway opography. The Coriolis effect is to constrain water masses gainst the continental slopes on the western margins of basins, where they become restricted and intensified forming distinct Western Boundary Undercurrents that commonly attain velocities of 10–20 cm s^{-1}. These velocities may exceed 100 cm s^{-1} where the flow is particularly restricted or the slope especially steep. Through narrow passages or gateways on the deep seafloor, flow velocities in excess of 200 cm s^{-1} have been recorded.

Many bottom currents, therefore, are a semi-permanent part of the thermohaline circulation pattern, and sufficiently competent in parts to erode, transport and deposit sediment, especially clay, silt and fine sand grades and, more rarely, coarser sands and gravels. The currents are also highly variable in velocity, direction and, therefore, in their precise location at any one time. Mean flow velocity generally decreases from the core to the margins of the current, where large eddies peel of and move at high angles or in a reverse direction to the main flow. Tidal, seasonal and less regular periodicities have been recorded during long-term measurements (i.e. > six-month duration), and complete flow reversals are also commonplace.

Other bottom currents that are distinct from purely thermohaline circulation are the major wind-driven systems (Fig. 3). In some cases, these act throughout much of the water column, still registering significant flow at 4000 m depth. This is especially true of those currents that flow along western margins of ocean basins and are intensified by the Coriolis Force, such as the Gulf Stream and Kuroshio Current. The Circumpolar Antarctic Current is also well known for its effect on the deep slope and rise around the Antarctic continent (**Rebesco *et al.*** and **Escutia & Nelson**). Eddy kinetic energy associated with sea-surface topographic variations in regions of surface current instability and meandering can be transmitted through the water column, and so result in marked variation in kinetic energy at the seafloor (Fig. 4). This in turn has been shown to result in the alternation of short (days to weeks) episodes of high bottom current velocity known as benthic storms, and longer periods (weeks to months) of lower velocity. Benthic storms can result in the erosion and resuspension of large volumes of sediment, that becomes incorporated into the bottom nepheloid layer (**McCave & Tucholke**), although we know little more about their cumulative, long-term effects on the nature of contourites.

Deep and intermediate depth water is also formed from relatively warm surface waters that are subject to excessive evaporation at low latitudes, and hence to an increase in relative density. This process is most effective in semi-enclosed marginal seas and basins. The Mediterranean Sea is currently the principal source of warm, highly saline, intermediate water, formed principally in the eastern Mediterranean or Levantine Sea (**Reeder *et al.***). The bottom water so formed flows through the Sicily gateway (between Sicily and North Africa), through the western Mediterranean, out

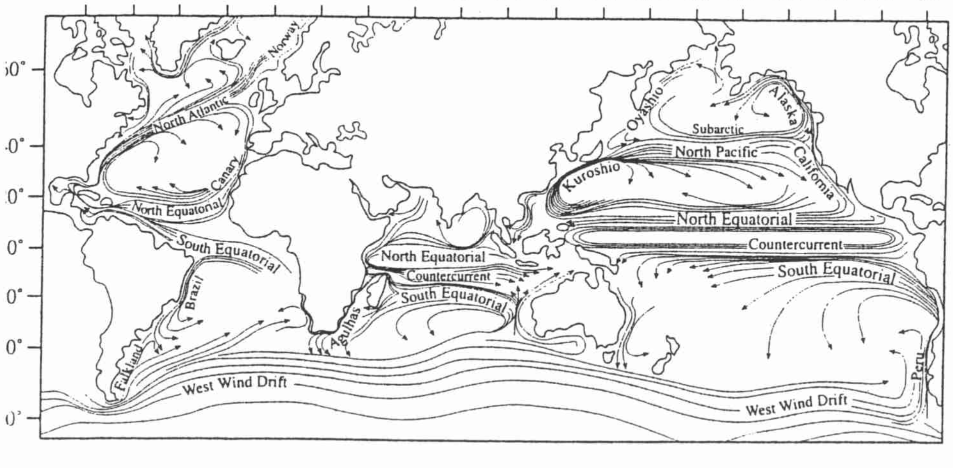

Fig. 2. Global pattern of surface circulation, showing some of the principal wind-driven currents that act as bottom currents along continental margins (after Charnock 1996).

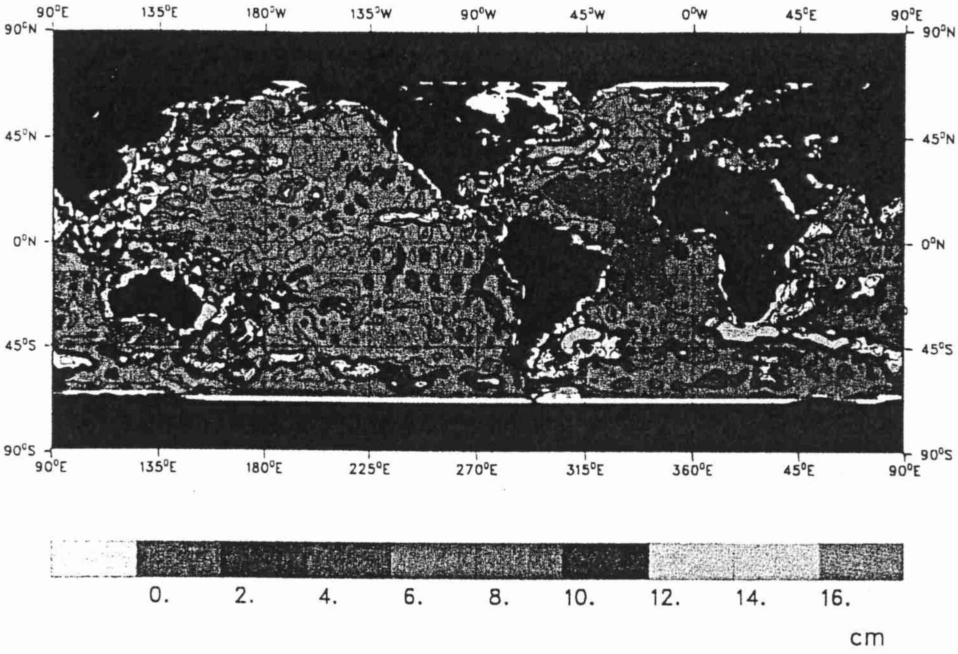

Fig. 3. Statistics of eddy energy derived from variability of sea-surface slope (obtained from the Topex/Poseidon satellite). Highest eddy energy is indicated by the yellow-red end of the spectrum. This can be transmitted through the water column to the seafloor (after Richards & Gould 1996).

through the Straits of Gibraltar and then northwards along the Iberian and north European margin (**Stow *et al.*** and **Faugères *et al.***). At different periods of Earth history warm saline bottom waters will have been equally or more important than cold water masses in the global thermohaline circulation.

Contourite drifts

The recognition of contourite drifts in seismic profiles, both at the surface and within section, has been a fast evolving field, with ever more examples and types of drift being added to the data base. At present, contourite accumulations can be grouped into six main classes on the basis of their overall morphology and setting: (i) contourite sheet drifts; (ii) elongate mounded drifts; (iii) channel-related drifts; (iv) confined drifts; (v) infill drifts; and (vi) modified drift-turbidite systems (Table 1, Fig. 4). It is important to note, however, that these distinctive morphologies are simply type members within a continuous spectrum, so that hybrid types also occur. They are also found at all depths within the oceans, including all deep water (> 2000 m) and mid-water (300–2000 m) settings. Those current controlled sediment bodies that occur in shallower water (50–300 m) on the outer shelf or uppermost slope are not considered contourite drifts *sensu stricto*, but may be referred to as shallow water drifts (**Viana *et al.***). The occurrence and geometry of these different types is controlled principally by five interrelated factors: the morphological context or topography; the current velocity and variability, at both a short-period and longer timescale; the amount and type of sediment available; the length of time over which the bottom current processes have operated; and modification by interaction with downslope processes and their deposits.

Contourite sheet drifts

These form extensive very low-relief accumulations, either as part of the fill of basin plains or plastered against the continental margin. They comprise a layer of more or less constant thickness (up to a few hundreds of metres) that covers a large area, but that demonstrates a very slight decrease in thickness towards its margins, i.e. having a very broad low-mounded geometry. The internal seismofacies is typically one of low amplitude, discontinuous reflectors or, in some parts, is more or less transparent.

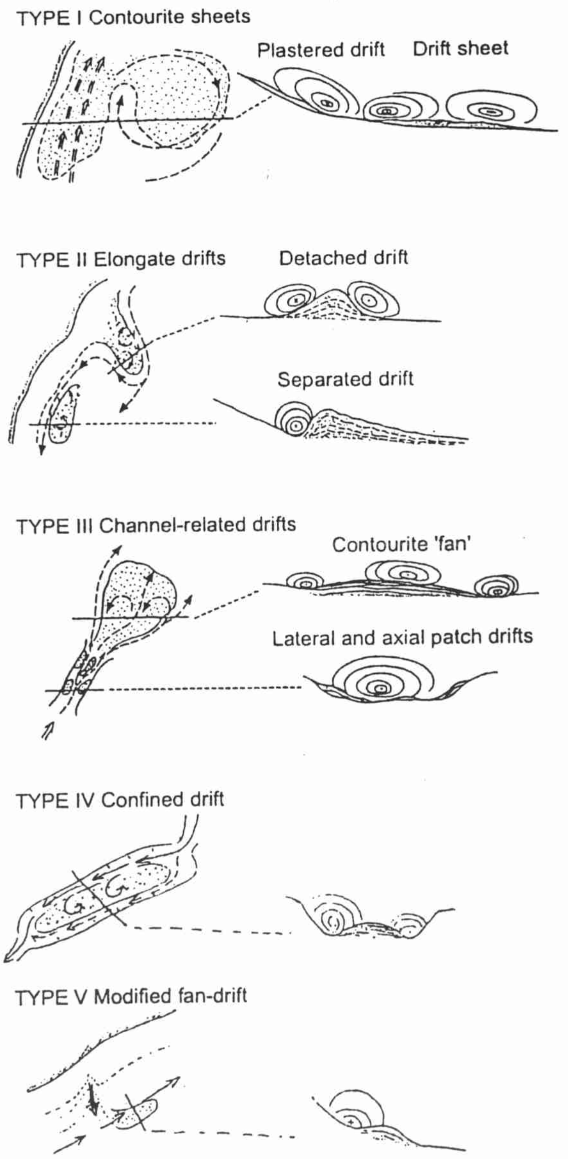

Fig. 4. Contourite drift models (modified from Faugères *et al.* 1999; Stow 2001).

Table 1. *Drift morphology, classification and dimensions. Modified from Faugères* et al. *(1999) and Stow (2001)*

Drift type	Subdivisions	Size	Examples
Contourite sheet drift	a) abyssal sheet	10^5–10^6 km ^{2}	a) Argentine basin; Gloria Drift
	b) slope (plastered sheet)	10^3–10^4 km^2	b) Gulf of Cadiz; Campos margin
	c) slope (patch) sheets	< 10^3 km^2	
Elongated mounded drift	a) detached drift	10^3–10^5 km^2	a) Eirek drift; Blake drift
	b) separated drift	10^3–10^4 km^2	b) Feni drift; Faro drift
Channel-related drift	a) patch-drift	10–10^3 km^2	a) NE Rockall trough
	b) contourite-fan	10^3–10^5 km^2	b) Vema Channel exit
Confined drift		10^3–10^5 km^2	Sumba drift; E Chatham rise
Modified drift – turbidite systems	a) extended turbidite bodies	10^3–10^4 km^2	a) Columbia levee S Brazil Basin; Hikurangi fandrift
	b) sculptured turbidite bodies	10^3–10^4 km^2	b) SE Weddell Sea
	c) intercalated turbidite-contourite bodies	can be very extensive	c) Hatteras rise

They may be covered by large fields of sediment waves, as in the case of the South Brazilian and Argentinian basins where they are also capped in the central region by giant elongate bifurcated drifts.

The different hydrological and morphological contexts define either abyssal sheets or slope sheets (also known as plastered drifts). The former carpet the floors of abyssal plains and other deep water basins including those of the South Atlantic and the central Rockall trough in the NE Atlantic. The basin margin relief partially traps the bottom currents and determines a very complex gyratory circulation. Slope sheets occur near the foot of slopes where outwelling or downwelling bottom currents exist, such as in the Gulf of Cadiz as a result of the deep Mediterranean Sea Water outwelling at an intermediate water level into the Atlantic, or around the Antarctic margins (e.g. the Weddell Sea slope) as a result of the formation and downwelling of cold AABW. They are also found plastered against the slope at any level, particularly where gentle relief and smooth topography favours a broad non-focussed bottom current, such as along the Hebrides margin and Nova Scotian margin.

Abyssal sheet drifts typically comprise fine-grained contourite facies, including silts and muds, biogenic-rich pelagic material, or manganiferous red clay, interbedded with other basin plain facies. Accumulation rates are generally low, around 2–4 cm ka^{-1}. Slope sheets are more varied in grain size, composition and rates of accumulation. Thick sandy contourites have been recovered from base-of-slope sheets in the Gulf of Cadiz, and rates of over 20 cm ka^{-1} are found in sandy-muddy contourite sheets on the Hebridean slope. Case studies in this volume that include sheet drifts are given by **McCave & Tucholke**, **Akhurst *et al.***, **Knutz *et al.***, **Stow *et al.*** (Barra) and **Reeder *et al.***

Elongate mounded drifts

This type of contourite accumulation is distinctly mounded and elongate in shape, with dimensions variable from a few tens of km to over 1000 km long, length to width ratios from 2:1 to 10:1, and thicknesses up to 2 km. They may occur anywhere from the outer shelf/upper slope, such as those east of New Zealand to the abyssal plains, depending on the depth at which the bottom current flows. They are very common throughout the North Atlantic, but occur also in all the other ocean basins and some marginal seas. One or both lateral margins are generally flanked by distinct moats along which the flow axis occurs and which experience intermittent erosion and non-deposition. Elongate drifts associated with channels or confined basins are classified separately.

Both the elongation trend and direction of progradation are dependent upon an interaction between the local topography, the current system and intensity, and the Coriolis Force. Elongation is generally parallel or subparallel to the margin, with both detached and separated types recognized, but progradation can lead to parts of the drift being elongated almost perpendicular to the margin. Internal seismic character reflects the individual style of progradation, typically with lenticular, convex-upward depositional units overlying a major erosional discontinuity. Fields of migrating sediment waves are common.

Sedimentation rates depend very much on the amount and supply of material to the bottom currents. On average, rates are greater than for sheet drifts, being between 2 and 10 cm ka^{-1}, but may range from < 2 cm ka^{-1} for open ocean pelagic biogenic-rich drifts, to > 60 cm ka^{-1} for some marginal drifts (e.g. along the Hebridean margin). The sediment type also varies according to input, including biogenic, volcaniclastic and terrigenous types. Grain size varies from muddy to sandy as a result of long-term fluctuations in bottom current strength. Many of the case studies presented in this volume include elongate mounded drifts: **Tucholke**, **Laberg *et al.***, **Howe *et al.***, **Stow *et al.*** (Faro), **Ercilla *et al.***, **Gomes & Viana**, **Uenzelmann-Neben**, **Michels *et al.*** and **Pudsey & Howe**.

Channel-related drifts

This type of contourite deposit is related to deep channels, passageways or gateways through which the bottom circulation is constrained so that flow velocities are markedly increased (e.g. Vema Channel, Kane Gap, Samoan Passage, Almirante Passage, Faroe–Shetland Channel etc.). Gateways are very important narrow conduits that cut across the sills between ocean basins and thereby allow the exchange of deep and intermediate water masses. In addition to significant erosion and scouring of the passage floor, irregular discontinuous sediment bodies are deposited on the floor and flanks of the channel, as axial and lateral patch drifts, and at the downcurrent exit of the channel, as a contourite fan.

Patch drifts are typically small (a few tens of square kilometres in area, 10–150 m thick) and either irregular in shape or elongate in the direction of flow. They can be reflector-free or with a more chaotic seismic facies, and may have either a sheet or mounded geometry. Contourite fans are much larger cone-shaped deposits, up to 100 km or more in width and radius and 300 m in thickness (e.g. the Vema contourite fan). Channel floor deposits include patches of coarse grained (sand and gravel) lag contourites, mud-clast contourites and associated hiatuses that result from substrate erosion, as well as patch drifts of finer grained muddy and silty contourites where current velocites are locally reduced.

Manganiferous mud contourites and nodules are also typical in places. Accumulation rates range from very low, due to non-deposition and erosion, to as much as 10 cm ka^{-1} in some patch drifts and contourite fans. The case studies in this volume from channel-related settings include those by: **Akhurst *et al.***, **Reeder *et al.***, **Roveri**, **Faugères *et al.*** (Vema and Columbia papers) and **Carter & McCave**.

Confined drifts

Relatively few examples are currently known of drifts confined within small basins. These typically occur in tectonically active areas, such as the Sumba drift in the Sumba forearc basin of the Indonesian arc system, the Meiji drift in the Aleutian trench and an unnamed drift in the Falkland Trough. Apart from their topographic confinement, the gross seismic character appears similar to mounded elongate drifts having distinct moats along both margins. Sediment type and grain size depend very much on the nature of input to the bottom current system, but are inadequately known to allow generalisation at this stage. The two case studies from this volume that include confined drifts are those by **Reeder *et al.*** and **Cunningham *et al.***

Infill drifts

This drift type is the most recent addition to our end-member models and so also lacks many well documented examples. They are mostly moderate relief, variable-shape, small scale features that are formed as the local infill of topographic depressions, which have developed beneath the flow pathway of a bottom current system. Typically they occur as infills and partial infills at the head of a slump scar, or at the margins and toe region of a large slump/slide mass. They were first recognized as such from the Hebridean slope on the NW UK continental margin, but are probably very widespread beneath other slope centred bottom currents. Drift infill of a channel of unknown origin has been noted on the Faro-Albufeira drift complex in the Gulf of Cadiz (**Stow *et al.*** and **Faugères *et al.***). The seismic geometry is one that has clearly moulded to fill progressively, with downcurrent prograding reflectors, the topographic depression or irregularity involved. We have no data on the sediment fill facies or rates. Some of the Campos margin contourites fit into this category (**Viana *et al.***).

Modified drift-turbidite systems

The interaction of downslope and alongslope processes and deposits at all scales is the normal condition on the margins as well as within the central parts of present ocean basins. Interaction with slow pelagic and hemipelagic accumulation is also the norm, but these deposits do not substantially affect the drift type or morphology. Over a relatively long timescale, there has been an alternation of periods during which either downslope or alongslope processes have dominated as a result of variations in climate, sea-level and bottom circulation coupled with basin morphology and margin topography. This has been particularly true since the late Eocene onset of the current period of intense thermohaline circulation, and with the marked alternation of depositional style reflecting glacial-interglacial episodes during the past 2 Ma.

At the scale of the drift deposit, this interaction can have different expressions as exemplified in the following examples:

(a) Nova Scotian Margin: regular interbedding of thin muddy contourite sheets deposited during interglacial periods and fine grained turbidites dominant during glacials; marked asymmetry of channel levees on the Laurentian Fan, with the larger levees and extended tail in the direction of the dominant bottom current flow.

(b) Cape Hatteras Margin: complex imbrication of downslope and alongslope deposits on the lower continental rise, that has been referred to as a *companion drift-fan.*

(c) The Chatham–Kermadec Margin: the deep western boundary current in this region scours and erodes the Bounty Fan south of the Chatham Rise and directly incorporates fine grained material from turbidity currents that have travelled down the Hikurangi Channel. This material, together with hemipelagic, is swept north from the downstream end of the turbidity current channel to form a *fan-drift* deposit.

(d) West Antarctic Peninsula Margin: eight large sediment mounds, elongated perpendicular to the margin and separated by turbidity current channels, have an asymmetry that indicates construction by entrainment of the suspended load of down-channel turbidity currents within the ambient southwesterly directed bottom currents and their deposition downcurrent.

(e) Hebridean Margin: complex pattern of intercalation of downslope (slides, debrites and turbidites), alongslope contourites and glaciomarine hemipelagites in both time and space; the alongslope distribution of these mixed facies types by the northward-directed slope current has led to the term *composite slope-front fan* for the Barra Fan.

Several of the case studies in this volume describe either modified drift-turbidite systems of the sort outlined above, or simply systems with close interbedding of turbidites and contourites. They include papers by **Knutz *et al.***, **Reeder *et al.***, **Faugères *et al.*** (Columbia), **Viana *et al.***, **Rebesco *et al.*** and **Escutia & Nelson**.

Seismic characteristics

In many cases, the first means of identification of contourite drifts will be on seismic profiles. However, with growing recognition of the widespread occurrence of drifts in the deep sea, their variety of types, scales and depositional settings, as well as their similarity to features typical of other deep-sea facies (such as turbidite lobes, levees and fans), it has become necessary to erect a set of seismic criteria that will help distinguish drifts from other similar bodies. This becomes much more difficult, of course, where close interbedding of different facies has occurred as in the mixed drift systems noted above. The current set of seismic criteria for enabling positive identification, slightly modified from the three-scale approach developed by Faugères *et al.* (1999), is summarized below. The key attributes are shown schematically in Figure 5, and abundantly illustrated in many of the case studies presented in this volume.

Large scale (i.e. drift scale)

Contourite drifts form as an integral part of the depositional environment in which they occur, in some cases as an isolated sediment body but more usually as a complex of drift types and other deep-water architectural elements. The large-scale features of these accumulations reflect long-lasting (temporally) stable conditions in the bottom current regime and/or oceanographic setting.

(1) *Drift geometry*. The variety of drift geometries now known to exist have been described in some detail in the previous section. Those with a more distinctly mounded rather than low-relief sheet-like geometry are most easily identified. This is especially true where the sediment body occurs beneath an existing bottom

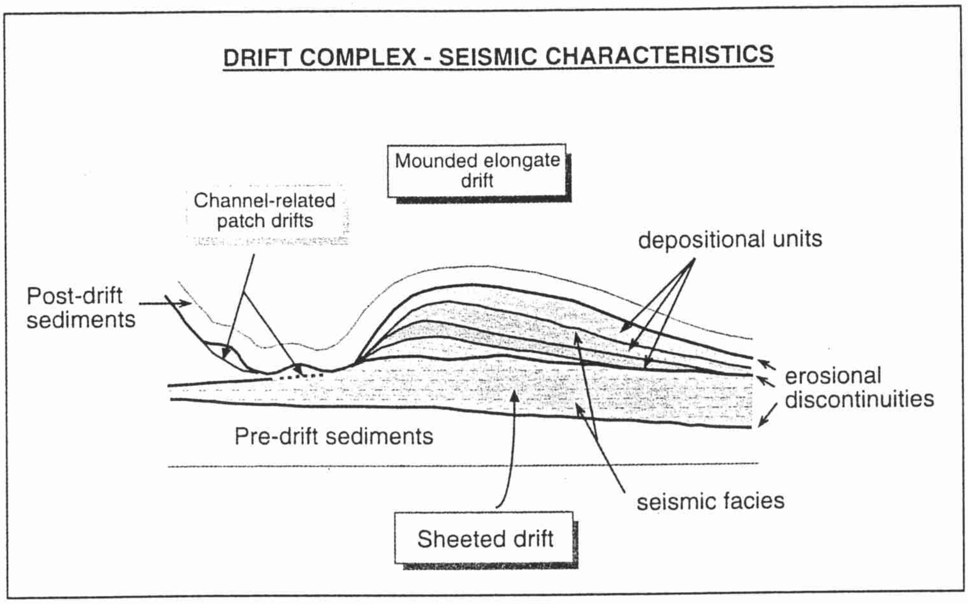

Fig. 5. Schematic model of principal seismic characteristics of contourite drifts.

current system and is clearly isolated from other possible sediment sources (such as downslope supply routes).

(2) *Drift elongation.* An overall downcurrent elongation direction is typical of most drifts.

(3) *Erosional discontinuities.* There are typically widespread discontinuities both at the base and within the drift, extending across the accumulation as a whole. These are commonly marked by continuous high-amplitude reflector, that may also underline a change in seismofacies. Some of these unconformities will be on a sub-regional scale, beyond the confines of the drift, while others (such as the basal horizon) will even link into oceanwide discontinuities. These reflect periodic changes in bottom current conditions.

(4) *Uniform reflector pattern.* Drifts are commonly represented by extensive, sub-parallel, moderate- to low-amplitude reflectors, with mainly gradational changes typical between seismic facies, in addition to the erosional discontinuities noted above. These reflect the long-lasting stable conditions, both laterally and temporally, that are the norm for drift accumulation.

Medium scale (i.e. depositional seismic units)

Internal architecture within a drift is generally complex, as a result of local variation in processes and accumulation rates linked to changes in current activity. In many cases, the history of drift construction is marked by an alternation of periods of sedimentation and periods of erosion or non-deposition. Medium- and small-scale features reflect these changes.

(1) *Seismic units.* Most of the larger drifts will comprise a series of broadly lenticular, upwardly-convex, seismic units.

(2) *Migration direction.* The stacking of units shows migration in downcurrent to oblique direction, coincident with the elongation direction of the drift as a whole. Any lateral migration direction is likely to be influenced by the Coriolis Force (to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere), providing the right morphological context, current direction and latitude.

(3) *Reflector terminations.* Downlapping and sigmoid progradational reflector patterns are typical, whereas a top-lapping pattern is less common.

Small scale (i.e. seismic facies)

In greater detail, the nature of individual seismic facies reflect changes in both depositional processes and in sediment types. They are not unique to contourite drifts and also depend very closely on the methods employed for seismic acquisition and processing. However, once a drift origin has been established, using a combination of seismic and other characteristics, much interesting detail can be gleaned from this small-scale approach.

(1) *Seismic facies.* A wide variety of seismic facies are typical of contourites, most of which are equally present in turbidite and/or hemipelagic systems. These include (i) semi-transparent, reflector-free intervals, (ii) continuous, sub-parallel, moderate- to low-amplitude reflectors, (iii) regular, migrating-wave, moderate- to low-amplitude reflectors, (iv) irregular, wavy to discontinuous, moderate-amplitude reflectors, and (v) an irregular, continuous, single high-amplitude reflector. We tentatively suggest that this order of seismic facies (i to v) reflects increasing strength in the bottom current regime (Fig. 6). Particular seismic facies associations may be more diagnostic of contourite systems, although this area also needs more work.

(2) *Seismic facies cyclicity.* Recent work (e.g. **Stow *et al.*, Faugères *et al.*** and **Roveri**) has revealed a common cyclical pattern in some drifts between a more transparent facies (T) and a moderate-amplitude continuous reflector seismic facies (R). Preliminary interpretation suggests seismic facies (R) reflects a greater proportion of silt/sand content contourites, more hiatuses and condensed sedimentation sections, due to increased bottom current intensity. Seismic facies (T), by contrast, is due to low silt/sand content within a more continuous and homogeneous muddy contourite section, reflecting decreased bottom current intensity. The driver for this cyclical model (Fig. 7) is most likely bottom current variation linked to climate change.

Morphological features and bedforms

High-resolution sesimic records, from echosounder, sidescan and deep-tow seismic techniques, coupled with swath bathymetric mapping and seafloor photography, have helped document the principal surface morphological features of contourite systems. 3D seismic reflection profiling, followed by time-slice seismic attribute mapping, has enabled us to interpret the same sorts of features at depth within the sedimentary succession.

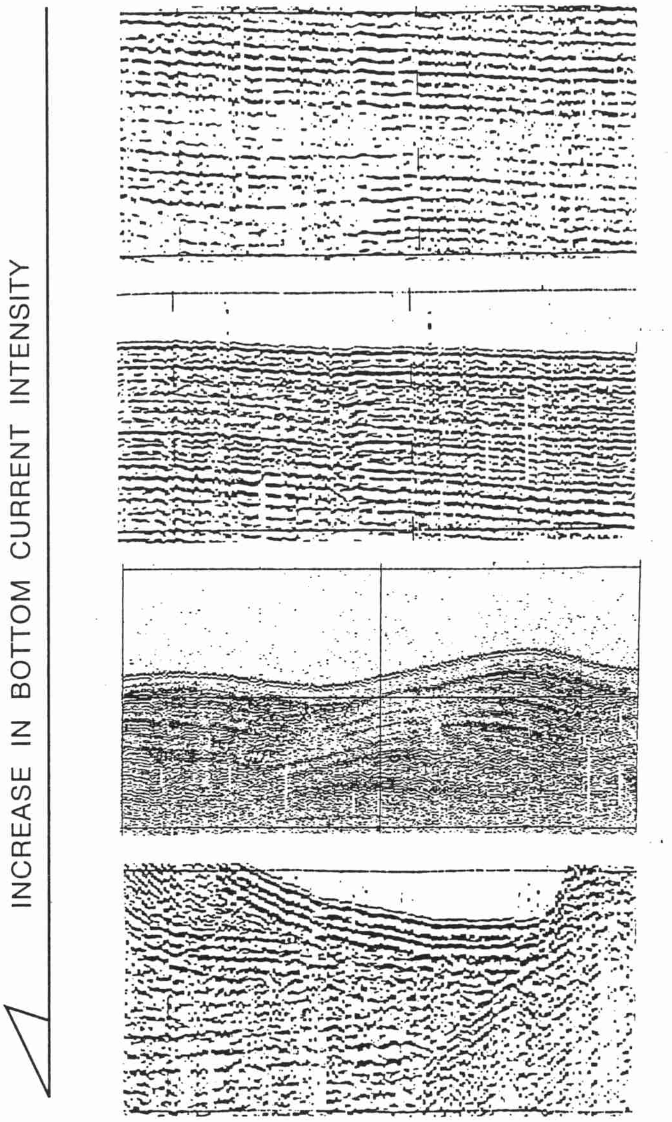

Fig. 6. Principal seismic facies found in contourite drifts and their inferred relationship to bottom-current velocity.

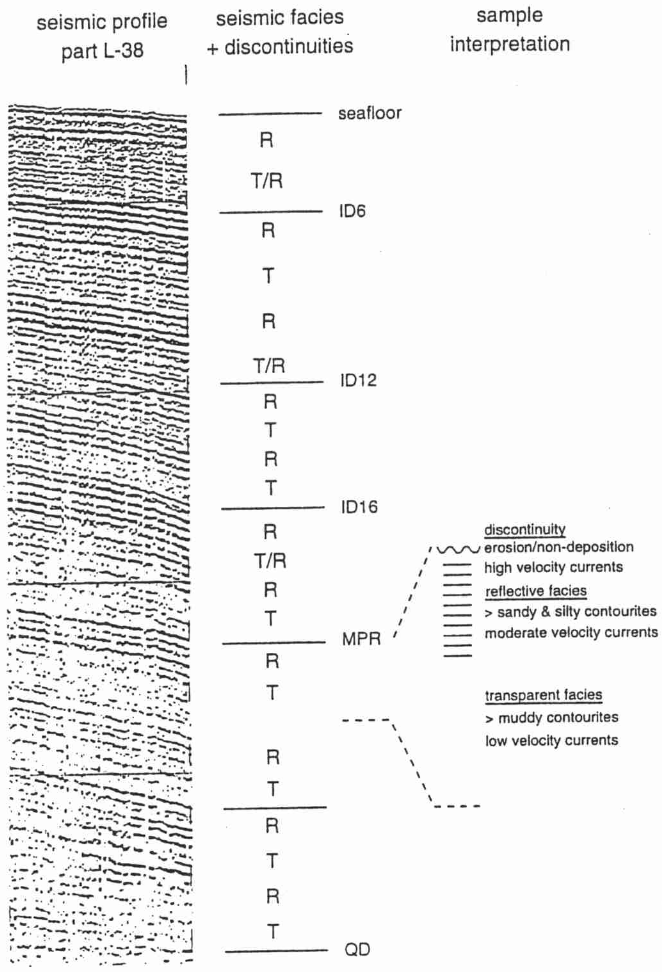

Fig. 7. Model for cyclic variation in seismic facies (based on **Stow *et al.*** and **Llave *et al.***).

Erosional features that result from strong bottom current activity include scours and moats at various scales, semi-indurated mud horizons, coarse-lag surfaces, gravel and rock pavements, and both large- and small-scale longitudinal furrows. Depositional bedforms observed under moderate to weaker bottom currents include giant sediment waves, large-scale waves and dunes (often barchanoid), and a host of small-scale waves, dunes, ripples and surface lineation features as found beneath any unidirectional current regime. The presumed relationship of these elements to bottom current velocity is illustrated in Figure 8. None of them is exclusive to bottom current systems alone.

Although originally considered diagnostic of contourite systems, regular migrating giant sediment waves are now known to be a very common feature in both contourite and turbidite systems. In addition, a regular wave-like pattern may develop as a result of slope deformation or downslope creep, and in response to the wholesale upward migration or escape of sediment pore-waters. The latest attempts to differentiate between these different processes of wave formation are discussed by Wynn & Stow (in press).

Contourite sediment facies

Tremendous advances have been made in the characterization of contourites since they were first described from a modern oceanographic setting nearly 40 years ago, although the majority of that work has remained in a marine setting. Some 50 different legs of the DSDP through ODP progammes have drilled drift and mixed-drift sites, with over 100 sites having recovered contourites. A great many more conventional cores have been taken from these and other drifts around the world during a variety of national and international campaigns. We can therefore be very confident that our present facies models for contourites are well founded, while recognizing that new contourite types may yet be discovered and some of those most recently described still require further elaboration. However, there is less consensus about the nature of bottom current; turbidity current interaction and of the bottom current reworked turbidite facies model. The original 'contourites' described by Hollister and co-workers were most probably of this latter type. The debate surrounding fossil contourites is outlined in a later section.

The wide variety of contourite facies that have been recognized on the basis of variations in grain size and composition are listed and briefly described below and illustrated schematically in Figure 9. Many of the papers in this volume present good photographs of most of these facies, but see in particular papers by **Akhurst *et al.***, **Knutz *et al.*** and **Stow *et al.*** (Faro).

(a) Siliciclastic contourites (muddy, silty, sandy and gravel-rich variations);
(b) Shale-clast/shale-chip contourites (all compositions possible);
(c) Volcaniclastic contourites (muddy, silty, sandy and gravel-rich variations);
(d) Calcareous bioclastic contourites (calcilutite, calcisiltite, calcarenite and calcirudite variations);

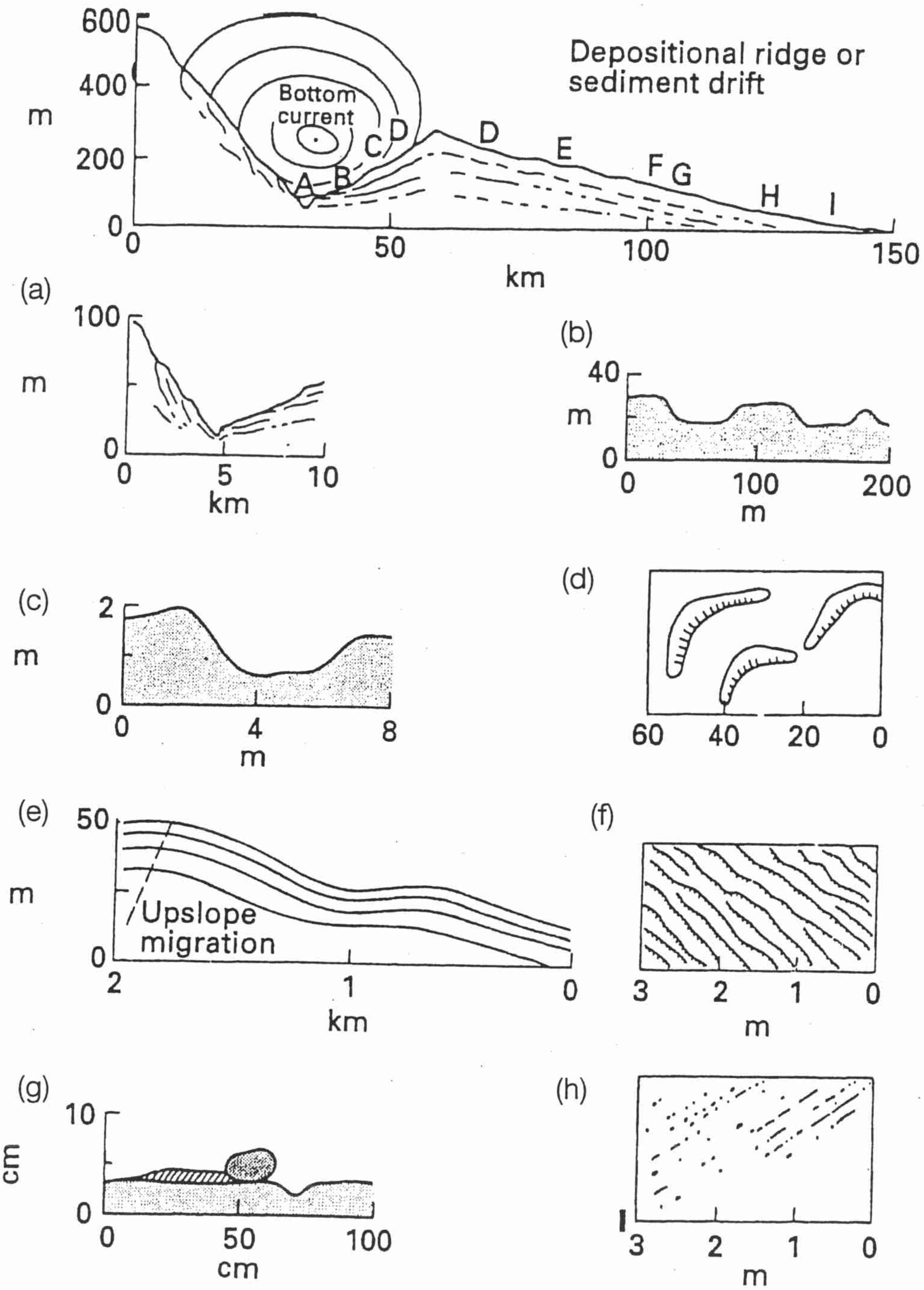

Fig. 8. Erosional features and depositional bedforms typically found on the seafloor beneath bottom-current systems.

(e) Siliceous bioclastic contourites (mainly sand grade recognized);
(f) Manganiferous muddy contourites (+ manganiferous nodules/pavements);
(g) Other contourite related facies ('shallow-water' contourites, reworked turbidites).

Muddy contourites are homogeneous, poorly bedded and highly bioturbated, with rare primary lamination (partly destroyed by bioturbation), and irregular winnowed concentrations of coarser material. They have a silty-clay grain size, poor sorting and a mixed terrigenous (or volcaniclastic), biogenic composition. The components are in part local, including a pelagic contribution and n part far-travelled.

Silty contourites (also referred to as *mottled silty contourites*) commonly show bioturbational mottling to indistinct discontinuous lamination, and are gradationally interbedded with both muddy and sandy contourite facies. Sharp to irregular tops and bases of silty layers are common, together with thin lenses of coarser material. They have a poorly sorted clayey-sandy silt size and a mixed composition.

Sandy contourites occur as both thin irregular layers and as much thicker units within the finer grained facies, and are generally thoroughly bioturbated throughout (e.g. **Stow *et al.*** (Barra)). In some cases, rare primary horizontal and cross-lamination is preserved (though partially destroyed by bioturbation), together with irregular erosional contacts and coarser concentrations or lags. The mean grain size is normally no greater than fine sand, and sorting is mostly poor due to bioturbational mixing, but more rarely clean and well sorted sands occur. Both positive and negative grading may be present. A mixed terrigenous-biogenic composition is typical, with evidence of abrasion, fragmented bioclasts and iron-oxide staining.

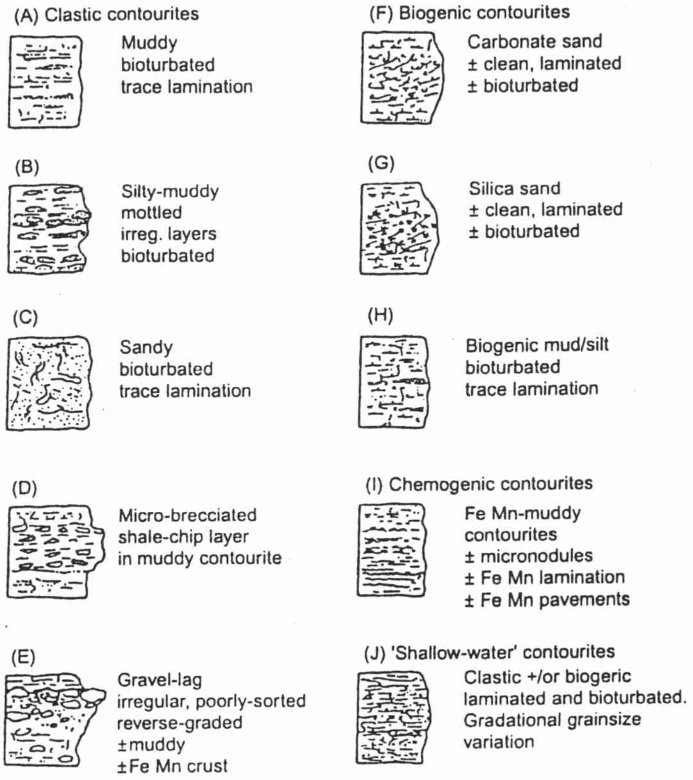

Fig. 9. Contourite facies models for clastic, biogenic, chemogenic and 'shallow-water' contourites (modified from Stow *et al.* 1996).

Gravel rich contourites are common in drifts at high latitudes as a result of input from ice-rafted material (e.g. **Howe *et al.*, Akhurst *et al.*** and **Laberg *et al.***). Under relatively low-velocity currents, the gravel and coarse sandy material remains as a passive input into the contourite sequence and is not subsequently reworked to any great extent by bottom currents. Gravel lags indicative of more extensive winnowing have been noted from both glacigenic contourites and from shallow straits, narrow moats and passageways, where gravel pavements are locally developed in response to high velocity bottom current activity.

Shale-clast or shale-chip layers in both muddy and sandy contourites have been recognized from relatively few locations to date (e.g. **Faugères *et al.*** (Vema)). They result from substrate erosion under strong bottom currents, where erosion has led.to a firmer substrate and, in some cases, burrowing on the omission surface has helped break up the semi-firm muds.

Calcareous and siliceous biogenic contourites occur in regions of dominant pelagic biogenic input, including open ocean sites and beneath areas of upwelling. In most cases bedding is indistinct, but may be enhanced by cyclic variations in composition, and primary sedimentary structures are poorly developed or absent, in part due to thorough bioturbation as in siliciclastic contourites. In rare cases, the primary lamination appears to have been well preserved. The mean grain size is most commonly silty clay, clayey silt or muddy sandy, poorly sorted and with a distinct sand size fraction representing the coarser biogenic particles that have not been too fragmented during transport. The composition is typically pelagic to hemipelagic, including nannofossils and foraminifera as dominant elements in the calcareous contourites and radiolaria or diatoms dominant in the siliceous facies. Many of the biogenic particles are fragmented and stained with either iron oxides or manganese dioxde. There is a variable admixture of terrigenous or volcaniclastic material.

Manganiferous contourites are those in which manganiferous or ferro-manganiferous rich horizons are common. This metal enrichment may occur as very fine dispersed particles, as a coating on individual particles of the background sediment, as fine encrusted horizons or laminae, or as micronodules. It has been observed in both muddy and biogenic contourites from several drifts (eg. **Faugères *et al.*** and **Vema & Columbia**).

Contourite-related facies. It is clearly important to recognise that bottom currents will influence to a greater or lesser extent other deep-water sediments, particularly pelagic, hemipelagic, turbiditic and glacigenic, both during and after deposition. Where the influence is marked and deposition occurs in a drift, then the sediment is termed *contourite.* Where the influence is less severe, such that features of the original deposit type remain dominant, then the sediment is said to have been influenced by bottom currents, as in *bottom current reworked turbidites.* Some silt-laminated facies, as well as the thin, clean, cross-laminated sands originally described by Hollister & Heezen (1972) from NE American margin, are most likely of this type. The features that we suggest best characterize reworked turbidites are summarised in Table 2, together with those of normal (depositional) contourites. These differ from the criteria proposed recently by several workers based purely on ancient turbidite successions (e.g. Stanley 1988; Mutti *et al.* 1992; Shanmugam *et al.* 1993, Shanmugam 2000), but we believe they are more reliable because of the inherent uncertainties of interpretation when dealing with ancient series.

Some of the sediments that have been described recently from mixed drift systems, such as those on the Antarctic Peninsula margin (**Rebesco *et al.***), as well as others from shallow-water, upper-slope to outer-shelf settings (**Roveri *et al.*** and **Sivkov *et al.***), are of a rather different facies. They show clear, but somewhat irregular lamination coupled with bioturbation throughout, and a poor to moderately well sorted, silty grain size. This may represent a hybrid turbidite-contourite facies type and/or a shallow-water contourite facies.

Contourite sequences and current velocity

Muddy, silty and sandy contourites, of siliciclastic, bioclastic, volcaniclastic or mixed composition, commonly occur in composite sequences or partial sequences a few decimetres in thickness (typical range 0.2–3 m). The ideal or complete sequence shows overall negative grading from muddy through silty to sandy contourites and then positive grading back through silty to muddy contourite facies (Fig. 10). Such sequences of grain size and facies variation are now widely recognized from many drifts although, as with the ideal turbidite sequences, partial sequences of different thickness are equally common. Following the turbidite analogy of notation for the *Bouma*, *Stow* and *Lowe* turbidite sequences (see Stow *et al.* 1996), we propose here that a useful advance for the shorthand description of the contourite sequence is to use the notation C1–5 as follows: C5, upper muddy contourite division; C4, upper mottled silty contourite division; C3, middle sandy contourite division; C2, lower mottled silty contourite division; C1, lower muddy contourite division.

Thus a complete sequence *of any composition* is referred to as C1–5. In a vertical succession of repeated sequences, there is a seamless transition from C5 of the underlying sequence to C1 of the overlying sequence. This should be arbitrarily taken at the mid-point of the C5/C1 couplet. Base-only partial sequences are referred to as C1–2 or C1–3, and top-only sequences as C3–5 or C4–5 as appropriate. Rather than introducing new division notation for the rare occurrence of other contourite facies within the sequence, it seems more sensible to highlight these departures from the standard sequence verbally. The base-only sequences that pass up into a gravel-lag and non-depositional surface as

Table 2. *Main characteristics of muddy contourites, sandy contourites and bottom current reworked turbidites (from Stow* et al. *1998a)*

	Muddy contourites (terrigenous or biogenic)	**Sandy contourites (terrigenous or biogenic)**	**Reworked turbidites (any composition)**
Occurrence	thick uniform sequences of fine-grained sediment in deep-water settings interbedded with turbidites and other resedimented facies on inferred continental margins	thin to medium beds in muddy contourite sequences, rarely thick/v.thick units reworked tops of sandy turbidites in interbedded sequences coarse lag in deep-sea channels and straits	in any normal turbidite setting where strong, permanent bottom currents have been active
Structure	dominantly homogeneous, bedding not sharply defined, but cyclicity common bioturbational mottling generally common to dominant distinct burrows (typical deep-water assemblage) present in many places coarse lag concentrations (especially biogenic) reflect composition of coarse fraction in mud primary silt/mud lamination – rare, but no regular sequence as in turbidites sharp and erosive contacts common in parts	generally bioturbated and burrowed throughout with little primary structure remaining parallel and cross-lamination more rarely preserved (often with bioturbation) no regular structural sequence as in turbidites may show reverse grading near top, with sharp/erosive contacts common	lower divisions of turbidite may be preserved, with the upper divisions either removed completely or modified by reworking bioturbation/burrowing common through reworked top reverse grading and irregular lag concentrations bi-directional cross-lamination, may be clean micro-cross-laminated silts with bioturbation sharp erosive contacts may occur within turbidite sequence
Texture	dominantly silty mud frequently high sand content (0–15%) of biogenic tests in clastic contourites medium to poorly sorted, ungraded, no offshore textural trends may show marked textural difference from interbedded turbidite if transport distances are different	silt to sand-sized, more rarely gravel may be relatively free of mud and well sorted in some cases tendency to low or negative skewness values no offshore trends	removed/non-deposition of fines significant textural differences from underlying turbidite (e.g. cleaner, better sorted, reverse grading + lag, negative skewness)
Fabric	mud fabric – typically more parallel alignment of clays than for turbidites, but not well present in fossil contourites primary silt laminae or coarse lag deposits show grain orientation parallel to the current (along-slope)	indication of grain orientation parallel to the bottom current (along-slope) or more randomised by bioturbation other features (eg structures) also indicate alongslope flow, where preserved	interbedded, reworked turbidite layers may show widely bimodal grain orientations or a more random playmodel fabric
Composition	mixed contourites have combination of biogenic and terrigenous material (may be distinct from interbedded turbidites) terrigenous material dominantly reflects nearby land/shelf source with some along-slope mixing and small amount of far travelled material (no down-slope trends)	mixed biogenic/terrigenous composition typical terrigenous composition dependent on local source biogenic material from pelagic, benthic and resedimented sources, typically fragmented and iron-stained organic-carbon content very low	composition entirely reflects that of turbidite, with part of fine fraction removed long exposure and winnowing may lead to chemogenic precipitation (probably rare) organic-carbon content very low
Sequence	typically arranged in decimetric cycles of grain-size and/or compositional variation with sandy contourites see model (Fig. 2) – partial sequences also common	typically arranged in decimetric cycles of grain-size and/or compositional variation with muddy contourites see model (Fig. 2) – partial sequences also common	presents a typical turbidite sequence (ie top-absent or top reworked) does not occur within standard cyclic contourite sequence

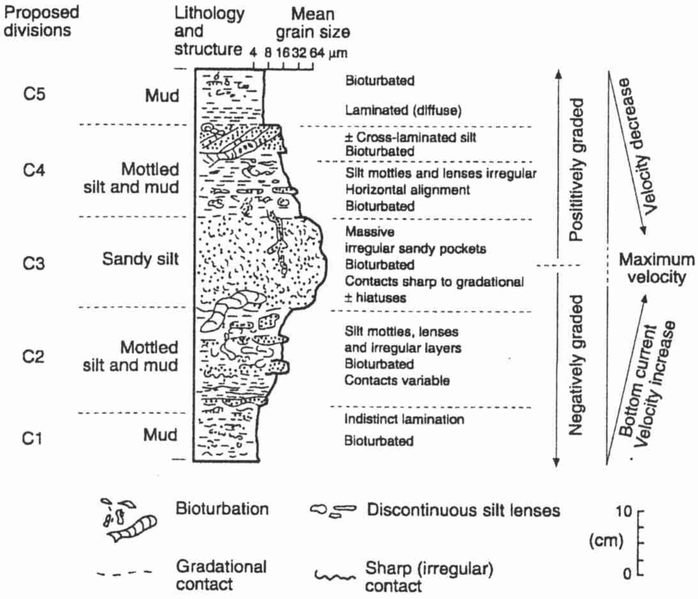

Fig. 10. Composite contourite facies model showing grain size variation through the standard mud-silt-sand contourite sequence, linked to variation in bottom current velocity (modified from Stow *et al.* 1996). The notation C1–C5 for the different facies divisions is introduced in this paper.

found in the Rockall Trough (**Howe *et al.***) should be described as C1–3 *with a gravel top*. Likewise, the top-only contourites of the Rockall Trough and Faroe–Shetland Channel (Stoker *et al.* 1998*a*; **Howe *et al.*** and **Akhurst *et al.***) can be referred to as C3–5 *with a sharp erosive base*.

The origin of the C1–5 sequence is related *either* to long-term fluctuations in the mean current velocity, *and/or* to variation in sediment supply. Stacked sequences indicate cyclic variation in the forcing variables. Although not enough data exist to be certain of the time scale of these cycles, some evidence points towards 5000–20 000 cycles for certain marginal drifts of terrigenous to mixed composition. In bioclastic successions, the cyclic facies pattern has a longer time-scale (20 000–40 000 years) in the few examples from which we have good dating, and is closely analogous to the Milankovitch cyclicity recognised in many pelagic and hemipelagic successions. It is therefore believed to be driven by the same mechanism of orbital forcing of climate that then effect changes in bottom current velocity.

Differentiating the relative importance of current velocity versus sediment supply is by no means simple. The most thorough approach is to analyse variation in bulk sediment mean grain size, and then to consider the co-variance or not of compositional attributes (e.g. terrigenous/biogenic ratios, benthic/planktonic ratios, percentage of coarse sand/gravel and shale chips, presence/absence of far-travelled components, clay/silt ratio), current indicators (e.g. scour surfaces, lamination, lag horizons, coarse-grained lenses, shale chip concentrations), and bioturbation intensity coupled with ichnofacies types. These data need to be collated and compared for different sites over the same drift in order to distinguish regional from local effects, and to observe down-current trends.

Considerable advances have been made, however, in utilizing simpler proxies for bottom current velocity. The most important of these is mean grain size of the sortable silt (10–63 microns) fraction (Robinson & McCave 1994; McCave *et al.* 1995), which has been most recently adapted to remove the effects of ice-rafted sediment supply in NE Atlantic drifts by Bianchi (2000). A more indirect proxy is to use variation in magnetic susceptibility to mirror the flux of terrigenous (magnetic) components. Further refinement in the reconstruction of paleocurrent variation is to undertake a detailed analysis of mass accumulation rates, as demonstrated by Hall & McCave (2000) using Th-230 excess oxygen systematics coupled with sortable silt grain size on the Iberian margin.

The link between contourite sequences and changes in paleoclimate and paleocirculation is an extremely important one. Where such sequences can be correctly decoded then we can build up a more accurate understanding of the palaeo-ocean and its environment. The occurrence of widespread hiatuses in the deep-ocean sediment record is best related to episodes of particularly intense bottom currents. More locally, such strong currents result in significant sediment winnowing and the accumulation of sand, gravel and shale-clast contourites.

Recognition of contourites and application to the ancient record

Identification of turbidites in both modern and ancient series is generally clear cut. They are single event deposits with well defined characteristics. Identification of contourites, however, is more complex. Bottom currents affect to a greater or lesser extent ambient sedimentation by other processes (pelagic, hemipelagic and turbiditic) so that a blend of characteristics is the common result. The slow and continuous nature of contourite accumulation means that primary features are often blurred or removed by secondary effects, especially bioturbation. Consequently, the recognition of contourites can never be a ‘quick-fix’ based on simple sediment or seismic appearance, but must always involve careful consideration of a range of characteristics and conditions. The three-stage approach to contourite identification favoured here is slightly refined and summarized from earlier work (Lovell & Stow 1981; Stow *et al.* 1998*a*), and presented in Table 3. Typical characteristics of muddy and sandy contourites in comparison with bottom current reworked turbidites are given in Table 2.

The application of these criteria, the facies and seismic models derived from modern systems, to ancient series exposed on land has been generally poor. The early erroneous interpretation of many fine grained turbidite successions as contourites has now been well documented (Stow & Lovell 1979; Pickering *et al.* 1989; Stow *et al.* 1998*a*). Several recent studies have addressed the problem of bottom current reworking of turbidites (Stanley 1988; Mutti *et al.* 1992; Shanmugam *et al.* 1993; Shanmugam 2000; Stow *et al.* 1998*a*) with some significant advances. But there remains much debate over the detailed sedimentary structures that can be attributed to one process or the other. It may be, in fact, that weak turbidity currents and strong bottom currents (e.g. benthic storm events) have very similar effects on the bottom sediment, so that their distinction on the basis of sediment characteristics alone will not be possible. This whole issue requires further work.

There are a small but growing number of examples of fossil contourites that fit most of our criteria for identification. These include parts of the Cretaceous Talme Yafe Formation in Israel (Bein & Weiler 1976), the Ordovician Jiuxi Drift (Duan *et al.* 1993) and Pingliang Drift (Gao *et al.* 1995) in China, the Paleogene Lefkara Formation in Cyprus (Kahler & Stow 1998), and the Neogene Misaki Formation in south central Japan (Stow *et al.* 1998*b*). All but the first of these are presented, with additional data and refinement, in this volume (**Stow *et al.*** (Cyprus and Japan); **Luo *et al.*** (China)). In addition, the paper by **Ito** describes Plio-Pleistocene sandy contourites within the turbidite-dominated Kasuza Group of southern Japan. We suggest that these may be a good example of a bottom current influence on fine-grained turbidites.

Implications and further research

There are of course many reasons to study bottom currents and contourites, not least because they represent such an important

Table 3. *Criteria for the recognition of contourites in both modern and ancient systems (from Stow* et al. *1998*a*)*

Stage 1: Small-scale (field, borehole or lab)

- Do the sediments have the range of features shown in Table 2 or as described in the text?
- Where there is a possibility of mixed turbidite/contourite sequences, can a distinction be made between the two facies on the basis of character and/or palaeocurrent evidence?
- Is there sufficient evidence to discount deposition from fine-grained turbidity currents? Particular care must be taken for inferred reworked turbidtes.
- Where there is a possibility of mixed hemipelagite–pelagite/contourite sequences, is there sufficient evidence for the influence of bottom currents during sedimentation?
- Can any cyclicity present be related to variation in bottom current velocity rather than to variations in terrigenous input or biogenic productivity?

Stage 2: Medium-scale (drift, formation or region)

- Do regional trends in facies occurrence, palaeocurrent directions, textures, mineralogical or geochemical tracers exist that would support a bottom current origin?
- Is there any other evidence of bottom current activity such as unconformities, condensed sequences, regional variation in thickness, drift geometry, etc?
- Is it possible to reconstruct the shape and 3D geometry of the whole sedimentary body? and, if so, are the elongation and propagation trends parallel or perpendicular to the inferred margin?
- Are the associated facies, paleontological data and rates of accumulation compatible with a contourite interpretation?

Stage 3: Large-scale (system, ocean or continent)

- Do the conclusions from Stages 1 and 2 above fit with what is known from other independent lines of evidence concerning major oceanographic or palaeoceanographic features and continental reconstructions?
- What kind of bottom current systems exist at present or might have existed in the study area at the time of deposition, taking into account constraints imposed by known palaeoclimatic conditions and inferred basin location and geometry?

component of the still little known deep ocean basins and their margins. Furthermore, they hold an important key to the decoding of paleocirculation records encapsulated in oceanic drifts and corresponding hiatuses, that are closely linked to past climatic change. Thick units of sandy contourites together with bottom-current reworked sandy turbidites are potentially important as hydrocarbon reservoirs where suitably buried in association with source rocks. The nature and effects of bottom currents on margin stability and subsea engineering projects need to be carefully evaluated.

Based on this overview and compendium of examples, together with the work of IGCP 432 over the past few years, we highlight below some of the key directions for future research in the contourite field.

(1) Integration of the physical oceanographic and sedimentological approaches – joint study of benthic storms and their effects, the nature of oceanic gateways, and long-term measurements of bottom currents coupled with their impact on the seafloor.

(2) Particular study of modified contourite drift-turbidite systems, sheeted drifts interbedded in margin settings, and shallow-water/marginal sea drifts.

(3) Further elaboration of the seismic facies of contourite sytsems and their relationship to flow velocity, and of the cyclic model of seismic facies presented here.

(4) Integration of biological oceanographic and sedimentological approaches – joint study of contourite ichnofacies and rates of accumulation, contourite sequences and periodicity, and of the nature and extent of sandy contourites.

(5) Further work on the links between contourite sequences and cycles and bottom current velocity fluctuation, and on potential proxies for characterising these changes.

(6) Collaboration between different specialists in the hunt for and decoding of fossil contourite successions exposed on land.

References

Bein, A. & Weiler, Y. 1976. The Cretaceous Talme Yafe Formation, a contour current shaped sedimentary prism of calcareous detritus at the continental margin of the Arabian Craton. *Sedimentology*, **23**, 511–532.

Bianchi, G. G. 2000. Iceland-Scotland overflow fluctuations over the past 82 ka using a novel approach. *31st International Geological Congress, Abstracts Volume,* Rio de Janeiro, Brazil.

Duan, T. Z., Gao Z. Z., Zeng, Y. F. & Stow, D. A. V. 1993. A fossil carbonate contourite drift on the Lower Ordovician palaeocontinental margin of the middle Yangtze Terrane, Jiuxi, northern Hunan, southern China. *Sedimentary Geology*, **82**, 271–284.

Ellwood, B. B. & Ledbetter, M. T. 1977. Antarctic bottom water fluctuations in the Vema Channel: effects of velocity changes on particle alignment and size. *Earth and Planetary Science Letters*, **35**, 189–198.

Faugères, J.-C. & Stow, D. A. V. 1993. Bottom-current-controlled sedimentation: a synthesis of the contourite problem. *Sedimentary Geology*, **82**, 287–297.

Faugères, J.-C., Gonthier, E. & Stow, D. A. V. 1984. Contourite drift moulded by deep Mediterranean outflow. *Geology*, **12**, 296–300.

Faugères, J.-C., Stow, D. A. V., Imbert, P., Viana, A. R. & Wynn, R. B. 1999. Seismic features diagnostic of contourite drifts. *Marine Geology*, **162**, 1–38.

Gao, Z. Z., Eriksson, K. A., He, Y. B., Luo, S. S. & Guo, J. H. 1998. *Deep-Water Traction Current Deposits*. Science Press, Beijing, New York. 57–105.

Gao, Z. Z., Luo, S. S., He, Y. B., Zhang, J. S. & Tang, Z. J. 1995. The Middle Ordovician contourite on the west margin of Ordos. *Acta Sedimentologica Sinica*, **13**(4), 16–26. (in Chinese with English abstract).

Gilbert, I. M., Pudsey, C. J. & Murray, J. W. 1998. A sediment record of cyclic bottom-current variability from the NW Weddell Sea. *Sedimentary Geology*, **115**, 185–214.

Gonthier, E., Faugères, J.-C. & Stow, D. A. V. 1984. Contourite facies of the Faroe drift, Gulf of Cadiz. *In*: Stow, D. A. V. & Piper, D. J. W. (eds) *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geological Society, London, Special Publications, **15**, 275–292.

Heezen, B. C., Hollister, C. D. & Ruddiman, W. F. 1966. Shaping the continental rise by deep geostrophic contour currents. *Science*, **152**, 502–508.

Hollister, C. D. 1993. The concept of deep-sea contourites. *Sedimentary Geology*, **82**, 5–11.

Hollister, C. D. & Heezen, B. C. 1972. Geologic effects of ocean bottom currents. *In*: Gordon, A. L. (ed.) *Studies in Physical Oceanography – A Tribute to George Wust on his 80th Birthday*. Gordon & Breach, New York, **2**, 37–66.

Howe, J. A., Stoker, M. S. & Stow, D. A. V. 1994. Late Cenozoic sediment drift complex, NE Rockall Trough, North Atlantic. *Palaeoceanography*, **9**, 989–999.

Kahler, G. & Stow, D. A. V. 1998. Turbidites and contourites of the Palaeogene Lefkara Formation, Southern Cyprus. *Sedimentary Geology*, **115**, 215–231.

Lovell, J. P. B. & Stow, D. A. V. 1981. Identification of ancient sandy contourites. *Geology*, **9**, 347–349.

Maldonado, A. & Nelson, C. H. 1999. Marine geology of the Gulf of Cadiz. *Marine Geology, Special Issue*, **155**.

McCave, I. N., Hollister, C. D. & Nowell, A. R. M. 1988. *Deep Ocean Sediment Transport: HEBBLE collected reprints 1980–1987.* Woods Hole Oceanographic Institute, Woods Hole.

McCave, I. N., Manighetti, B. & Robinson, S. G. 1995. Sortable silt and fine sediment size/composition slicing: parameters for paleocurrent speed and paleoceanography. *Paleoceanography*, **10**, 593–610.

Mienert, J. 1998. European North Atlantic Margin (ENAM): Sediment pathways, processes and flux. *Marine Geology, Special Issue*, **152**.

Mutti, E. *et al.* 1992. *Turbidite Sandstones*. AGIP/Istituto di Geologia, Universita di Parma, Parma, 236 pp.

Nowell, A. R. M. & Hollister, C. D. 1985. Deep Ocean Sediment Transport - Preliminary Results of the High Energy Benthic Boundary Layer Experiment. *Marine Geology*, **66**.

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

Pudsey, C. J., Barker, P. F. & Hamilton, N. 1988. Weddell Sea abyssal sediments: a record of Antarctic Bottom Water flow. *Marine Geology*, **81**, 289–314.

Rebesco, M. & Stow, D. A. V. in press. Seismic expression of contourites and related deposits. *Marine Geophysical Researches Special Issue*, in press.

Robinson, S. G. & McCave, I. N. 1994. Orbital forcing of bottom-current enhanced sedimentation on Feni Drift, NE Atlantic, during the mid-Pleistocene. *Palaeoceanography*, **9**, 943–972.

Shanmugam, G. 2000. Fifty years of the turbidite paradigm (1950's to 1990's): Deep-water processes and facies models - a critical perspective. *Marine & Petroleum Geology*, **17**, 285–342.

Shanmugam, G., Spalding, T. D. & Rofheart, D. H. 1993. Process sedimentology and reservoir quality of bottom-current reworked sands (sandy contourites): An example from the Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, **77**, 1241–1259.

Shanmugam, G., Spalding, T. D. & Rofheart, D. H. 1995. Deep marine bottom current reworked sands (Pliocene and Pleistocene): Ewing Bank 826 Field, Gulf of Mexico. *Proceedings SEPM Core Workshop*, **20**, 25–54.

Stanley, D. J. 1988. Turbidites reworked by bottom currents; Upper Cretaceous examples from St. Croix, US Virgin Islands. *Marine Science*, **22**, 79 pp.

Stoker, M. S., Akhurst, M., Howe, J. A. & Stow, D. A. V. 1998*a*. Sediment drifts and contourites on the continental margin off NW Britain. *Sedimentary Geology*, **115**, 33–52.

Stoker, M. S., Evans, D. & Cramp, A. 1998*b*. *Sedimentation, Mass Wasting and Stability.* Geological Society, London, Special Publication, **129**.

Stow, D. A. V. 1979. Distinguishing between fine-grained turbidites and contourites on the deep-water margin off Nova Scotia. *Sedimentology*, **26**, 371–387.

Stow, D. A. V. 1982. Bottom currents and contourites in the North Atlantic. *Bull. Inst. Geol. Bassin d'Aquitaine*, **31**, 151–166.

Stow, D. A. V. 1994. Deep-sea processes of sediment transport and deposition. *In*: Pye, K. (ed.) *Sediment Transport and Depositional Processes*. Blackwell, Oxford, 257–291.

Stow, D. A. V. 2001. Deep-Sea Sediment Drifts. *In*: Steele, J. H., Turekian, K. K. & Thorpe, S. A. (eds) *Encyclopedia of Ocean Sciences*. Academic Press, London.

Stow, D. A. V. & Lovell, J. P. B. 1979. Contourites: their recognition in modern and ancient sediments. *Earth Sciences Reviews*, **14**, 251–291.

Stow, D. A. V. & Faugères, J.-C. 1993. Contourites and Bottom Currents. *Sedimentary Geology*, *Special Volume* **82**, 1–310.

Stow, D. A. V. & Faugères, J.-C. 1998. Contourites, Turbidites and Process Interaction. *Sedimentary Geology*, *Special Issue*, **115**.

Stow, D. A. V. & Tabrez, A. 1998. Hemipelagites: facies, processes and models. *Geological Society Special Publication*, **129**, 317–338.

Stow, D. A. V. & Mayall, M. 1999. Deep-water Sedimentary Systems: New Models for the 21st Century. *Marine and Petroleum Geology, Special Issue* **17**.

Stow, D. A. V., Faugères, J.-C. & Gonthier, E. 1986. Facies distribution and textural variation in Faroe drift contourites: velocity fluctuation and drift growth. *Marine Geology*, **72**, 71–100.

Stow, D. A. V., Reading, H. G. & Collinson, J. D. 1996. Deep Seas. *In:* Reading, H. G. (ed.) *Sedimentary Environments (3rd ed.)*. Blackwell Science, Oxford, 395–454.

Stow, D. A. V., Faugères, J.-C., Viana, A. & Gonthier, E. 1998*a*. Fossil contourites: a critical review. *Sedimentary Geology*, **115**, 3–32.

Stow, D. A. V., Taira, A., Ogawa, Y., Soh, W., Taniguchi, H. & Pickering, K. T. 1998*b*. Volcaniclastic sediments, process interaction and depositional setting of the Miocene–Pliocene Miura Group, SE Japan. *Sedimentary Geology*, **115**, 351–382.

Viana, A., Faugères, J.-C., Stow, D. A. V. & Imbert, P. 1998*a*. Bottom-current controlled sand deposits: a review from modern shallow to deep water environments. *Sedimentary Geology*, **115**, 53–80.

Viana, A. *et al.* 1998*b*. Hydrology, morphology and sedimentology of the Campos continental margin, offshore Brazil. *Sedimentary Geology*, **115**, 133–158.

Wynn, R. B. & Stow, D. A. V. in press. Recognition and interpretation of deep-water sediment waves. *Marine Geology, Special Issue*.