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Bottom-current-controlled sedimentation: a synthesis of the contourite problem

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ABSTRACT

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An overview of the main items concerning deep bottom-current-controlled deposits is presented. These include: the definition of contourites, their processes of deposition and facies characteristics; contourite drift types and seismic patterns; the interplay of turbidity and bottom-current processes; and the correlation between bottom-current processes and global changes in climate/sea-level.

From this discussion, several of the more significant problems are highlighted, which we believe should be priority targets for future research: (1) identification of contourites, especially in ancient series, where they are interbedded with turbidites and other facies; (2) refinement of the numerous parameters used as tracers of palaeocirculation patterns; (3) understanding the interaction between the different types of bottom currents, and also between bottom-current and other deep-water processes; (4) distinction in the sedimentary record between the effects of short time-scale bottom-current variations due to regional causes like benthic storms, and geological-scale current fluctuations related to climatic or astronomic control; (5) understanding the control of glacial/interglacial climatic cycles on the nature and rate of contourite deposition.

Introduction

During the last three decades, we have seen an increasing amount of work on bottom-current-controlled deposition and it is now apparent that contourites form a significant proportion of deep oceanic margin sediments. In the paper we present a synthesis of current knowledge on this type of deep-water sedimentation, at the same time elucidating some of the problems that have not yet been resolved.

The study of contourites covers a large range of investigations from which we will select several major items for discussion: (1) What types of deposits should be called contourites? (2) What do we know about processes of deposition from bottom currents? (3) What are the diagnostic lithological characteristics of contourites? (4) What are the main current bedforms and types of contourite drifts? (5) What are the seismic patterns of contourite drifts and how are palaeocirculation patterns recorded? (6) How can we recognise the interplay of turbidity and bottom-current processes? (7) How do contourite accumulations reflect sea-level/climatic variations?

In a synthesis of this kind, it is impossible to refer to the enormous volume of literature that pertains to the topic. Instead, we have attempted to reference only selected studies of broad scope or particular importance, and also to make mention of other papers in this special volume where they are pertinent to the topic under discussion.

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Defining the term contourite

The first definition of contourites has been given by Heezen et al. (1966; Hollister, 1993): sediment deposited from thermohaline-driven bottom currents flowing parallel to bathymetric contours. Since that time, the term has been used for bottom-current-derived sediments deposited anywhere from the deep-sea to shallow marine water even in the lacustrine environment, hence moving rather far from the original definition. As a consequence, different authors have suggested that a wide range of bottom-current types is involved in the deposition of contourites (among others: Lovell and Stow, 1981; Okada and Ohta, 1993; Mariani et al., 1993).

Contourites deposited by deep geostrophic currents are the most frequently cited, from the abyssal plain at depths greater than 5000 m (McCave and Tucholke, 1986), to shallow plateaus (500–700 m), as found along the Mediterranean outflow pathway along the south Portuguese margin (Faugères et al., 1984), and on the northwestern UK continental margin (Leslie, 1993). They occur on passive margins (especially in the North Atlantic Ocean, Heezen et al., 1966) as well on active margins (Reed et al., 1987).

Contourites that have been described from shallow water depths of a few hundreds to about one thousand metres are commonly related to currents originating from various other processes including: internal waves, as found on top of abyssal guyots (Cacchione et al., 1988); internal tides as found through the sill both south and north of Sicily (Collela, 1990); wind-derived surficial currents on continental shelves, up-welling systems and up-and-down clear-water currents in canyons (Okado and Ohta, 1993). Finally, the term contourite has also been used for sediment deposited in Lake Superior under the influence of fluvial-driven lacustrine currents (Flood and Johnson, 1984).

It seems to us that the most confusing use of the term contourite is for the shallow marine deposits formed under currents which are not of thermohalyne origin. These currents show typically very rapid changes of intensity and direction and in some instances are distinctly bidirectional. Generally, we would not expect such currents to construct important sedimentary bodies, but rather to produce a veneer of reworked material deposited by another process.

Among ancient examples of contourite accumulations, some are interpreted as having been deposited in relatively shallow offshore settings, possibly due to strong wind-driven currents acting at depth (e.g. Upper Cretaceous of the Prealpine chains, Villars, 1990). True deep-water contourite accumulations that are clearly linked to geostrophic currents have not yet been described from ancient series with any degree of certainty (but see Stow and Faugères, 1993; Stanley, 1993). It may be that, for the development of strong thermohaline circulation, there must be a significant temperature differential between polar and equatorial regions, such as existed during the late Palaeozoic (Carboniferous) and late Cenozoic glacial/postglacial episodes. We should therefore focus our search for ancient contourites along, for example, young emerged active margins such as those of New-Zealand, Japan and the West Indies.

In order to clarify the confusion and to advance the debate on what should and should not be termed *contourite*, in either modern or ancient systems, we propose returning to the original concept of Hollister and Heezen (1972) and a narrowed definition of the term. *Contourite* should therefore be used only for sediments in relatively deep water (e.g. greater than about 500 m), deposited or significantly reworked by stable geostrophic currents. The more general term, *bottom-current deposits*, would then include *contourites sensu stricto*, as well as the deposits of all the other types of bottom currents outlined above. Where the palaeo-water depth is not well constrained, it is unwise to refer to ancient sediments as contourites.

Deposition from bottom currents

Deep-water bottom currents have a pronounced effect on several aspects of deep-sea sedimentation. They may erode large areas on the continental rise during certain periods (see data from numerous DSDP Legs in the North

Atlantic; Tucholke and Mountain, 1986; Westall et al., 1993), cut deep channels into older sediments (like the Vema channel, Johnson, 1984; or Kane gap, Meinert, 1986), form moats along the base of steep slopes or at the upstream flank of isolated abyssal (volcanic) hills (Davies and Laughton, 1972; Roberts et al., 1974; Von Stackelberg et al., 1979) and scour the sea floor through deep-sea passages and sills (Mélières et al., 1970; Kenyon and Belderson, 1973; Gardner et al., 1989).

Bottom currents are also efficient agents of particle transport and redistribution, both terrigenous and biogenic, throughout the oceans, over distances of thousands of kilometres (McCave, 1986; Cremer et al., 1993). In this way, they play a major role in shaping deep-sea morphology by constructing sediment drifts, ranging from giant sediment bodies of over 1000 km in length, on the continental margins or in the major ocean basins, to much smaller features related to deep-sea passages.

For many years, we have had no very good understanding of the exact nature of erosional and depositional processes by bottom currents. Whereas the velocities commonly recorded by current-meter measurements are adequate to transport fine-grained material, they are insufficient to effect marked erosion of very cohesive deep-sea muds. There has also been a debate centred around the role and extent of reworking of silts and sands by bottom currents compared with transport and deposition. However, the result of the HEBBLE programme on the lower continental rise off Nova Scotia (Hollister and McCave, 1984), and of several detailed studies of the nepheloid layer (McCave, 1986) have, more recently, shed much light on this whole problem.

We know that the hydrodynamic processes acting on the deep-sea floor are the result of an interplay of deep-sea circulation and surface current activity, which is mainly controlled by atmospheric conditions. What the HEBBLE work clearly demonstrated is that temporary very high surface energy conditions may propagate downward and induce high energy over the deep-sea floor. Very high surface kinetic energy in the oceans, as shown by maximum variability in the level of the sea surface (Richardson, 1983; Cheney et al., 1983), is only observed in relatively few areas, such as in the NW Atlantic along the eastern US margin, or in the SW Atlantic along the Argentine margin. These are also areas of significant contourite sedimentation.

The variation of bottom kinetic energy conditions in the HEBBLE area results in an alternation of short episodes of erosion associated with high-velocity currents (over periods of a few days to a few weeks), and longer periods of deposition associated with lower velocity (a few weeks to months duration). Episodes of high current velocity, called "benthic" or "abyssal" or "deep-sea" storms (Gardner and Sullivan, 1981; Hollister and McCave, 1984), correspond to high surface kinetic energy, due to local very low atmospheric pressure. During these episodes, a large volume of material is resuspended and thus contributes to a very high-density nepheloid layer. This material may be then transported over long distances in the Western Boundary Undercurrent before eventual deposition. Between abyssal storm events, the current velocities are much lower and very high sedimentation rates occur (up to 1.4 cm/month) over these short time periods. However, the net sedimentation rate at the scale of Holocene deposits on this part of the continental rise is very low (5.5 cm/10^3 yrs) as a result of the very frequent and active erosion episodes (estimated annual deposition/preservation ratio of 3,100). At a greater geological scale (Neogene), similar rates of deposition (2 to 10 cm/10^3 yrs) are observed on the giant contour drifts in the North Atlantic Ocean.

Resuspension of sea-floor sediments is not the only process feeding the nepheloid layer and hence bottom-current transport. Several other processes may be involved including: (1) inputs of terrigenous particles from the adjacent margins by turbidity currents; (2) advection along isopycnal surfaces via suspension cascading or some other hemipelagic process; (3) direct settling of biogenic pelagic particles and pellets; (4) resuspension of particles by the burrowing activity of benthic organisms. Whatever the origin of the particles, it appears that there is a close relationship between high-turbidity nepheloid layers and active bottom-current transport, including both erosion and deposition.

However, the presence of high turbidity in the nepheloid layer is not a necessary condition to have active deposition. In some cases, the benthic energy and current activity are strong enough, even during "calm" periods, to prevent deposition, so that erosion and transport are the dominant processes, despite the introduction of abundant terrigenous supply from the continent. This appears to be the case along the Argentine basin, where a very strong Antarctic Bottom Water flow is coupled with very high surface kinetic energy as a result of the affrontment of the Malvina and Brazilian surface currents (Cheney et al., 1983; McCave, 1986)

Lithological characteristics of contourites

The problem of diagnostic lithological features of both modern and fossil contourites has long been addressed (Bouma, 1972; Hollister and Heezen, 1972; Stow and Lovell, 1979; Lovell and Stow, 1981; Gonthier et al., 1984; Stow and Piper, 1984; Pickering et al., 1989; Duan et al., 1993; Jones et al., 1993; Sarnthein and Faugères, 1993; Stow and Faugères, 1993). It still remains a partly unresolved problem as contourites may mimic sediments deposited by other processes, and bottom-current may rework, to a greater or lesser extent, other types of deposits.

Depending on the composition of the sediment supply, deposits controlled by bottom currents may range from siliciclastic and volcaniclastic contourites to calcareous and siliceous biogenic contourites. Depending on the grain size that the bottom current is able to transport, contourites range from muddy, to sandy with a range of transitional facies composed of admixture of sand, silt and clay, typically displaying a mottled appearance. Very strong currents may scour the sea floor and result in gravel-lag contourites.

The majority of these deposits are strongly bioturbated, and any primary current structures (lamination, ripples, erosional surfaces) are consequently not well preserved. Better preservation of primary features may occur where there has been an interaction of different processes (e.g. bottom currents and turbidity currents), or in the case of shallower-water bottom-current deposits, which we do not consider here as true geostrophic contourites.

A "standard sequence" has been recognised in some modern contourite drift deposits (Faugères et al., 1984; Stow et al., 1986), in which the grain size varies from fine mud through mottled silty mud to silt and fine sand grade. Where this variation is mirrored by subtle changes in remnant sedimentary structures and concomitant changes in the biogenic/terrigenous composition, it is possible to interpret the sequence in terms of long-term variation in mean current velocity (Stow et al., 1986). Unlike the standard Bouma (1962) sequence in turbidites, which is the result of instantaneous deposition, the contourite sequence is built up gradually over longer periods, in the order of tens of thousands years.

However, it is not always possible to use grain size parameters alone as tracers of bottom-current intensity, because various other factors such as variations in terrigenous sediment supply or biogenic productivity may also influence grain size. The interplay of different controlling factors may explain the more irregular "sequences" or lack of sequences recorded in some drift deposits.

Muddy contourites are the most commonly encountered facies of modern oceanic drifts. Because they are generally structureless or homogeneous to the naked eye, typically with intense bioturbational mottling, they may easily be confused with hemipelagites or with thick muddy turbidites ("unifites" of Stanley, 1981). They are also very similar to the new mixed turbidite/hemipelagite facies described by Stow and Wetzel (1991) from the distal Bengal Fan and termed "hemiturbidites". It is only through detailed studies using X-radiography, grain-size analyses and compositional determination (Gonthier et al., 1984; Dowling and McCave, 1993; Leslie, 1993) that we can hope to make reliable distinction between these various deep-water facies. Muddy contourites are gradational with silty or mottled silty-mud contourites.

Deep drilling through the giant contourite drifts of the North Atlantic has encountered *bio-*

genic-rich contourites that are very similar to pelagic/hemipelagic deposits (Stow and Holbrook, 1984; Kidd and Hill, 1986, among others). They even display a marked cyclicity of biogenic carbonate content that appears to be climatically induced (i.e. Milankovich cycles).

Sandy contourites are relatively rare in the modern ocean. Apart from those associated with muddy contourite drifts, they occur mainly in particular morphotectonic environments where the bottom currents are very intense, such as deep-water sills and passages. They may be mainly terrigenous or biogenic (commonly planktonic foraminiferal tests), or of mixed composition and have either a homogenous/bioturbated aspect or display a distinct ripple cross-lamination (Faugères et al., 1985a). It is not always easy to distinguish them from any other current-worked sandy deposit such as outer shelf sands or thin sandy turbidites that are not clearly graded.

Several examples have been described from the present ocean basins of sediments resulting from an *interplay of turbidity and bottom-current* processes. In these cases, the contour currents may winnow the sands and transport the finer turbiditic material downstream as suspended load. The sandy portion of the turbidites are partly reworked to leave a top-cut-out turbidite sequence, overlain by a veneer of sandy–silty contourite of variable thickness (Stanley, 1993).

There is continuing debate on the role of bottom currents in the developments of deep-sea manganiferous sediments (Lonsdale, 1981). In some areas affected by bottom currents, manganiferous deposits are associated with various types of contourites. Where the currents are very active, like on the floor of deep valleys (Lonsdale and Malfait, 1974), manganese pavements, blocks and nodules are found, associated with patches of sandy contourites. Where more sluggish currents flow over a broad area of abyssal basin floor, and where pelagic carbonate accumulation is prevented by depths greater than the CCD, muddy sediments, including pelagic red clays, are deposited in association with manganiferous laminations and fine manganese nodules (Mézerais et al., 1993; Faugères et al., 1993). Should we term these sediments "*manganiferous contourites*" as their origin appears to be partly controlled by contour currents?

Contour-current bedforms and contourite drifts

Bedforms controlled by contour currents have been described in detail by many authors (Heezen and Hollister, 1971; Allen, 1982; Stow, 1982; McCave and Tucholke, 1986; Nowell and Hollister, 1985; Dorn and Werner, 1993; Haskell and Johnson, 1993; Mézerais et al., 1993; Nelson et al., 1993). They occur at a range of scales from large sediment waves and erosional furrows to small scale ripples, scour and tail marks, etc. Bedform assemblages have been related to bottom-current intensity (Hollister and McCave, 1984), although the exact processes of formation still remain questionable for some of them, especially for giant sediment waves.

According to different authors working in different areas, sediment waves may be parallel, perpendicular or at an angle to current flow; they may propagate downstream or upstream, and if they are formed on a gentle slope, they can migrate downslope or upslope (Hollister et al., 1974; Asquith, 1979; Lonsdale and Hollister, 1979; Embley et al., 1980; Kolla et al., 1980; Flood and Shor, 1988). Furthermore, sediment waves similar in dimensions and morphology to contour-current sediment waves, can be formed by turbidity currents. They are particularly common on deep-sea fans, where they may cover large areas of turbidite levees adjacent to the main channel axis (Normark et al., 1980). The waves tend to show an upslope and upstream migration. The problem of a contour-current or turbidity-current origin for sediment waves is highlighted by the examples from the Tyrrhenian Sea cited by Mariani et al. (1993).

From the many examples of modern contourite accumulation that have been recognised and studied in the ocean basins, we propose that three main morphological types can be identified (Faugères et al., 1993).

(a) *Giant elongate drifts*. At least fifteen large-scale drifts have been described from the North Atlantic alone where they occur at different depths, along both the continental margins and the flanks of the Mid-Ocean Ridge system. Various mechanisms of growth have been involved which explains the variations observed in their morphology and internal seismic patterns (McCave and Tucholke, 1986). They also occur in other oceans along passive as well active margins (Reed et al., 1987; Carter and Mitchell, 1987), and, in some cases, in a more central basin location.

(b) *Contourite sheets*. These sheet-like contourite drift systems appear to be deposited in fairly closed abyssal basins where the deep circulation is partly trapped (Egloff and Johnson, 1975; Flood and Shor, 1988). They may present a generally flat morphology, or be capped by a widespread field of sediment waves, including some less regular-shaped drift forms (eg. bifurcated-crest drifts). The growth patterns of such sheet drifts are not well-known.

(c) *Channel-related drifts*. These types of drift are quite varied according to their morphological location. Contourite lag-deposits associated with manganiferous sediments may be formed on the floor of the channel; contourite sediment waves may cover valley terraces at various elevations above the channel floor; both are of limited extent (Johnson, 1984). At the downstream exit of the channel, a rather larger area of contourite drift accumulation may form, in some cases having a distinct fan-like shape (Mézerais et al., 1993). Such sediment bodies, or *contourite-fans*, show certain characteristics that are similar to those of distal turbidite fans; i.e. the general fan morphology, the fine-grained muddy nature of the sediments, and the apparent growth by migration of contourite "channel–levee" systems displaying comparable seismic patterns and general downstream progradation.

Seismic patterns of contourite drifts

The nature of the seismic tools employed, the water depth and sea conditions during recording, and the type of processing employed, all affect the seismic records obtained. Nevertheless, it is clear that a generally transparent or structureless appearance is the most frequently observed seismic facies of giant contourite drifts, in some cases with a few prominent internal reflectors, as illustrated by numerous studies (mainly published in the D.S.D.P. volumes related to North Atlantic Legs). This is presumably due to the extremely fine-grained and homogeneous nature of the sediments. The top surface of transparent drifts may show a regular wavy reflector pattern and, in other cases, this sediment wave geometry is apparent through more of the drift thickness. As discussed earlier, such sediment waves reflect the depositional process from bottom currents, although they are not solely diagnostic of contourites as they can also be formed by turbidity currents.

Moderate to high amplitude subparallel reflectors occur within some drift sequences. Their interpretation must be more speculative because they may reflect either a change in sediment structure or texture, probably due to bottom circulation variations, or a slight change in sediment composition (relative proportions of calcareous versus siliciceous biogenic material, for example), more likely due to variations in the surface water masses and productivity.

Marked erosional surfaces are a common feature of bottom-current deposits and give the more prominent internal reflectors. Deep-sea drilling allowed many of such reflectors to be dated. Some of these surfaces have been correlated through the whole Atlantic or larger oceanic areas and correspond to major hydrologic events in the Cenozoic, linked to ice-sheet formation or to episodes of major growth in Antarctic ice (Tucholke and Mountain, 1986, among others). Although not all erosional surfaces are the result of intense bottom-current activity, especially if they are of limited geographical extent, they are certainly very characteristic of contourite drift deposits.

A number of examples have been described for which the seismic patterns show clear evidences of bottom-current deposition in the form of a *drift-moat morphology*. They have been called "separated drifts" by McCave and Tucholke (1986) and the whole system is typically seen to migrate upslope. Three different seismic facies may be identified (Faugères et al., 1985b): (a) a chaotic facies that corresponds to the moat-lag deposits; (b) a prograding lens facies with irregular laminated sediment downlapping onto the moat bottom; (c) a more regularly laminated facies, in some cases draped by sediment waves, on the back-side of the drift where the bottom currents are assumed to be more sluggish and the deposits more muddy. Such seismic patterns may be confused with turbidite "channel–levee" systems. However, the major difference is that, in the case of bottom-current processes, the entire sedimentary system migrates upslope or alongslope instead of downslope.

The interplay of turbidite and contourite deposits

It is clear that the interplay of downslope and alongslope processes is the rule rather than the exception for deep-water ocean-margin sedimentation. Even in isolated drift settings far from a continental source, the interbedding of thin far-travelled or local, seamount-derived turbidites must be expected. This interplay process is well illustrated on the eastern margin of North America, where numerous downslope channels deliver abundant terrigenous material to the rise, which is swept by an active Western Boundary Undercurrent below 4000 m depth (Tucholke and Laine, 1983; Tucholke and Mountain, 1986; Myers and Piper, 1988; McMaster et al., 1989; among others), and also along the Eastern margin of South America, where the Antarctic Bottom Water flow is known to intercept and rework material introduced by downslope processes (Ewing et al., 1971; Klaus and Ledbetter, 1988). However, distinction between the two processes, both at the level of seismic facies and sediment facies, is still not fully resolved. Some recent advances in our understanding of this problem have been made by Locker and Laine (1993), who describe models for what they call a "companion fan-drift" system, from the middle U.S. Atlantic margin, and by Stanley (1993) in his detailed analysis of bottom-current reworking of turbidites.

The influence of climate and sea-level changes

Still more problematic is understanding the relationship between global changes of climate and/or sea level, patterns of bottom water circulation that result and the consequent effect on the deposition/erosion of contourites (Haq, 1990).

Major *climatic changes* that produce alternating glacial and interglacial episodes do not appear to produce a simple global response in terms of bottom-current circulation (Corliss et al., 1986). This response will depend on latitude and on the morphological context, and will not necessarily be the same for both North Atlantic Bottom Water (NABW) and Antarctic Bottom Water (AABW).

There is good evidence that major build-up of sea ice over the Norwegian–Greenland seas inhibits the influx of surface water from the south and hence, dampens the production and outflow of Norwegian sea water. More limited deep circulation does occur around the Rockall and Iceland basins. However, it has been recently assumed that deep-water formation may locally occur in these basins at the end of the last Glacial (from $\delta^{18}O$ and $\delta^{13}C$ data: Duplessy, 1982; Duplessy et al., 1988; or from micro-grain-size data: Dowling and McCave, 1993), and thus glacial/interglacial transitions with unstable climatic conditions would be the episodes of strongest bottom circulation activity.

The effect of maximum extension of sea ice around Antarctica on bottom water production is equally unclear and directly opposite views can be cited. However, some studies support the idea of enhanced AABW circulation during interglacial periods and/or interglacial–glacial transition. (Ledbetter and Ciesielski, 1986; Ledbetter, 1986; Pudsey et al., 1988).

There is a complex linkage, also, between the two main cold water masses. For example, intensified production and southward dispersion of NADW introduces both a mechanical and climatic drive on the production and circulation of AABW (Kennett, 1982).

Perhaps, the most important response that has been demonstrated from a large amount of work on erosional, isotopic and other signatures from Cenozoic drift deposits, is that episodes of major increase in bottom circulation seem to correspond with periods of climatic instability or crisis. These lead to widespread erosional rather than depositional events within the contourite record.

Sea-level changes seem to have a more direct effect on the supply of terrigenous material to deep ocean basins and, as a consequence, an indirect effect on contourite deposition. During high-stands of sea level, much sediment is trapped on the shelf, turbidity-current activity is reduced and hence the record of bottom-current activity is better preserved. Low-stands of sea level, by contrast, tend to favour major downslope reworking of sediment and a consequent masking of bottom-current activity. Some recent work (Cremer et al., 1992, 1993) has proposed that the most important episodes of downslope resedimentation are during periods of marked sea-level change, especially during sea-level up-rising, rather than stand still, although evidence for this remains partly speculative.

A further effect of higher sea level is to favour the exchange of water masses, both surface and bottom, between marginal basins and the main ocean basins. This, in turn, would tend to enhance bottom-water circulation.

Conclusion

We have presented a brief survey, only, of a large amount of work that is currently in progress on contourites and bottom currents, and have focussed, in particular, on some of the topics that we believe require special attention in future research. From this survey, it is apparent that there are at least four major problems that should be addressed in any future study:

(a) How to extrapolate short-term measurements/observations of present-day systems to their cumulative effect over a geological scale, how to be certain that even the surface sediments/seismic features of contourites relate to existent bottom-current conditions.

(b) How to recognise contourites with certainty where they are interbedded with other facies and, most significantly, how to identify ancient contourites.

(c) How best to identify the overlap and interaction between bottom currents and other deep-water processes, and also between the different types of bottom current identified;

(d) How to confidently read the record of global changes in sea-level and climate, and of palaeocirculation patterns in the deep-oceans, from contourite drift deposits worldwide.

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