CHAPTER 17

Identification of Ancient Contourites: Problems and Palaeoceanographic Significance

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Contents

17.1. Introduction

Contourites are well established and well described from recent and sub-recent deposits throughout the world's deep ocean environments. In over 40 years of research, they have been amply described in terms of contourite drift architecture and seismic facies (e.g. Faugères et al., 1993, 1999; Rebesco and Stow, 2001), the erosional features and depositional bedforms associated with contour current flow pathways, and their specific sediment characteristics (e.g. Stow and Faugères, 1993, 1998; Stow et al., 2002c, f). The same cannot be said for their identification in ancient sedimentary series now exposed on land (Pickering et al., 1989; Shanmugam, 2000), although some further significant progress has been

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made in this direction since the problem of fossil contourites was critically reviewed for the last time (Stow et al., 1998a).

Many of the existing large-scale drifts present in the various oceans have now been drilled, principally during DSDP and ODP scientific expeditions spanning the past 35 years. Nearly 100 contourite drift sites were listed in the review by Stow et al. (1998a), the deposits drilled ranging in age from Eocene to recent. Together with a much larger number of gravity and piston cores recovered from these and other drift systems, they provide clear evidence of the nature and variability of contourite facies. Such data have been variously reported and synthesized in numerous papers (e.g. Stow and Faugères, 1993, 1998; Stow et al., 2002f) and form the basis of documenting the contourite facies in this volume (Giresse, 2008; Hernández-Molina et al., 2008a, b; Martín-Chivelet AU1 et al., 2008; Stow et al., 2008).

There also exists a growing body of examples of contourites in ancient rock series, ranging in age from Cambro-Ordovician to Neogene. Here, we review those case studies with which we are most familiar and for which the body of evidence used in their interpretation as contourites is most persuasive. We then discuss some of the important common attributes from these studies, preservation conditions of contourite deposits, and the paramount need for caution when trying to interpret ancient deep-water successions. It is important to note that controversy still surrounds the recognition and interpretation of (contour-current) reworked turbidites in ancient series (see Stanley, 1988b; Stow et al., 1998a, 2002a; Shanmugam, 2000). This problematic discussion is further detailed in other chapters of the present volume (see Martín-Chivelet et al., 2008; Shanmugam, 2008; Stow et al., 2008), but will not be addressed here.

17.2. Examples of Fossil Contourites

17.2.1. Neogene contourites, Miura–Boso region, SE Japan

The thick middle Miocene to Pliocene sedimentary succession, which is particularly well exposed along the coastline of the Miura and Boso peninsulas, south of Tokyo Bay in Japan, has been recently accreted to the main Honshu Arc from its former position as part of the Izu–Bonnin forearc (Soh et al., 1989, 1991; Taira and Ogawa, 1991). Within the mixed assemblage of predominantly hemipelagic and volcaniclastic sediments, which is known locally as the Misaki Formation and was originally deposited at bathyal depths on the forearc slope–apron system, detailed study has revealed the marked influence of bottom currents (Stow and Faugères, 1990; Stow et al., 1998b, 2002e). The intervals of muddy or calcilutitic contourites occur most notably in the light-coloured, fine-grained, background slope sediments, which are associated with distinct beds of dark-coloured, scoriaceous, volcaniclastic sediments, mainly deposited as turbidites, debrites and direct pyroclastic, sub-aqueous fall-out.

The principal characteristics of these contourite facies are as follows (Stow et al., 2002e):

- a notable absence of clear primary sedimentary structures, but presence of indistinct and discontinuous parallel lamination in parts;
- irregular concentrations and lenses of coarser-grained (silt/sand grade) scoriaceous and bioclastic material; some of these thin lenses show remnants of micro-cross-lamination and parallel lamination, now partially obscured by a bioturbational fabric;
- sharp and erosional contacts in places associated with the coarser-grained horizons, and locally as minor discontinuities (non-deposition surfaces) within the fine-grained facies;
- an ichnofacies assemblage dominated by *Chondrites, Helminthoides, Planolites* and *Zoophycos* within an intensely bioturbated sediment; below localized omission surfaces, the ichnofacies include small-scale vertical and sub-vertical traces.
- a mean grain size of clayey silt, poorly sorted with dispersed sand-sized material and localized concentrations of slightly better sorted coarse silt and sand; cyclic grain-size variations evident over intervals of approximately 10–100 cm;
- a mixed composition of biogenic and volcaniclastic material; the biogenic fraction is dominated by pelagic foraminifers, nannofossils, diatoms and radiolarians, mixed with relatively fewer benthic and shallow-water fossils, in some cases fragmented and iron-stained; the volcanic material is mainly pumiceous glass, devitrified glass and resultant clays, with minor amounts of basaltic scoriaceous grains.

Although the Misaki Formation contourites are well preserved in terms of detailed sedimentary characteristics, the accretion process generated considerable structural complexities and sequence repetition onto the Honshu Arc. This has made it impossible to reconstruct regional distribution of facies associations or thickness variations and hence to reconstruct a meaningful original depositional geometry. The obvious slope setting and intercalated deposits of turbidites and debrites suggest a closely interbedded system of down-slope and along-slope facies. Down-slope facies were evidently derived from the Izu–Bonin Arc, which lay to the west of the slope system, based on dominant palaeocurrent directions and magnetic-fabric measurements (Kanamatsu, 1995; Lee and Ogawa, 1998). Similar magnetic-fabric measurements in the fine-grained facies show mixed current directions to the SSE, NNW and NE, which are not incompatible with an element of along-slope transport by bottom currents.

17.2.1.1. Palaeoceanography

For the late Neogene, the palaeoceanographic reconstruction is generally very good so that we can be confident that the Misaki Formation sediments were originally deposited on the Pacific-facing slope of the Izu–Bonin Arc. The older part of the succession would have started out several hundred kilometres further south, followed by slow, steady northward movement. Ancestral precursors of both the southward flowing North Pacific Deepwater and (probably) northward-flowing Antarctic Bottom Water would have been in existence at this time, and both would, as can be deduced from comparison with measurements of the equivalent present-day deep-water current systems (Lee and Ogawa, 1998), have been capable of moving at least relatively fine-grained sediment along the Izu–Bonin slope. Whereas the ancestral Kuroshio surface current would also have existed and been capable of affecting sedimentation at depths in excess of 2000 m (Taft, 1978; Stow et al., 2002e, f), its influence is unlikely to have extended far enough south for the onset of contourite deposition as noted in the Misaki Formation.

17.2.1.2. Problems

We recognize three principal problem areas with respect to this case study.

1. The sedimentary features of these fine-grained contourites are very subtle, as is generally the case in ancient contourites, and although the authors have followed the full three-stage approach recommended by Lovell and Stow (1981) and Stow et al. (1998a); evidence based on regional and large-scale considerations is not unequivocal. These lines of enquiry indicate the potential of, rather than requirement for, contourite deposition.
2. Whereas most of the detailed facies characteristics strongly suggest contourite deposition, the cause of cyclicity in grain size remains uncertain. It is unclear to what extent it may be the result of long-term fluctuations in the mean bottom-current velocity, and to what extent a function of variable input of the coarser-grained volcaniclastic fraction. There is evidence that both were involved.
3. Most of the coarse-grained scoriaceous beds show clear evidence of primary deposition from down-slope processes, but as bottom currents were also active at this time, it is possible that the top parts of some turbidite beds have been reworked by along-slope processes. Direct evidence for this has been proposed by Lee and Ogawa (1998), but has been disputed by Stow et al. (1998b). The question remains unresolved to date.

17.2.2. Carbonate contourite drift, oligocene palaeoslope, Cyprus

The late Cretaceous to early Miocene Lefkara Formation is well known to have been deposited over newly formed oceanic crust (Cretaceous ophiolite sequence) of the Tethys Ocean (Malpas et al., 1990; Robertson, 1990). It forms a mostly continuous succession, up to some 600 m thick, and is relatively free from tectonic deformation, except where it abuts most closely the now exposed crustal basement rocks. Whereas pelagic biogenic sediments dominate throughout, they are intercalated with a series of both carbonate and siliceous turbidites that are more common in the lower two-thirds of the formation. The Lefkara Formation passes gradationally upwards into the Pakhna Formation, which was deposited on the flanks of the Troodos ophiolite complex that was being uplifted, and therefore shows progressive upward shallowing (Roberston, 1990; Stow et al., 2002d).

First proposed by Robertson (1976) and later identified by Kahler (1994), contourites are recognized within the upper part of the Lefkara Formation. Considerable work has now been undertaken to fully characterize these deposits (Kahler and Stow., 1998; Stow et al., 2002e; Turnbull, 2004), and so designate them as a type example of mainly Oligocene contourites (Figure 17.1). The associated facies are principally calcareous biogenic pelagites, and some rare, more

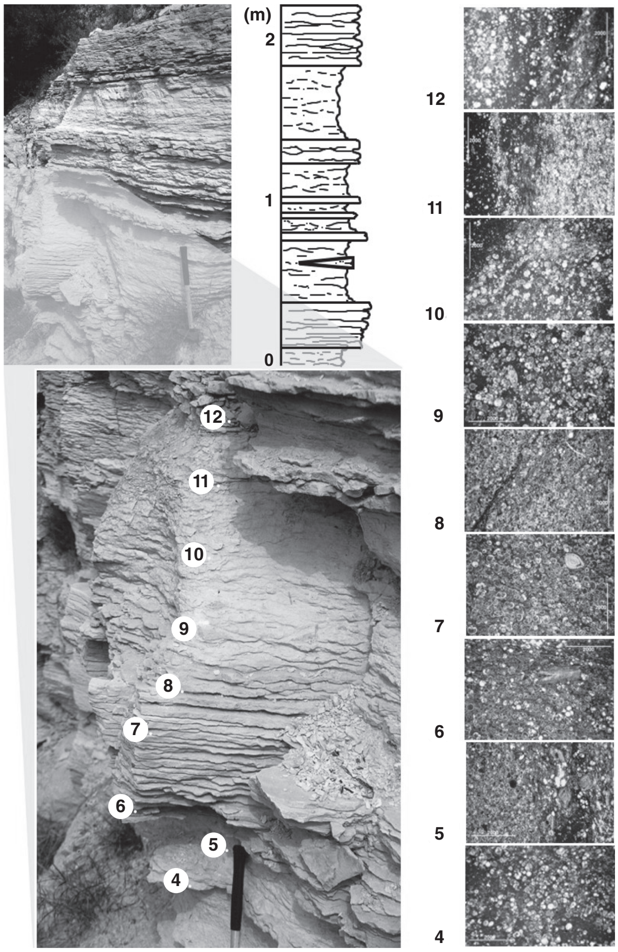

Figure 17.1 Oligocene calcareous sediments interpreted as calcicontourites, Petra Tou Romiou, southern Cyprus. Detailed log of section shown in photograph, together with representative microfacies at sample points 4–12 (from Turnbull, 2004, with permission). Cyclic grain-size variations evident over approximately 50 cm of the section, between bioturbated calcilutite and lenticular calcarenite macrofacies. Thin-section micrographs show a clear sequence from wackestone with pelagic foraminifers and nannofossils (4), through fine-grained, well-sorted packstone, with lenses including benthic foraminifers, shallow-water algal and echinoid debris (5–8), and back to wackestone (9 and 10). A multicolour version of this figure is on the included CD-ROM.

silty clay-rich hemipelagites. Some thin-bedded calcareous turbidites and probably reworked turbidites have been identified in parts of the contourite succession.

The principal characteristics of these calcareous contourite facies are as follows (Stow et al., 2002d; Turnbull, 2004):

- there are three main facies: a fine calcilutite, generally structureless but with some faint discontinuous laminae, and lenses of calcisiltite; a more clay-rich calcilutite (or marl), which is too strongly weathered to still exhibit detailed features; and a

calcarenite/calcisiltite with a distinctive thin-bedded lenticularity and only very rare internal lamination and cross-lamination (Figure 17.1);
- in addition to an ubiquitous small-scale lenticularity, the calcarenite facies shows in places what may be interpreted as shallow scours (2–10 cm deep) into the underlying calcilutites, and larger-scale lenses (up to 30 cm thick and several metres in lateral extent);
- for the most part, the sediments are thoroughly bioturbated and burrowed; distinct burrow traces include small-scale *Chondrites*, *?Helminthoides*, and less regular micro-traces, as well as larger-scale forms including *Planolites*, *Thalassinoides* and sub-vertical *Ophiomorpha*, the latter typically developed below a probable omission surface;
- original grain-size attributes are partially obscured by carbonate diagenesis, but the size variation between calcilutite and calcarenite most likely reflects the original conditions, and hence the clear but irregular cyclicity that occurs on a decimetre scale between these two facies and is interpreted as the result of fluctuations in the mean bottom-current velocity, leading to winnowing, cleaning and sorting of the calcarenites;
- the contourite microfacies are dominantly packed biomicrites (including wackestones and foraminiferal packstones, with the finer beds and pelagites being sparse biomicrites). Much of the finer fraction is now diagenetic micrite with relict coccolith plates, whereas the coarser fraction, dominant in calcarenite facies, is better preserved. This includes dominant pelagic foraminifers (*Globergerina* sp.), together with a variable admixture of benthic foraminifers, radiolarians, echinoid spines, calcareous red algae and terrigenous grains (quartz, mica, feldspar and ferromagnesian minerals). Bioclast fragmentation and iron staining is common.

At a regional scale, certain aspects of the upper parts of the Lefkara Formation are significant in supporting the contourite interpretation. The Upper Marl unit shows a notable variation in thickness across southern Cyprus from little more than 10 m to over 200 m, which Stow et al. (2002d) interpret as most likely due to deposition as part of a contourite drift system. There is also a widespread hiatus (or hiatuses) in sedimentation, which is variable in duration but everywhere present for the mid-Oligocene interval, below or within the Upper Marl unit (Kahler, 1994). The distinctive lenticular calcarenite facies is present immediately above the Upper Marl unit in all sections so far examined across southern Cyprus over a lateral extent of some 80 km. This is interpreted as the result of bottom-current intensification, simultaneously over an extensive area.

17.2.2.1. Palaeoceanography

Tectonic reconstruction of the region shows that the Lefkara Formation as a whole was deposited in the closing Tethys ocean, in a basin plain to distal slope–apron setting (Robertson et al., 1991; Kahler and Stow, 1998; Robertson and Comas, 1998). Palaeodepths have been estimated as between 2000 and 3000 m, and land was at least 50–80 km away to the north. The nature of bottom circulation in the closing Tethys during the Oligocene is not well known. Earlier in the Palaeogene, almost certainly warm, saline bottom waters flowed from east to west through the Tethys Seaway, as did a strong surficial flow of the Tethyan Current. It is a matter of debate just how long this circulation pattern lasted, and to what extent the growing development of cold, deep waters generated at high latitudes influenced the region. Stow et al. (2002d) believe that continued constriction of the Tethys at this time led to intensification of both surface and bottom-current systems and that this is reflected in the development of regional hiatuses and contourite drifts.

17.2.2.2. Problems

The overall interpretations of this Oligocene succession on Cyprus that we suggest are supported by evidence at the small, medium and large scale, and constitute one of the better examples of ancient contourites. The main problems remaining are largely related to the nature and effects of diagenetic modifications to the original facies:

1. diagenesis of carbonates typically yields dissolution seams of softer marly layers between well-cemented horizons, and it is uncertain to what extent the lenticular bedding characteristic of the calcarenite contourites results from dissolution and to what extent it reflects an original depositional fabric; similarly, the larger-scale scours, calcarenite lenses and omission surfaces may have all been affected in part by diagenetic dissolution.
2. the exact nature of grain size characteristics is also obscured by subsequent diagenesis, but the cyclic variation in facies and grain size is believed to reflect the original distribution.

17.2.3. Carbonate contourite drifts, Late Cretaceous–Palaeocene Chalk Group, Danish Basin

Distinct Santonian–Maastrichtian seismic units of the Late Cretaceous chalk in the Danish Basin have, based on seismic profiles in the Kattegat and Øresund areas (Lykke-Andersen and Surlyk, 2004; Esmerode et al., 2007; Surlyk and Lykke-Andersen, 2007), been interpreted as contourites deposited in an epeiric sea. The seismic stratigraphic sequence boundaries were tied to lithostratigraphic and chronostratigraphic information obtained from boreholes and the coastal cliff at Stevens Klint outside the principle contourite area. Topographic elements such as moats, channels, sediment wave fields, and elongate mounded and sheeted drifts have been identified. Large erosional channels are also known from outcrops of the Normandy coast of NW France (Quine and Bosence, 1991) and southern England (Evans et al., 2003).

The Cenomanian–Danian Chalk Group in the North Sea and the Danish Basin was deposited in a relative deep epeiric sea (300–800 m), considerably deeper than the 300 m water depth generally suggested as a minimum for contourite deposition (Stow et al., 2002c). The NW–SE trending Sorgenfrei–Tornquist Zone formed an important and influential elongate topographic ridge with a SW-facing slope, separating a northeastern shallow shelf from the deeper Danish Basin towards the SW (Figure 17.2).

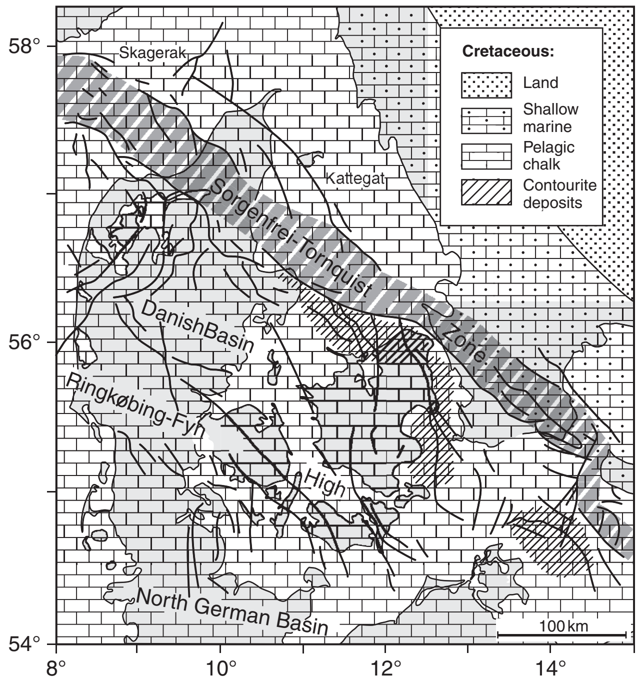

Figure 17.2 **Map of Denmark and adjacent areas indicating the Late Cretaceous epeiric sea with the inferred contourite systems and the position of main structural elements (from Surlyk and Lykke-Andersen, 2007, and Esmerode et al., 2007, with permission from the Geological Society, London). Light grey background indicates modern geography; the Sorgenfrei–Tornquist Zone is shown in dark grey.**

In the Kattegat area, a deep moat adjacent to the topographic ridge formed over the inverted NW–SE trending Sorgenfrei–Tornquist Zone (Surlyk and Lykke-Andersen, 2007). During the Maastrichtian, the moat was up to 120 m deeper than its southwestern flank that was formed by an internally complex elongate drift passing distally into a drift sheet (Figures 17.2 and 17.3). Moat-related patch drifts, channels, and elongate multicrested drifts and waves occur in addition to the large-scale features.

The current is interpreted, on the basis of the internal architecture of the elongate drift and the NW-ward branching and decrease in moat relief, to have flowed from the SE towards the NW. The region of highest current velocity was gradually shifted NE-wards towards the inversion zone ridge, resulting in the formation of the deep moat in the Kattegat area flanked by the elongate drift along its southwestern margin.

In the Øresund area, a system of major WNW–ESE oriented ridges and valleys reflects the influence of strong bottom currents (Lykke-Andersen and Surlyk, 2004). The ridge/valley system can be traced into the succession exposed at Stevens Klint, where it corresponds to the relief of the Cretaceous/Palaeogene boundary. High-resolution seismic structures are interpreted to represent real topographic

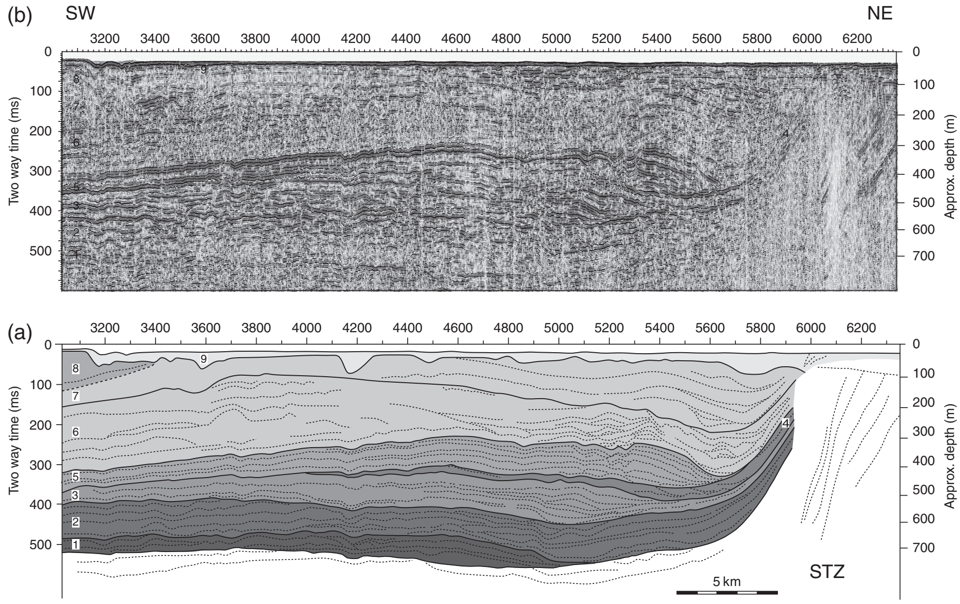

Figure 17.3 Section K90-4b crossing northeastern parts of the Danish Basin and parts of the inverted Sorgenfrei–Tornquist zone in the Kattegat area. Note the alternation between relatively sheet-like units (2, 4 and 6) and units showing marked wedging and clinoform bedding towards NE (1, 3 and 5) considered diagnostic of contourite drift formation. STZ = Sorgenfrei–Tornquist Zone. (a) Seismic section. Seismic units 1–6: mainly Maastrichtian (and uppermost Campanian?); 7: Danian; 8: Selandian; 9: Pleistocene and Holocene. (b) Its seismic stratigraphic interpretation (after Surlyk and Lykke-Andersen, 2007, with permission from Blackwell Publishing). A multicolour version of this figure is on the included CD-ROM.

elements of the Late Cretaceous sea floor, including: a complex mounded drift (late Maastrichtian), a sediment wave complex (late Santonian–early Maastrichtian), an elongate moat–drift system (Campanian) and erosional scours or channels of a major unconformity (late Campanian–early Maastrichtian) (Esmerode et al., 2007).

The regional-scale unconformity separates two intervals of dominant drift sedimentation and indicates the presence of strong or more focused bottom currents during the late Campanian to early Maastrichtian, coinciding with a stage of significant Late Cretaceous transgression (Haq et al., 1987). The erosive event was more pervasive in the northeastern part of the Øresund area, i.e. closer to the southwesterly dipping slope of the Sorgenfrei–Tornquist Zone. This supports the idea of a main contour current flowing northwestward through the area with a positive lateral velocity gradient towards the slope, generated by the Coriolis force (Esmerode et al., 2007).

The complex mounded drift (~15 km long and up to 160 m thick) comprises wedge-shaped seismic units that show opposing migration directions. The units are interpreted to represent intervals during which the current axis shifted laterally across the Øresund area (Esmerode et al., 2007). The internal architecture and the crests of the sediment waves (~2 km in wavelength and up to 30 m in amplitude) trend roughly parallel to the basin margin.

17.2.3.1. Palaeocirculation

Lykke-Andersen and Surlyk (2004), Esmerode et al. (2007) and Surlyk and Lykke-Andersen (2007) consider the Late Cretaceous epeiric current system of the NW European "chalk sea" as analogous to thermohaline current systems flowing parallel to the contours of continental margins and being responsible for modern contourite deposition. The slope of the Sorgenfrei–Tornquist Zone acted as an analogue to a continental margin during the Late Cretaceous high sea-level stand. The rise in sea level caused a worldwide overstepping of the Early Cretaceous basin margins and the opening of seaways linking the colder water Arctic and Barents Shelf with the warmer water North Atlantic and the warm water Tethys ocean (Ziegler, 1990). The bottom currents affecting the Danish Basin probably had their origin in warm shallow shelf waters along the northern margin of the Tethys Ocean. Strong thermohaline circulation would be initiated with the formation of northwestward flowing bottom currents that crossed the European epeiric sea due to the density difference between the warm salty waters of the northern Tethys and the colder but probably less saline waters of the North Atlantic.

17.2.3.2. Problems

Identification of these Late Cretaceous contourites is based mainly on medium- and large-scale features such as regional variations in thickness, unconformities, drift geometry, elongation and propagation trends, palaeoceanographic features, continental reconstructions and basin location. Unfortunately, hardly any small-scale criteria such as sediment facies characteristics and distinctive micro-sequences are provided by the authors. Neither gamma-ray logs nor sedimentary logs indicate a facies change at the Campanian/Maastrichtian regional unconformity in the Øresund area. Self-potential and resistivity curves vaguely indicate the presence of slightly coarser material at and above the unconformity surface, which may represent reworked and winnowed deposits (Esmerode et al., 2007). Referring to erodibility experiments on modern pelagic carbonate ooze (Black et al., 2003), however, Surlyk and Lykke-Andersen (2007) argue for a very low threshold stress for entrainment of chalk ooze due to the non-spherical nature of coccolith platelets. Non-deposition and erosion of pure chalk ooze probably resulted from current velocities of 8–20 cm s^{-1} at approximately 20 m above the sea floor.

17.2.4. Carbonate contourites, Devonian pelagic successions, Europe and North Africa

Oczlon (1990) highlighted the fact that condensed sections and stratigraphic hiatuses are widespread and extensive in Middle (to Late) Devonian successions of Europe and North Africa, and interpreted the related disconformities as erosional features caused by strong bottom currents. He claimed various siliciclastic and carbonate formations in Algeria, Morocco, France, Spain, Germany and Czechia as examples of contourites that are bounded by such disconformities. Unfortunately, the sedimentary characteristics have been insufficiently specified and the criteria used by Oczlon (1991, 1994) for recognition were those of Hollister and Heezen (1972), which date from the early, erroneous interpretations of many fine-grained turbidite successions as contourites (see Stow and Lovell, 1979; Pickering et al., 1989; Stow et al., 1998a).

Nevertheless, recent work by Hüneke (2001, 2006, 2007a, b) has demonstrated that there are contourites bordering such hiatuses within otherwise pelagic and hemipelagic successions. Based on a combination of sedimentological evidence, facies and microfacies interpretation, taphonomic observation, biostratigraphic age control and correlation, Hüneke (2001, 2006, 2007a, b) provides clear evidence of ancient carbonate contourites in the Givetian–Frasnian successions of the Moroccan Central Massif, the Harz Mountains in Germany and the Carnic Alps in Austria/Italy. In all cases, the contourites are associated with phosphatic hardgrounds and phosphorites.

Grain-size analysis and sediment characterization are based on thin sections of closely sampled successions. Locally, the formation of neomorphic sparite is a limiting diagenetic phenomenon, but non-carbonate particles provide a point of reference for the primary grain size of calcite particles (Figure 17.4). By analogy with modern contourite facies, calcarenites, laminated calcisiltites as well as mottled calcisiltites and calcilutites have been distinguished (Hüneke, 2007a). Calcarenites are mainly represented by styliolinid grainstones to packstones with rarely preserved horizontal and cross-lamination (Figure 17.5). Laminated calcisiltites are particularly rich in non-carbonate components with a higher density than calcite (conodonts, phosphatic intraclasts). Grain fragmentation and reworking of older bioclasts are evident. Both calcarenites and laminated calcisiltites show generally faint structures indicative of current-induced deposition, together with bioturbation throughout. Burrow mottled calcisiltites and calcilutites formed under conditions of weak currents.

Parts of coarsening-upward and fining-upward micro-sequences are best preserved in the Moroccan record. These micro-sequences are mostly between 2 and 10 cm thick, and in many cases include an omission surface, which separates the top of the coarsening-upward interval from the base of the fining-upward interval (Figure 17.6). The vertical facies variation can be interpreted in terms of fluctuations in velocity of the transporting bottom currents or shifts of the current axes, whereas the nature and distribution of components result from both long-lasting phases of high current strength and the fragility of the biogenic particles (Hüneke, 2007b). The transition from mud- to grain-supported textures within the coarsening-upward unit obviously represents the waxing phase of the current. As the current continues to accelerate, the non-cohesive bioclastic sediment may easily be reworked. Repeated and long-lasting high current velocities favour sediment bypassing and the formation of pristine or condensed phosphorites (see Föllmi, 1996). Concurrently, thin-shelled biogenic tests such as styliolinids became more

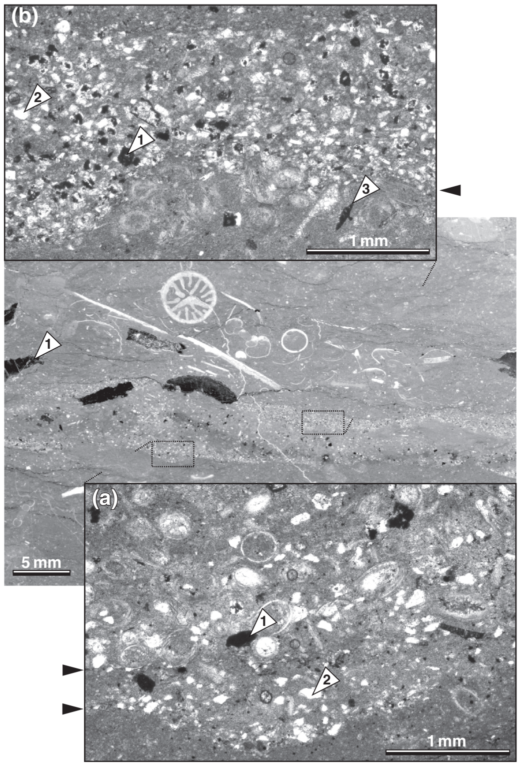

Figure 17.4 Early Frasnian limestones interpreted as calcareous contourites, Gara de Mrirt, Moroccan Central Massif. Thin sections show microfacies of mottled calcisiltites and calcilutites (bioclastic wackestones) and laminated calcisiltites at sample point M52 (see Hüneke, 2007). Indistinct lamination and non-deposition surfaces are partly obscured by bioturbational mottling. (a) Bioclastic wackestones overlain by laminated calcisiltite. (b) Styliolinid packstone blanketed by calcisiltite showing normal grading. Black triangles at photograph margin indicate non-deposition surfaces. Erosional character is well preserved since pressure-dissolution seams apparently do not mask facies boundaries. The laminated calcisiltites are particularly rich in phosphate intraclasts (1), quartz (2), feldspar and conodonts (3). Grain-size of non-carbonate particles indicates that carbonate diagenesis has not substantially modified the original grain size of the coarser carbonate fraction, whereas much of the finer fraction is now diagenetic micrite.

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and more fragmented. As the current waned, there were hardly any sand-sized particles left and silt-sized bioclasts were first deposited with subsequent calcareous mud deposition.

Regional trends and other medium-scale characteristics are compatible with a contourite interpretation. Overall, very low net accumulation rates prevailed during bottom-current-induced deposition, bypassing or erosion. Strongly condensed successions with distinctive reduced intervals and biostratigraphic hiatuses, which occur mainly at the base of the bottom-current deposits, characterize the Givetian and early Frasnian record, in contrast to the more expanded and

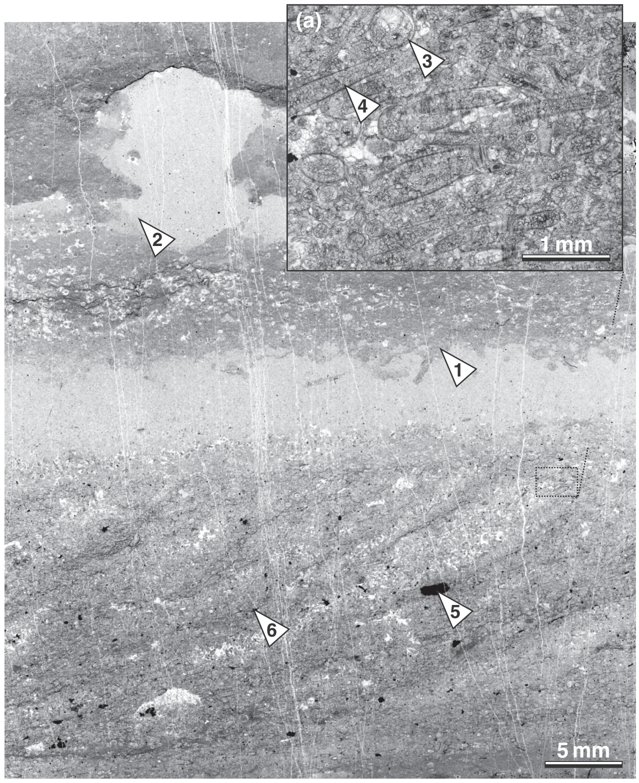

Figure 17.5 Early Frasnian limestones interpreted as calcareous contourites, Gara de Mrirt, Moroccan Central Massif. Cross-laminated calcarenite (styliolinid grainstones–packstones) overlain by mottled calcisiltites and calcilutites (styliolinid wackestones, bioclastic wackestones) at sample point MG1 (see Hüneke, 2007). Note burrowed/mottled omission surface (1) and palimpsest biogenic traces (2). (a) The calcarenite is represented by styliolinid grainstones–packstones. The thin section is oriented perpendicular to the bedding and traces of the cross-lamination run at an angle from upper right to lower left. Nearly all the conical styliolinid shells have their long axis oriented perpendicular to the slip-face dip direction (3; O-shaped sections) but an orientation with the frustum of the cone in dip direction (downcurrent) is common, too (4; V-shaped sections). Pore space is mainly filled by radiaxial acicular calcite. Phosphorite intraclasts (5) and conodonts (6) commonly occur within the calcarenite facies.

complete sequences of older and younger deposits. In addition, erosional surfaces and hardgrounds are widespread. Marked variations in thickness, accumulation rates, volumes of eroded sediment, and microfacies of the principle fossil contourite units have been documented across the three regions. Stratification types of the associated phosphatic sediments give additional evidence of increased hydraulic energy. These features are best compatible with moat areas of contourite drifts that experienced bottom currents with higher velocities and more marked erosion than the drift crests (see Faugères et al., 1993; Stow et al., 2002c).

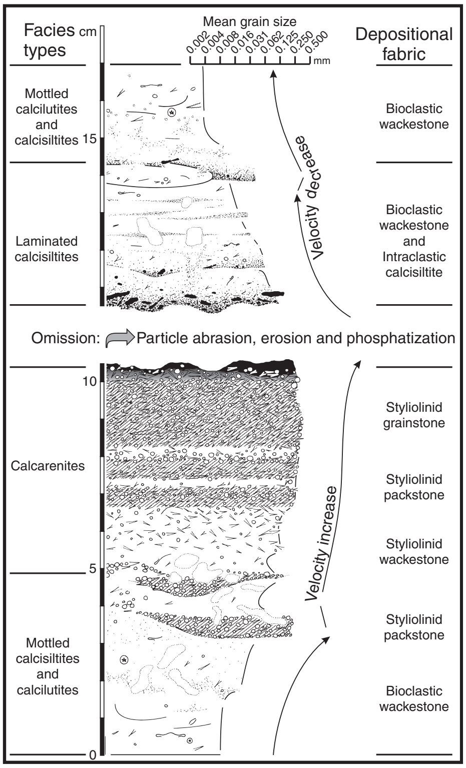

Figure 17.6 Composite facies model for Devonian bottom-current deposits showing the complete vertical superposition of a coarsening-upward and a fining-upward micro-sequence (see also Hüneke, 2007b). These idealized micro-sequences are between 2 and 15 cm thick and include in many cases an omission surface in between. The variation in mean grain size, composition and depositional texture is interpreted as recording an increase and decrease in bottom-current velocity, respectively, for the coarsening-upward and fining-upward micro-sequence. Oblique hatching (light blue in the coloured figure in the CD-ROM) indicates calcarenites that are cemented by coarse sparry calcite (packstones–grainstones). A multicolour version of this figure is on the included CD-ROM.

17.2.4.1. Palaeocirculation

Bottom-current-induced deposition occurred contemporaneously in different settings of the narrow oceanic passageways between the approaching continents of Gondwana and Laurussia (Figure 17.7). The areas affected were the southeastern Rhenish Sea shelf, which occupied the distal passive margin of Laurussia, the disintegrated northern continental margin of Gondwana, whose sedimentary record is now preserved in the Moroccan Meseta, and deep marginal plateaus of the Noric Terrane in the western part of the Prototethys (Hüneke, 2006, 2007a). While the contourite accumulation in the Harz Mountains and the nappe of Ziar–Mrirt occurred on pelagic carbonate platforms, the reworking in the Carnic Alps occurred in proximity to a carbonate slope–apron system. The contemporaneous occurrence and the likelihood of bottom currents according to the

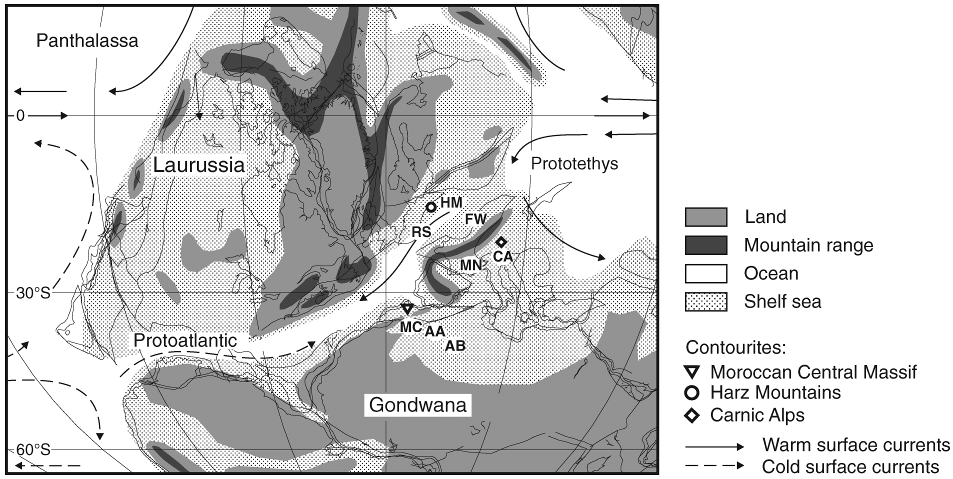

Figure 17.7 Palaeogeographic reconstruction of Laurussia and northern Gondwana during the Givetian–Frasnian (370 Ma), showing expected pattern of oceanic surface circulation as well as distribution of deep-sea, shelf-sea, land and mountain ranges (from Hüneke, 2006, with permission from the Geological Society, London). The map is based on reconstructions by Kiessling (in Copper, 2002) and Golonka (2002). Pelagic successions of Europe and northern Africa that include hiatuses at the Givetian/Frasnian boundary are sedimentary records of Gondwana (MC = Moroccan Central Massif; AA = Anti-Atlas; AB = Ahnet Basin), the Armorican terrane assemblage (MN = Montagne Noire; FW = Frankenwald), the Noric terrane (CA = Carnic Alps) and Laurussia (RS = Rhenish Slate Mountains; HM = Harz Mountains). A multicolour version of this figure is on the included CD-ROM.

palaeogeographic reconstruction both support, independently, the interpretation as ancient contourites.

The nature of bottom circulation within the oceanic passages between Gondwana and Laurussia during the Devonian is not well known. Contrasting palaeotectonic–palaeogeographic models are the main reason (Ziegler, 1989; Scotese and Mc Kerrow, 1990; Golonka, 2002; Stampfli and Borel, 2004; Torsvik and Cocks, 2004). Among them, close-fit reconstructions explain the Givetian/Frasnian circulation event most convincingly. Under such conditions, the time span witnessed constriction of the main surface flow from the Prototethys to the Protoatlantic (Hüneke, 2006, 2007a). It seems most likely that continued constriction of the oceanic seaways led to an intensification of the westward-directed oceanic current, which was therefore capable of influencing sedimentation at greater depths. Alternatively, there may have been a deeper counter flow to the east. According to the principle of continuity, a broad and thin surface current which has to pass a narrow oceanic strait may accelerate or swell to greater depth (Brown et al., 1991). Under both circumstances, the sediment accumulation in pelagic depositional environments would have been strongly affected, particularly on the top of topographic highs.

This intensified exchange of warm saline water and cold less saline water between the equatorial ocean in the northeast and the sub-polar oceanic realm in the southwest ended during the middle Frasnian, when continued convergence between Gondwana and Laurussia led to firm contact of their continental margins (e.g. Ziegler, 1989; Golonka, 2002).

17.2.4.2. Problems

In general, the interpretation of these Devonian fossil contourites is well supported by evidence at three different scales of observation. The principal problems mainly relate to the relative age of the deposits as follows.

1. Diagenesis in older carbonate successions becomes progressively more intense so that many of the original depositional features may become obscured. Nevertheless, the centimetre-scale cycles of grain size, structure and compositional variation are very similar to the standard mud–silt–sand contourite sequence of Stow et al. (2002c). The coarsening-upward micro-sequences of the Moroccan case may be considered as base-only partial sequences (C1–3), and the fining-upward micro-sequences may be referred to as top-only partial sequences (C3–5). The main differences compared to the standard sequence are those in the Moroccan example: (1) the coarsening-upward and fining-upward micro-sequences are commonly separated by a sharp contact or erosional surface, which may be phosphatized; and (2) the overall sequence is on a rather smaller scale than that of the sequence model. However, both these aspects can be related to deposition under relatively high-energy currents.
2. Further work is required on these examples as well as on comparable Devonian successions elsewhere in related depositional areas to reconstruct the shape and 3-D geometry of the entire sedimentary bodies and to find reliable indications of palaeocurrent directions. However, the tectonically disturbed stratification – due to the Variscan deformation in the studied areas – makes a geometric reconstruction of the contourite drift bodies very difficult.
3. Precise palaeoceanographic reconstructions are notoriously difficult for the Palaeozoic, and hence the discussion of bottom-current patterns and influence is less rigorous than for the Cenozoic, for example. Nevertheless, we are confident that the inferred palaeocirculation pattern is correct.

17.2.5. Carbonate contourites, Ordovician Jiuxi Drift, China

An ancient carbonate contourite drift has been identified within an Early Ordovician deep-water succession in the Hunan province of China, near Jiuxi on the Yangtze Platform (Duan et al., 1993; Luo et al., 2002). Its recognition is based on small-, medium-, and large-scale criteria as set out by Stow et al. (1998b, 2002c).

Analysis of field data, thin sections and polished slabs reveal that the general sedimentary characteristics of the Jiuxi Drift deposits are typical of those described from many modern drift systems (Luo et al., 2002). The main contourite facies are bioturbated calcilutites and burrow-mottled calcisiltites, both of which show some irregular discontinuous lamination, together with a lesser proportion of irregular laminated and highly bioturbated calcarenites.

These occur in repeated coarsening-upward to fining-upward micro-sequences typically 30–80 cm thick, locally up to 2 m. Possible calcirudite contourite lag deposits and coarser-grained bioclastic contourites are also identified. The bioclastic contourites usually form lenticular beds and comprise grains of a varied assortment of biogenic debris (pelagic, benthic and resedimented origin) and some non-biogenic admixtures (terrigenous clays and rounded quartz grains).

Based on detailed logging and on fourteen sections, the geometry of the contourite body has been reconstructed (Duan et al., 1993). The Jiuxi contourites form a distinct mound-like drift some 350–450 m thick elongated parallel to the southern continental margin of the Yangtze Terrane. It accumulated at a sedimentation rate of 35–40 m Ma^{-1}. Features of traction flow coupled with intense bioturbation and along-slope current indicators support a bottom-current origin. Large-scale cross-stratified units found in parts of the calcilutitic contourite section are believed to result from sea-floor development of mud waves and/or erosion furrows under the influence of a semi-permanent bottom-current regime (Duan et al., 1993). In addition, pelagites, hemipelagites and distal turbidites make up a small proportion of the drift.

The Jiuxi Drift formed during the Tremadocian along the relatively stable passive margin in an inferred mid-slope position south of the Yangtze shallow-water carbonate platform (Luo et al., 2002). The depositional area had been a deep-water environment dominated by gravity flows since the Middle and Late Cambrian, and continued to receive some carbonate shallow-water debris during the early Ordovician global sea-level rise. The drift formation may have been prompted both by the rise in sea level and by a change in strike orientation of the slope from SW–NE to more or less E–W.

17.2.5.1. Palaeocirculation

The Yangtze Terrane and related continental blocks of China were probably incorporated within or close to the Australian–Antarctic section of east Gondwana, which spanned a large part of the southern hemisphere and was continuous from the south pole to equator (Metcalfe, 1996). The Jiuxi contourite drift formed in close proximity to the western Gondwanan shelf margin at low palaeolatitudes. The low palaeolatitude of the Yangtze Terrane gave way to bryozoan, lithistid and *Calathium* reef growth on the bordering shallow, warm-water Yangtze platform during the Tremadocian (Webby, 2002).

The palaeogeographic reconstructions suggest that the slope of the Yangtze Terrane was influenced by the Eastern Boundary Current of the Palaeo-Asian Ocean at low northern latitudes (Golonka, 2002; Rowland and Shapiro, 2002; Webby, 2002). This southward-directed surface current transported cool water towards the equator, similar to the California Current in the western Pacific today. By analogy with recent conditions (e.g. Cornuelle et al., 2000; Bograd et al., 2001), we should take the view that much of the transport occurred as "squirts and jets": upwelling centres associated with capes and promontories, offshore transport in intense jets deep into the epeiric seas, and a vigorous field of meso-scale eddies that affected the slope of the Yangtze continental margin.

17.2.5.2. Problems

The three principal concerns we have with respect to this interpretation of the Ordovician contourites relate in part to their age and in part to some of the facies interpretations.

1. As already noted, diagenesis in older carbonate successions obscures many primary features. Most of those described from the Jiuxi Drift appear compatible with a contourite interpretation, although the presence of large-scale cross-stratification and its interpretation as the result of sediment waves or erosional furrows remain speculative. We know of little modern data of comparable type that would help support the authors' interpretation (see Martín-Chivelet et al., 2008).
2. The regional context and variation in unit thickness certainly appears to conform with a mounded-drift geometry. However, there must remain some caution concerning the rigour of dating and correlation between measured sections, and whether or not tectonic factors may have influenced variations in section thickness.
3. More crucial for contourite-drift formation, the nature of bottom circulation during the Ordovician is not well known. The period is part of Fischer's (1981, 1984) global late Cambrian to Devonian greenhouse state, with oceanic modes represented by warmer seas, gentler latitudinal and vertical gradients, sluggish circulation, an expanded oxygen minimum zone below the thermocline, and higher sea levels (Fischer and Arthur, 1977; Martin, 1996). Berry and Wilde (1978) emphasized the greatly different oceanic circulation conditions during the Early–Middle Ordovician. Almost the entire oceanic water column, except for the oxygenated wind-mixed upper surface waters (~100 m), was represented by warm, poorly ventilated anoxic waters.

17.3. Discussion

17.3.1. Recognition of ancient contourites

It is first important to reaffirm the point made in several previous publications on fossil contourites (e.g. Stow et al., 1998a), that it is both *difficult and time-consuming* to recognize the influence and deposits of bottom currents in ancient series. Whereas many turbidites or debrites, for example, are readily identified as such even with cursory field examination, the same is not true for contourites. Several different lines of evidence must be carefully gathered, following the three-stage approach most recently summarized in Stow et al. (2002c) and repeated here in Table 17.1.

With regard to the *small-scale criteria* and the sedimentary characteristics of contourite facies, the examples discussed in the present chapter all conform to the specific characteristics as encompassed by the standard facies model for contourites and tabulated in previous works (e.g. Stow et al., 1998a, 2002c; see also Martín-Chivelet et al., 2008). We will not repeat this summary here, but note that all the examples highlighted are, in fact, carbonate-rich contourites, and that some of their

Table 17.1 Criteria for the recognition of contourites in both modern and ancient systems

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

Do the sediments have the range of features as summarized in the discussion or as described by Stow et al. (2002d)?

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 turbidites.

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 3-D 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, palaeontological 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?

Source: Modified from Stow et al. (1998a, 2002d).

features may be more closely associated with the calcicontourite facies. These include:

Occurrence and facies: within thick successions of pelagic and hemipelagic sediments, possibly associated with regional hiatuses and/or condensed sequences with phosphorite or ferromanganese hardgrounds; calcilutite, calcisiltite and calcarenite facies most common.

Structures and ichnofacies: mostly very subtle structures and ghost primary structures after intense bioturbation; calcarenites can show distinctive lenticular, very thin-bedded character, and less bioturbation; range of normal deep-water burrow traces including some vertical burrows from omission surfaces.

Texture and sequences: diagenesis tends to preserve the original calcilutite to calcarenite grain-size differences and hence grain-size/facies sequences; such sequences can be of limited thickness (<20 cm) and incomplete.

Microfacies and composition: packed to sparse biomicrites (including wackestones, packstones and some grainstones) are common as microfacies; dominant bioclasts, mostly of pelagic type but including admixture of benthic and reworked older biogenic material, and variable proportion of terrigenous grains/clays; diagenetic micrite, microspar and sparite all present. Bioclast fragmentation and iron staining is common.

The sedimentary characteristics are best discernible where contourites are found embedded in typically fine-grained pelagic sediments, whereas in basin fills substantially supplied by sub-aqueous density flows, which may transport coarse or fine sediment, these small-scale criteria are commonly of limited value. The identification of ancient contourites becomes even more speculative where diagenesis, metamorphism and tectonic deformation have largely modified the depositional structures. Diagenetic alteration can be intensive in particular in calcareous and siliceous biogenic contourites. Therefore, investigations should always include careful examination of the diagenetic effects on particle size by neomorphic processes or tectonic stress. Admixtures of siliciclastic components and more stable phosphatic grains may serve as a point of reference for the primary particle size (Figures 17.4 and 17.5).

With careful fieldwork and observation, where exposure permits, *medium-scale criteria* can be extremely useful in helping to elucidate a contourite interpretation. For the examples cited above, the recognition of hiatuses and condensed sequences has been important, as well as regional variation in the thickness of depositional units allowing reconstruction of mound-like geometry. The associated facies are dominantly of deep-water pelagic and hemipelagic type, although more work is required to observe any regional trends in detailed facies characteristics.

Where the palaeowater depth is not well constrained and the type of current system unknown, it is crucial to analyse the geological context. Very deep tidal currents, storm waves, internal waves and other clear-water currents may operate on outer shelves, upper slopes and in straits. The resulting traction deposits are not contourites sensu stricto (Faugères and Stow, 1993; Stow et al., 2002c). In ancient series, above all, 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, this should be made clear in the terminology applied.

Large-scale criteria for the recognition of contourites, including palaeoceanographic features and continental reconstructions, are generally more problematic and difficult to rely on too heavily, especially in older systems. Most Palaeozoic–Mesozoic plate-tectonics models only roughly outline the real palaeoceanographic conditions. A possible affirmation of a contourite origin is even more complicated in cases of different palaeogeographic models showing conflicting interpretations. In such cases, the disposition of fossil contourites may be used to evaluate palaeotectonic–palaeogeographic reconstructions and one should be aware of circular reasoning. The Devonian situation as discussed by Hüneke (2006) may serve as an example. The close-fit reconstructions (Pangaea-A reconstructions) of Golonka (2002) and Kiessling (in Copper, 2002) explain the Givetian/Frasnian circulation event most convincingly. The disposition of the fossil calcareous contourites and faunal data corroborate palaeogeographic reconstructions that show an advanced convergence between Gondwana and Laurussia and the smaller continental plates such as the Armorican and Noric terranes during the Givetian and Frasnian.

17.3.2. Sea level and preservation of contourite drifts

All the cases of Palaeozoic and Mesozoic contourites exemplified above reveal the influence of bottom currents in times of global sea-level highstand and greenhouse conditions (see Copper, 2002; Johnson et al., 2002; Rowland and Shapiro, 2002). At least the second is surprising since greenhouse conditions should be associated with more sluggish bottom currents due to a less strong thermohaline oceanic circulation. The Meso- and Palaeozoic examples document, however, that bottom currents have had the competence to rework pelagic sediments at least where they traversed shelf and epeiric seas.

The Ordovician is characterized as a period of maximum eustatic high within the older (Palaeozoic) first-order cycle with consequent maximum flooding, peaking in the Early and again in the Late Ordovician (Vail et al., 1977a; Hallam, 1992; Ross and Ross, 1995). During the Early Ordovician, the Jiuxi contourite drift formed in close proximity to the western Gondwanan shelf margin at low palaeolatitudes (Luo et al., 2002). The sea level was probably at one of its highest points of the entire Phanerozoic. The resultant Ordovician epeiric seas are depicted as covering at least 40%, possibly even 60%, of earlier land areas. During the Devonian, the Palaeozoic first-order sea-level rise culminated again in Middle/Late Devonian times (Johnson and Sandberg, 1988; Hallam, 1992; Golonka and Kiessling, 2002). In this episode, bottom currents reworked pelagic carbonate oozes along southern margin of Laurussia, the disintegrated northern continental margin of Gondwana, and on deep marginal plateaus of several adjoining micro-continents (Hüneke, 2007a). The Late Cretaceous is the time of maximum eustatic high within the younger (Mesozoic-Cenozoic) first-order cycle (Haq et al., 1987). The Albian–Cenomanian was an interval of increasing continental submergence. The highest Phanerozoic sea level was reached during the early Turonian. Following a temporary lowstand, the Campanian sea level was again high, which slowly lowered during the Maastrichtian and than dropped dramatically during the Palaeocene.

During the Early Ordovician, the Middle/Late Devonian and the Late Cretaceous, the continents were extensively flooded. At high sea-level stands, the combination of reduced source areas for terrigenous sediments and the expansion of epeiric seas with water depths of more than 300 m may, therefore, have created generally favourable conditions for deposition of contourite drifts on the continental lithosphere. The preservation potential of these drifts is relatively high since the continental lithosphere is non-subductible, and this may lead to a stratigraphic bias in the record of ancient contourites. Pre-Cenozoic cases are preferentially preserved from periods of high-stand sea level, which favour the deposition of contourites on the continental lithosphere and thus its preservation. At least, pre-Jurassic contourite drifts that were originally deposited on oceanic lithosphere have been destroyed on a large scale due to global subduction processes.

However, the same does not appear to be true regarding the Cenozoic examples discussed. Sea levels during the Oligocene and then during the mid to late Miocene were relatively low, and climatic conditions moved towards an icehouse world. The Cyprus contourites were deposited over oceanic crust and later preserved by ophiolite obduction and uplift during subduction of the late Tethys Ocean. The Japanese examples are also inferred to have been deposited in a distinctly oceanic setting and their preservation on land related to arc–arc accretion.

17.3.3. Sequence interpretation and non-deposition surfaces

The standard contourite sequence may reflect at least sub-regular periodicity in mean bottom-current velocity, related to climatic variations or other external factors. For many recent and sub-recent examples cited in the literature, little attempt has been made to calculate the duration of the deposition of such sequences. This is partly because sequences show very variable absolute thicknesses and also because there is considerable evidence for the presence of hiatuses and intervals of reduced sedimentation. However, based on data provided for various examples in the recent contourite compilation (Stow et al., 2002f), we have calculated approximate sequence periodicities for several examples (Gulf of Cadiz, Rockall Margin, West Shetlands, and Norwegian Margin), and in each case obtain a figure of between 5000 and 20,000 years.

By comparison, the ancient examples cited above, for which reliable estimates can be made, yield an average periodicity of 200,000 years for the Ordovician Jiuxi Drift (Luo et al., 2002), and 20,000–250,000 years for the Cyprus examples (Stow et al., 2002d). For the Devonian contourites, various non-deposition surfaces are documented, representing periods of sediment bypassing or even temporary minor erosion (Hüneke, 2007a). Omissions surfaces, which mark temporary halts in deposition but involve little or no erosion (Heim, 1924; Bromley, 1975), are most widespread. Burrowed hardgrounds, pristine and condensed phosphates, erosional surfaces and encrusted surfaces commonly occur. Although many of the omission surfaces record long time spans of non-deposition, encrusted surfaces with micro-stromatolitic crusts may record breaks of no longer than annual or even noctidiurnal length. The duration of the depositional hiatuses associated with the formation of hardgrounds has been estimated at somewhere between months to hundreds or even thousands of years (Flügel, 2004). Fluorapatite precipitation is generally relatively slow, having growth times between 500 and 2000 years in modern phosphorites within the top few tens of centimetres of the sediment/water interface, where microbial activity is greatest (Glenn, 1990). Taking these omission surfaces into account, the periodicity can be roughly estimated as 50,000–100,000 years for the Devonian case.

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Query No	Contents
AU1	''Martin Chivelet et al. 2008'' has been changed to ''**Martín-Chivelet et al., 2008''.** Please check.
AU2	Please confirm as to which year does ''Hüneke, 2007'' refers to ''2007a or 2007b''.
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