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Contourites within a deep-water sequence stratigraphic framework

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Abstract Sequence stratigraphy has proven to be an extremely useful predictive tool in the search for hydrocarbons along the continental margins. However, of the several models in use, none includes the effects of alongslope processes in deep-water. This paper, therefore, is a first attempt to place contourite depositional systems (CDSs) firmly within a sequence stratigraphic framework, based on detailed examination of over 20 CDSs worldwide. It also presents a new view of how sea level variation influences bottom current generation and intensity. Two key controls on contourite drift formation are identified: sediment influx and bottom current velocity. Sea level directly influences the sediment influx to a basin and, therefore, the contourite response fits nicely into the downslope sequence stratigraphy model. Bottom current velocity variations in response to sea level are more complex, and two key controls are identified: (1) oceanic gateways can effectively constrict and accelerate water masses and are therefore closely associated with CDS evolution; fluctuating sea level will affect the water exchange through a gateway; (2) changing rates of bottom-water generation: some water masses appear more vigorous during periods of lowstand, whereas others appear more sluggish. In order to accommodate this variation, two new sequence stratigraphy models are herein presented, comprising both downslope and alongslope processes. The first model reveals a CDS where bottom current activity is markedly more vigorous during times of sea level highstand, whereas the second model indicates margin evolution where bottom-water currents are most vigorous during times of sea level lowstand. It is recognised that there are additional controlling factors linked to sea level variation which can significantly modify the distribution and development of contourite elements.

Introduction

One of the dominant paradigms for the description and interpretation of continental margin sedimentary systems is sequence stratigraphy, as developed from the seminal work of Peter Vail and others in the late 1970s. Sequence stratigraphy provides a dynamic view of stratigraphy in which direct linkages can be made between variations in sea level and sedimentation, and a hierarchy of cycles of eustatic sea level changes can be recognised at a worldwide scale (Mitchum et al. 1977; Vail et al. 1977; Haq et al. 1987). Much progress has been made since that time and several different schools have emerged which promote rather different models. In their recent review of sequence stratigraphy, Catuneanu et al. (2009) state that "each model is justifiable *in the context in which it was proposed* and may provide the optimum approach under the right circumstances."

However, despite ever-growing interest in deep-water sedimentation for hydrocarbon exploration, there is still almost no mention in any of these models of contourites and bottom currents. Even in Catuneanu et al. (2009), the discussion of deep-water settings makes no reference to the alongslope system. This is despite the recognition of contourites as a possible seismic mounded facies in early

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work on seismic stratigraphy (Mitchum et al. 1977). Furthermore, it is now clearly recognised that contourite deposits are a hugely important component of deep-water depositional systems, everywhere from the upper continental slopes to the abyssal plains (e.g. Stow et al. 2002a; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008). These deep-water systems, especially along continental margins where many of the contourites are found, are currently frontier areas for hydrocarbon exploration and production (Stow and Mayall 2000; Haughton and Kendall 2009; Nielsen et al. 2011, this volume). The integration of contourite depositional systems (CDSs) with downslope systems is of paramount importance in this context.

Whereas individual drifts have been previously evaluated in terms of sequence stratigraphy (e.g. Llave et al. 2001, 2006, 2007), and sea level has been considered as one of the important controls on contourite drift evolution (e.g. Faugères et al. 1993, 1999), no generally applicable sequence stratigraphic model has yet been developed. The problem is indeed challenging because the interaction of additional controls is complex, there is an apparent disconnection between Northern and Southern Hemisphere systems, and there is no simple relationship between alongslope and downslope systems. But, the time is well overdue and the database does now exist for this important first attempt to place contourite depositional systems firmly within a sequence stratigraphic framework by modifying the conventional downslope model. This paper develops concepts introduced by Faugères et al. (1993, 1999), Diez et al. (2008) and Hernández-Molina et al. (2008). It is an additional challenge to refine the model by detailed analysis of industry-generated seismic data which are age-controlled with well calibrations.

The principal aims of this work, therefore, are (1) to consider the range of controls which influence contourite drift development and bottom current erosion in deep-water; (2) to consider specifically the role of sea level variation in this regard; and (3) to develop a new deep-water model which places the contourite depositional system within a sequence stratigraphic framework.

Sequence stratigraphy: existing models and problems

Sequence stratigraphy can be defined as “the analysis of genetically related depositional units within a *chronostratigraphic framework*” (Reading and Levell 1996). It grew out of the subsurface analysis of continental margins during oil explorations based on seismic profiling and deep borehole techniques, and has now become a fully fledged sub-discipline of geology (Vail et al. 1977, 1991; Haq et al. 1987; Posamentier and Vail 1988; Posamentier et al. 1988; Van Wagoner et al. 1988; Emery and Myers 1996; Catuneanu 2006).

Individual units recognisable on seismic profiles are known as depositional sequences. These are bounded by distinctive unconformity surfaces (type 1 or 2), and comprise an internal arrangement of sub-units (or systems tracts) associated to particular variations of sea level. One of the basic tenets of sequence stratigraphy is that sea level acts as a fundamental control on margin sedimentation by influencing the delicate balance between accommodation space and sediment influx (Myers and Milton 1996). Individual systems tracts result from the changing relationship between these two important controlling factors.

The most widely used sequence stratigraphic model is illustrated in Fig. 1. At the base, the sequence boundary represents a surface along which significant erosion and/or a hiatus in sedimentation occurred. This can result from a strong drop in eustatic sea level, causing the continental shelf to be exposed to sub-aerial erosion (type 1 boundary) or not (type 2 boundary). The subsequent lowstand systems tract (LST) is normally subdivided into three depositional units in deep-water: the basin-floor fan, slope fan, and lowstand wedge. The basin-floor fan signifies bypass of sediment from the shelf downslope into the deep basin.

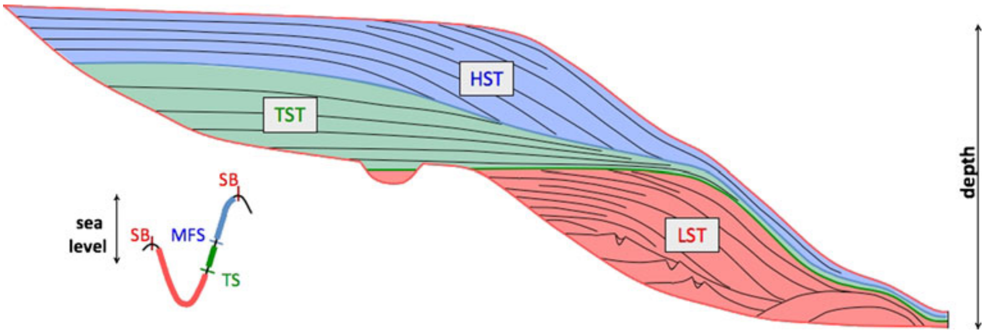

Fig. 1 Basic sequence stratigraphic model for a continental margin sequence architecture where right is basinwards: in the threefold systems tracts model, *LST* lowstand, *TST* transgressive, *HST* highstand. Important bounding surfaces are *SB* sequence boundary, *TS* transgressive surface, *MFS* maximum flooding surface. Important components of the LST are the basin-floor fan and slope fan. Most basin sedimentation occurs during the LST. Figure not to scale but approx. 10s–100s km across and 100 m–few km deep (modified from Haq et al. 1988)

Following or simultaneous with basin floor-fan deposition, muddier turbidite and debrite downslope processes result in the formation of a slope fan. Slow relative sea level rise and restored slope stability is responsible for the generation of an overlying prograding lowstand wedge, which develops into a transgressive wedge when the accommodation space exceeds sediment deposition. Collectively, the lowstand elements present a retrogradational architecture. The overlying transgressive systems tract (TST) is bounded by the transgressive surface at its base and the maximum flooding surface along its upper limit (Posamentier and Vail 1988; Posamentier et al. 1988). This is then overlain by the highstand systems tract (HST), which represents deposition at a time of limited accommodation space resulting from the slowing of relative sea level rise. If sediment supply is sufficient, then a progradational depositional architecture will be observed.

While this model reflects a simplified response to eustatic sea level variation and presents a schematic sedimentary architecture for siliciclastic systems, the reality on many continental margins is more complex (Posamentier and James 2009). Key issues include (*1*) carbonate-dominated systems behave quite differently, as has been clearly demonstrated by numerous authors (e.g. Emery and Myers 1996; Schlager 2005; Catuneanu 2006). Mixed systems present a further challenge for interpretation. (*2*) Synsedimentary tectonic activity can significantly affect accommodation space and/or sediment supply, in some cases completely masking sea level effects (Bridge and Demico 2008). Therefore, 'relative sea level' is a more accurate term to be used when discussing continental margin sedimentary architecture. (*3*) The presence of ice along a margin can significantly alter the sedimentary architecture (Powell and Cooper 2002). (*4*) In reality, the lowstand wedge and prograding highstand systems tract rarely downlap onto the deep-water elements, as demonstrated by Haughton and Kendall (2009). Furthermore, the so-called slope fan is not everywhere distinct from the basin-floor fan, but commonly represents its channel-levee feeder system. (*5*) Much of the continental margin system around the world has a slope-apron fringe of sediment and no distinct slope or basin-floor fan, a point long emphasised by various authors (e.g. Stow et al. 1996). In these cases, the lowstand systems tract, in particular, will be very different from that of the standard model (Shanmugam 2006). (*6*) In the standard model, depositional sequences reflect mostly second- and third-order changes of sea level (i.e. duration of $1–10\times10^6$ years), whereas systems tracts and parasequences reflect third- and fourth-order changes (100×10^3 to 1×10^6 years). The growth and development of large submarine fan systems may span two or more normal depositional sequences, while internal variation or sequences can occur with higher frequency (e.g. $10–100\times10^3$ years; Myers and Milton 1996). (*7*) Pliocene and Quaternary sequence stratigraphy models are rather complex and present important differences to conceptual models. In contrast to idealised sequence stratigraphic models, the existence of the regressive (forced or not) systems tracts (RSTs) is likely to predominate in the Pliocene and Quaternary sedimentary record (e.g. Hunt and Gawthorpe 2000; Hernández-Molina et al. 2000). (*8*) Finally, as stated above, none of the existing models accounts for the very significant and sometimes dominant elements of alongslope sedimentation—the contourite depositional systems. This is the primary focus of the paper presented.

Controls on deep-water sedimentation

For the interpretation of any sedimentary system, including deep-water systems, it is important to consider the full range of factors which have influenced the accumulation of sediment and its preservation. These comprise both external and internal controls. The principal external controls include (1) sediment supply—the nature, rate and source of supply, as well as the type of sediment; (2) sea level changes—eustatic and relative sea level fluctuations, as well as short-term tidal, seasonal and storm effects; and (3) climate—temperature, precipitation and wind regimes, as well as short- and long-term climatic changes.

Internal controls can be equally significant in affecting sedimentation. These include (1) tectonic activity—isostatic movements, subsidence and uplift, plate tectonic setting, seismicity and volcanicity; (2) local physical, biological and chemical processes—the nature and intensity of bottom currents, and the degree of interaction with other processes; (3) post-depositional processes—compaction, deformation, biogenic and chemogenic effects, amongst others; (4) regional bathymetry—water depth, slope gradient and seafloor irregularities; and (5) accommodation space—controlling progradation and/or aggradation.

The rates and length of time over which the controlling processes operate is also of vital importance. For example, sediment supply and, hence, accumulation rates can be 2–3 orders of magnitude greater for deltas than for contourite drifts. These various controls have been more extensively discussed by numerous authors (Walker and James 1992; Reading 1996; Allen 1997; Leeder 1999; Bridge and Demico 2008, amongst others).

In order to simplify our understanding of this complex interplay of controls, conventional sequence stratigraphic models assume two primary controls: sediment supply and sea level variation. Myers and Milton (1996) have more recently expressed this as sediment supply and accommodation space (where the latter is a function of eustatic sea level, tectonics and compaction), as shown in Fig. 2. The

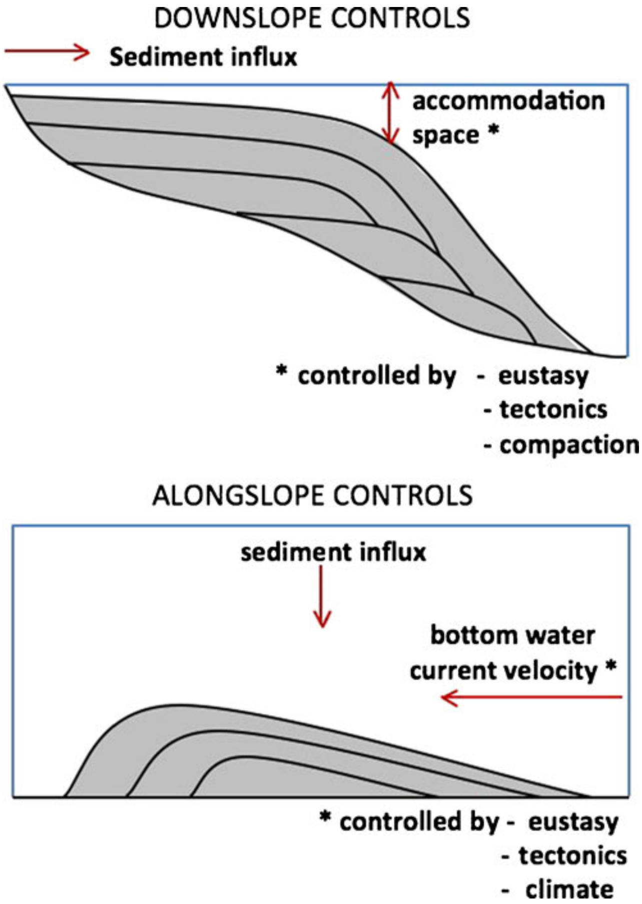

Fig. 2 Controls on downslope and alongslope depositional systems

balance between accommodation space and sediment supply forms the stratigraphic stacking patterns in the original downslope model (Fig. 1).

Controls on contourites

Previous attempts to understand the controls on contourite development have clearly emphasised the numerous interlinked factors listed above (e.g. Faugères and Stow 1993, 2008; Viana et al. 1998; Faugères et al. 1999; Shannon et al. 2005; Diez et al. 2008). These can be resolved into *two primary controls* for contourite sedimentation: bottom current intensity and its variation, and sediment supply (Fig. 2). Unlike for near-shore depositional systems, accommodation space is a less significant factor (except in the case of shallow-water contourites). Sea level affects the system mainly by influencing bottom current intensity, as discussed below.

Bottom current variations

It has long been realized that the nature of contourite deposition, both in the long and short term, is controlled primarily by the existence of and variation in bottom currents (see Stow et al. 2008, 2009). Bottom current velocities control the facies and bedforms of a drift, in addition to determining areas of deposition and erosion on the seabed. Drift development requires bottom-water currents to be stable and effective for a prolonged period of time. Mean current velocities must be maintained at >0.1 m/s to enable significant reworking, transportation and deposition of contourites, whereas non-deposition and seafloor erosion become more prevalent at velocities >0.5 m/s (Stow et al. 2009). Long-term fluctuations in bottom-water currents lead to an apparent cyclicity of seismic facies from which palaeoceanographic information may be extracted.

The cause of these fluctuations is still a major topic of debate and ongoing research; however, general consensus would identify the very important effects of (1) oceanic gateways, and (2) prevailing conditions in the source areas (or kitchens) for bottom-water generation. There is a considerable body of research which seeks to explain short-term (e.g. decadal) variation in ocean circulation, especially following the findings of Bryden et al. (2005) on the slowing of meridional overturning circulation in the North Atlantic linked to climate change. There is also an extensive palaeoceanographic literature on climate change and circulation patterns over the recent glacial–interglacial cycles (e.g. Rahmstorf 2002). However, to the authors' knowledge there has been no attempt to directly link deep-water circulation with sea level change (Bacon, personal communication 2010; Piola, personal communication 2011). The theoretical considerations presented below are therefore proposed as a new explanation of just how variations of sea level act to influence bottom current generation and intensity. This is an important step in understanding the link between sea level and contourite development.

Gateway effects

Oceanic gateways are critical to the exchange of both surface- and deep-water masses between ocean basins (Fig. 3). They are therefore pivotal in determining the presence or absence as well as the relative intensity of bottom currents associated with intermediate- and deep-water masses. At times of high sea level, there is a normal and full exchange of water masses through the gateway and, hence, bottom currents will be strong and well developed. At intermediate sea level (during either transgressive or regressive phases), a gateway's cross-sectional area will be reduced, thereby limiting bottom-water exchange and intensifying the associated bottom currents. It may be that upper, less dense strands of bottom currents are intensified, whereas lower, denser strands are

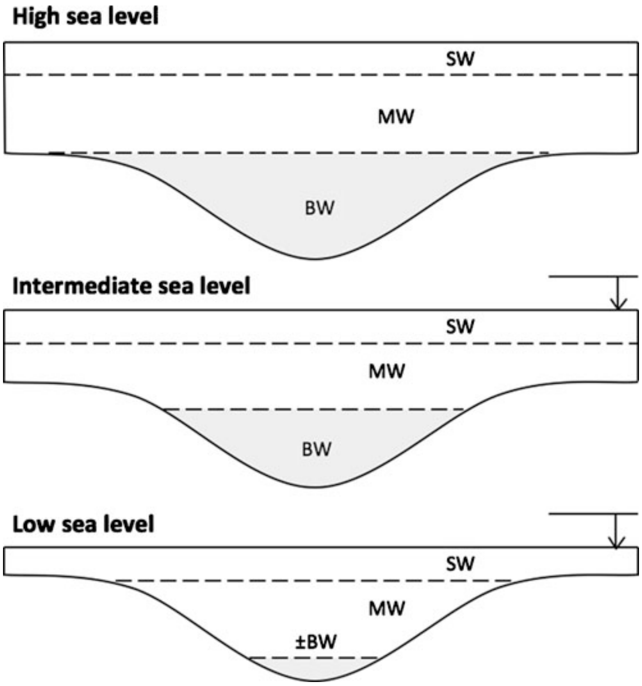

Fig. 3 Effects of changing sea level on the exchange of water masses through oceanic gateways. *BW* Bottom water, *MW* middle water, *SW* surface water

diminished. During sea level lowstands, the bottom-water mass becomes severely limited or completely shut off, such that bottom currents are also reduced in intensity or are non-existent.

Bottom-water kitchen conditions

The global thermohaline circulation system is fed by the continued and abundant generation of cold, saline bottom waters in specific cold-water kitchens at high latitudes, including the Norwegian-Greenland Sea, Labrador Sea, Bering Sea, Weddell Sea and other locations around Antarctica (Rahmstorf 2006). Empirical differences have been noted in the timing of generation between Northern and Southern hemispheres, and have been referred to as the see-saw effect (Steig 2006).

For the *Northern Hemisphere* deep-water kitchens in the Arctic regions, high rates of bottom-water generation and accelerated overturning in the North Atlantic have been noted during interglacials and associated highstands (Rahmstorf 2002; Piotrowski et al. 2004; Lynch-Stieglitz et al. 2007; Knutz 2008). The following mechanism is here proposed.

Cooling of surface waters is most effective where it occurs over broad shelf areas, both with and without floating ice shelves, at periods of relative high sea level when the heat-exchange dynamics between the atmosphere/ice shelf and ocean surface are particularly effective. The consequent active generation of cold dense water leads to vigorous overturn, off-shelf spillover and downslope flow of the dense bottom water (Fig. 4a). Where this reaches its density equilibrium, the cascading water mass turns alongslope under the influence of Coriolis force and proceeds away from the source area, hugging the bottom contours. Slightly warmer waters are then drawn over the shelf to replace that lost to cold-water generation, and the process continues.

At low relative sea level (Fig. 4b) the shelf becomes subaerially exposed and, where an ice shelf had existed, it becomes grounded. This results in a smaller, or non-existent, shelf contribution to the cold-water kitchen area and, hence, a reduction in the most effective bottom-water generation. In other words, both the lack of shelf area and the grounding of ice on shelves prevent the influx of ‘warmer’ surface water to drive the overturn. Heat

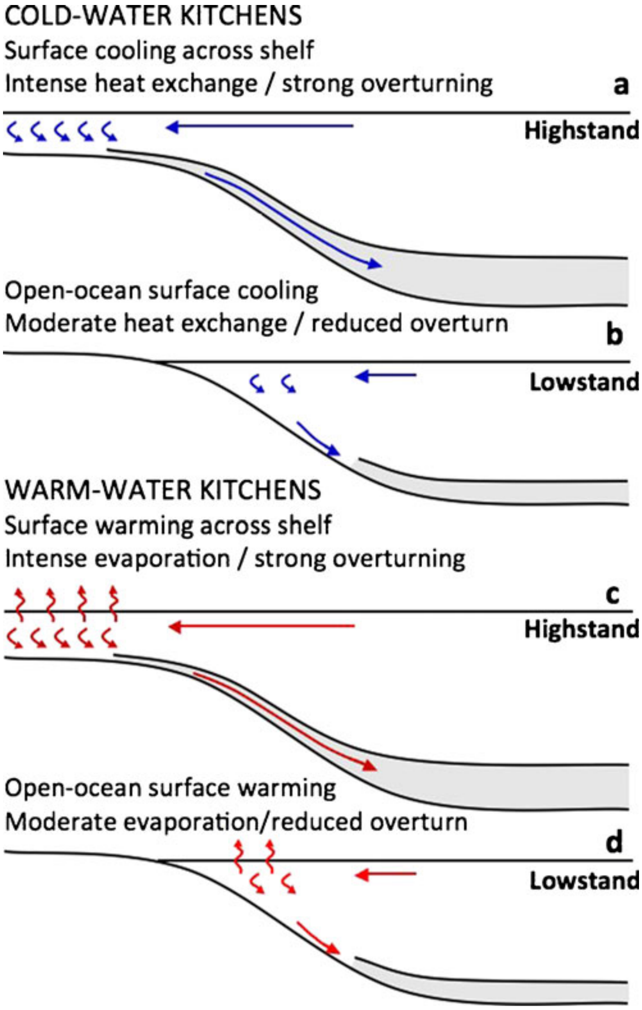

Fig. 4 Effect of sea level on the generation of bottom water. **a** High-latitude cold-water kitchens, sea level highstand. **b** High-latitude cold-water kitchens, sea level lowstand. **c** Low-latitude warm-water kitchens, sea level highstand. **d** Low-latitude warm-water kitchens, sea level lowstand

exchange still occurs between the atmosphere and the open ocean surface but is less dynamic across the main body of the open ocean. Although large areas of the open ocean may become covered in floating sea ice, the generation and sinking of denser water is relatively diffuse and the bottom water does not become focussed along a continental margin. The overall result is a slowing of cold dense water generation, and less vigorous thermohaline overturn. This leads to more sluggish bottom currents and circulation.

In reality, the system is not necessarily as simple as the model postulates. For example, the generation of Arctic Intermediate Water may show an increase during cold-climate lowstands. There are also changes and interruptions to meridional overturning caused by short-term climatic events.

It is also very difficult to *directly* observe the formation of cold water and its subsequent sinking (Rahmstorf 2006). Thus, determining the relative contribution of the shelf and open ocean areas to the overall cold-water kitchen is problematic. Validation of the mechanism proposed above requires further observational data from high-latitude kitchen areas.

For the *Southern Hemisphere* there is even less unequivocal evidence for the link between climate/sea level and bottom-water generation, and the whole process appears very complex. Whereas there is certainly evidence of an expanded influence of Antarctic Bottom Water into the Atlantic during glacial times and lowered sea level, there is less direct evidence for increased bottom current velocity (McCave et al. 1995; Orsi et al. 1999; Schmittner 2003; EPICA Community Members 2006; Negre et al. 2010). It is quite possible that this expanded influence is largely the result of the infilling of the 'accommodation space' left by reduced generation of Northern Hemisphere deep waters. There is better evidence for an accelerated Antarctic Circumpolar Current at depth during glacial periods but, as this is driven largely by surface wind shear, it is not necessarily correlated with increased bottom-water generation in cold-water kitchen areas.

Furthermore, during times of extensive sea-ice development, all water circulation is pushed basinwards, and therefore the core location for bottom-water generation is likewise shifted. This is particularly visible in the water masses surrounding Antarctica where the Antarctic Circumpolar Current moves northwards at times of sea-ice development (Rebesco et al. 1997). This may push the bottom-water currents away from the continental slope where morphological forcing was likely to have caused accelerated bottom-water velocities. On the other hand, at least part of the extremely deep shelf areas around Antarctica still maintained floating ice shelves during glacial lowstands and, hence, the same effective method of bottom-water generation as during highstands. With colder water and a greater level of freezing to form sea ice, there is potential for increased bottom-water generation during glacial periods. This would support the inferences of higher bottom current velocities being linked to colder climates for the Southwest Pacific gateway (Goosse et al. 2001; Carter et al. 2004), and along the Argentine margin (Hernández-Molina et al. 2009, 2010).

Warm-water kitchen effects

The principal warm-water kitchen for intermediate/deep saline water today is found in the Mediterranean Sea (Fig. 4c, d). This ultimately gives rise to the Mediterranean Outflow Water (MOW), which escapes through the Gibraltar gateway into the North Atlantic Ocean. During previous greenhouse conditions on the planet, such warm-water kitchens of the geological past would have been still more important than today and, at times (such as much of the Cretaceous), would have provided the dominant source of bottom water.

At high relative sea level stands, broad shallow shelf areas in arid and semi-arid climatic zones provide the most effective regions for heat exchange, leading to a rapid evaporation of surface waters, increased salinity and, hence, density of the seawater left behind, and its consequent sinking and downslope flow to form intermediate and bottom water masses (Fig. 4c). Coriolis force deflects the newly generated water mass to flow alongslope as a dense but warm-water bottom current. Cooler surface waters flow across the shelf region to replace that lost to warm-water generation.

At low relative sea level stands (Fig. 4d) the shelf may become sub-aerially exposed and unable to provide such a large warm-water kitchen area. Heat exchange still occurs between the atmosphere and the ocean surface but evaporation is less efficient across the main body of the open ocean, warm saline and dense water is generated more slowly and/or more diffusely, and there is less vigorous overturn. This leads to less vigorous bottom currents and circulation, in exactly the same way as for cold-water kitchens.

Whereas this model is true in general for warm-water kitchens and higher sea levels in the geological past, there remains some controversy in the literature with regard to Plio–Quaternary variations for the Mediterranean and Red Sea warm-water kitchens. According to Rohling and Zachariasse (1999), the Red Sea outflow was severely reduced during the last glacial maximum (and lowered sea level). For the Mediterranean, however, Cacho et al. (2000) see evidence for enhanced overturning rates during the last lowstand, while several authors working in the Gulf of Cadiz infer an increased bottom current flow of the lower strand of the MOW (Hernández-Molina et al.

2006; Voelker et al. 2006; Toucanne et al. 2007; Schmiedl et al. 2010). The upper strand, by contrast, appears to have higher velocities during warm-water highstands (Stow et al. 2002b).

Sediment supply variations

The second fundamental control on contourite development is sediment supply. For contourite accumulation to occur, sediment supply must be greater than background pelagic and hemipelagic fallout. Stow et al. (2008) identified the potential sediment influx as sourced from turbidity currents, pro-delta plumes, slope spillover, and hemipelagic and pelagic settling from both upstream and directly at the drift site. Additionally, erosive bottom currents are capable of reworking previously deposited sediments.

The influence of sea level on these different sediment sources is not easy to ascertain and is not everywhere the same. As recognised in conventional sequence stratigraphic models for siliciclastic systems, deep-water clastic sedimentary systems are enhanced during sea level fall and lowstand periods (RST and LST) on account of an increase in clastic sediment influx to the deeper basins. This is due to enhanced erosion of the shelf, direct sediment supply to the shelf edge/upper slope, increased activity of downslope processes and increased sediment bypass of the slope. Although more material is therefore likely to be available for redistribution by bottom currents, contourite depositional systems may become masked by the dominance of downslope systems (Faugères et al. 1999; Fulthorpe et al. 2010).

On the other hand, during times of high relative sea level, clastic sediment is more likely to become trapped on the shelf until the accommodation space has reduced sufficiently to enable progradation to the shelf edge. However, large rivers will still feed pro-delta plumes across the shelf, especially in the case of narrow shelves, and contribute to some degree of hemipelagic sedimentation. Off-shelf sediment spillover processes will become more prevalent as more mobile sediment is fed to and reworked across the shelf (Viana et al. 1998; Stow et al. 2002c). It should be noted that sediment supply to the deep ocean basins is by no means driven solely by eustatic sea level fluctuation. Climate and local tectonics are additional concerns, although such factors are outside the scope of this study.

Sequence stratigraphy of drifts: case studies

This paper investigates 20 contourite drifts for which good data exist, either in the literature and/or from first-hand studies. An extensive published database includes (1) over 150 scientific drill sites (DSDP, ODP, IODP) which have penetrated contourite/bottom current systems; (2) published seismic profiles from over 30 separate drifts and CDSs, some with good seismic grids but poor age control (Faugères and Stow 2008). Published industry data with good well control through contourite systems are very rare, partly because the alongslope component has either not been recognised or is too shallow in the section to be of economic interest. From a survey of this database, information for 20 well-documented drift systems has been compiled in Table 1. They cover a wide range of environments including those from high and low latitudes, Northern and Southern hemispheres and different tectonic settings. Of these, four examples have been selected as case studies; the CDS off the Antarctic Peninsula in the SE Pacific Ocean, the Argentine Basin CDS in the SW Atlantic, the Eirik Drift in the North Atlantic, and the Gulf of Cadiz CDS. They have been chosen to enable a direct comparison of Northern and Southern Hemisphere systems in addition to cold-water vs. warm-water systems.

Antarctic Peninsula drifts

Location and setting Twelve drifts have been identified on the continental rise off the Antarctic Peninsula, in the SE Pacific Ocean. They have been deposited by a boundary current which flows south-westwards from the Weddell Sea region, via the Drake Passage (Fig. 5). This current flows counter to the eastward-flowing Antarctic Circumpolar Current. As a result, the evolution of these drifts is closely related to the palaeoceanography of the Antarctic region and the opening of the Drake Passage. The most thoroughly researched of these, Drift 7 (Rebesco et al. 1997, 2002; van Weering et al. 2008), is documented here.

Evolution and controls Pre-drift sediments are mainly turbiditic, aged between 36 and 15 Ma, and cover the oceanic basement. Drift growth began at ca. 15 Ma (Fig. 6) when bottom current velocities increased sufficiently to dominate over downslope processes. This has been linked to continued deepening of the Drake Passage, and the drop in sea level following the mid-Miocene climatic optimum and subsequent expansion of the East Antarctic Ice Sheet. Climatic changes continued to affect the drift throughout its evolution, as the Antarctic ice sheets extended seawards and glacio-eustatic levels fluctuated. ‘Drift growth’ and ‘drift maintenance’ stages have been identified (Fig. 6). Drift growth is accounted to combined high bottom-water velocities and high sediment influx during glacial conditions and associated eustatic lowstands. There is some change in drift accumulation rates during the Plio–Pleistocene and this succession is named the ‘drift maintenance stage’ (Fig. 6). This was probably related to the onset of

Table 1 Summary of drifts used to create a revised sequence stratigraphy model which incorporates alongslope deposits

Drift	Influencing water mass(es)[a]	Time of most vigorous BW velocity	Time of highest sediment influx	Time of greatest contourite sediment accumulation	Model
Antarctic Peninsula drifts	AABW; ACBW	Glacial lowstand	Glacial lowstand	Late Miocene lowstand	2
Argentine Basin, elongate mounded	AABW	Glacial lowstand	Glacial lowstand	Late Oligocene–Early Miocene lowstand	2
Balke Bahama outer ridge	NADW	Interglacial highstand	Glacial lowstand	Pliocene transgression and highstand	1
Barra Fan Drift	NADW; LDW	Interglacial highstand	Glacial lowstand	Holocene transgression and highstand	1
Canterbury Basin drifts	SC	Glacial lowstand	Glacial lowstand*	Middle–Late Miocene lowstand	2
Ceuta Drift	MU	Glacial lowstand	Glacial lowstand	Quaternary lowstand	2
Chatham Terrace Drift	AABW	Glacial lowstand	Glacial lowstand	Masked by local tectonic activity	2
Cosmonaut Sea margin drifts	AABW	Glacial lowstand	Glacial lowstand	Middle–Late Miocene lowstand	2
Eirik Drift	NADW	Interglacial highstand	Glacial lowstand	Pliocene transgression and highstand	1
Faro-Albuferia Drift	MOW	Glacial lowstand	Glacial lowstand	Plio–Pleistocene lowstands	2
Feni Drift	NSOW; LDW	Glacial lowstand	Glacial lowstand	Mid–late Pleistocene lowstand	2
Hatton Drift	NADW	Interglacial highstand	Glacial lowstand	Plio–Quaternary transgression and regressions	1
Lofoten Drift	AIW	Interglacial highstand	Glacial lowstand	Quaternary lowstands	n/a
NE Rockall Trough Drift	NADW; NSOW; LDW	Interglacial highstand	Glacial lowstand	Unknown	1
Nyk Drift	AIW	Interglacial highstand	Glacial lowstand	Quaternary highstands	1
Upper slope Campos Basin drifts	BC	Interglacial highstand	Glacial lowstand	Present highstand	1
Vema contourite fan	AABW	Glacial lowstand	Glacial lowstand	Transgressive and highstand**	n/a
Vesterålen Drift	AIW	Interglacial highstand	Glacial lowstand	Quaternary lowstands	n/a
West Shetland drifts	ISOW	Interglacial highstand	Glacial lowstand	Neo-Quaternary transgression and highstands	1
Wilkes Land drifts	AABW	Glacial lowstand	Glacial lowstand	Neo-Quaternary lowstands	2

[a] *AABW* Antarctic bottom water, *ACBW* Antarctic circumpolar bottom water, *AIW* Antarctic intermediate water, *BC* Brazil current, *ISOW* Iceland-Shetland overflow water, *LDW* lower deep water, *MOW* Mediterranean outflow water, *MU* Mediterranean undercurrent, *NADW* North Atlantic deep water, *NSOW* Norwegian sea overflow water, *SC* Southland current

[*] AND low relative sea level resulting from uplift; local uplift has now resulted in the downslope sediment 'drowning' (covering) this contourite system

[**] Does not fit with model due to unusually high erosion of contourite sediments occurring during lowstand (information compiled from Stow and Holbrook 1984; Robinson and McCave 1994; Laberg et al. 2001; Ercilla et al. 2002; Escutia et al. 2002; Faugères et al. 2002; Howe et al. 2002; Rebesco et al. 2002; Stow et al. 2002c; Viana et al. 2002; Laberg and Vorren 2004; Carter et al. 2004; Hohbein and Cartwright 2006; Hernández-Molina et al. 2006; Llave et al. 2007; Hunter 2008; Diez et al. 2008; Fulthorpe et al. 2010; Hernández-Molina et al. 2010)

permanent ice in the Arctic and the increased importance of bipolar deep-water generation mechanisms. At present there is little bottom-water activity over the area.

Sequence stratigraphy This high-latitude CDS is under a strong glacial control which has three main effects on the drift. First, numerous authors have noted an increased rate in Antarctic Bottom Water (AABW) formation during times of glacial advance (see EPICA Community Members 2006; Rahmstorf 2006). Second, glacial advance across the continental shelf alters the sediment input to the margin significantly, with enhanced contourite sedimentation rates being observed at times of sea level lowstand. Third, it has been hypothesized that the Antarctic circumpolar currents are pushed northwards during glacial times (Rebesco et al. 1997) and, therefore, there is less interaction between the bottom-water currents and the drifts. The bottom-waters along this margin rarely reach velocities capable of eroding sediment. When observations on seismic records and evidence on shorter timescales using core data are considered with respect to drift evolution off the Antarctic Peninsula, it is seen that glacial periods are preferential to drift growth due to higher-velocity bottom-water currents and increased sediment supply which can be pirated by this enhanced flow.

Argentine Basin drifts

Location and setting A complex CDS has recently been described from the continental margin offshore Argentina (Hernández-Molina et al. 2009, 2010; Violante et al. 2010). Alongslope activity in the basin initiated close to the

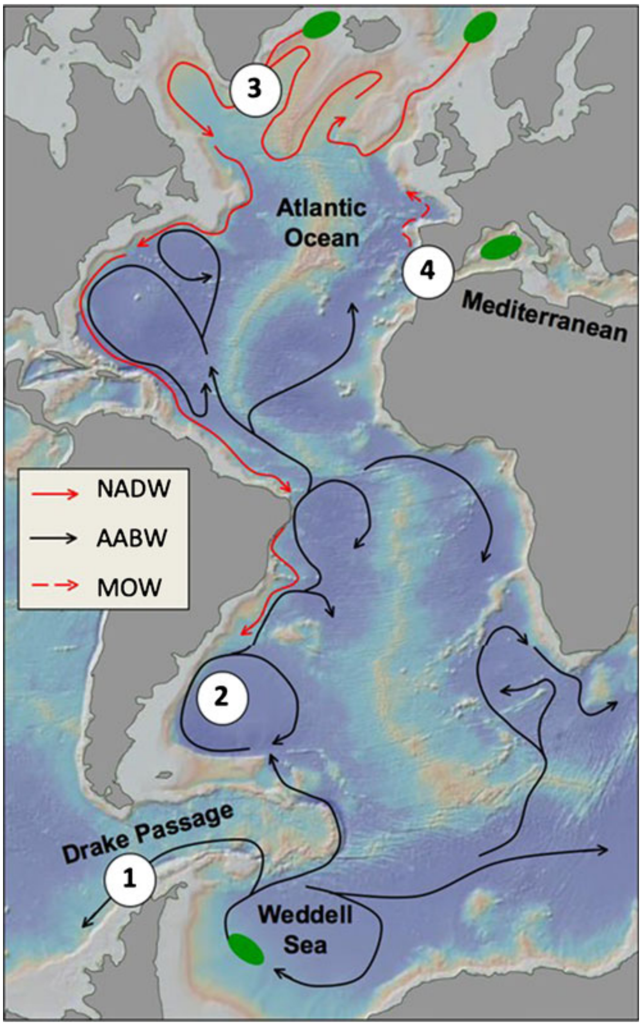

Fig. 5 Principal bottom-water circulation trends (*arrows*) around the Atlantic continental margins. *Green* Bottom-water source kitchens: low-latitude cold-water kitchens in the Arctic and Weddell seas, warm-water kitchen in the Mediterranean. Main water masses: *NADW* North Atlantic Deep Water, *AABW* Antarctic Bottom Water, *MOW* Mediterranean Outflow Water. Numbered contourite drifts are those referred to in the text: *1* Antarctic Peninsula drifts; *2* Argentine Basin drifts; *3* Eirik Drift; *4* Gulf of Cadiz drifts (modified from McCave and Tucholke 1986; Faugères et al. 1993)

Eocene–Oligocene boundary (Fig. 7) and has been attributed to the opening of the Drake Passage. The Argentine Basin has since been affected by the deep Antarctic water masses. From the Middle Miocene onwards, the development of thermohaline circulation in the Northern Hemisphere has facilitated the additional influence of the North Atlantic Deep Water on this contourite depositional system. Water masses enter the Argentine Basin via deep narrow passageways in the topographic highs which enclose it. The water masses are then pushed against the continental margin due to the Coriolis force, to form an intensified boundary current. Plastered drifts developed along the upper continental slope and, on the lower continental slope, a mounded drift formed under the influence of complex basin circulation pathways.

Evolution and controls This CDS is made up of distinct erosional and depositional features developed in response to tectonic gateway opening and bottom-water variations caused by climatic and eustatic changes. Three major depositional units (Fig. 7) have been identified on seismic records. Contourite activity in the basin commences with an erosional surface relating to the onset of AABW formation at approx. 33 Ma (Hinz et al. 1999). This occurred due to a deepening of the Drake Passage, and the extension of the East Antarctic ice sheet and associated cooling which triggered the thermohaline circulation system in the Southern Hemisphere (Goosse et al. 2001; Carter et al. 2004). The subsequent sediment accumulation forms the lower seismic unit (LU) and signifies a phase of major progradational drift growth. Bottom-water velocities throughout LU formation are thought to have fluctuated in response to the changing cross-sectional area of the Drake Passage. The main phase of vertical drift growth occurred during a major global transgressive event. A second major erosional discontinuity is thought to be related to the Middle Miocene lowering of eustatic sea level. This is followed by low accumulation rates and aggradational stacking patterns in the intermediate seismic unit (IU) associated with third-order highstand (Ogg and Ogg 2008; Hernández-Molina et al. 2009). The final major seismic unit, the upper unit (UU), has developed under the present-day oceanographic configuration of the basin. Three sub-units have been recognised in the LU and three in the UU which may have formed in response to third-order T–R cycles (Fig. 7).

Sequence stratigraphy Although seismic analysis is the main source of data in this region, some conclusions may be drawn on the sequence stratigraphy of the Argentine Basin CDS. Bottom-water velocities tend to be more rapid at times of glacio-eustatic lows and this may lead to erosion, although sediment influx will be high. The Argentine margin therefore provides an example of a CDS under the influence of a bottom-water current which is accelerated during glacial times and global eustatic low-stands. The evidence presented above shows that erosion is likely to occur during lowstands, whereas sediment accumulation preferentially occurs during the lowstand to transgressive phases of systems tract development.

The Eirik Drift

Location and setting The Eirik Drift is a large Cenozoic elongated drift located off the southern tip of the Greenland

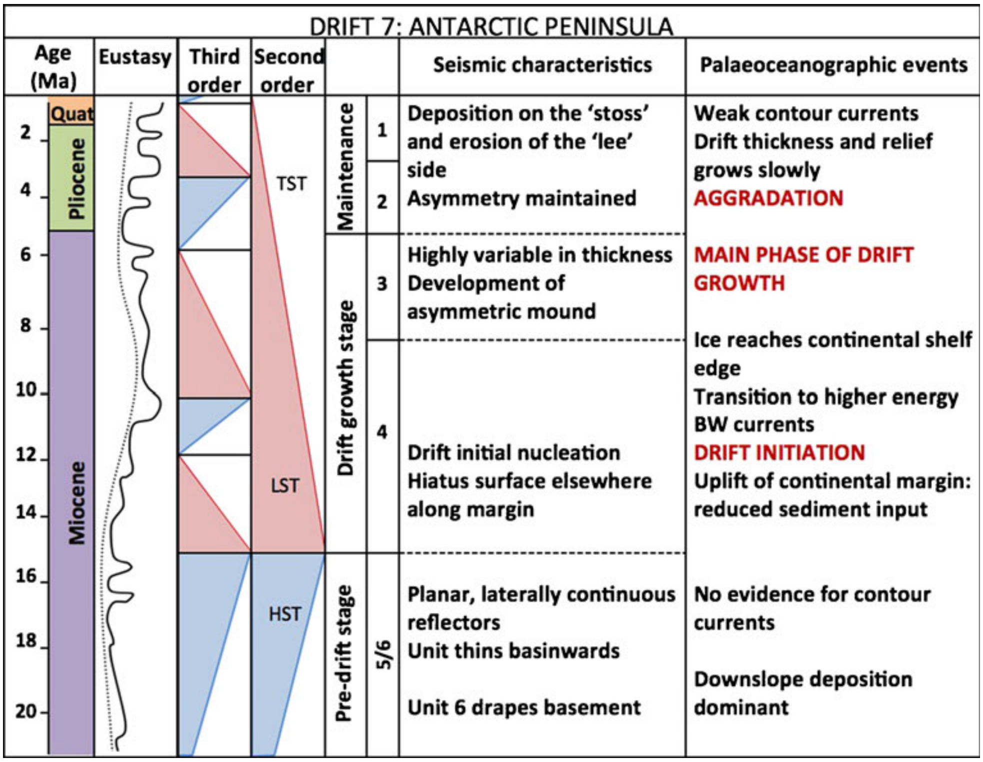

Fig. 6 Palaeoceanographic events and seismic characteristics associated with the evolution of Drift 7, Antarctic Peninsula. The main phase of drift building coincides with rising relative sea level. It should be noted that the local tectonic evolution of the margin is the dominant control over relative sea level, and glacial activity is an additional important control (adapted from Haq et al. 1987; Rebesco et al. 2002; Hunter 2008; Ogg and Ogg 2008)

continental margin (Hunter et al. 2007; Hunter 2008). It is one of a number of contourite drifts formed in the northern Atlantic Ocean which are closely linked to gateways and overflow waters from the Nordic and Arctic seas (Fig. 5). Located at depths up to 3,400 m, it is elongated in a NE–SW orientation in response to the oceanographic setup of the Greenland margin. Here, several deep-water masses overspill from the Arctic Basin through gaps in the Greenland-Iceland Ridge and combine to form the Deep Water Boundary Current (Hunter 2008).

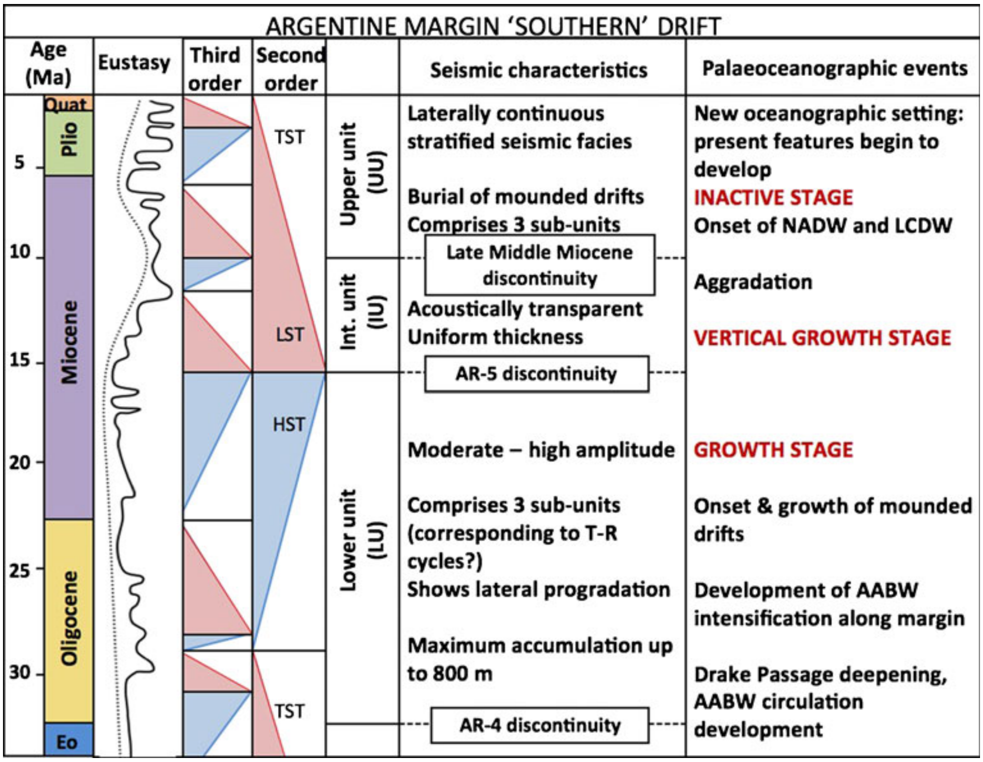

Fig. 7 Palaeoceanographic events and seismic characteristics associated with the evolution of the Southern Drift, Argentine Basin. After contour current initiation in the Early Miocene, drift growth was rapid. Despite a global lowstand in the Middle–Late Miocene, localised deepening of the Drake Passage enabled drift growth to continue, illustrating the importance of gateways on CDS evolution (adapted from Haq et al. 1987; Hunter 2008; Ogg and Ogg 2008; Hernández-Molina et al. 2010)

Evolution and controls The palaeoceanographic events are summarized in Fig. 8. There is evidence for bottom-water currents in the region from the Middle Miocene, when the relative sea level over the Greenland-Iceland Ridge reached sufficiently high levels to enable the exchange of water masses between the Atlantic and Arctic oceans. At that time, bottom-water formation in the Northern Hemisphere was vigorous and contourite sediment accumulation increased as more deep-water was able to escape into the North Atlantic. Through the Late Miocene and Early Pliocene the bottom-water circulation increased in intensity, as is evident from the formation of migrating sediment waves, drift progradation and localised erosion (Diez et al. 2008). Late Pliocene global sea level fall and ice sheet advance in response to cooling is coincident with a weakening of the bottom-water current in the Eirik Drift region between 3 and 0.9 Ma (Knutz 2008), a marked reduction in drift progradation and slowing in the rate of accumulation. The Holocene has seen evidence of renewed intensification of the Deep Water Boundary Current, coincident with increased rates of bottom-water formation during times of global eustatic highs.

Sequence stratigraphy The sequence stratigraphic response of the Eirik Drift is in concurrence with observations in many other Northern Hemisphere contourite depositional systems influenced by deep Arctic water masses (e.g. Howe 1995; Stoker et al. 1998; Weaver et al. 2000; Gröger et al. 2003; Øvrebø et al. 2006). Thus, during the warm interglacials (sea level highstands and transgressions) strong bottom-water currents prevailed, leading to erosional surfaces, active bedform growth and CDS development. During lowstands, high downslope sediment influx can dominate and current velocities are seen to wane.

The Gulf of Cadiz CDS

Location and setting The Gulf of Cadiz CDS has developed over the past 4–5 Ma in response to Mediterranean Outflow Water (MOW) exiting through the Gibraltar gateway (Hernández-Molina et al. 2003, 2006; Llave et al. 2007). The MOW generates an intermediate mid-slope bottom current comprising relatively warm but saline water produced in the warm-water kitchen of the eastern Mediterranean Sea (Fig. 5). In this respect it is thought to resemble palaeoceanographic conditions during the extremely high sea levels and warm greenhouse conditions of the middle and Late Cretaceous. Diapiric ridges orientated perpendicular to MOW flow (Tasianas 2010) form morphologic obstructions and create distinct channels through which the water mass splits into two pathways: the Mediterranean upper and lower waters. As a consequence, a complex drift system has developed along the northern margin of the Gulf of Cadiz, including both erosional and depositional domains and numerous different drift types (Hernández-Molina et al. 2006).

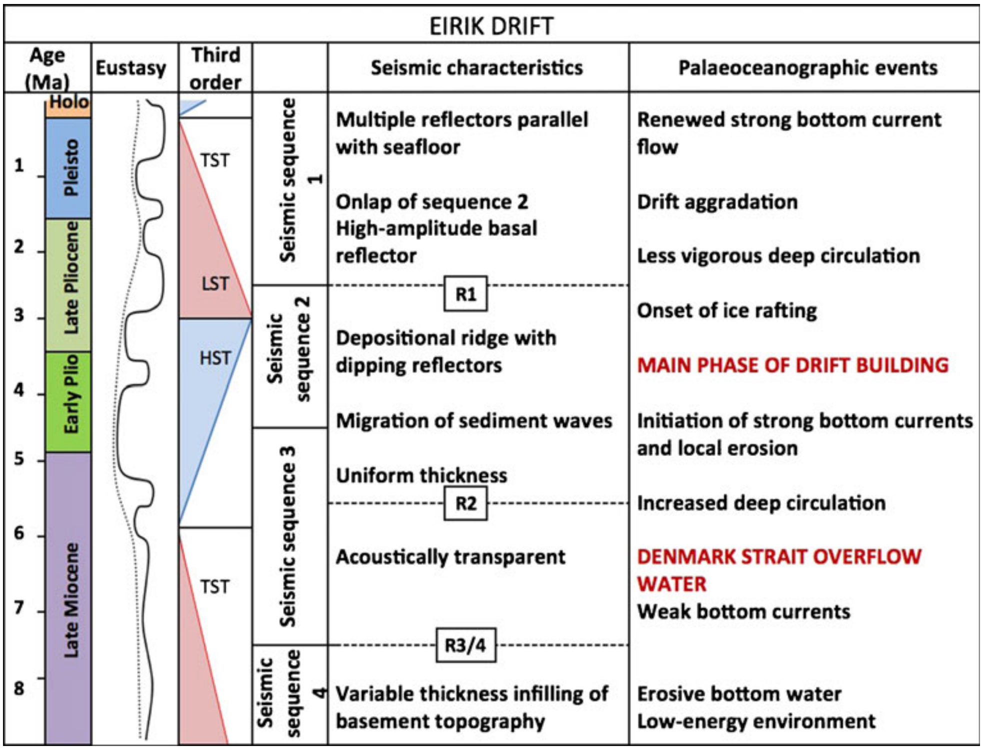

Fig. 8 Palaeoceanographic events and seismic characteristics associated with the evolution of the Eirik Drift, North Atlantic Ocean. The main phase of drift building coincides with highstand conditions. The Late Pliocene lowstand leads to slower deep-water circulation in the region (adapted from Haq et al. 1987; Hunter 2008; Ogg and Ogg 2008)

Evolution and controls Drift initiation occurred when the Gibraltar gateway opened and deepened sufficiently to enable significant MOW escape into the Atlantic. This occurred during the Early Pliocene, ca. 5.3–4 Ma (Fig. 9). Contourite drifts such as the Faro-Albufeira Drift are seen to be highly cyclical in nature, comprising numerous seismic sequences and sub-sequences (Llave et al. 2001, 2006; Stow et al. 2002a). These are interpreted as being due to major long-term fluctuations in bottom current intensity (and location), although it is not yet clear to what extent these have been caused by climatic-eustatic fluctuations or tectonic adjustments at the Gibraltar gateway. Several authors have demonstrated higher velocities of the lower branch of the MOW during glacial times (Cacho et al. 2000; Hernández-Molina et al. 2006; Llave et al. 2006; Toucanne et al. 2007). Other work, however, points to an increased velocity of the upper branch of the MOW during the recent highstand period (Stow et al. 2002b). There appears to be a basinward shift in the Mediterranean Outflow Water during times of lowstand due to increased MOW density and lowered sea level. Other key observations which relate to sequence stratigraphy are increased sedimentation rates on drifts in the upper core of the MOW, and a change from progradational to aggradational stacking patterns in response to rising sea level. Nelson et al. (1993) proposed a direct link between drift accumulation and relative sea level due to the changing cross-sectional area of the Strait of Gibraltar, although other factors such as fluctuating density of the MOW and tectonic activity have also played an important role in the development of the CDS during each evolutionary stage (Llave et al. 2007).

Sequence stratigraphy Various regions of the Gulf of Cadiz CDS appear to respond differently to eustatic changes. This is most likely due to the complexity of the region and the additional morphological and tectonic control along the margin. The available evidence indicates that greatest contourite accumulation occurs during times of glacio-eustatic lowstand.

New sequence stratigraphic model

This section attempts to combine the more theoretical considerations of controls on deep-water sedimentation, including the influence of sea level variation on bottom currents and sediment supply, with the observational data gained from a detailed study of contourite depositional systems, especially those documented in Table 1 and in the four case studies presented above. These data show that eustatic sea level changes affect bottom current generation and intensity differently, which is especially evident between the two hemispheres. It has therefore been necessary to propose two new sequence stratigraphic models of shelf–slope–basin sedimentation which focus on alongslope (contourite) elements developed on alongslope-dominated margins (Fig. 10).

Model 1: enhanced bottom-water currents during HST

Sequence boundary and LST As with the conventional downslope 'slug' diagram (Fig. 1), the new model containing

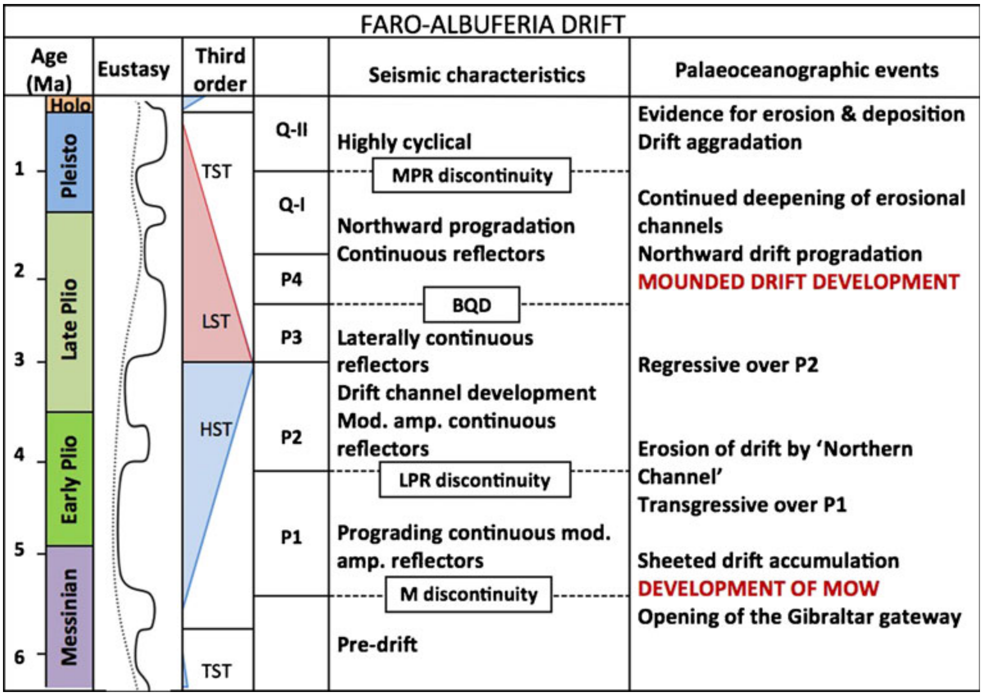

Fig. 9 Palaeoceanographic events and seismic characteristics associated with the evolution of the Faro-Albuferia Drift region in the Gulf of Cadiz (adapted from Haq et al. 1987; Nelson et al. 1993; Stow et al. 2002a; Llave et al. 2007; Hunter 2008; Ogg and Ogg 2008). *M* Messinian, *LPR* lower Pliocene revolution, *BQD* base Quaternary discontinuity, *MPR* mid-Pleistocene revolution

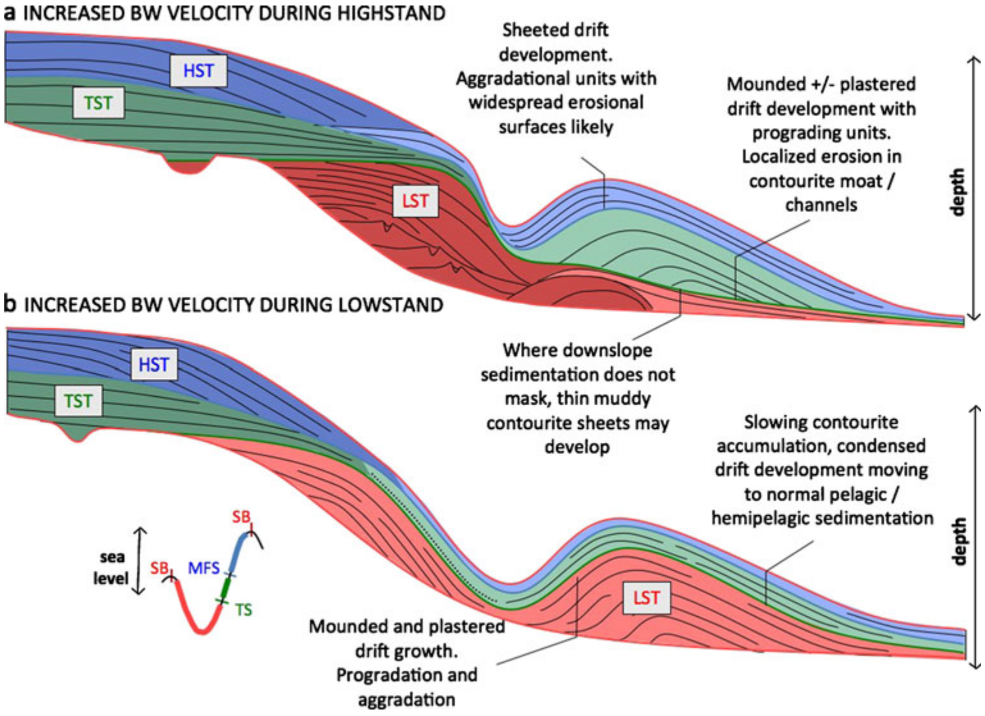

Fig. 10 Revised deep-water sequence stratigraphic models, applicable along margins where bottom-water circulation is more vigorous during times of **a** highstand or **b** lowstand. *Darker colours* Downslope deposits, *lighter colours* alongslope deposits, *LST* lowstand, *TST* transgressive, *HST* highstand, *SB* sequence boundary, *TS* transgressive surface, *MFS* maximum flooding surface. Figure not to scale but approx. 10s–100s km in the horizontal and 100 m–few km in sediment thickness (modified from an original model by Haq et al. 1988)

contourite deposits begins at the base with a sequence boundary which is overlain by the lowstand systems tract (LST). During low relative sea level, the continental shelf may be subjected to sub-aerial erosion and the slope generally experiences sediment bypass. As a result, there is enhanced sediment deposition in the deep ocean basins, and basin-floor and slope-apron fans typically develop. This increase in downslope sediment volume will affect contourite drift development by masking alongslope processes. Furthermore, the marked reduction in bottom current activity and velocity at times of low relative sea level provides conditions unfavourable for contourite development (Fig. 10a). However, at least on some margins there is evidence for muddy contourite deposition leading to the accumulation of thin, fine-grained sheeted drifts. In other cases these are commonly interbedded with more dominant turbidite and debrite sediments, leading to the formation of mixed contourite drifts as seen off the eastern USA and the Argentine continental margins (Faugères and Stow 2008; Huppertz, personal communication 2010).

TST During the transgressive systems tract (TST), the influence of downslope processes wanes and there is renewed activation of bottom currents and contourite deposition. This is typically expressed in the reworking of downslope sediment and the formation of elongate mounds along the slope apron, showing active alongslope progradation and/or aggradation (Fig. 10a). Sediment supply over the shelf edge is moderate and much of it fine-grained, greatly favouring drift development. Erosional unconformities are also common throughout the succession because minor fluctuations in bottom current velocity lead to repeated cycles of erosion and deposition.

This last point reveals an important departure from the existing models. Using conventional sequence stratigraphy laws (Van Wagoner et al. 1988), any erosional unconformity is tied to sub-aerial erosion and therefore requires a sea level fall. By contrast, the revised model shows that regionally extensive unconformities can be associated with increased bottom current velocities and sea level rise. This is amply supported by observational as well as theoretical data (e.g. Shannon et al. 2005, for the NW UK continental margin).

HST The gradation between transgressive and highstand systems tracts is indistinct with respect to contourite development and depends on the oceanographic setting of the margin in question. However, a trend of increasing bottom-water generation in response to sea level rise will see more active bottom-waters throughout the TST, climaxing in the HST. Downslope processes become muted, so that bottom current activity is uninterrupted and better preserved. Elongate, mounded contourite drifts continue to accumulate, showing both alongslope progradational and aggradational patterns. Assuming that the maximum bottom-water velocities reached are sufficiently high, contourite facies will have larger mean grain sizes, so that sandy contourites will be more widely dispersed, commonly as sandy sheeted drifts (Fig. 10a). Under still stronger currents, non-deposition surfaces and erosional features become significant, including channels, gullies, furrows, moats and other less regular scour features. These too may be the focus of sandy contourite deposition.

Sediment supply to the bottom currents which construct contourite drifts will be variable during the HST, depending partly on geographic location of the margin and partly on other additional controls—especially tectonics and climate. During development of the prograding highstand wedge in the conventional model, sediment supply to the slope will increase and there is thus potential for enhanced sediment supply to any drift system active at this stage.

Model 2: enhanced bottom-water currents during LST

Sequence boundary and LST As with the previous model, low sea level triggers enhanced erosion of the shelf and terrigenous sediment bypass into the oceanic basins. Wherever bottom-water current velocities peak during times of sea level lowstand, the pirating of downslope sediments by bottom-water currents can result in the domination of contourite systems over the normally expected downslope LST sequence (Fig. 10b). The result is high drift growth rates along the slope apron; some margins show accumulation rates which are an order of magnitude higher during LSTs where enhanced bottom waters redistribute large sediment influxes associated with glacial margins (Laberg et al. 2001; Rebesco et al. 2002).

Erosional processes driven by contour currents may also be prevalent along continental margins at the times when bottom-waters reach sufficient velocities. This is particularly common in regions where gateways may constrict and, therefore, further amplify bottom-water velocities (e.g. Hernández-Molina et al. 2009) or where specific morphological forcing accelerates the flow (e.g. Viana et al. 2002).

Expected sediment facies include sandy contourites where the maximum bottom-water velocities are sufficiently high to transport larger grain sizes. Where erosional features become significant, channels, moats and terraces are likely to develop. These too may be the focus of sandy and, in exceptional cases, also gravel-lag contourite deposition.

TST During transgressive systems tract (TST) development, downslope processes become more limited to the continental shelf and contour current cores begin to shoal. This is a transitional time for the system, during which accumulation rates slow down. Aggradational units are highly likely and sheeted drifts thus prevail (Fig. 10b). Bottom-water currents begin to slow down and therefore smaller average grain sizes are expected, although highly cyclical deposits will accumulate and ice-rafted debris may be found in drifts deposited at higher latitudes.

As with the model proposed for enhanced bottom-water currents during HSTs, erosional unconformities are common throughout the succession. These are formed in response to fluctuating bottom current velocities over the duration of deglaciation.

HST Where high eustatic sea level is associated with relatively low rates of bottom-water formation, contourite development is severely limited in the HST (Fig. 10b). At such times, downslope sediment supply to ocean basins is low as sediment is trapped on the continental shelves. The combination of low bottom-water velocities and limited sediment supply results in little to no contourite drift development, and hemipelagic and pelagic sedimentation may become the dominant process along the continental slopes. Some degree of contourite drift deposition may occur where current speed is adequate for reworking of sediments supplied by slope spillover or normal pelagic settling (Stow et al. 2008).

As with model 1 HST, certain circumstances such as tectonic or climatic changes enable downslope sediment progradation across the continental shelf and into the pathway of contour currents. If water velocities are insufficient to redistribute sediment entering the basin, then downslope processes may prevail.

Discussion and conclusions

The stratigraphy of contourite drifts has been used extensively to identify major global palaeoceanographic events. This paper is a first attempt to link these observations, together with theoretical considerations of sea level and other controls on bottom current variation, to sequence stratigraphic concepts by revising the original downslope model. This has been met with a number of challenges.

The original sequence stratigraphy model for downslope processes provided the definitions of systems tract boundaries—the changing balance between sediment supply and accommodation space determines the systems tracts. For example, the maximum flooding surface (separating the transgressive and highstand systems tracts) is the point over which there is a shift from sediment supply being unable to fill the accommodation space to sediment supply exceeding the available accommodation space. Since accommodation space is not a primary control on deep-water sediments, this distinction between systems tracts cannot be strictly valid in that case. As a result, it can be expected that there is a more gradual change between systems tracts in the deep-water. Hence, the contourite systems tracts identified in the revised model may not exactly match the downslope systems tracts of the conventional model. More work is in progress to elucidate any possible disconnection.

A further consideration in placing alongslope processes into the existing sequence stratigraphic model is related to the orientation of system evolution. Downslope processes develop from the continent basinwards. Conversely, contourite depositional systems evolve *parallel* to the continental margin and, therefore, along a different axis from that of downslope systems. This should be carefully considered when applying the models to an existing continental margin, since a depositional sequence found at a location where downslope processes dominate (i.e. at a turbiditic fan) will differ from that of a continental margin adjacent to a turbidite fan. This is particularly important when examining contourites downcurrent of turbiditic processes where pirating of sediment plays a key role.

It should be noted that the new models (Fig. 10) are, in fact, idealised conceptual end-member models and, in reality, there will be complications when applying the models to any existing geological system. This is exactly the same as for any existing sequence stratigraphic model and, as a consequence, many of the same problems arise when considering the sequence stratigraphy of downslope and alongslope systems. These problems have been discussed above in this paper. The considerations which are most significant to alongslope sequence stratigraphy are elaborated upon below.

1. Synsedimentary tectonic activity can significantly affect sedimentary architecture along continental margins, in some cases completely masking sea level effects (Bridge and Demico 2008). Local tectonic adjustments will affect both downslope and alongslope systems similarly. Added complications to contourite systems arise from the extremely important role played by tectonics in CDS placement and development, since oceanic circulation is controlled by gateways. All the case study examples of contourite depositional systems presented in this paper illustrate the intimate relationship between contourite drift development and gateway opening. Perhaps the creation of gateways is the primary control on oceanic circulation on a first- or second-order timescale.
2. The presence of ice along a margin can significantly alter the sedimentary architecture, sediment influx to a basin and/or rate of bottom-water generation (Goosse et al. 2001; Powell and Cooper 2002; van Weering et al. 2008). High-latitude systems can therefore be difficult to predict and may not always fit into the end-member model as seen in small-scale glacio-climatic fluctuations along the Antarctic Peninsula (Rebesco et al. 1997) and the NW European margin (Laberg and Vorren 2004; Laberg et al. 2005).
3. In the standard model, depositional sequences reflect mostly second- and third-order changes of sea level (i.e. duration of $1–10\times10^6$ years), while systems tracts and parasequences reflect third- and fourth-order changes (100×10^3 to 1×10^6 years). The same will be true for alongslope systems; however, as with deep-water turbidite fans, drift systems are capable of spanning two or more normal depositional sequences. This is clearly evident along the Canterbury Basin drifts, which continue to grow through numerous downslope systems sequence boundaries (Fulthorpe et al. 2010).

Where applied with care and a good understanding of a margin system, the models proposed here can greatly facilitate the interpretation of margins which include or are dominated by contourites. External controls, in addition to sea level, should always be carefully considered with respect to how they might affect a given contourite depositional system—models will never be applicable everywhere. Sequence stratigraphy has proven to be a highly valuable tool in hydrocarbon exploration of downslope sedimentary systems and it is therefore highly likely that a sequence stratigraphic model for contourite systems could prove to be a strong predictive tool.

A next step in this line of research is to assess how robust the models are in other settings and drift types—for example, in shallow-water and abyssal plain contourites or sheeted contourite systems. Work by Viana et al. (2002) has begun to address this topic in the Campos Basin shallow-water contourites. Here, sea level lowstand events are associated with distinctive current waning and increased downslope facies deposition. Subsequent sea level rises lead to the deposition of sandy facies with bedforms and increasing erosion. This suggests that the sequence stratigraphy model put forward in this paper can also be applied to shallow-water contourites in addition to the deep sea contourite systems for which it was developed. Future work should specifically focus on the collection of datable material in order to provide better time constraints for the assessment of the sequence stratigraphic evolution of a given drift at numerous timescales.

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