Yaps 2001

Surprisingly few thermophilic *Bacteria* have been obtained from deep-sea vents; however, culture-independent approaches may change this perception. Thermophilic *Bacillus* and *Thermus* species have been reported from deep-sea vents, as have members of sheathed thermophilic heterotrophs, the *Thermotogales*. More recently, and perhaps more significantly, representatives of two new lineages never previously reported from vents have been isolated. One, named *Desulfurobacterium*, is the only sulfur-reducing obligate chemolithotrophic thermophile in the domain *Bacteria*. Additional isolates of this group have confirmed that it may represent a new order. A second lineage, relatively closely related to the deeply branching *Aquificales* lineage, has also been isolated and is a microaerophilic hydrogen oxidizer.

Interestingly, this *Aquificales* lineage was first recognized as existing at deep-sea vents by analyzing the diversity associated with the deployment of an *in situ* growth chamber using a culture-independent approach. This chamber is placed on top of a hydrothermal vent for a predetermined time. The fluid flows through the chamber, and microbes can colonize surfaces that are placed in the chamber. Upon retrieval, the chamber is brought back to the surface and the diversity of organisms that are present in the chamber is analyzed using DNA-based techniques. Several interesting surprises emerged from one such study. Not only were there novel bacterial lineages prevalent in this environment, but the epsilon *Proteobacteria* also thrived in this chamber, raising the question whether these prevalent types are perhaps thermophilic inhabitants of deep-sea vents. Additionally, novel archaeal lineages were detected that were related to known iron oxidizers and thermoacidophiles (acid- and heat-loving organisms). In an independent study that explored the archaeal diversity of deep-sea vent chimneys, many novel very deeply diverging lineages were identified. Molecular-based inventories of deep-sea microbial diversity provide the baseline database for rigorous microecological studies at vents. Additionally, these assessments provide guidance for enrichment culturing strategies.

Subsurface Biosphere

It has been estimated that the subsurface is the major biosphere for microbes. Deep-sea hydrothermal vents may represent surface manifestations of this biosphere, and offer 'windows' into the Earth's interior ecosystem. The challenges now are to explore the extent of this biosphere. These include ocean drilling of hydrothermal environments, but also monitoring of microbial, geochemical, and biological changes that occur after new eruptions on the ocean floor. Perhaps one of the most spectacular examples of indirect evidence for an extensive subsurface biosphere at deep-sea vents is the initial biogenic sulfur flocs that are seen being emitted from eruptions (**Figure 6**). As described above, this flocculant material is produced by a mesophilic vibriod microbe that produces strands of filamentous sulfur at the sulfide–oxygen interface.

Deep-sea Hydrothermal Vents and the Origins of Life

As the early Earth accreted more than 4.0 billion years ago, it had a hot volcanic environment and a surface bombarded by asteroids. As the Earth started to cool, hydrothermal activity was extensive, and it is estimated that there was three times more heat flow due to hydrothermal activity in the Archaean Earth, than there is today. Some of the first evidence for life dates back to 3.8 Ga and some of the first microfossils date to about 3.5 Ga when there is no evidence for oxygen in the environment. Additionally, the deepest branching lineages within the tree of life are all represented by thermophilic microbes. These microbes may represent modern day analogues of their thermophilic ancestors. If life did originate in a hot hydrothermal environment, it is likely that the rich CO_2 environment and geochemical disequilibrium associated with the hydrothermal venting was an excellent energy source for the evolution of chemolithotrophs. Prior to the evolution of life, it is also possible that some of the first molecules may have evolved in this environment. A patent attorney and chemist, Gunter Wächterhäuser has proposed an elegant theory of how some of life's precursor molecules could have assembled on positively charged surfaces such as pyrite, an abundant mineral in hydrothermal systems.

Conclusion

Deep-sea hydrothermal ecosystems represent a frontier in science. Microbiologists have only begun to explore this new frontier. With the use of molecular techniques, rapid genomic sequencing, and better methods for sampling microbial niches at ridge ecosystems we will gain a much more comprehensive insight into the roles that microbes play in these ecosystems. Furthermore, understanding how these organisms thrive in this hostile deep environment, how they may influence the precipitation of minerals, and how they may become fossilized into the rock has implications in our search for the evidence of life (past or present) on other planets.

See also

Hydrothermal Vent Biota. Hydrothermal Vent Deposits. Hydrothermal Vent Ecology. Hydrothermal Vent Fauna, Physiology of. Mid-ocean Ridge Seismic Structure.

Further Reading

Bock GR and Goode JA (eds) (1996) *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*. New York: Wiley.

Jeanthon C (2000) Molecular ecology of hydrothermal vent microbial communities. *Antonie van Leeuwenhoek* 77: 117–133.

Karl DM (ed.) (1995) *The Microbiology of Deep-sea Hydrothermal Vents*. Boca Raton, FL: CRC Press.

McCollom TM and Shock EL (1997) Geochemical constraints on chemolithoautotrophic metabolism by microorganisms in seafloor hydrothermal systems. *Geochimica et Cosmochimices Acta* **61**: 4375–4391.

Van Dover CL (2000) *The Ecology of Deep-sea Hydrothermal Vents*. Princeton, NJ: Princeton University Press.

Wächterhäuser G (1988) Before enzymes and templates. Theory of surface Metabolism. *Microbiological Reviews* **52**: 452–484.

Ward DM, Ferris MJ, Nold SC and Bateson MM (1998) A natural view of the microbial biodiversity within hot spring cyanobacterial mat communities. *Microbiology and Molecular Biology Reviews* **62**: 1353–1370.

Whitman WB, Coleman DC and Wiebe WJ (1998) Prokaryotes: the unseen majority. *Proceedings of the National Academy of Sciences of the USA* **95**: 6578–6583.

DEEP-SEA SEDIMENT DRIFTS

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Introduction

The recognition that sediment flux in the deep ocean basins might be influenced by bottom currents driven by thermohaline circulation was first proposed by the German physical oceanographer George Wust in 1936. His, however, was a lone voice, decried by other physical oceanographers and unheard by most geologists. It was not until the 1960s, following pioneering work by the American team of Bruce Heezen and Charlie Hollister, that the concept once more came before a critical scientific community, but this time with combined geological and oceanographic evidence that was irrefutable.

A seminal paper of 1966 demonstrated the very significant effects of contour-following bottom currents (also known as contour currents) in shaping sedimentation on the deep continental rise off eastern North America. The deposits of these currents soon became known as contourites, and the very large, elongate sediment bodies made up largely of contourites were termed sediment drifts. Both were the result of semipermanent alongslope processes rather than downslope event processes. The ensuing decade saw a profusion of research on contourites and bottom currents in and beneath the present-day oceans, coupled with their inaccurate identification in ancient rocks exposed on land.

By the late 1970s and early 1980s, the present author had helped establish the standard facies models for contourites, and demonstrated the direct link between bottom current strength and nature of the contourite facies, especially grain size. Discrimination was made between contourites and other deep-sea facies, such as turbidites deposited by catastrophic downslope flows and hemipelagites that result from continuous vertical settling in the open ocean. Since then, much progress has been made on the types and distribution of sediment drifts, the nature and variability of bottom currents, and the correct identification of fossil contourites.

Of particular importance has been the work at Cambridge University in decoding the often very subtle signatures captured in contourites in terms of variation in deep-sea paleocirculation. As this is closely linked to climate, the drift successions of ocean basins hold one of the best records of past climate change. This clear environmental significance, together with the recognition that sandy contourites are potential reservoirs for deep-sea oil and gas, has spurred much current research in the field.

Bottom Currents

At the present day, deep-ocean bottom water is formed by the cooling and sinking of surface water

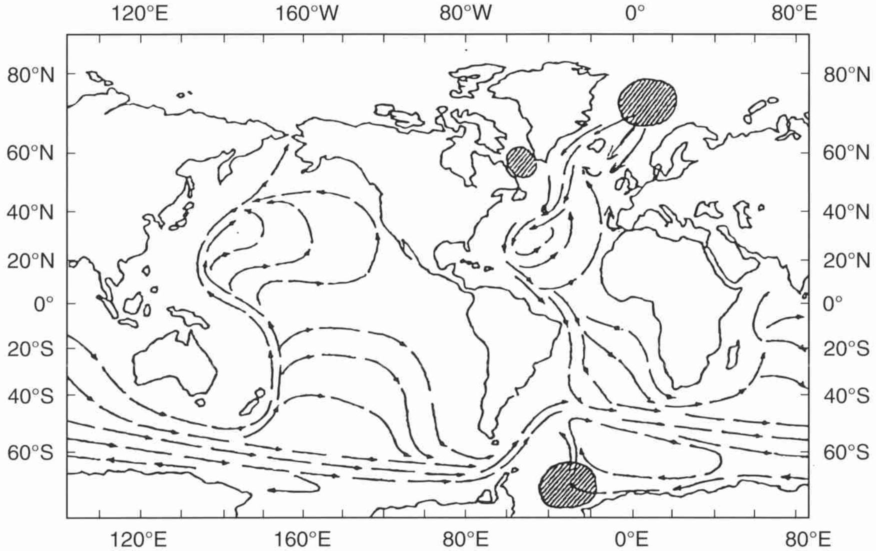

Figure 1 Global pattern of abyssal circulation. Shaded areas are regions of production of bottom waters. (After Stow *et al.*, 1996).

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

Arctic Bottom Water (ABW) forms in the vicinity of the subpolar surface water gyre in the Norwegian and Greenland Seas and then overflows intermittently to the south through narrow gateways across the Scotland–Iceland–Greenland topographic barrier. It mixes with cold deep Labrador Sea water as it flows south along the Greenland–North American continental margin. Above these bottom waters, the ocean basins are compartmentalized into water masses with different temperature, salinity, and density characteristics.

Bottom waters generally move very slowly ($1\text{–}2\,\mathrm{cm\,s^{-1}}$) throughout the ocean basins, but are significantly affected by the Coriolis Force, which results from the Earth's spin, and by topography. The Coriolis effect is to constrain water masses against the continental slopes on the western margins of basins, where they become restricted and intensified forming distinct Western Boundary Undercurrents that commonly attain velocities of $10\text{–}20\,\mathrm{cm\,s^{-1}}$ and exceed $100\,\mathrm{cm\,s^{-1}}$ where the flow is particularly restricted. Topographic flow constriction is greater on steeper slopes as well as through narrow passages or gateways on the deep seafloor.

Bottom currents are a semipermanent part of the thermohaline circulation pattern, and sufficiently competent in parts to erode, transport and deposit sediment. They are also highly variable in velocity, direction, and location. Mean flow velocity generally decreases from the core to the margins of the current, where large eddies peel off and move at high angles or in a reverse direction to the main flow. Tidal, seasonal, and less regular periodicities have been recorded during long-term measurements, and complete flow reversals are common. Variation in kinetic energy at the seafloor results in the alternation of short (days to weeks) episodes of high velocity known as benthic storms, and longer periods (weeks to months) of lower velocity. Benthic storms lead to sediment erosion and the resuspension of large volumes of sediment into the bottom nepheloid layer. They appear to correspond to episodes of high surface kinetic energy due to local storms.

Deep and intermediate depth water is also formed from relatively warm surface waters that are subject to excessive evaporation at low latitudes, and hence to an increase in relative density. This process is generally most effective in semi-enclosed marginal seas and basins. The Mediterranean Sea is currently the principal source of warm, highly saline, intermediate water, that flows out through the Strait of Gibraltar and then northwards along the Iberian and north European margin. At different periods of

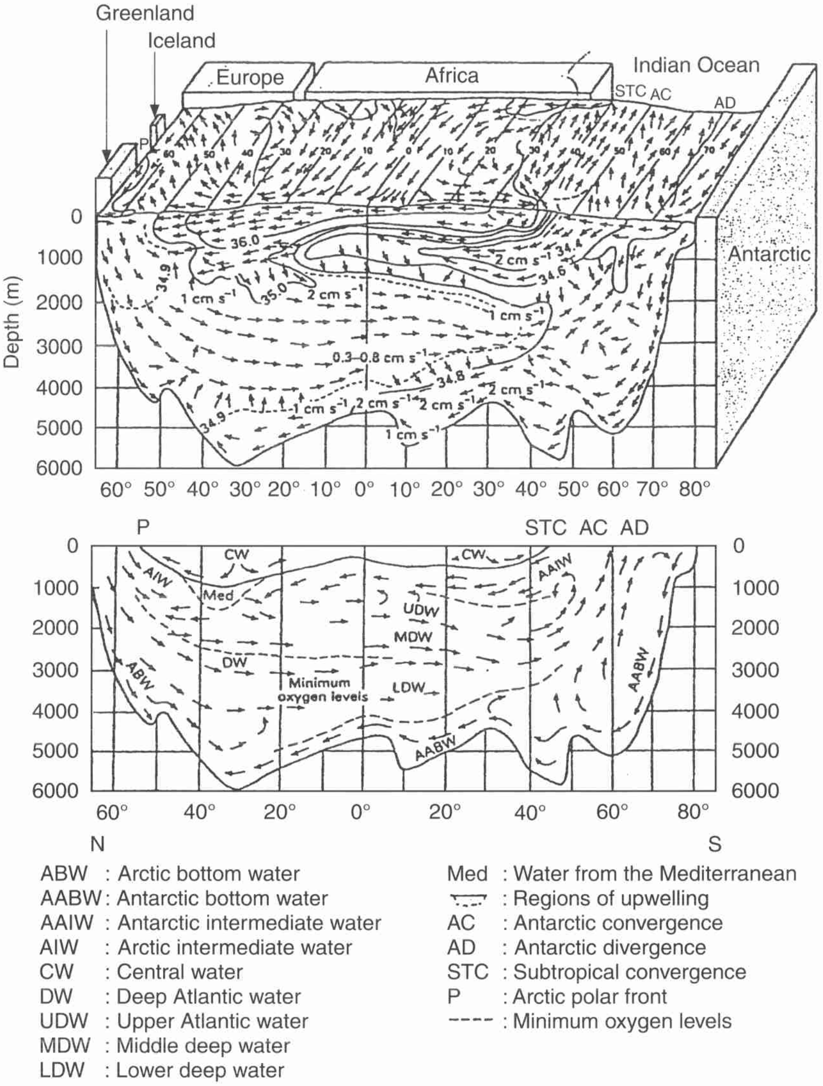

Figure 2 Bottom water masses in the North Atlantic Ocean (Reproduced from Stow *et al.*, 1996).

Earth history warm saline bottom waters will have been equally or more important than cold water masses.

Contourite Drifts

Contourite accumulations can be grouped into five main classes on the basis of their overall morphology: (I) contourite sheet drifts; (II) elongate mounded drifts; (III) channel-related drifts; (IV) confined drifts; and (V) modified drift–turbidite systems (**Table 1**, **Figure 3**). It is important to note, however, that these distinctive morphologies are simply type members within a continuous spectrum, so that all hybrid types may also occur. They are also found at all depths within the oceans, including all deep-water (> 2000 m) and mid-water (300–2000 m) settings. Those current-controlled sediment bodies that occur in shallower water (50–300 m) on the outer shelf or uppermost slope are not considered contourite drifts *sensu stricto*. The occurrence and geometry of these different types is controlled principally by five interrelated factors: the morphological context or bathymetric framework; the current velocity and variability; the amount and type of sediment available; the length of time over which the bottom current processes have operated; and modification by interaction with downslope processes and their deposits.

Contourite Sheet Drifts

These form extensive very low-relief accumulations, either as part of the fill of basin plains or plastered against the continental margin. They comprise

Table 1 Drift morphology, classification and dimensions

Drift type	*Subdivisions*	*Size* (km^2)	*Examples*
Contourite sheet drift	Abyssal sheet	10^5–10^6	Argentine basin; Gloria Drift
	Slope (plastered sheet)	10^3–10^4	Gulf of Cadiz; Campos margin
	Slope (patch) sheets	10^3	
Elongated mounded drift	Detached drift	10^3–10^5	Eirek drift; Blake drift
	Separated drift	10^3–10^4	Feni drift; Faro drift
Channel-related drift	Patch-drift	10–10^3	North-east Rockall trough
	Contourite-fan	10^3–10^5	Vema Channel exit
Confined drift		10^3–10^5	Sumba drift; East Chatham rise
Modified drift–turbidite systems	Extended turbidite bodies	10^3–10^4	Columbia levee South Brazil Basin; Hikurangi fandrift
	Sculptured turbidite bodies	10^3–10^4	South-east Weddell Sea
	Intercalated turbidite–contourite bodies	Can be very extensive	Hatteras rise

a layer of more or less constant thickness (up to a few hundred meters) that covers a large area, but that demonstrates a very slight decrease in thickness towards its margins, i.e., having a very broad low-mounded geometry. The internal seismofacies is typically one of low amplitude, discontinuous reflectors or, in some parts, is more or less transparent. They may be covered by large fields of sediment waves, as in the case of the South Brazilian and Argentinian basins where they are also capped in the central region by giant elongate bifurcated drifts.

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

Abyssal sheet drifts typically comprise fine-grained contourite facies, including silts and muds, biogenic-rich pelagic material, or manganiferous red clay, interbedded with other basin plain facies. Accumulation rates are generally low – around

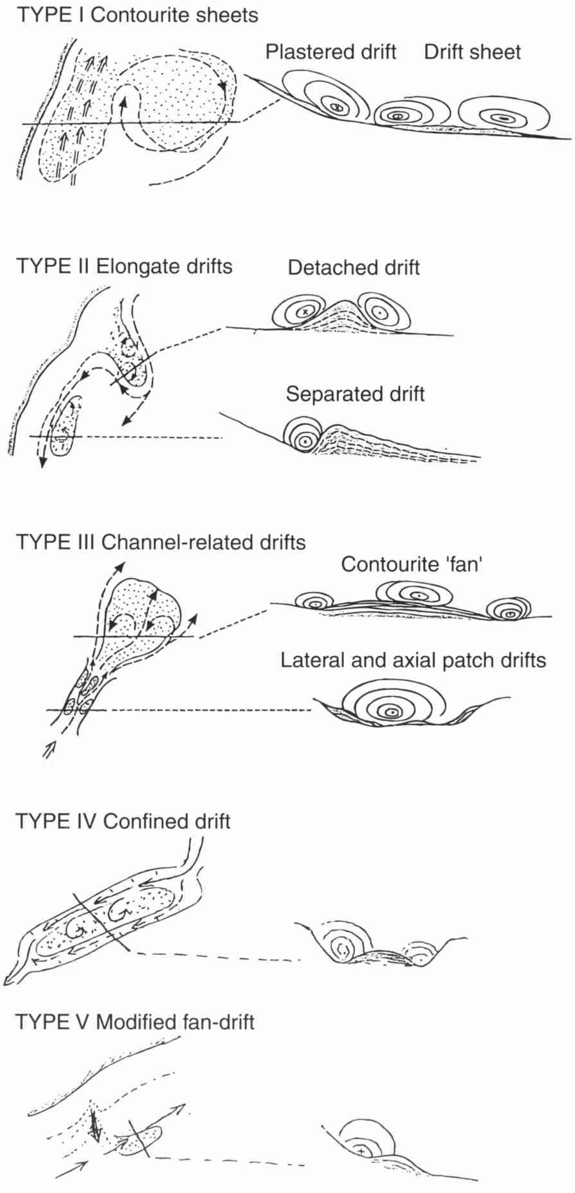

Figure 3 Contourite drift models. (Modified from Faugeres *et al.*, 1999.)

2–4 cm ky^{-1}. Slope sheets are more varied in grain size, composition and rates of accumulation. Thick sandy contourites have been recovered from base-of-slope sheets in the Gulf of Cadiz, and rates of over 20 cm ky^{-1} (1000 years) are found in sandy–muddy contourite sheets on the Hebridean slope.

Elongate Mounded Drifts

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

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

Sedimentation rates depend very much on the amount and supply of material to the bottom currents. On average, rates are greater than for sheet drifts, being between 2 and 10 cm ky^{-1}, but may range from < 2 cm ky^{-1} for open ocean pelagic biogenic-rich drifts, to > 60 cm ky^{-1}, for some marginal drifts (e.g., along the Hebridean margin). The sediment type also varies according to input, including biogenic, volcaniclastic, and terrigenous types. Grain size varies from muddy to sandy as a result of long-term fluctuations in bottom current strength.

Channel-related Drifts

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

Patch drifts are typically small (a few tens of square kilometers in area, 10–150 m thick) and either irregular in shape or elongate in the direction of flow. They can be reflector-free or with a more chaotic seismic facies, and may have either a sheet or mounded geometry. Contourite fans are much larger cone-shaped deposits, up to 100 km or more in width and radius and 300 m in thickness (e.g., the Vema contourite fan).

Channel floor deposits include patches of coarse-grained (sand and gravel) lag contourites, mud–clast contourites and associated hiatuses that result from substrate erosion, as well as patch drifts of finer-grained muddy and silty contourites where current velocities are locally reduced. Manganiferous mud contourites and nodules are also typical in places. Accumulation rates range from very low, due to nondeposition and erosion, to as much as 10 cm ky^{-1} in some patch drifts and contourite fans.

Confined Drifts

Relatively few examples are currently known of drifts confined within small basins. These typically occur in tectonically active areas, such as the Sumba drift in the Sumba forearc basin of the Indonesian arc system, the Meiji drift in the Aleutian trench and an unnamed drift in the Falkland Trough. Apart from their topographic confinement, the gross seismic character appears similar to mounded elongate drifts with distinct moats along both margins. Sediment type and grain size depend very much on the nature of input to the bottom current system.

Modified Drift-turbidite Systems: Process Interaction

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

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

1. Scotian Margin: regular interbedding of thin muddy contourite sheets deposited during interglacial periods and fine-grained turbidites dominant during glacials; marked asymmetry of channel levees on the Laurentian Fan, with the larger levees and extended tail in the direction of the dominant bottom current flow.
2. Cape Hatteras Margin: complex imbrication of downslope and alongslope deposits on the lower continental rise, that has been referred to as a companion drift-fan.
3. The Chatham–Kermadec Margin: the deep western boundary current in this region scours and erodes the Bounty Fan south of the Chatham Rise and directly incorporates fine-grained material from turbidity currents that have traveled down the Hikurangi Channel. This material, together with hemipelagic material, is swept north from the downstream end of the turbidity current channel to form a fan-drift deposit.
4. West Antarctic Peninsula Margin: eight large sediment mounds, elongated perpendicular to the margin and separated by turbidity current channels, have an asymmetry that indicates construction by entrainment of the suspended load of down-channel turbidity currents within the ambient south-westerly directed bottom currents and their deposition downcurrent.
5. Hebridean Margin: complex pattern of intercalation of downslope (slides, debrites, and turbidites), alongslope contourites and glaciomarine hemipelagites in both time and space; the alongslope distribution of these mixed facies types by the northward-directed slope current has led to the term composite slope-front fan for the Barra Fan.

Erosional Discontinuities

The architecture of deposits within a drift is complex, stressing variations of the processes and accumulation rates linked to changes in current activity. In many cases, the history of contourite drift construction is marked by an alternation of periods of sedimentation and erosion or nondeposition, the latter corresponding to a greater instability of and/or a drastic change in current regime. The result is the superposition of depositional units whose general geometry is lenticular and whose limits correspond to major discontinuities, that are more or less strongly erosive. These discontinuities can be traced at the scale of the accumulation as a whole and are marked by a strong-amplitude continuous reflector, commonly marking a change in seismofacies linked to variation in current strength. Such extensive and synchronous discontinuities are typical of most drifts. The principal characteristics of drifts evident in seismic records are shown in **Figure 4**.

Contourite Sediment Facies

Several different contourite facies can be recognized on the basis of variations in grain size and composition. These are listed and briefly described below and illustrated in **Figures 5 and 6**.

- Siliciclastic contourites (muddy, silty, sandy and gravel-rich variation)
- Shale-clast/shale-chip contourites (all compositions possible)

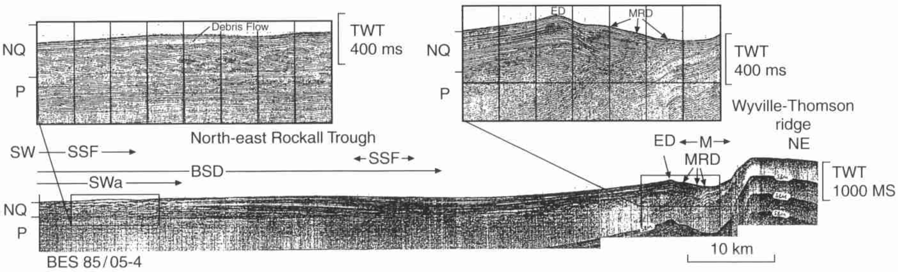

Figure 4 Seismic profiles of actual drift systems.

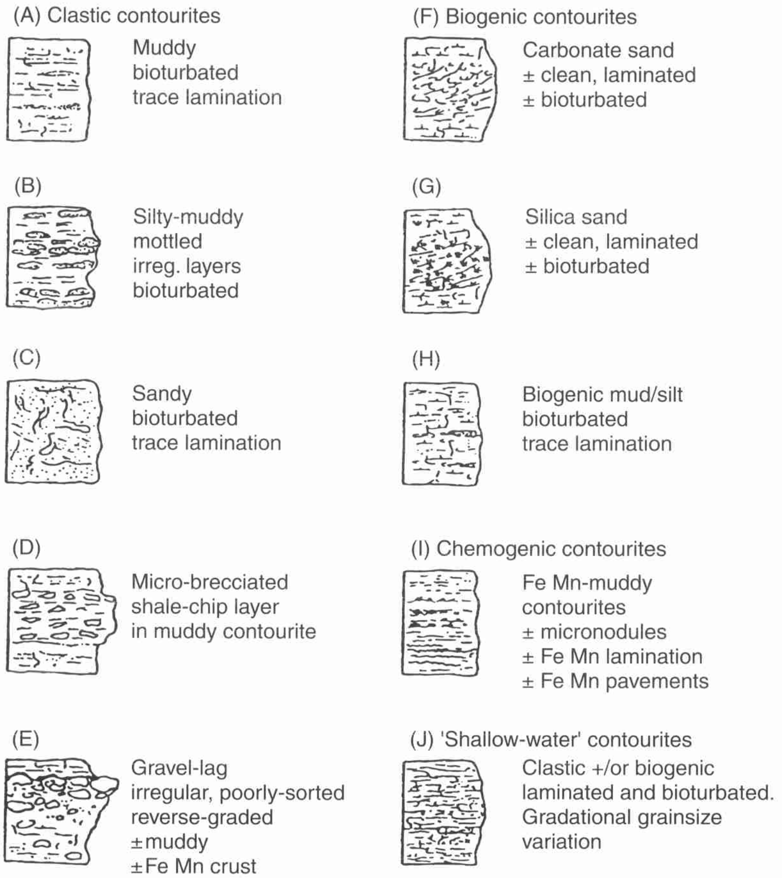

Figure 5 Contourite facies models for clastic, biogenic, chemogenic, and 'shallow-water' contourites. (Reproduced from Stow *et al.*, 1996.)

- Volcaniclastic contourites (muddy–silty–sandy variations)
- Calcareous biogenic contourites (calcilutite, -siltite, -arenite variations)
- Siliceous biogenic contourites (mainly sand grade)
- Manganiferous muddy contourites (+manganiferous nodules/pavements)

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

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

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

Gravel-rich contourites These are common in drifts at high latitudes as a result of input from ice-rafted

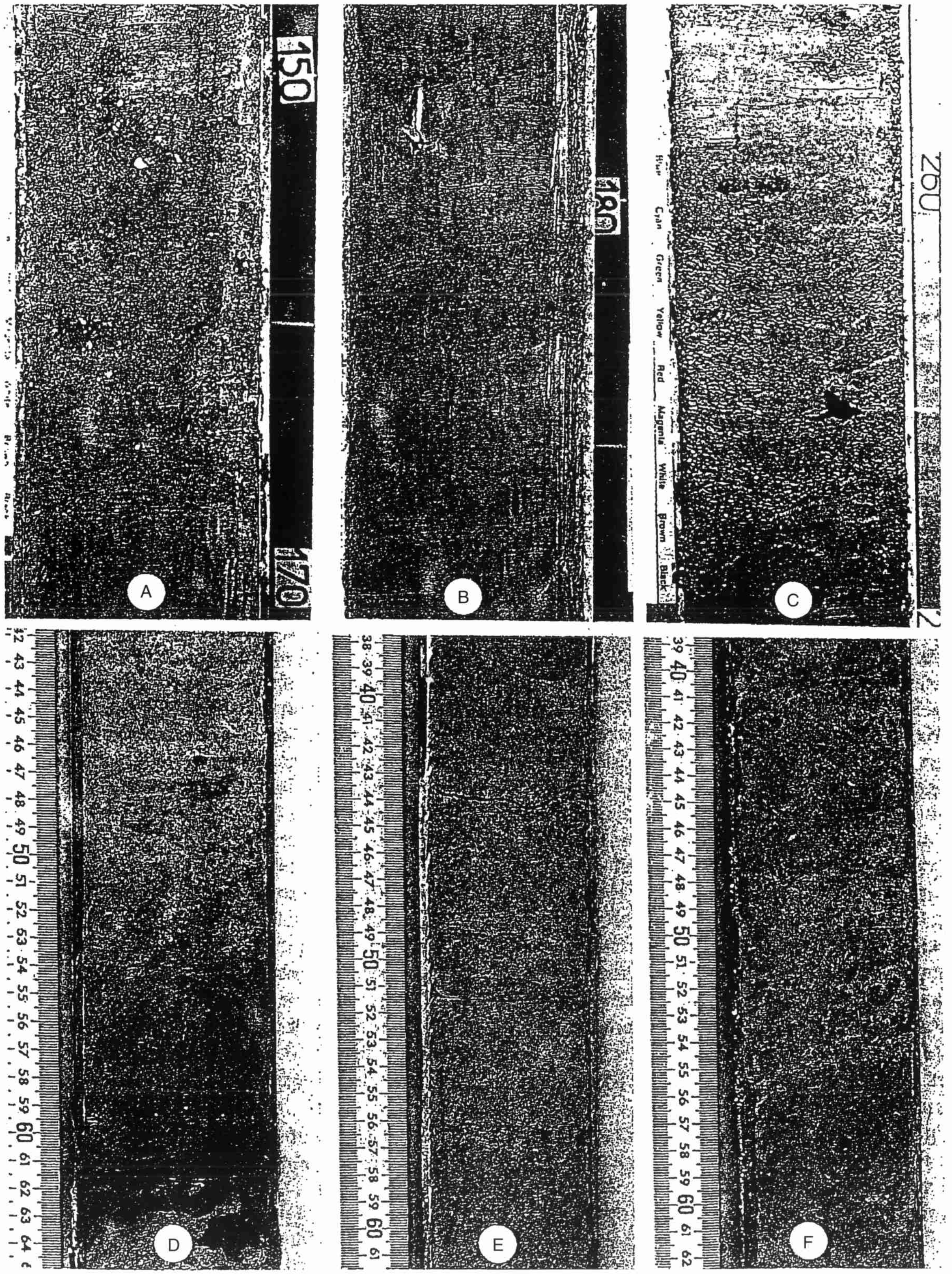

Figure 6 Photographs of contourite facies from cores drilled through existing drift systems. Vertical scales labelled in cm.

material. Under relatively low-velocity currents, the gravel and coarse sandy material remains as a passive input into the contourite sequence and is not subsequently reworked to any great extent by bottom currents. Gravel lags indicative of more extensive winnowing have been noted from both glacigenic contourites and from shallow straits, narrow moats, and passageways, where gravel pavements are locally developed in response to high-velocity bottom current activity.

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

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

Manganiferous contourites These manganiferous or ferromanganiferous-rich horizons are common. This metal enrichment may occur as very fine dispersed particles, as a coating on individual particles of the background sediment, as fine encrusted horizons or laminae, or as micronodules. It has been observed in both muddy and biogenic contourites from several drifts.

Bottom-current influence It is important to recognize that bottom currents will influence, to a greater or lesser extent, other deep-water sediments, particularly pelagic, hemipelagic, turbiditic, and glacigenic, both during and after deposition. Where the influence is marked and deposition occurs in a drift, then the sediment is termed contourite. Where the influence is less severe, so that features of the original deposit type remain dominant, then the sediment is said to have been influenced by bottom currents, as in bottom-current reworked turbidites. Some more-laminated facies, as well as the thin, clean, cross-laminated sands originally described from the north-east American margin, are most likely of this type.

Contourite Sequences and Current Velocity

Muddy, silty, and sandy contourites, of siliciclastic, volcaniclastic, or mixed composition, commonly occur in composite sequences or partial sequences a few decimeters in thickness. The ideal or complete sequence shows overall negative grading from muddy through silty to sandy contourites and then positive grading back through silty to muddy contourite facies (**Figure** 7). Such sequences of grain size and facies variation are now widely recognized, although not always fully developed, and are most probably related to long-term fluctuations in the mean current velocity. Not enough data exist to be certain of the timescale of these cycles, though some evidence points towards 5000–20 000 cycles for certain marginal drifts.

The occurrence of widespread hiatuses in the deep-ocean sediment record is best related to episodes of particularly intense bottom currents. More locally, such strong currents result in significant sediment winnowing and the accumulation of sand, gravel, and shale-clast contourites. Thick units of sandy contourites together with sandy turbidites reworked by the bottom current are potentially important as hydrocarbon reservoirs where suitably buried in association with source rocks.

Biogenic contourites typically occur in similar sequences of a decimetric scale that show distinct variation in biogenic/terrigenous ratio, generally linked to the grain size variation. This cyclic facies pattern has a longer timescale, in the few examples from which there is good dating, and is closely analogous to the Milankovitch cyclicity recognized in many pelagic and hemipelagic successions. It is, therefore, believed to be driven by the same mechanism of orbital forcing superimposed on changes in bottom-current velocity.

The link between contourite sequences and changes in paleoclimate and paleocirculation is an extremely important one. Where such sequences can be correctly decoded then a more accurate understanding of the paleo-ocean and its environment can be built up.

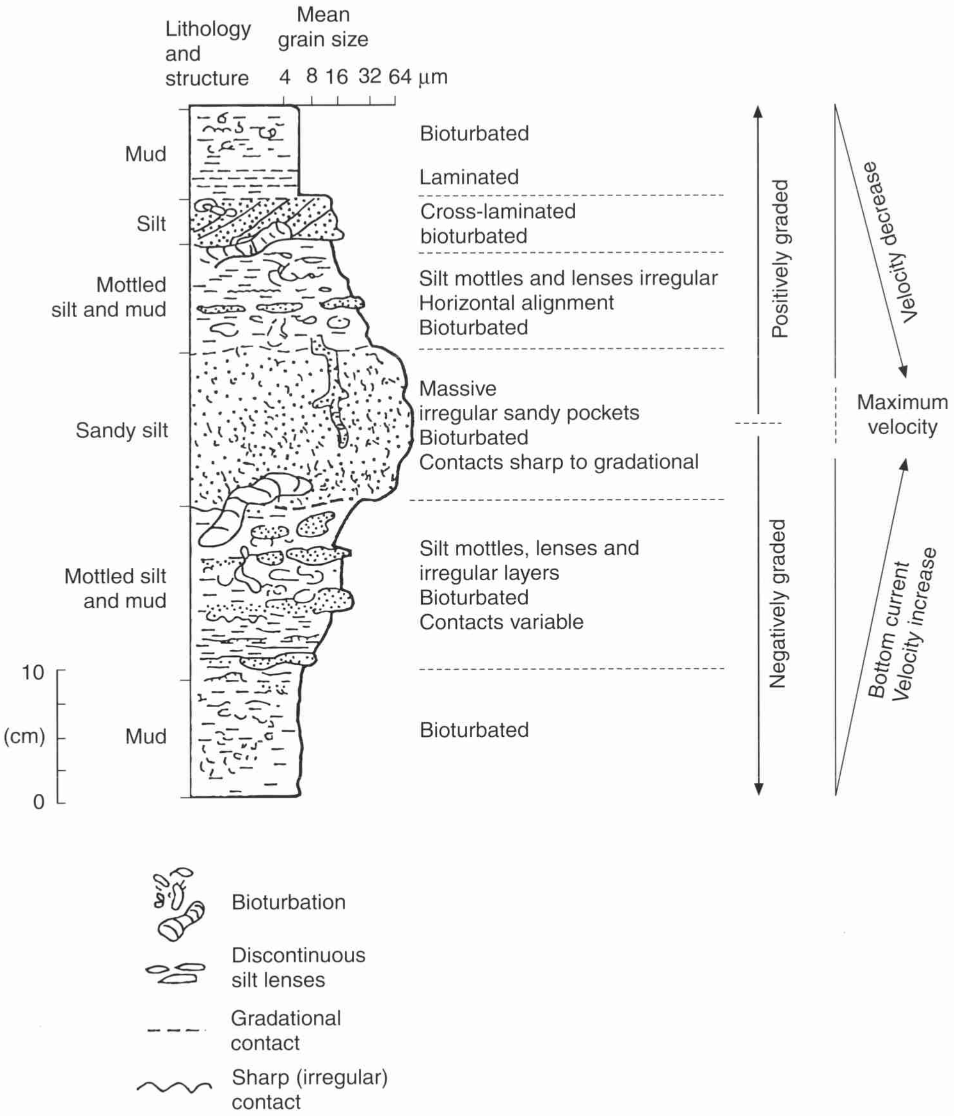

Figure 7 Composite contourite facies model showing grain size variation through a mud–silt–sand contourite sequence. (Modified from Stow *et al.*, 1996.)

See also

Bottom Water Formation. Nepheloid Layers. Ocean Margin Sediments. Sea Level Change. Thermohaline Circulation.

Further Reading

Faugeres JC, Stow DAV, Imbert P, Viana A and Wynn RB (1999) Seismic features diagnostic of contourite drifts. *Marine Geology* 162: 1–38.

Heezen BC, Hollister CD and Ruddiman WF (1966) Shaping the continental rise by deep geostrophic contour currents. *Science* 152: 502–508.

McCave IN, Manighetti B and Robinson SG (1995) Sortable silt and fine sediment size/composition slicing: parameters for paleocurrent speed and paleoceanography. *Paleoceanography* 10: 593–610.

Nowell ARM and Hollister CD (eds) (1985) Deep ocean sediment transport – preliminary results of the high energy benthic boundary layer experiment. *Marine Geology* 66:

Pickering KT, Hiscott RN and Hein FJ (1989) Deep-*Marine Environments: Clastic Sedimentation and Tectonics*. London: Unwin Hyman.

Stow DAV and Faugeres JC (eds) (1993) Contourites and Bottom Currents. *Sedimentary Geology* Special Volume 82: 1–310.

Stow DAV, Reading HG and Collinson J (1996) Deep seas. In: Reading HG (ed.) *Sedimentary Environments and Facies*, 3rd edn, pp. 380–442. Blackwell Science Publishers.

Stow DAV and Faugeres JC (eds) (1998) Contourites, turbidites and process interaction. *Sedimentary Geology Special Issue* 115.

Stow DAV and Mayall M (eds) (2000) Deep-water sedimentary systems: new models for the 21st century. *Marine and Petroleum Geology* Special Volume 17.

DEMERSAL FISHES

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Introduction

Fishes of many families, shapes, and sizes obtain their food in the near-bottom zone and show morphological and behavioral adaptations for life on or near the seabed. These are the demersal fishes, comprising both benthic and benthopelagic species, the latter usually performing vertical migrations to feed.

Demersal fishes occur at all depths and in all near-bottom habitats of the oceans. In this chapter the emphasis will be on species inhabiting the continental shelves, i.e., mainly waters shallower than about 200 m but deeper than the littoral and shallower part of the sublittoral. Some 7.5% of the marine environment belongs to this category, very little compared with oceanic waters (91.9%), but considerably more than estuaries, algal beds, and reefs that together cover only 0.6%. More emphasis will be placed on fishes living in offshore waters than those inhabiting typical shallow coastal environments, although it is recognized that very shallow habitats may constitute highly significant nursery areas for many shelf species.

Worldwide about 85% of the total continental shelf area has sandy or muddy substrate. Only about 6% is rocky or gravelly, and the remaining areas are coral reefs or shellbeds (e.g., mollusc shells). However, there are both latitudinal and depth-related patterns. Corals are almost entirely confined to low latitudes where organically enriched muddy areas are also most extensive, particularly near the mouths of major rivers or below highly productive upwelling areas. Sandy, rocky, and gravelly sediments are more common at high latitudes. Regional and local modification of the distribution and character of soft sediments is common, e.g., due to water currents flushing the shelves.

In addition to offering a range of physical habitats to fishes, continental shelves are usually highly productive, and especially in temperate and boreal regions, demersal species of the shelf waters are very abundant and support some of the world's major fisheries. Of the approximately 13 500 marine fish species, 1000–2000 inhabit continental shelf water of temperate and boreal zones. The majority of these are demersal species. In the subtropical and tropical zones, the richness and diversity is much greater.

Taxonomic Diversity, Geographical Patterns, and Assemblages

A wide range of families, including both cartilaginous and bony fishes, has demersal representatives in shelf waters. There are some rather consistent geographical patterns, however, both on a worldwide and regional scale. The taxonomical diversity tends to be higher at low than at high latitudes. Both species richness and evenness is normally highest in tropical and subtropical waters. An example is the Gulf of Thailand, a rather shallow soft-substrate shelf sea, where 850–900 fish species from around 125 families occur, of which at least 300 demersal species are commercially important. By comparison, the number of species in the boreal North Sea is only 160–170, belonging to about 70 families. Of these roughly 70 may be caught regularly in bottom trawl surveys offshore and only 10–15 are commercially important demersal species. These numbers decline even further in subArctic shelf waters.

However, the abundance and biomass of demersal fish is considerably higher at high latitudes, i.e., in temperate and boreal waters. The latter is normally due to high abundances of a few species, especially gadiform fishes such as hakes (Merlucciidae) and cod-like fishes (Gadidae), but also flatfishes (Pleuronectiformes) and rockfishes (Scorpaenidae) (**Figure 1**). Moreover, consistent differences between the oceans have evolved, e.g., gadiform fishes being more diverse on temperate Atlantic shelves than on North Pacific shelves where scorpaenids are very diverse and few gadiforms occur. The evolutionary history forms the background for present-day species composition patterns that are maintained by the rather strong structuring influence of regional and local environmental conditions, including the patterns of biological production in the surface layers.

Upwelling areas, well-mixed shallow shelf seas or shoals, and hydrographical frontal zones along the shelf-break are typical highly productive areas. Each of these environments is inhabited by subsets of the fish species found in the zoogeographical province to which they belong. Also, within such environments there may be a range of demersal habitats characterized by their hydrographical regime, currents, substrate quality, depth range, demersal