Chapter 25

Surficial sedimentary processes revealed by echo-character mapping in the western North Atlantic Ocean

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INTRODUCTION

The development of high-resolution precision depth recorders (PDR) in the 1950s (Luskian and others, 1954; Knott and Hersey, 1956) not only permitted continuous and accurate measurement of ocean depths, but also provided a new tool for the study of deep-sea sedimentation processes. Changes in acoustic reflectivity and microtopography of the seafloor as observed on these early 12-kHz PDR records were found in many cases to be caused by erosional/depositional processes (Heezen and others, 1959). One of the first studies helped to confirm the existence of the Western Boundary Undercurrent (WBUC), a thermohaline, contour-following bottom current which is important in shaping the continental rise off eastern North America (Heezen and others, 1966; see also McCave and Tucholke, this volume). As part of this study, Hollister (1967) constructed an “echo character” map of the continental rise off Nova Scotia by classifying and mapping the regional changes of acoustic reflectivity observed on 12-kHz echograms. This map suggested that certain types of echoes (e.g. hyperboles and prolonged echoes) were apparently reflected from sand waves or other depositional bedforms created by the WBUC. Regionally, these echo types were thought to be aligned parallel to bathymetric contours beneath the WBUC axis (Heezen and others, 1966; Hollister, 1967; Hollister and Heezen, 1972). Although subsequent and more detailed studies using much better quality 3.5-kHz echograms have shown that the regional pattern of echo character along the Nova Scotian margin is primarily downslope rather than along slope, this pioneering work by Hollister and Heezen demonstrated the usefulness of echo-character mapping as a tool to infer sedimentary processes and environment. Several subsequent studies in the western North Atlantic included mapping and/or analysis of 12-kHz echograms in order to study the paths of flow and erosional/depositional effects of the WBUC and the Antarctic Bottom Water (AABW) on the seafloor (Clay and Rona, 1964; Schneider and others, 1967; Schneider and Heezen, 1966; Bryan and Markle, 1966; Rona and others, 1967; Fox and others, 1968; Rona, 1969).

In the late 1960s many oceanographic institutions began to collect continuous 3.5-kHz PDR echograms in addition to 12-kHz recordings. 12-kHz echograms generally show limited (<10 m) penetration of acoustic energy below the seafloor because of the preferred attenuation of high-frequency sound by both the water column and the seabed, but the lower-frequency 3.5-kHz records generally obtain 20 to ~100 m of sub-bottom penetration. Thus 3.5-kHz echograms reveal much more information about the nature and orientation of physical stratification (e.g. presence or absence of reflectors, truncation or migration of reflectors, etc.) in the upper part of the seabed (Damuth, 1975; Embley, 1975). Consequently, most studies of echo character since 1970 have used primarily 3.5-kHz echograms.

Such echo-character mapping studies are now widely used to evaluate regional seafloor sedimentation processes in many parts of the world's oceans, including portions of the western North Atlantic (see Damuth, 1980, for a review). The information obtained from 3.5-kHz and 12-kHz echograms generally can be used to define both the types and the regional influences of sedimentation processes such as contour-following bottom currents, turbidity currents, and mass-transport processes. These data are greatly enhanced when combined with other data such as sediment cores, bottom photographs, hydrographic and nephelometer measurements, and low-frequency (<100 Hz) seismic reflection profiles.
CLASSIFICATION AND DISTRIBUTION
OF ECHO TYPES

Introduction

The principles and methods of echo-character mapping have been described in detail in a series of previous papers (see Damuth, 1980 and references therein), and they are not repeated here except for a brief discussion of geometrical effects. The classification of echo types used here is based on Damuth (1975; 1978; 1980) and Damuth and Hayes (1977). To produce a legible map for publication at the required scale (Plate 7), we simplified the more detailed original maps used for this compilation. In addition, the echo-character classification used here is, of necessity, a combined and simplified version of the original classification. Although the map consequently loses local detail, it allows us to illustrate the regional variation in echo character and sedimentary processes.

The same physical and geometrical principles which cause the distortion of conventional land-based seismic reflection profiles and thereby make their interpretation difficult (Hagedoorn, 1954; Hilterman, 1970; Smith, 1977) also influence the echograms on which this study is based (Flood, 1980). Because of the great depths in most instances to seafloor features, and the wide (30° to 60°) beam width of conventional surface-ship echo sounders, the echograms generated by such systems can appear significantly different from true seafloor morphology. This is because wide-beamwidth echo sounders sonify large areas of the seafloor that are not directly beneath the ship. Echoes returning from these areas can then confuse or distort the recorded echogram. In the simplest case, slopes measured on echograms taken over a sloping seafloor will be less than the true slope (Krause, 1962). More difficult to interpret than this simple distortion of shape are echograms taken over peaks or sharp changes in slope. These are generally recorded as hyperbolic echoes (Hoffman, 1957; Bryan and Markl, 1966; Flood, 1980). Echograms taken over sinusoidal or periodic bedforms may also be distorted (Flood, 1980).

The speed of the ship, its course (when passing over linear features), and water depth all play a role in determining the exact nature of the distortions appearing in any given echogram. For example, Flood (1980) has demonstrated that a trough between migrating sediment waves (Echo Type V, Plate 7) may appear very different in echograms having different water depths. In shallower water (<2.5 km) the troughs will only be slightly distorted, the main effects being altered slopes within the limbs and intensification of the echoes from beneath the trough. At significantly greater depths (~5.5 km) the same feature appears as a V-folded "valley" with strong and confused echo returns from beneath the valley.

The classification and distribution of echo types in the western North Atlantic Ocean are discussed below. For reference to geographic locations, the reader should consult Plate 2 at the back of the volume.

Distinct and Indistinct Echoes

Among the most commonly observed echo types within the western North Atlantic are those with distinct to indistinct bottom echoes. These echo types are commonly found within all of the well-mapped provinces from the continental shelf across the continental margin to the abyssal plains and basinal plateaus.

Echo Type IA. Distinct, sharp bottom echoes with several sharp, parallel sub-bottom reflectors which are continuous for tens of kilometers: seafloor is flat to undulating (Plate 7). This echo type is one of the most widespread and is recorded from many portions of the continental rises and abyssal plains, as well as from the plateaus of the Bermuda Rise Drift northeast of Bermuda. On the abyssal plains, these echoes are generally recorded from more distal portions, especially on the Demerara and Ceara abyssal plains in the Guiana Basin (Damuth, 1975; 1980). On the Bermuda Rise flanks, the seafloor is generally undulating to hilly where these echoes are recorded. In areas returning Type IA echoes, the maximum acoustic penetration observed in the western North Atlantic (often 100 m or more) is generally achieved.

Echo Type IB. Distinct echoes with no sub-bottom reflectors (Plate 7). This echo type is the most common return from the consolidated sediments of the continental shelves. Distinct, sharp echoes with no sub-bottoms are observed because most of the sound energy is reflected and acoustic penetration is limited to a few meters. Isolated examples are also found in the deep basin in areas where Quaternary cover has been removed, thus exposing reflective, semi-consolidated Neogene sediments (e.g. the northern Bermuda Rise).

Echo Type IIA. Indistinct, semi-prolonged bottom echoes with intermittent or discontinuous, indistinct (fuzzy), sub-bottom reflectors: seafloor is flat to undulating (Plate 7). This echo type is recorded from extensive regions of the continental rise and abyssal plains. It is apparently the result of sound-pulse reflections from laterally discontinuous sub-bottom sedimentary beds.

Echo Type IIB. Very prolonged bottom echoes with no sub-bottom reflectors: seafloor is flat to undulating (Plate 7). Prolonged echoes are recorded from many locations on the continental rises and abyssal plains, although they are commonly less extensive than Type IA and IIA echoes. Prolonged echoes also are recorded from the floors of submarine canyons and channels such as the Northwest Atlantic Mid-Ocean Channel (Plate 2). These echoes characterize the entire lower part of the Amazon deep-sea fan and adjacent Demerara Abyssal Plain (5°-11°N, 45°-50°W; Plate 7). Prolonged echoes similar to Type IIB are also recorded from debris-flow deposits; however, in this paper we have classified echoes from debris flows separately (Echo Type IV) in order to distinguish these important deposits (Plate 7).

In reality, there are wide variations in appearance of echo Types IA, IIA, and IIB, mainly in the depth of acoustic penetration below the seafloor, and the thickness, number, and clarity of sub-bottom reflectors. Thus distinct echoes with continuous sub-bottoms (IA) and very prolonged echoes with no sub-bottoms (IIB) form two end members of echo character. Numerous grada-
tional forms (mostly variations of IIA) occur between these end members (see Damuth, 1980, and references therein for other examples). The relationship of these three echo types to the distribution of coarse terrigenous sediment is discussed later.

**Hyperbolic Echoes**

Hyperbolic echoes are the result of reflections from point or line reflection sources on or sometimes beneath the sea floor. Point reflection sources are most commonly rugged basement topography such as that found along the mostly unseminated crest and flanks of the Mid-Atlantic Ridge. Line sources are commonly sedimentary features such as sea floor furrows or scars associated with sediment mass movements.

**Echo Type IIIA.** *Large, irregular, overlapping and single hyperbolas with widely varying vertex elevations: sea-floor morphology is hilly to very rugged* (Plate 7). These echoes are recorded from isolated seamounts, knolls, and basement outcrops; seamount chains such as the New England Seamounts; oceanic ridges and rises such as the Mid-Atlantic Ridge, Barracuda Ridge, and Ceara Rise; fracture-zone ridges; tectonized sediment wedges such as the Barbados Ridge; and steep, rugged areas of the continental slope. The morphology of such regions (excluding the continental slope and the Barbados Ridge) is controlled by the configuration of oceanic basement; the basement normally is rugged and either crops out or is covered by only a thin veneer of pelagic sediments. The rugged morphology of the basement rocks (numerous projections of unequal height above the seafloor) gives rise to the large irregular hyperbolas recorded on 3.5-kHz records. Although this echo type is generally not created by sedimentation in such areas, it indirectly suggests the nature of localized, small-scale sedimentation processes. Pelagic sedimentation, slumpings, and debris flows all are important within steep-sloped regions such as these; however, these features are of such small scale that they are not resolved in our mapping (Plate 7), and often they are not even recorded in broad-beamwidth 3.5-kHz and 12-kHz echograms.

Along the western Atlantic continental slopes, the rugged topography creating echo Type IIIA is formed from semi-consolidated and consolidated sedimentary rocks. Down-cutting by turbidity currents, local and regional slope failure, and other forms of canyon and gully formation all have contributed to the dissection of these sedimentary rocks to create irregular topography. Beneath the Barbados Ridge, sediments and sedimentary rocks have been tectonized to form rugged topography. Thrusting, folding, and mud volcanism associated with underthrusting of the North Atlantic plate beneath the Caribbean plate all have contributed to the deformation of this sedimentary wedge and the creation of an irregular surface with steep slopes.

**Echo Type IIIB.** *Regular overlapping hyperbolas with vertices approximately tangent to the seafloor* (Plate 7). Amplitudes of these echoes are generally less than 50 m and wavelengths are short (100-500 m). The hyperbolas are recorded mainly from relatively small, scattered patches along the continental margin and in the basin interior where the seafloor has been affected by contour-following currents (Plate 7). The largest regions of these echoes are observed on the Blake-Bahama Outer Ridge system. Type IIIB hyperbolas are generally associated with regions of Type IIIC hyperbolas and with sediment waves or drift deposits (Echo Type V, see below). Some Type IIIB hyperbolas show changes in wavelength with profile azimuth, indicating that the bedforms from which they are reflected have a regular orientation (Damuth, 1975, 1980; Flood, 1980). In some areas such hyperbolas are observed not only at the seafloor but also along one or more discrete sub-bottom horizons.

**Echo Type IIIC.** *Regular overlapping hyperbolas with varying vertex elevations above the seafloor; conformable sub-bottom reflectors may be present* (Plate 7). Wave lengths are generally less than one kilometer although longer ones are occasionally observed. Amplitudes generally range from 10 to 100 m. These Type IIIC hyperbolas are recorded mainly from isolated locations on the continental rise and rarely in the basin interior (Plate 7). The most extensive occurrences of Type IIIC hyperbolas are observed on the Blake-Bahama Outer Ridge and adjacent portions of the continental rise. Type IIIB and IIIC hyperbolas are reflected from erosional/depositional bedforms that were created by thermohaline flows of bottom water (contour currents).

**Type IIID.** *Regular overlapping hyperbolas with varying vertex elevations above the seafloor* (Plate 7). These hyperbolas are very similar in appearance and size to IIIC hyperbolas. However, Type IIID hyperbolas are slightly less regularly spaced and vertically more variable than Type IIIC hyperbolas, and they are often found in association with debris-flow deposits (Echo Type IV) in isolated locations. They apparently represent displaced slump and slide material at the heads of slump and debris-flow deposits. Type IIID hyperbolas generally have no sub-bottom reflectors.

**Miscellaneous Echo Types**

**Echo Type IV.** *Transparent lenses with prolonged bottom echoes* (Plate 7). These echoes have a seafloor reflection similar to Type IIIB echoes but are distinguished from them by the presence of a transparent lens. They are the deposits from submarine debris flows. Such debris-flow deposits generally appear as thin (<100 m), acoustically non-laminated lenses which extend for tens to hundreds of km down the continental rise (Embley, 1976, 1980; Embley and Jacobi, 1977; Jacobi, 1976; Jacobi and Hayes, 1982; Damuth and Embley, 1981). Well-stratified, undisrupted sediments occasionally are observed beneath the debris flows, but generally internal reflections within the lens are not observed because the sediments are homogenized during the transport process. Failure to observe these transparent lenses is not necessarily diagnostic of the absence of debris flows because the deposits can be so thick that underlying reflectors are not observed. In this case only a prolonged surface echo is recorded.
and no transparent "lens" is observed. Type IV echoes trend downslope at many locations on the continental rise off eastern North America (Plate 7). Two large zones of such echoes are also observed extending seaward of irregular, Type III D echoes on the Amazon Deep-Sea Fan (4°-6° N; Plate 7).

**Echo Type V. Broad distinct, sediment waves with distinct conformable to unconformable sub-bottom reflectors: seafloor is undulating to hummocky.** These echoes are recorded from large-scale sediment waves. They are found on drift deposits created by contour currents, or on levees deposited on the flanks of submarine canyons (Plate 7). The waves contain unconformable to conformable sub-bottom reflectors that often show erosional truncation and lateral migration. The sediment waves and associated drift deposits are widely distributed off North and South America, both along the continental margins and in the interior of the basins.

**SEDIMENTATION PROCESSES REVEALED BY ECHO CHARACTER**

**Compilation of the Echo Character Map (Plate 7)**

The echo character map of the western North Atlantic at the back of this volume (Plate 7) was compiled mainly from maps which were constructed for smaller, regional studies. Data sources include published maps (Damuth, 1975; Silva and others, 1976; Damuth and Hayes, 1977; Shipley, 1978; Mullins and others, 1979; Laine and others, 1983; Vasallo and others, 1984a, b; and Damuth and others, 1986), unpublished theses (Kristoffersen, 1977; Flood, 1978; McCreery, 1983), and unpublished compilations (Damuth, Flood, and Laine). The eastern continental margins of both North and South America are well-studied, as are the adjacent abyssal plains. Other areas that are characterized by thick sediment accumulations and that are affected by contour currents (Blake-Bahama Outer Ridge, northern Bermuda Rise, and portions of Labrador Basin) have also been studied in detail.

Where possible, we have also examined echograms and mapped the echo character in regions of the western North Atlantic where no previous mapping had been done. In this way we attempted to achieve continuity between existing maps and to map as many uncharted regions as time and data permitted. In many cases, the data spacing in unmapped regions was too wide to permit meaningful determination of echo character distributions. As a result, the abyssal hills province on the flanks of the Mid-Atlantic Ridge, the ridge crest itself, and fracture zones were not systematically mapped in this study. Although these are regions of generally thin sediment cover, previous small-scale studies (van Andel and Komar, 1969; Shipley, 1978) have shown that pelagic sedimentation, gravity flows (turbidity currents and mass movements), thermohaline currents, and tectonic processes all shape the sedimentary deposits within these provinces. In these poorly mapped areas of the western Atlantic, we have shown generalized echo character, based on examination of scattered track lines and our knowledge of seafloor morphology. Province boundaries in these regions are based for the most part on the boundaries given by Emery and Uchupi (1984, Plate X). The resulting generalizations imply no rigorous interpretation of sedimentary processes in these areas, but they provide the reader an overview of the relative areal importance within the western North Atlantic of both the various echo types and their associated sedimentary processes.

The continental margins and adjacent abyssal plains and plateaus of the western North Atlantic are the areas of densest and most reliable echogram coverage. Three sedimentary processes are dominant there: deposition from turbidity currents (Pilkey and Cleary, this volume), deposition and erosion by bottom currents (MCCave and Tucholke, this volume), and mass movements (Embley and Jacobi, this volume). Along the flanks, foothills and crest of the Mid-Atlantic Ridge where we have the lowest density of echograms, pelagic sedimentation and local sediment mass movements are dominant (van Andel and Komar, 1969; Shipley, 1978).

For each sedimentary process, several echo types are usually closely associated. Thus, it is the mapped assemblage of echo types rather than any one echo type which is most diagnostic of sedimentary processes within an area. For example, Echo Type V is created either by contour-following bottom currents, or by turbidity currents in a region of channel-bank overflow. When found in association with Echo Types III B and III C on sediment drift deposits, these echoes are usually interpreted as having a bottom-current origin. When found on the levees of submarine canyons in association with Echo Types I A, IIA, and IIB they are interpreted as having a turbidity-current origin.

**Deposition from Turbidity Currents**

Turbidity currents are important in depositing sediments along the continental rises, submarine canyon and fan systems, and abyssal plains of the western North Atlantic (Pilkey and Cleary, this volume). In almost all cases except the Blake-Bahama Abyssal Plain, turbidites containing terrigenous sediments of gravel to clay size have been deposited by these turbidity currents.

Previous echo-character studies in the Atlantic (Damuth, 1975, 1978, 1980; Damuth and Hayes, 1977) demonstrated that a qualitative relationship exists between the relative abundance of coarse (silt, sand, gravel), bedded sediment in the upper few meters of the seafloor, and the degree of development of Echo Types I A, IIA, and IIB. Regions returning distinct echoes with continuous sub-bottom reflectors (Type I A; Plate 7) generally contain little or no bedded silt/sand (normally <5%); regions of semi-prolonged echoes with intermittent sub-bottom reflectors (Type IIA) have low to moderate amounts of bedded silt/sand (normally 5-30%); and regions returning very prolonged echoes with no sub-bottom reflectors (Type IIB) exhibit large amounts of bedded silt/sand (up to 100%). The reasons for the observed relationship between echo type and quantity of bedded silt/sand are complex, but the relation probably is due to changing signal interference patterns in response to changes in thickness and fre-
quency of silt/sand beds and to variable development of small-scale bedforms at and below the seafloor. These sediment-echo correlations have been discussed in detail in previous reports (Damuth, 1980, and references therein) but they still are not well understood in a quantitative sense. However, they do provide an empirical method of predicting concentration and distribution of coarse terrigenous sediment over large regions.

An example of the relationship between echo type and distribution of coarse terrigenous sediment is the region of the Amazon Deep-Sea Fan and adjacent abyssal plains off northeast Brazil (Plate 7; 3°–10°N; 43°–52°W). Relationships have been confirmed by extensive piston coring (Damuth, 1975, 1980; Damuth and Kumar, 1975). Most coarse sediment from the Amazon River bypasses the upper and middle fan via large distributary channels (<4.2 km depth) and it is deposited across the lower fan and on the adjacent Demerara and Ceará abyssal plains. The sediments of the upper and middle fan consequently return distinct echoes with continuous sub-bottom reflectors (Type IIA). In contrast, the lower fan (4.2–4.8 km) and the adjacent portion of the abyssal plain to the north return very prolonged echoes (Type III). Around the perimeter of this depocenter the prolonged echoes give way to semi-prolonged echoes with intermittent sub-bottoms (Type IIA) which indicate moderate amounts of bedded silt/sand. Farther downslope, to the east and west on the distal parts of the Ceará and Demerara abyssal plains, distinct echoes with continuous sub-bottoms (Type IIA) are again returned from seafloor sediments containing little coarse sediment. The echo-character pattern of the Amazon Fan region thus reflects the sedimentation patterns on the fan. Coarse sediments bypass the upper and middle fan, are deposited mostly across the lower fan and proximal portions of abyssal plains, and become progressively less abundant radially outward from the lower fan towards distal regions (Damuth 1975, 1980; Damuth and Kumar, 1975).

Farther north along the margin of the eastern United States are two large provinces of turbidity current deposition, one principally along the continental rise to depths of about 4.5 km and a second across the Hatteras Abyssal Plain. The major turbidity pathways across the continental slope and rise appear as narrow zones of prolonged bottom echoes with no sub-bottom reflectors (Echo Type IIB), suggesting deposition of coarse sediments along these pathways. The flanking levee and inter-canyon regions (where not disrupted by debris flows) appear as sharp, continuous bottom echoes with continuous sub-bottom reflectors (Echo Type IIA) or as migratory sediment waves (Echo Type V). In many instances these echo types reflect spillover of fine material from turbidity currents moving down Hudson, Wilmington and Norfolk Canyons. In other areas they represent deposition from bottom currents, the sediment source being either the bottom nepheloid layer or material pirated from turbidity currents traversing the continental rise. It is important to note that the migrating sediment waves (Echo Type V) found on canyon levees are very similar in appearance to those formed by thermohaline flow in this region. Their occurrence in association with canyon pathways of turbidity currents demonstrates that overbank flow of turbidity currents can form migratory sediment waves similar to those formed by thermohaline flow (Embley and Langseth, 1977; Damuth, 1978, 1980).

Near the base of the Hatteras and Wilmington fan systems, which are two major entry points to the Hatteras Abyssal Plain (Pilkey and Cleary, this volume), semi-prolonged echoes (Type IIA) with intermittent sub-bottom reflectors are observed, suggesting deposition of moderate amounts of bedded silt/sand. Away from these entry points and southward to about 24°N, distinct echoes with continuous sub-bottom reflectors are observed beneath the Hatteras Abyssal Plain; this reflects a fining of sediment grain size away from the source areas. Farther southeast, the Nares Abyssal Plain receives distal turbidites from the Hatteras Abyssal Plain through Vema Gap (Plate 2). Very well-developed Type IIA echoes are found there, indicating deposition of turbidite clays with occasional silt beds (Tucholke, 1980).

The Sohm Abyssal Plain is the primary depocenter for Laurentide-derived glacial-age terrigenous sediments in the western North Atlantic (Laine, 1980). The echo character of the western, well mapped part of the Sohm Abyssal Plain is consistent with a massive influx of coarse, terrigenous sediments from the Hudson Fan and Laurentian Fan; very prolonged bottom echoes with no sub-bottom reflectors are found beneath the northwest limb of the Sohm Abyssal Plain. Similar echo character probably extends farther east around the lower perimeter of the Laurentian Fan, although this remains to be mapped.

Further to the north, in the Labrador and Flemish Basins, the most conspicuous feature related to turbidity currents is the Northwest Atlantic Mid-Ocean Channel which funnels turbidity currents southward onto the Sohm Abyssal Plain (Cleary and Pilkey, this volume). Very prolonged echoes with no sub-bottom reflectors (Echo Type IIB) are found beneath the axis of the channel, and semi-prolonged echoes with intermittent sub-bottom reflectors (Echo Type IIA) flank the channel. This suggests deposition of coarse sands within the channel and spillover and deposition of smaller amounts of sand and silt in adjacent areas.

**Bottom-Current Processes**

Three current systems have an influence on sea-floor sedimentary processes in the western North Atlantic Ocean: the Western Boundary Undercurrent (WBUC), the deep Antarctic Bottom Water current, and the Gulf Stream system (McCave and Tucholke, this volume). Their influence is most readily seen in echograms across regions which are protected or distant from the masking influence of turbidity currents and sediment mass movements. These areas include portions of the continental rise deeper than 4.5 km off the eastern United States (e.g. Hatteras Outer Ridge); the continental rise off eastern Canada north of about 43°N; outer ridge (drift) deposits such as the Blake, Bahamas, Greater Antilles, Eirik, and Gulf Stream ridges; and other sediment-drift deposits including the Bermuda Rise Drift and
particularly the Gloria Drift (Plate 2). At least five separate echo
types are observed in these provinces (Plate 7): distinct echoes
(IA and IB), hyperbolic echoes (III B and III C), and sediment
waves (V).

Both Type III B and III C hyperbolic echoes are reflected from
deformations below the resolving capability of standard ship-
board, broad-beam echosounding systems. It is necessary either to
collect near-bottom observations or to migrate surface-ship echo-
grams in order to determine the true morphology of the deformations
that create hyperbolic echoes. Where such studies have been done
they have shown that hyperbolic echo Types III B and III C are
generalized by a series of erosional/depositional deformations
termed “furrows” (Hollister and others, 1974a; Flood, 1978,
1980, 1983; Flood and others, 1979; Lonsdale, 1978; Tucholke,
1979; Embey and others, 1980; McCave and others, 1982).
Furrows are found in the deep North Atlantic as fields of
regularly-spaced, parallel grooves in cohesive sediments. They
range from 1-100 m in width and 0.5-20 m in depth, and are
spaced 20-350 m apart (Flood, 1978; 1983). While the origin of
at least some furrows is erosional, developing through secondary
circulation patterns in the turbulent oceanic bottom boundary
layer (Flood, 1983), others are thought to be syndepositional
(Tucholke, 1979). The balance between erosional and deposi-
tional episodes over time determines whether individual furrows
enlarge through erosion, maintain their form during sedimentary
upbuilding, or are smoothed over by sedimentation (Embey and
others, 1980; Flood, 1983).

While hyperbolic echoes are widely distributed throughout
the basin wherever bottom currents have an effect, they are most
extensively developed and studied on the Blake-Bahama Outer
Ridge. Type III C hyperbolic cover the northeast flank of the
Blake Outer Ridge and the west flank of the Bahamas Outer
Ridge. The smaller Type III B hyperbolic are found in similar
proportion on these ridges, with major fields developed in the
central areas of both features. This distribution of Type III B
and III C hyperbolic echoes suggests that erosion is greatest on the
perimeter of these drifts, with less erosion or perhaps
syndepositional development occurring within their central regions.
This implies more intense bottom currents flowing along the perimeter
with more tranquil flow above the central regions of the Blake
and Bahamas Outer Ridges.

Echo Type V represents another class of deep, sediment
waves, commonly found within provinces influenced by bottom
currents. These deformations are quasi-periodic undulations of
the seafloor with characteristic amplitudes of 10-100 m and wave-
lengths of 2-11 km. Some sediment waves are regular and almost
sinusoidal with conformable sub-bottom reflectors; others are sys-
tematically distorted, with differing slopes on each limb and in-
ternal thickness variations between reflectors that indicate
migration of the deformations (Plate 7). When the true orientation
of the wave crests is known, it is generally oblique to regional con-
tours, oriented 35° - 45° upslope in a clockwise direction from
the regional contours (Clay and Rona, 1966; Hollister and others,
1974b; Flood, 1978; Embey and Langseth, 1977). Where the
migration direction can be determined the waves appear to mi-
grate upslope and in most cases upcurrent (Embey and Langseth,
1977; Flood 1978).

In the North Atlantic a 1200-km zone of sediment waves
extends discontinuously north from the southern tip of the Ba-
hama Outer Ridge near 25°N to the vicinity of the Hudson
Canyon near 36°N (Plate 7) between about 4.5 and 5.2 km water
depths. Sediment waves also extend eastward about 1000 km
onto the northern Bermuda Rise. North of the New England
Seamounts, waves occur in the same depth range on the Nova
Scotian continental rise between 40° and 42°N.

Farther north, several fields of sediment waves are found
within the Flemish and Labrador basins. In the Labrador Basin
these waves are associated with the counterclockwise flow of the
Western Boundary Undercurrent as it moves southward from its
Norwegian Sea source area. Extensive wave fields are developed
on Gloria Drift. The smaller wave fields on the eastern margin of
the Flemish Basin are poorly studied; however their position
away from the continental margin suggests the influence of some
kind of mid-basin circulation such as that above the Bermuda
Rise Drift.

Sediment waves observed deeper than 4.5 km along the
continental margin and Blake-Bahama Outer Ridge are asso-
ciated with deep, thermohaline flow in the lower part of the
Western Boundary Undercurrent. It has been suggested that at
these depths the Western Boundary Undercurrent contains a
high-velocity core (Bullin and others, 1982). At these depths
along both the continental rise between 33° and 36°N and on the
Blake-Bahama Outer Ridge, the wave deposits comprise a signifi-
cant proportion of the sedimentary section (Markl and Bryan,
1983; Tucholke and Laine, 1983). The waves have actively ac-
creted since the beginning of the last phase of contour-current
deposition during the middle Miocene (Tucholke and Mountain,
this volume).

All recent models for the sedimentary evolution of the
northern Bermuda Rise (Laine and Hollister, 1981; Ayer and
Laine, 1982; Tucholke and Laine, 1983) suggest that currents at
the base of the Gulf Stream system were important in shaping the
seafloor during the Neogene and Quaternary, although models
differ as to the specific pattern of currents. The arcuate distribu-
tion of sediment waves across the northern rise and their apparent
continuity with waves along the U.S. Atlantic margin suggest a
possible eastward extension of bottom-sensing flow of the Gulf
Stream during the Neogene (Tucholke and Laine 1983). How-
ever, the apparent sediment-wave distribution may be an artifact
of preservation, because large portions of the northern Bermuda
Rise have been strongly eroded during the Neogene and Quater-
nary (Laine and others, 1983).

Distinct Type IA echoes with sub-bottom reflectors are
found in all provinces influenced by bottom currents. In these
regions the echo character results from deposition of fine-grained
sediments from the bottom nepheloid layer. However, this echo
type is not diagnostic of deposition from currents. For example, in
well studied regions of the Pacific, echoes of similar character are
recorded from entirely pelagic sediments (Mayer, 1979; Damuth and others, 1983), and the same kinds of echoes occur in distal abyssal plain areas such as the eastern Nares Abyssal Plain (Tucholke, 1980). Thus the interpretation of current-controlled deposition is usually made with supporting evidence of high sedimentation rates, terrigenous lithology, direct current observations, and particularly association with other diagnostic echo types such as sediment waves (Laine and Hollister, 1981; McCave and others, 1982).

Type IA echoes commonly are found in association with hyperbolic echoes and sediment waves. In many instances the hyperbolae are developed on the surface of Type IA, well-stratified sediments, and the hyperbolae degrade the resolution and continuity of the sub-bottom reflectors. Where found adjacent to sediment waves, the sub-bottom reflectors in the Type IA echoes are often continuous with those in the sediment waves.

**Mass Wasting Processes**

Mass wasting in the western North Atlantic is an extremely important down-slope sediment transport mechanism, primarily along the continental margins and to a lesser extent within the center of the basin. The widespread development of mass wasting, however, only became clear with careful study of 3.5-kHz echograms and more advanced observational techniques (e.g., side-scan sonar and submersibles) (Walker and Massingill, 1970; Embly, 1976, 1980; Embly and Jacobi, 1977; Embly and Jacobi, this volume; McGregor and Bennett, 1979; Jacobi and Hayes, 1982; Popeneo and others, 1982; Ryan 1982; Farre and others, 1983).

These studies show that mass wasting is accomplished by slumps and/or sediment slides. Slumps are blocks that have undergone downslope translation along a slump fault, but the blocks have only minor internal deformation. In contrast, sediment slides have experienced sufficient liquefaction to promote internal flow and deformation, commonly resulting in pebbly mudstones (debris flows) and other highly deformed deposits (Embly and Jacobi, 1977). Large slump blocks (ca. 10-50 km width) are not as easily recognized in 3.5-kHz echograms as they are in low frequency (<100 Hz) seismic reflection profiles. However, smaller slump blocks (ca. 1 km width) can be identified readily in echograms, primarily on the basis of the slump fault and the surface morphology of the block (Jacobi, 1976; Embly, 1980; Popeneo and others, 1982).

On echograms the slump faults are observed as reflector dislocations, and/or as Type IIID hyperbolae (Plate 7) that are reflections from the fault surfaces; they also are sometimes observed as ductile faults (Jacobi and Hayes, 1982). Surface morphology over small slump blocks consists of Type IIID hyperbolae (Plate 7), isolated areas of elevated multiple reflectors (for smaller slump blocks), or variable wave forms on blocks containing ductile faults.

Perhaps the "best-known" slump block is the Grand Banks slump (Heezen and Ewing, 1952) located on the continental slope at the head of the Laurentian Fan. However, preliminary analysis (Piper and Normark, 1982a, b) suggests that the proposed slump block probably is a channel-levee complex. Similar problems of interpretation may exist for apparently large slump blocks along the central U.S. east coast margin (McGregor and Bennett, 1977). Nevertheless, smaller slump blocks do exist and they are well documented along the upper continental slope and on walls and floors of submarine canyons and channels (Malahoff and others, 1980; Twitchell and Roberts, 1982; Farre and others, 1983). They occur more rarely on the lower continental slope and rise and in mid-basin areas (Silva and others, 1976). No slumps are shown on Plate 7 because of the small map scale.

Sediment slides consist of a zone of sediment removal bounded by one or more slide scars, and a downslope zone of deposition. The main slide plane generally parallels a prominent reflector. The resulting scarp generally has about 50 m relief but rarely may reach 250 m. The slide scars are recognized on echogram and low-frequency seismic reflection profiles primarily by the truncation of reflectors. The zone of deposition contains a number of echo types, including Type IIID hyperbolae and Type IV transparent lenses (Plate 7). Slide-generated turbidity flows can also occur but they are not considered part of the slide complex.

Type IIID hyperbolae with high relief (>40 m valley to vertex) are termed hummocky terrane (Jacobi, 1976). They generally result from (1) large slide blocks (olistoliths), (2) areas of relatively limited and discontinuous sediment removal, or (3) more rarely, large piles of highly deformed slide material. Both of the first two kinds of occurrences have been observed in the eastern North Atlantic (Jacobi, 1976; Flood and others, 1979), although most large Type IIID hyperbolae in the western North Atlantic appear to result from slide blocks (Embly, 1980; Ryan, 1982; Vasallo and others, 1984 a, b). Smaller Type IIID hyperbolae (with valley to vertex relief <40 m) are termed blocky terrane (Jacobi, 1976) and probably result from smaller slide blocks and piles of highly deformed slide material. Both hummocky and blocky terranes are combined in Type IIID hyperbolae on Plate 7.

Type IV transparent lenses (Plate 7) are generally the most prevalent of the slide-associated seismic facies and they consist of debris-flow material (Embly, 1976; Jacobi, 1976). Piston cores retrieved from these echo types confirm the disturbed nature of the sediment (Embly, 1976, 1980; Jacobi, 1976; Jacobi and Mrozowski, 1979).

Small slide complexes are common along submarine canyons and channels in the mapped area (Plate 7) and in these locations they are a response to slope oversteepening along canyon walls. Such slides may also be responsible for most canyon development (Farre and others, 1983). In contrast, large sediment-slide complexes often occur on the continental slope and rise independent of canyon position. These slide complexes are up to 700 km long, and some stretch from the upper slope to the abyssal plain (Plate 7). Three of the larger slide complexes on the U.S. east coast margin are the Blake and Hudson slides (Em-
bley and Jacobi, this volume), and the Grand Banks slide (Jacobi, in prep.). The Blake slide complex (Plate 7) extends to the abyssal plain and exhibits a large zone of blocky terrane (ECHO Type IID). The debris-flow material (ECHO Type IV) surrounding the hyperbolated zone may be more liquefied sediment mobilized during the same slide event, or it may be a younger slide event. In contrast, both the Hudson and Grand Banks slide complexes consist almost entirely of debris-flow material (ECHO Type IV, Plate 7).

On the U.S. east coast margin, few large slides are observed south of 31°N, probably because of relatively low sediment accumulation rates. The low rates are due to two factors: low sediment supply in areas south of the margin of the Laurentide Ice Sheet, and the barrier formed by the Gulf Stream to direct seaward transport of sediment in this area (Emery and Uchupi, 1972).

SUMMARY AND CONCLUSIONS

In well mapped portions of the western North Atlantic Ocean, echo character shows that three sedimentary processes are of primary importance along the continental margins, abyssal plains, and basinal plateaus of the basin. These are deposition from turbidity currents, sediment mass movements, and deposition and erosion by bottom currents.

Turbidity currents have been the areally most important sedimentary process within the well mapped portions of the western North Atlantic Ocean. This dominance is reflected in the distribution of abyssal plains all along the perimeter of the continental margins from the Labrador Basin to the Guiana Basin. On the continental margins themselves, downslope sediment transport by turbidity currents is reflected by cross-contour patterns in the echo character. Canyon axes and levee deposits are the predominant sedimentary features.

Mass movements compete with turbidity currents as the principal mechanism of sediment transport along the continental margins. Debris flows and other mass movements also display cross-contour patterns in echo character.

The strong influence of both of these processes along the margins reflects the importance of steep slopes and an abundant source of sediments from adjacent landmasses in controlling the sedimentary regime along the continental margin. Significantly, off Newfoundland and Labrador where a wide shelf and a lack of major rivers have restricted sediment supply to the continental slope and rise, the cross-slope patterns of echo character are not observed.

Bottom-current effects dominate the seafloor echo character within those well mapped portions of the western North Atlantic that are not influenced by downslope processes. These regions include parts of the continental rise off eastern North America which are protected from the masking effects of turbidity currents and mass movements, outer-ridge deposits which trend obliquely away from the continental rise, and other drift deposits which lie in the central portions of the basin completely separated from the continental rise.

In the less well mapped areas of the western North Atlantic where we have presented only a generalized echo character map, there are echo character patterns that deserve future study. Our mapping and that of Emery and Uchupi (1984, Plate X) suggests a large, semi-continuous band of current-controlled deposition trending northeastward from the southern portions of the Bermuda Rise into the Labrador Basin. This band roughly parallels the flanks of the Mid-Atlantic Ridge. If this is indeed a distinct and continuous province, it would suggest an organized current system, perhaps Antarctic Bottom Water, flowing northward along the western flank of the Mid-Atlantic Ridge. However, if this pattern is not continuous but is comprised of individual, small-scale drift deposits, it may imply that small-scale deep circulation cells are active within the basin. Along the flanks and crest of the Mid-Atlantic Ridge, modern studies of echo character are non-existent. We have presumed on the basis of morphology and very limited sedimentary studies that pelagic sedimentation, sediment mass movements, and turbidity currents all play roles within this region; however, until the proper echo character studies are completed we will not be able to assess their relative importance.

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