The Greater Antilles Outer Ridge: development of a distal sedimentary drift by deposition of fine-grained contourites

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Abstract: The Greater Antilles Outer Ridge, located north and northwest of the Puerto Rico Trench, is a deep (>5100 m), distal sediment drift more than 900 km long and up to 1 km thick. It has been isolated from sources of downslope sedimentation throughout its history and is formed of clay- to fine silt-size terrigenous sediments that have been deposited from suspended load carried in the Western Boundary Undercurrent, together with 0–30% pelagic foraminiferal carbonate. Because of the fine, relatively uniform grain size of the sediments, the outer ridge consists of sediments that are seismically transparent in low-frequency reflection profiles. Sediment tracers (chlorite in sediments and suspended particulate matter, reddish clays in cores) indicate that at least a portion of the ridge sediments has been transported more than 2000 km from the eastern margin of North America north of 40°N. The outer ridge began to develop as early as the beginning of Oligocene time when strong, deep thermohaline circulation developed in the North Atlantic and the trough initiating the present Puerto Rico Trench had cut off downslope sedimentation from the Greater Antilles. The fastest growth of the outer ridge probably occurred beginning in the early Miocene, about the same time that large drifts such as the Blake Outer Ridge were initiated along the North American margin. Since that time, the most rapid sedimentation has been along the crest of the northwestern outer ridge where suspended load is deposited in a shear zone between opposing currents on the two ridge flanks.

Many contourite deposits occur on continental margins or in close proximity to sources of clay- to sand-size sediment fed downslope in gravity flows. In these environments it can be difficult to quantify and differentiate the geological effects of downslope processes from the effects of bottom current processes, which generally act along slope. In contrast, sediment drifts that are physiographically isolated from downslope sources do not exhibit these complications. Aside from a pelagic component settling from the overlying water column, they are pure contourite sediments, and they exhibit structures and characteristics developed solely from current-controlled sedimentation.

The Greater Antilles Outer Ridge (GAOR) north of the Puerto Rico Trench in the western North Atlantic (Fig. 1) is a well developed example of a distal and isolated contourite drift. It is a large sedimentary feature that has been totally disconnected from downslope sediment sources since middle to late Eocene time. It lies at depths greater than about 5100 m and thus is mostly below the calcite lysocline. Consequently the outer ridge consists dominantly of fine-grained sediments that have been deposited from suspended load carried in abyssal currents, with only a minor component of pelagic sedimentation. Although the Greater Antilles Outer Ridge was studied in detail in the early 1970s (Tucholke *et al.* 1973; Tucholke & Ewing 1974; Tucholke 1975), there has been almost no subsequent research in this region. In this synthesis I review the modern geological and oceanographic setting of the outer ridge together with its depositional history since middle Eocene time, based largely on this earlier work.

Geological setting and physiography

The Greater Antilles Outer Ridge overlies middle Cretaceous ocean crust north of the easternmost Bahama Banks and the Puerto Rico Trench. It is bounded to the northwest by the southern Hatteras Abyssal Plain at depths of *c.* 5520 m and to the northeast by the deep (>5800 m) Nares Abyssal Plain (Fig. 1). Vema Gap, which is a conduit for turbidity currents flowing from the Hatteras to Nares abyssal plain, lies along part of the northern margin of the ridge. To the west, the Silver Abyssal Plain isolates the outer ridge from downslope deposition of sediments derived from the Bahama Banks. A small sedimentary drift, the Caicos Outer Ridge, lies near the base of the Bahama Banks. A slightly elevated sedimentary sill extends east from Caicos Outer Ridge to connect with the northwesternmost GAOR. An elevated sill (Navidad sill) also connects the southeasternmost Bahama Banks to the central part of the GAOR; this elevation is largely due to a basement bulge that has been created as ocean crust is deformed and obliquely subducted in the Puerto Rico Trench. The trench itself bounds the southern side of the GAOR, isolating it from sediments moving in gravity flows from the Greater Antilles.

The GAOR can be divided into two provinces, each with somewhat different geological characteristics and depositional history. East of about 67°W the ridge parallels the Puerto Rico Trench for more than 450 km and is 5300–5400 m deep along its axis. Much of the ridge's physiographic elevation is due to the fact that it overlies the crustal outer-high seaward of the trench. The bathymetry is irregular, partly because high-amplitude basement peaks interrupt the sedimentary sequence and partly because current-controlled deposition is uneven around these obstacles (Figs 2 & 3). Drift deposits that define the ridge thin markedly east of about 62.5°W, but the actual eastward extent of these deposits is uncertain.

The GAOR west of 67°W trends north and northwest for about 450 km and has minimum depths of 5100–5200 m. Here the physiographic expression of the ridge is due entirely to accumulation of drift deposits. There is no underlying bulge in basement topography and basement interruptions of the sedimentary sequence are rare (Figs 4–7).

Finer-scale morphology of the ridge varies between relatively smooth seafloor and sediment waves. The sediment waves in some places are regular (Fig. 7), but more commonly they have variable form, wavelength and amplitude. Small flat ponds occasionally occur in depressions between sediment waves, and they appear to have formed from local mass wasting and turbidity currents. The best developed of these is in relatively complex topography on the northeast flank of the ridge near 22.5°N, 67.5°W (Fig. 1). There the sediment waves have been modified into a dendritic drainage system extending toward the Nares Abyssal Plain, forming a network of 'layered valleys' (Tucholke 1975). This kind of ponding and layering is restricted entirely to the western sector of the GAOR (see Fig. 13).

Outer ridge sediments

Sediments forming the GAOR are homogeneous, terrigenous, brown, gray and reddish clays (<2 μm) and fine silts that are locally enriched in carbonate (Figs 8 & 9). They exhibit little

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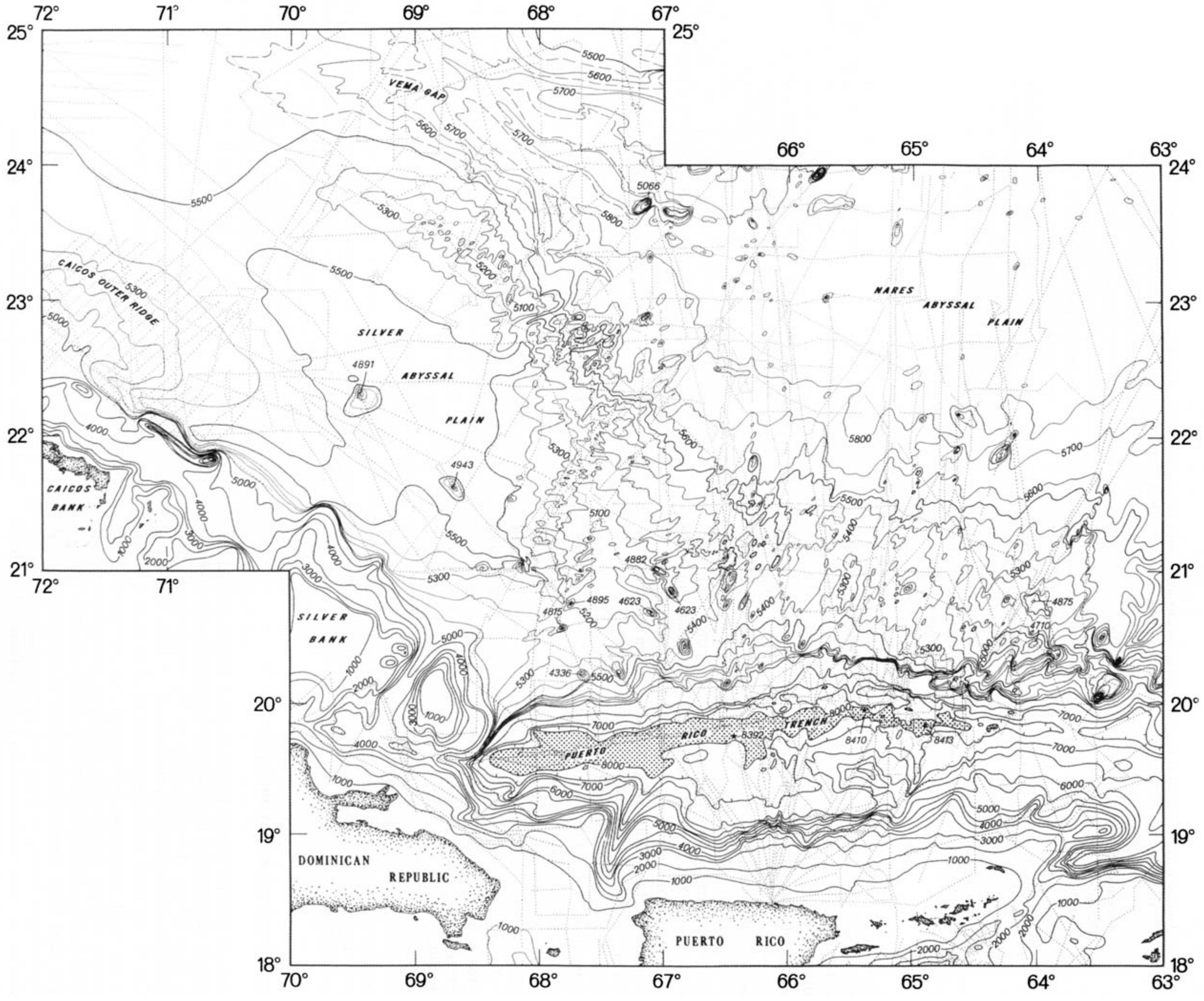


Fig. 1. Bathymetry of the Greater Antilles Outer Ridge and vicinity (from Tucholke *et al.* 1973). The outer ridge extends east–west north of the Puerto Rico Trench and to the NW between Silver Abyssal Plain and Vema Gap. Contours are in corrected metres.

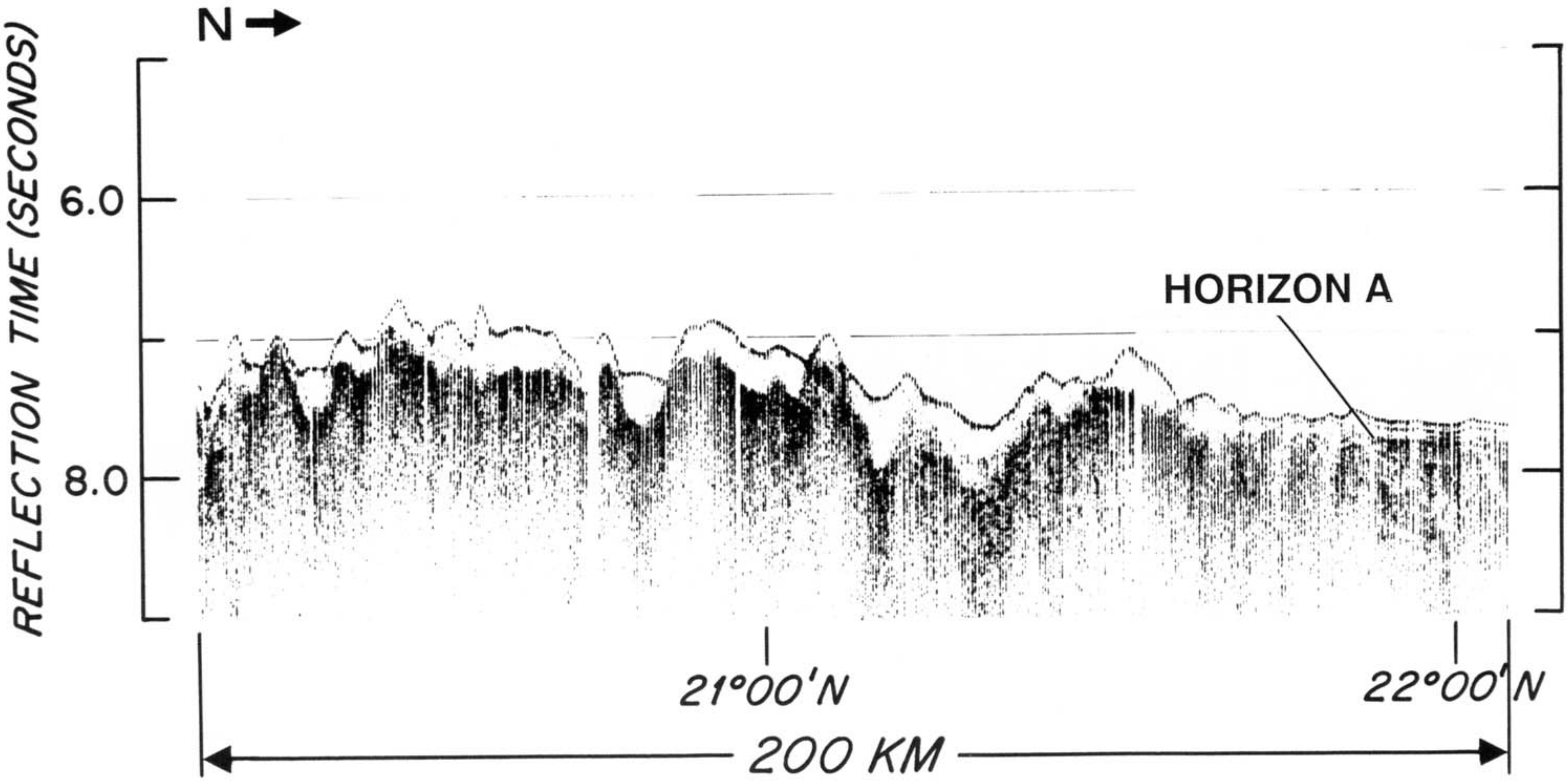


Fig. 2. Seismic reflection profile extending north–south across the Greater Antilles Outer Ridge to the southernmost Nares Abyssal Plain along 62°52′W, between 20°13′N and 22°04′N (R/V Conrad Cruise 8). The top of the middle to upper Eocene Horizon A complex is labeled where it is observed under the edge of Nares Abyssal Plain. At this far-eastern end of the GAOR, seismically transparent outer ridge sediments directly overlie oceanic basement. Figure from Tucholke & Ewing (1974).

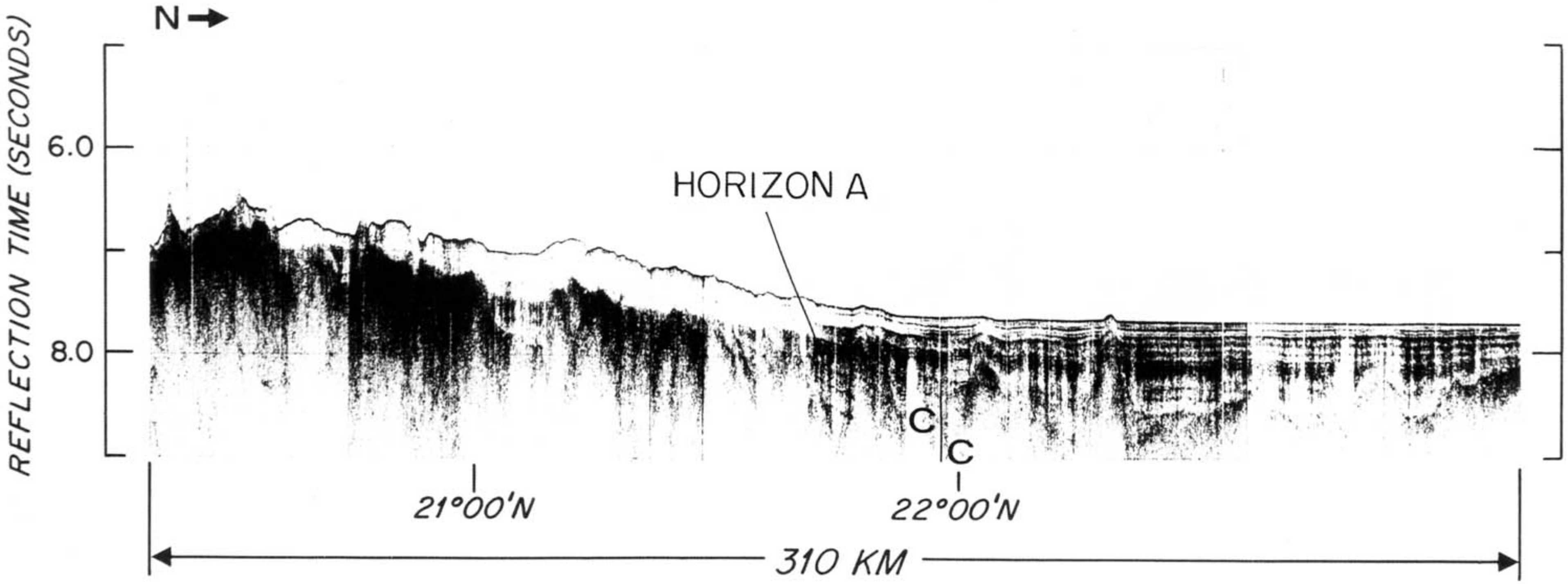


Fig. 3. Seismic reflection profile across the Greater Antilles Outer Ridge and southern Nares Abyssal Plain near 64°W (R/V Conrad Cruise 10). Location in Figure 8. The Horizon A complex extends beneath the outer ridge but is interrupted by numerous basement peaks. Note that seismically transparent sediments have accumulated faster than the abyssal plain sediments and the outer ridge has prograded onto the abyssal plain. Figure from Tucholke & Ewing (1974).

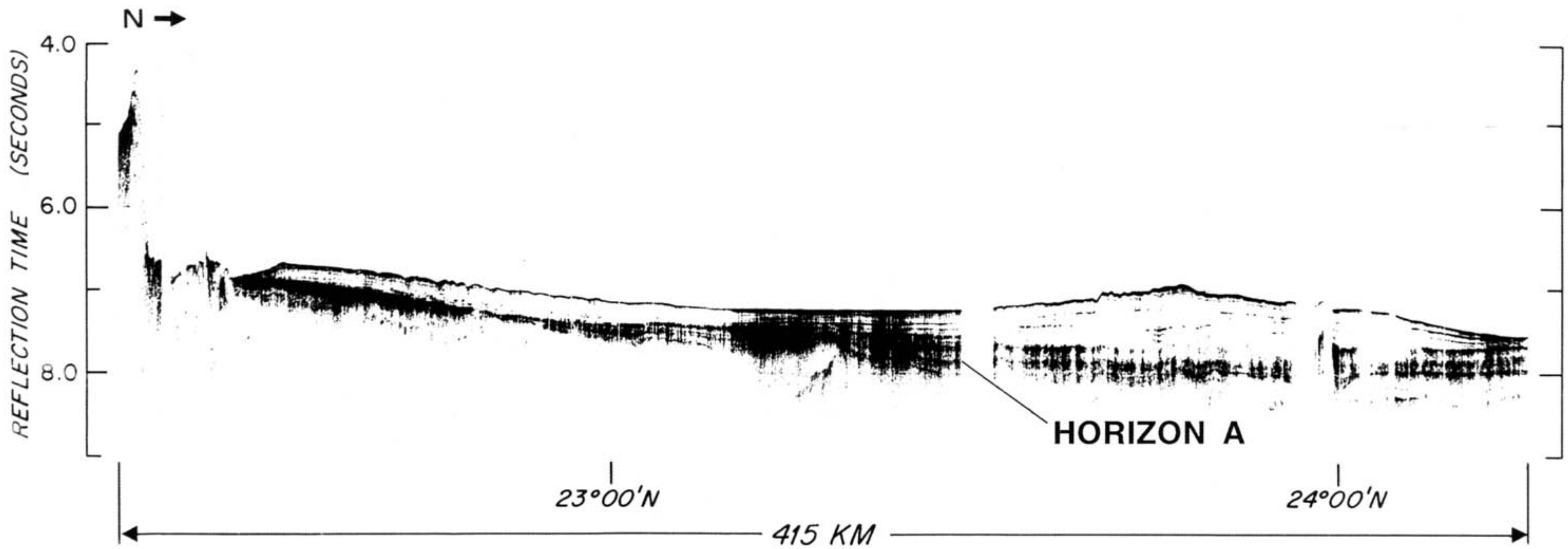


Fig. 4. Seismic reflection profile extending from the base of the Bahama Banks across the Caicos Outer Ridge, Silver Abyssal Plain, and northwestern Greater Antilles Outer Ridge to Vema Gap (R/V Conrad Cruise 10). Location in Figure 8. Seismically transparent sediments forming the core of the GAOR appear above the flat-lying Horizon A complex and the ridge subsequently expanded outward, interfingering with abyssal plain sediments. Note that the Horizon A complex beneath the Caicos Outer Ridge is truncated in an angular unconformity (Horizon A^U) that was eroded by abyssal currents in late Eocene to Oligocene time. Figure from Tucholke & Ewing (1974).

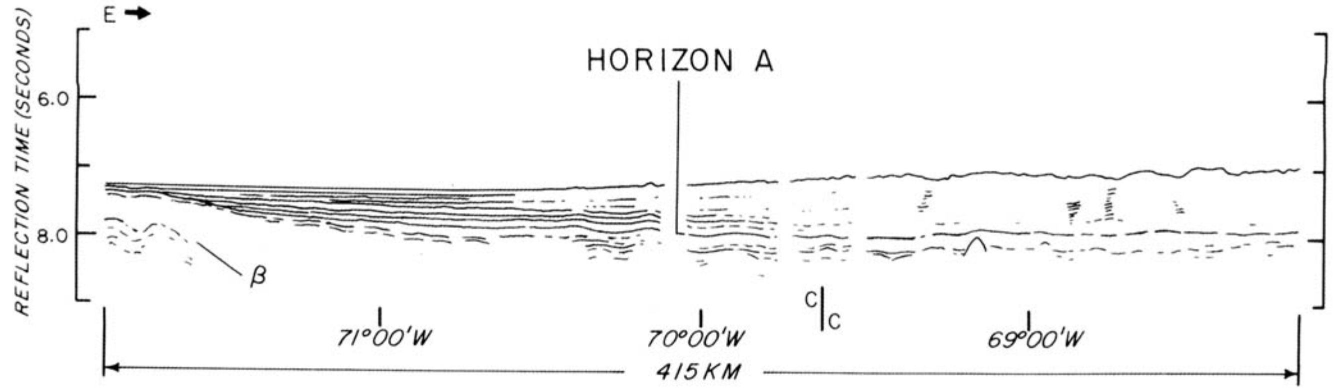


Fig. 5. Tracing of a seismic reflection profile across the southern Hatteras Abyssal Plain and along the axis of the northwestern Greater Antilles Outer Ridge (R/V Vema Cruise 22). Location in Figure 8. Sediments of the Horizon A complex and deeper beds completely cover basement beneath this section of the outer ridge. Seismically transparent outer-ridge sediments have prograded northwestward, interfingering with turbidites of the Hatteras Abyssal Plain. Weak, stacked reflections within the transparent sediments mark the locations of layered valleys developed between sediment waves. Figure from Tucholke & Ewing (1974).

textural stratification except where carbonates occur, although colour contacts between units are often distinct. Layers of sediment coarser than clay size are rare, and where present they are thin (<1 cm) and contain concentrations of ash derived from the Antilles, carbonate, or manganese micronodules. Cored sediments show extensive reworking by burrowing organisms. This is apparent from color mottling and in carbonate-enriched patches worked downward from higher-carbonate zones into underlying clay-rich intervals.

Grain size is very uniform, averaging 80% clay (<2 µm) and 20% silt (2–62 µm) with a variation of 10%. Sand content (>62 µm) rarely exceeds 5% and the sand consists entirely of biogenic and authigenic components (foraminifera, manganese micronodules, fish teeth, siliceous sponge spicules, and rare radiolaria and diatoms, in order of decreasing abundance). None of the silt or sand components in cores are organized into identifiable structures that might be attributed to current-controlled deposition. The fine grain size of the dominant clay component also precludes megascopic identification of current-produced bedforms.

Distinct silt layers occur only in local turbidite ponds between sediment waves, as for example in the layered valleys noted above. The silts form micaceous laminae 1–2 mm thick, interbedded with clays. Individual turbidites in these areas, identified from textural and colour criteria, are usually less than 10 cm thick.

Total carbonate content of the outer-ridge sediments normally ranges from 0–30%, averages 10–15%, and is dominated by foraminifera with usually minor amounts of coccoliths and unidentified detrital carbonate. Carbonate concentrations vary cyclically downcore, and the variations are interpreted to be controlled by a combination of changes in surface-water productivity and seafloor dissolution, with the latter probably related to changes in flux or temperature of bottom water flowing around the outer ridge. The surface-water productivity and bottom-water dissolution effects appear not to be correlated in phase (Tucholke 1975).

The clay-fraction mineralogy is comprised of the clay minerals montmorillonite, illite, chlorite and kaolinite. It is notable that chlorite concentrations in outer ridge sediments are richer than expected (Fig. 10); weathering in sediment source areas at these tropical to sub-tropical latitudes tends to produce kaolinite- and montmorillonite-rich sediments (Biscaye 1965; Hathaway 1972). The chlorite enrichment has been attributed to southward transport of higher-latitude, mechanically weathered sediments by abyssal currents (Tucholke 1975). Taking into account the mineralogy and average concentration of the silt fraction, bulk mineralogy of the terrigenous component in outer ridge sediments is 89% layered silicates, 7% quartz, and 4% plagioclase.

Sediment accumulation rates on the GAOR have been determined both from radiocarbon dating and from foraminiferal zonations (Tucholke 1975). The fastest accumulating sediments are along the crest of the outer ridge west of 67°W, where rates range from about 6 cm ka^{-1} up to more than 30 cm ka^{-1}. Lower rates of 3–4 cm ka^{-1} prevail on the adjacent ridge flanks. Comparably low rates also occur on the eastern ridge crest and north flank. On the south flank of the eastern GAOR and along the north wall of the Puerto Rico Trench, unfossiliferous to sparsely fossiliferous, ash-rich sediments of lower Eocene to upper Miocene age have been piston-cored. The very low sedimentation rates indicated by these data probably result from a combination of sediments being displaced into the trench by gravity flows and isolation of the south flank from deep currents with significant sediment load (Tucholke & Eittreim 1974).

Hydrography and abyssal currents

Data from hydrographic sections show that the bottom water over the GAOR has temperatures colder than 1.7°C (mostly colder than 1.6°C) and salinities less than 34.875 ‰ (Tucholke *et al.* 1973) (all temperatures given here are potential temperatures). Water with these characteristics is Antarctic Bottom Water (AABW) and has an ultimate source in the circum-Antarctic (Wright & Worthington 1970). Isotherms and isohalines both are spaced more closely between about 1.6°C and 1.8°C than in the rest of the deep-water column, and this gradient marks the transition with overlying North Atlantic Deep Water (NADW).

Water masses over the GAOR are part of the deep current system, classically termed the Western Boundary Undercurrent (WBUC), that flows from north to south along the continental margin of eastern North America (Fig. 10). Shallower currents in this system (*c.* 3000 to 4900 m depths) move NADW derived largely from the Norwegian Sea, but deeper currents contain an increasing component of AABW. The AABW is thought to be incorporated from flows entering the western North Atlantic along the west flank of the Mid-Atlantic Ridge; the AABW circulates clockwise around the Bermuda Rise and also reaches northwestward as far as the Newfoundland-Nova Scotia continental rise where it is recirculated southward at the base of the WBUC (McCave & Tucholke 1986).

Dynamic calculations based on hydrographic measurements over the GAOR indicate that the bottom water enters the region in a southeast-directed flow along the base of the Bahama Banks, circulates clockwise around the northwestern part of the outer ridge, and flows east along the north flank of the eastern outer

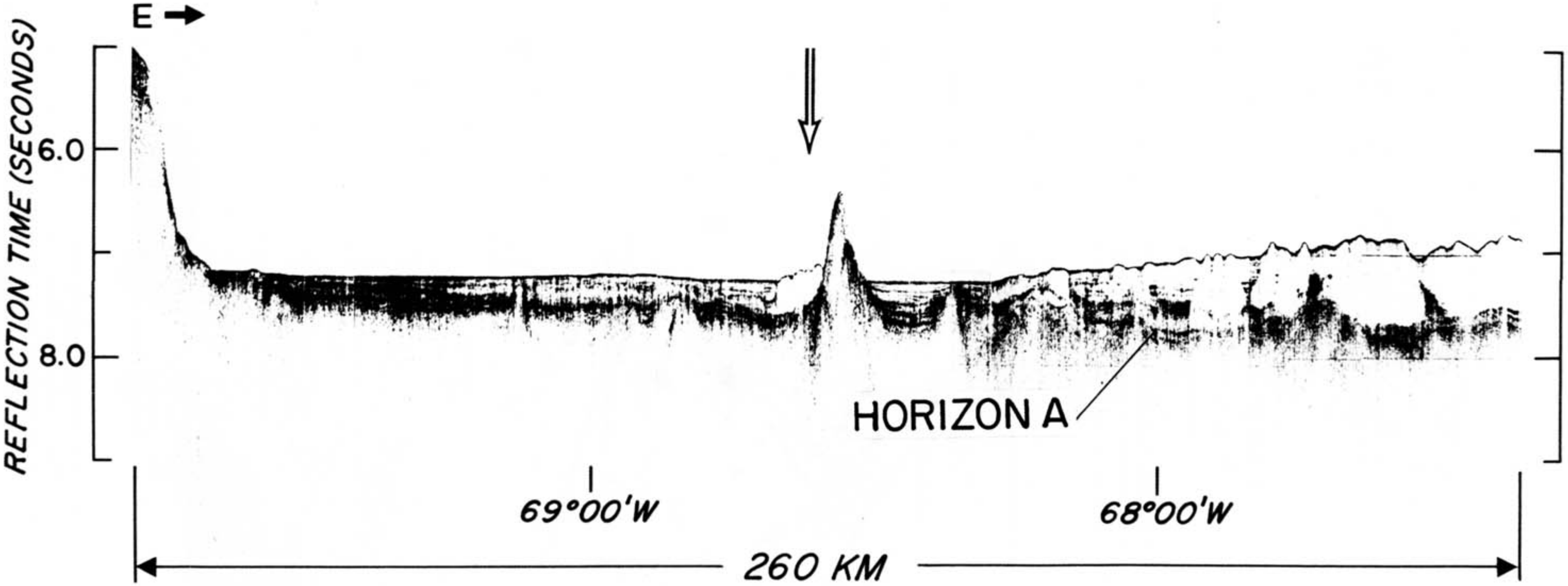


Fig. 6. Seismic reflection profile extending from the base of the Bahama Banks across the southern Silver Abyssal Plain and onto the central Greater Antilles Outer Ridge (R/V Conrad Cruise 10). Location in Figure 8. Irregular sediment waves and local, stacked reflections marking layered valleys appear in the seismically transparent outer ridge sediments. A small current-deposited drift (arrow) flanks the seamount in the southern Silver Abyssal Plain. Figure from Tucholke & Ewing (1974).

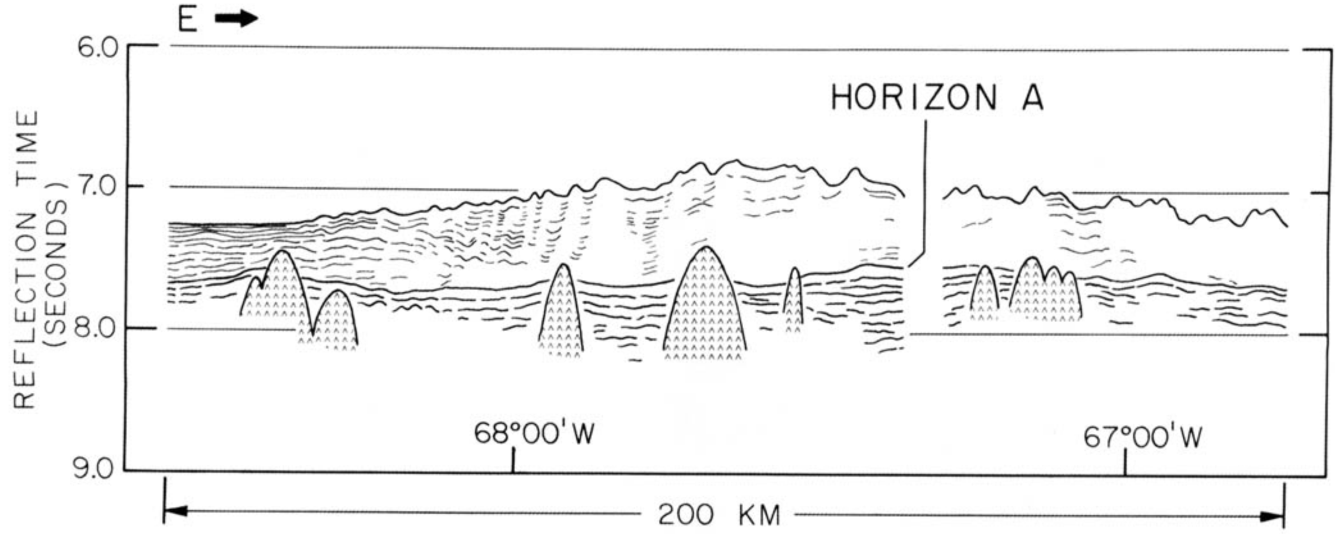


Fig. 7. Tracing of a seismic reflection profile across the central Greater Antilles Outer Ridge (R/V Conrad Cruise 10). Location in Figure 8. Basement peaks locally interrupt the Horizon A complex. Migrating sediment waves and reflections from intervening layered valleys appear in the seismically transparent outer-ridge sediments. Figure from Tucholke & Ewing (1974).

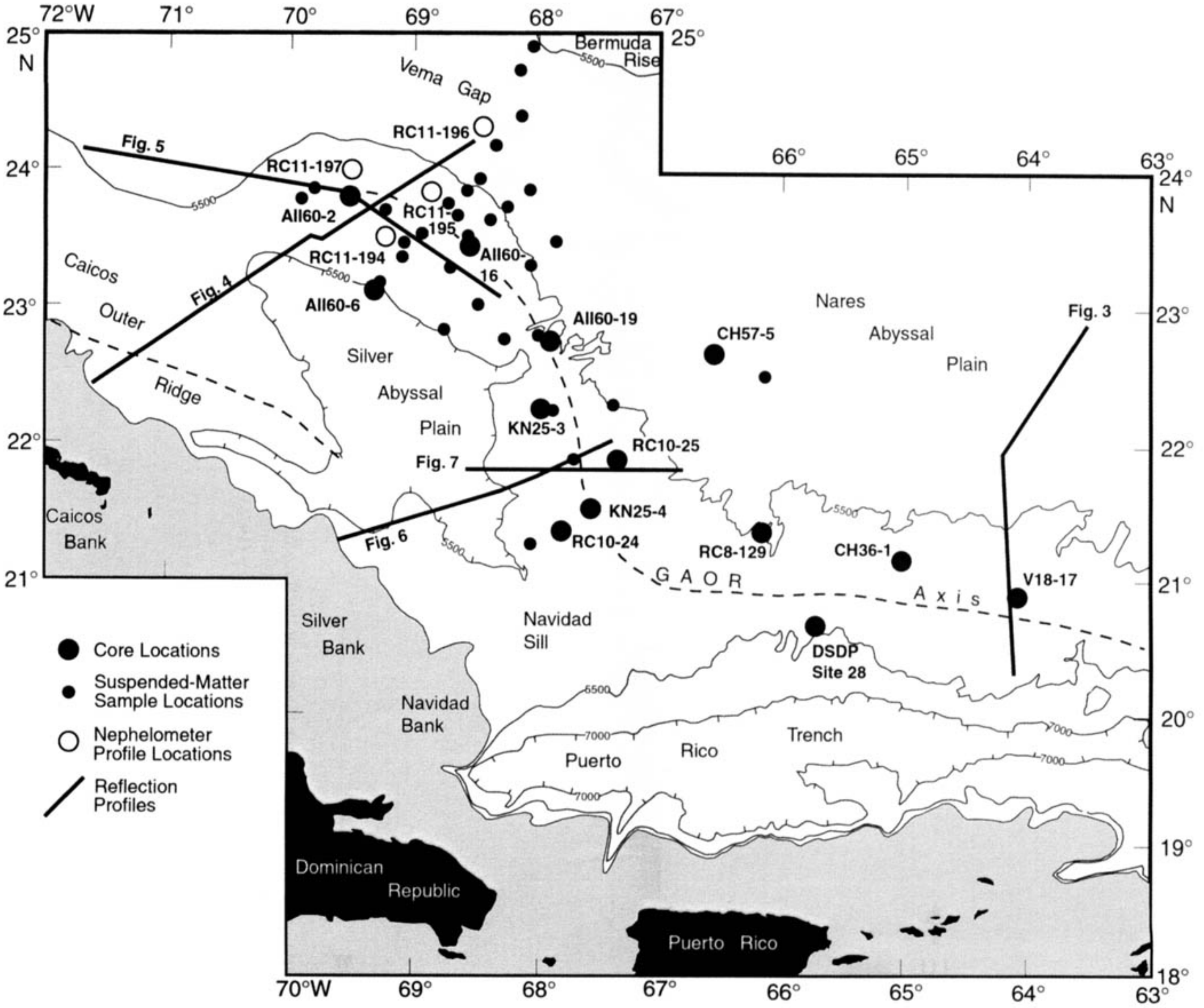


Fig. 8. Simplified bathymetric map showing locations of seismic reflection profiles in Figures 2 to 7, locations of cores illustrated in Figure 9, and locations of suspended particulate matter sampling stations and nephelometer profiles in Figure 12. DSDP Site 28 (Bader *et al.* 1970) recovered two cores of brown clay from the outer ridge at subbottom depths of 59–78 m, and six cores from deeper, stratified sequences below 169 m subbottom. Contours are in corrected metres, with depths less than 5000 m shaded. The axes of the Greater Antilles Outer Ridge and Caicos Outer Ridge are indicated by dashed lines.

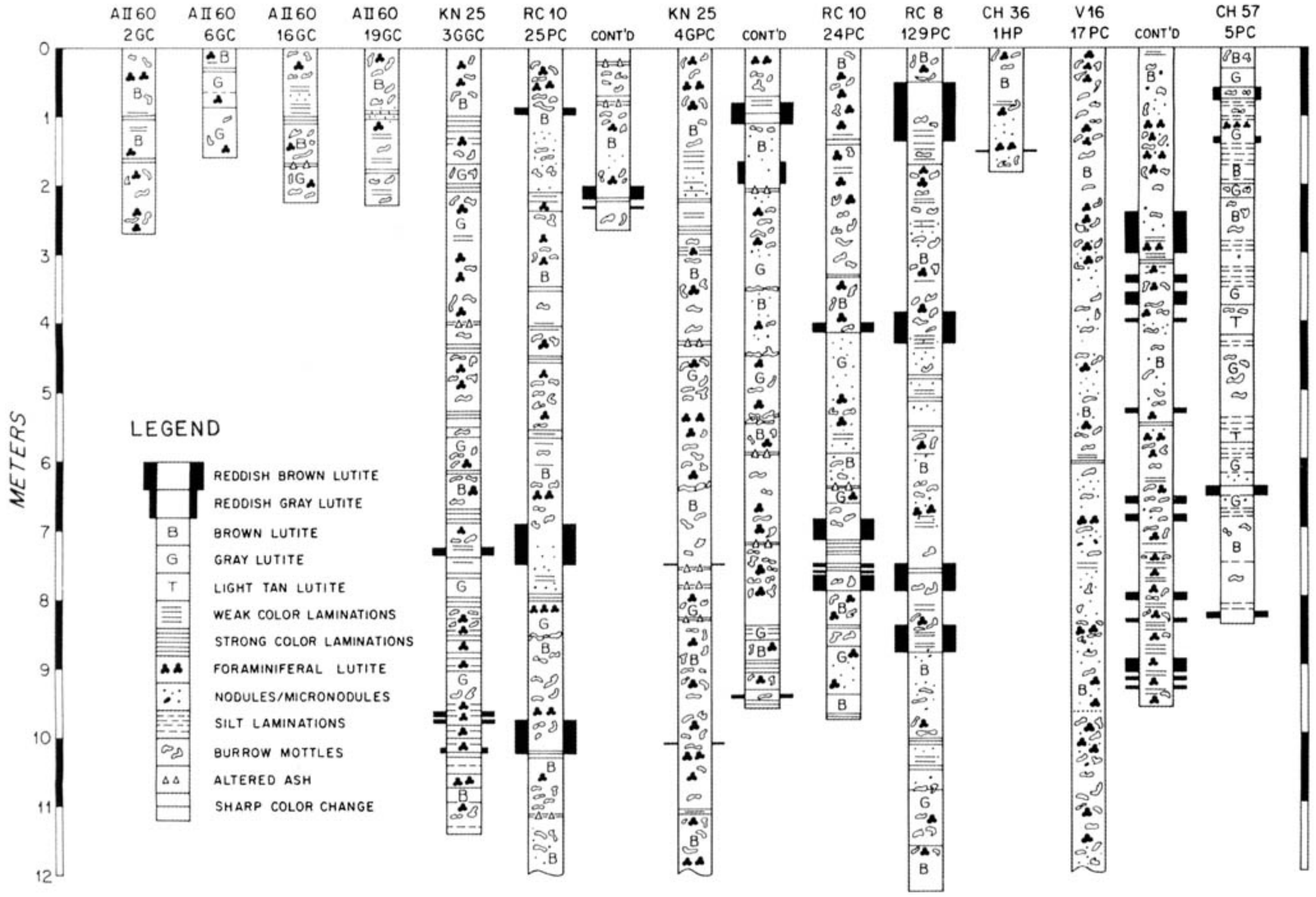


Fig. 9. Lithological summary of cores taken from the Greater Antilles Outer Ridge, arranged from west (left) to east and contrasted against one core containing fine-grained turbidites from the Nares Abyssal Plain (far right). Core locations in Figure 8. The outer-ridge cores are dominantly bioturbated clay (lutite) with varying admixtures of foraminiferal carbonate, usually 0–30%. GC, gravity core; GGC, giant gravity core; PC, piston core; GPC, giant piston core; HP, heat-probe gravity core. Figure from Tucholke (1975).

ridge (Fig. 11). Part of this circulation passes southeastward over Navidad sill and then flows east along the south wall of the Puerto Rico Trench. A northwesterly flow of AABW on the northern side of Vema Gap (southern margin of the Bermuda Rise) opposes southeasterly flow on the north flank of the northwestern outer ridge; it appears to divert some of the outer ridge flow to the north along the eastern edge of the Hatteras Abyssal Plain as part of the clockwise AABW circulation around the Bermuda Rise.

Direct current measurements and interpretations of bottom currents from seafloor photographs support the directional patterns of abyssal circulation around the GAOR derived from hydrographic calculations (Fig. 11). Measured currents on the north flank of the eastern outer ridge show dominantly easterly flow at <2 to 10 cm s^{-1} with short-term reversals (Fig. 11, location 2), while currents farther north on the southern Nares Abyssal Plain show both westerly and easterly currents at about the same speeds (location 1). The westerly flow in the Nares measurements may be part of the AABW circulation that courses around the Bermuda Rise. The boundary between this and the easterly flow on the northern ridge flank may shift episodically, thus accounting for flow reversals in both areas.

Measured currents on the southwest flank of the western outer ridge are strongly unidirectional to the northwest over a measurement period of about six months, while currents on the northeast flank flow in the opposite direction, to the southeast, over the same period (Fig. 11). Current speeds in both locations range from 2–17 cm s^{-1}, with maximum three-day-average speeds of 13–15 cm s^{-1}. Current-direction indicators from bottom photographs are available mostly from camera stations over the western outer ridge. They confirm a contour-parallel flow that circulates clockwise around the western outer ridge and then eastward along the north flank of the eastern outer ridge.

Suspended sediment

The character and distribution of the suspended sediment load in abyssal currents over the GAOR are known from a limited number of light-scattering (nephelometer) profiles and from filtration of bottom-water samples collected in large-volume Niskin bottles (Figs 8 & 12) (Tucholke & Eittreim 1974, Tucholke 1975). The nephelometer profiles show a near-bottom nepheloid layer that is concentrated in the AABW (colder than 1.8°C) but that also extends into overlying NADW up to about 1.9°C (Fig. 12). Concentrations of suspended matter in the nepheloid layer range from <10 μg l^{-1} up to 63 μg l^{-1}. The concentrations do not follow a smooth pattern with depth as suggested by the nephelometer profiles but instead indicate that there may be considerable small-scale patchiness in sediment distribution within the nepheloid layer. Nonetheless, both maximum concentrations and depth-averaged concentrations follow the contour of the light-scattering profiles and suggest a core of enhanced sediment load in AABW at about 1.6°–1.7°C, i.e. at depths of *c.* 5050–5400 m.

AABW flow that passes over Navidad sill (Fig. 11) is accompanied by a nepheloid layer that appears as a mid-water maximum at about 1.5°–1.9°C in the southern part of the Puerto Rico Trench (Tucholke & Eittreim 1974). Maximum suspended matter concentrations, based on in situ calibration of the nephelometer (Biscaye

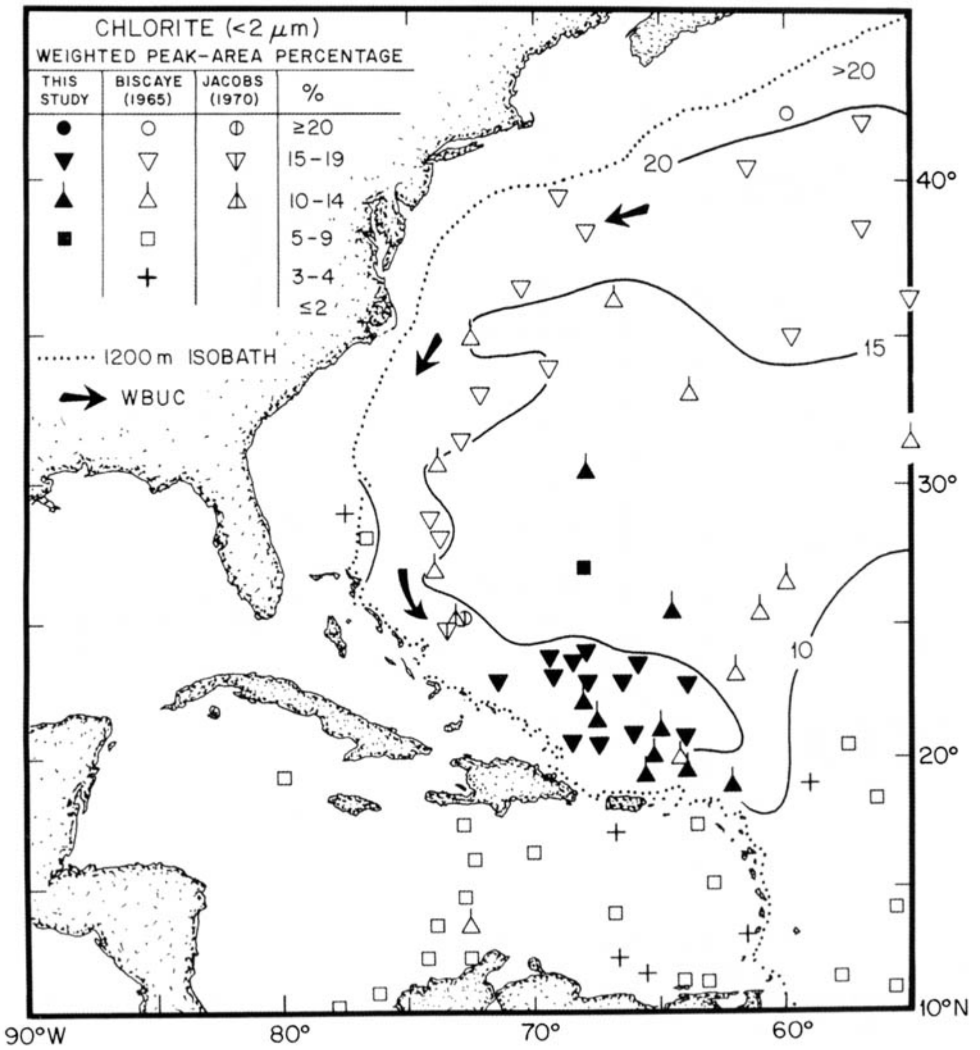


Fig. 10. Chlorite abundance in the clay-size (<2 µm) fraction of surface and near-surface sediments in the western North Atlantic, determined from X-ray diffraction (from Tucholke 1975). Compositions (weighted peak-area percentage) were determined using peak areas and weighting factors of Biscaye (1965). The chlorite-enriched tongue extending southward along the continental margin of North America and to the Greater Antilles Outer Ridge is interpreted to indicate long-distance sediment transport by the Western Boundary Undercurrent (WBUC).

& Eittreim 1974), are up to 30 µg l^{-1} over the western part of the trench and decrease down current to the east. A weak flow of AABW appears to circulate westward into the trench and along its north wall (south wall of the eastern outer ridge). This flow is accompanied by a poorly developed bottom nepheloid layer (Tucholke & Eittreim 1974), and it is not likely to be a significant source of sediment for the outer ridge.

Mean grain size of suspended matter sampled over the GAOR as determined in scanning electron microscope (SEM) samples is in the order of 3–4 µm, slightly coarser than that of the underlying outer-ridge sediments. However, the SEM technique probably underestimates the very fine-grained component (<0.2 µm), so this apparent difference may be artificial (Tucholke 1975).

Composition of the <2 µm fraction is more than 90% clay mineral platelets, with feldspar, quartz, and fragments of calcareous nannoplankton and biogenic silica constituting the remainder. The same components make up the silt-size fraction, but only 30–50% of this fraction is layered silicates. X-ray diffraction of bulk suspended-matter samples shows that chlorite is enriched in the samples (about 2 parts in 10), much as is observed in the underlying sediment. Unlike the seafloor sediment, however, illite appears to be strongly enriched and montmorillonite depleted. It is possible, though not certain, that this may be an artifact caused by incomplete development of the montmorillonite mineral lattice, and thus poor X-ray detection, in the very small-volume suspended matter samples analysed (Tucholke 1974).

Seismic stratigraphy and sediment distribution

As would be expected from the fine, uniform grain size and lack of coarse beds, impedance contrasts in GAOR sediments are small. Consequently, the sediments mostly are seismically transparent in conventional reflection profiles obtained at frequencies in the range of 10's–100's Hz (Figs 2–7). Weak internal reflections locally suggest migration of sediment waves as the outer ridge was constructed (Figs 5 & 7); most of these reflection packets are similar to the layered valleys noted earlier, and they probably exist because gravity flows locally remobilized sediments and redeposited them in sorted or graded beds.

The transparent layer that forms the GAOR overlies a markedly different seismic reflection sequence that consists of flat, reflective beds (Figs 3–7). These beds are part of the 'Horizon A complex' that is widespread in the western North Atlantic and consists of upper lower to lower middle Eocene biosiliceous sediments and cherts (Horizon A^C), as well as middle to possibly upper Eocene turbidites (Horizon A^T) (Tucholke & Mountain 1979). Sediments within and below this complex are thickest beneath the western outer ridge, where they bury most of the basement topography (Figs 4–7). Beneath the outer ridge east of 67°W this sequence thins and is commonly interrupted by basement peaks (Fig. 3), and east of about 63°W it is absent except under the Nares Abyssal Plain (Fig. 2). Cores recovered from the stratified sequence at DSDP Site 28 near 66°W (Fig. 8) contain clays, silts, chalk and chert (Bader *et al.* 1970).

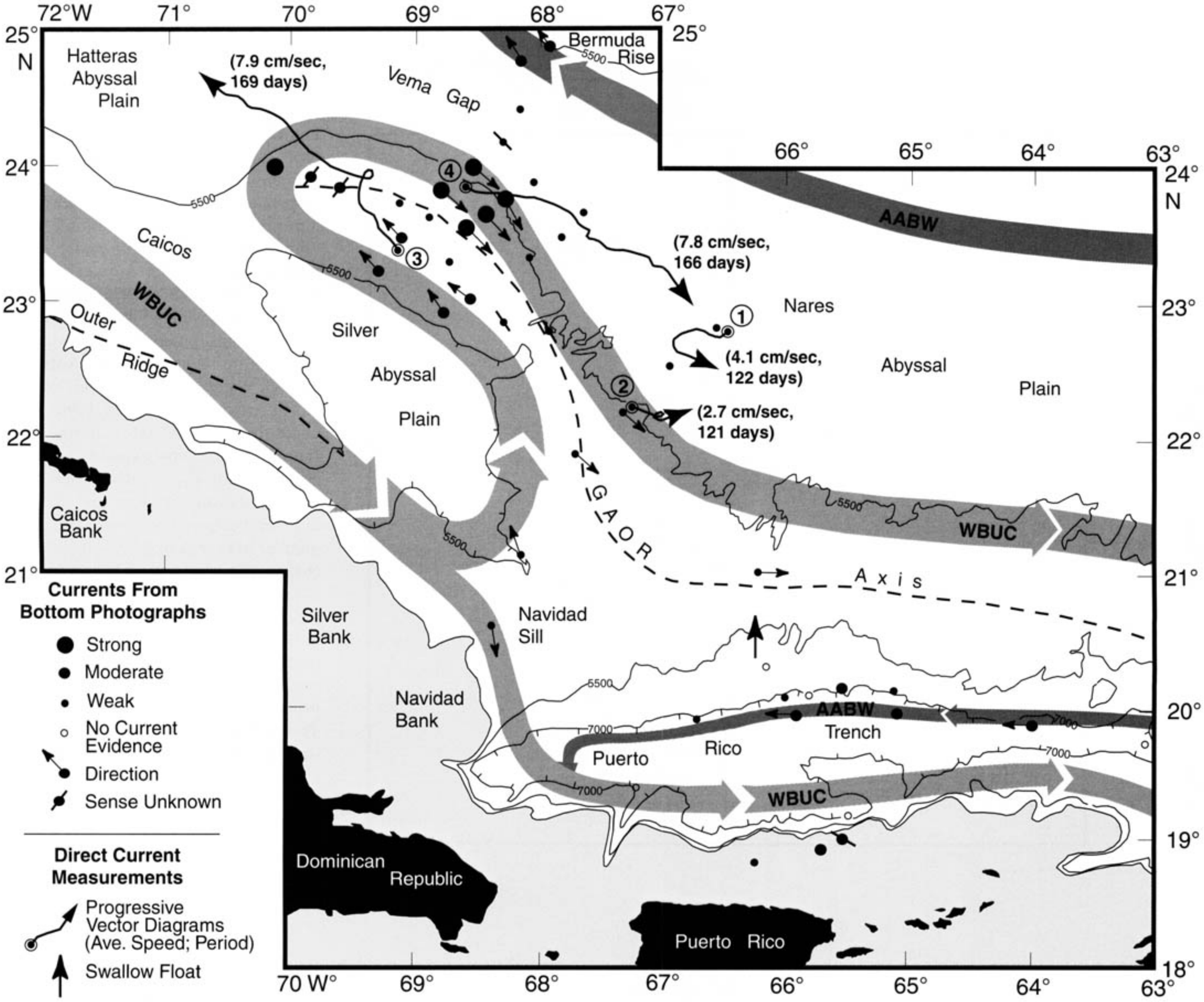


Fig. 11. Summary of abyssal current patterns in the region of the Greater Antilles Outer Ridge, based on all available data including hydrographic calculations (Tucholke *et al.* 1973; Tucholke & Eittreim 1974). Base map as in Figure 8. The shaded arrows show generalized circulation of the Western Boundary Undercurrent and of Antarctic Bottom Water entering from the South Atlantic. Current-metre measurements (circled numbers) are summarized as progressive vector diagrams with the starting point at the measurement location; durations of measurements in days and average current speed for the durations are indicated in parentheses. Measurements were made 15 m above the seafloor at locations 1 and 2, and 100 m above the seafloor at locations 3 and 4.

The transition from seismically laminated pre-Horizon A sediments to seismically transparent post-A sediments differs beneath the eastern and the western GAOR. Under the central and eastern outer ridge the change is abrupt (Figs 3, 6 & 7); over time the transparent layer accumulated more rapidly than sediments in the Nares Abyssal Plain and it has slowly prograded several tens of kilometres northward into the abyssal plain (Fig. 3). Under the northwest end of the outer ridge, deposition of laminated sediments persisted for 100–200 m above the Horizon A complex, interfingering with a small lens of transparent sediment that was probably the nascent core of this limb of the outer ridge (Fig. 4). As the ridge here was constructed, the zone of interfingering expanded outward in all directions from the ridge core, and the ridge has prograded more than 100 km to the northwest (Fig. 5).

Isopachs of sediment thickness above the Horizon A complex (Fig. 13) clearly reflect the physiographic form of the GAOR. Maximum sediment thickness is up to 0.9–1.0 km beneath the axis of the western outer ridge but only about 0.5 km beneath the eastern outer ridge. The adjacent Nares Abyssal Plain, which accumulates sediments from very distal turbidity currents passing through Vema Gap, has an average thickness of only 0.3–0.4 km of post-Eocene sediments. The Silver Abyssal Plain west of the outer ridge has slightly thicker post-Eocene sediments because it is proximal to a sediment source in the southeast Bahama Banks. At the extreme northwest end of the GAOR, isopachs show that the outer-ridge trend of thickened sediments extends into stratified sediments at the southern end of Hatteras Abyssal Plain (Fig. 13). This pattern suggests that sediment accumulation there is not entirely from turbidity currents but is enhanced by an additional component of current-controlled deposition. Because the seafloor in this area is flat, a slight regional depression of underlying basement is required to accommodate the thickening.

The reflective, flat-lying character of sediments within and below the Horizon A complex indicates that they were deposited from downslope gravity flows, and the source area is thought to be the northeastern Antilles arc (Tucholke & Ewing 1974). The abrupt upward change from these reflective sediments to seismically transparent sediments beneath the eastern GAOR is interpreted to coincide with middle to late Eocene initiation of the

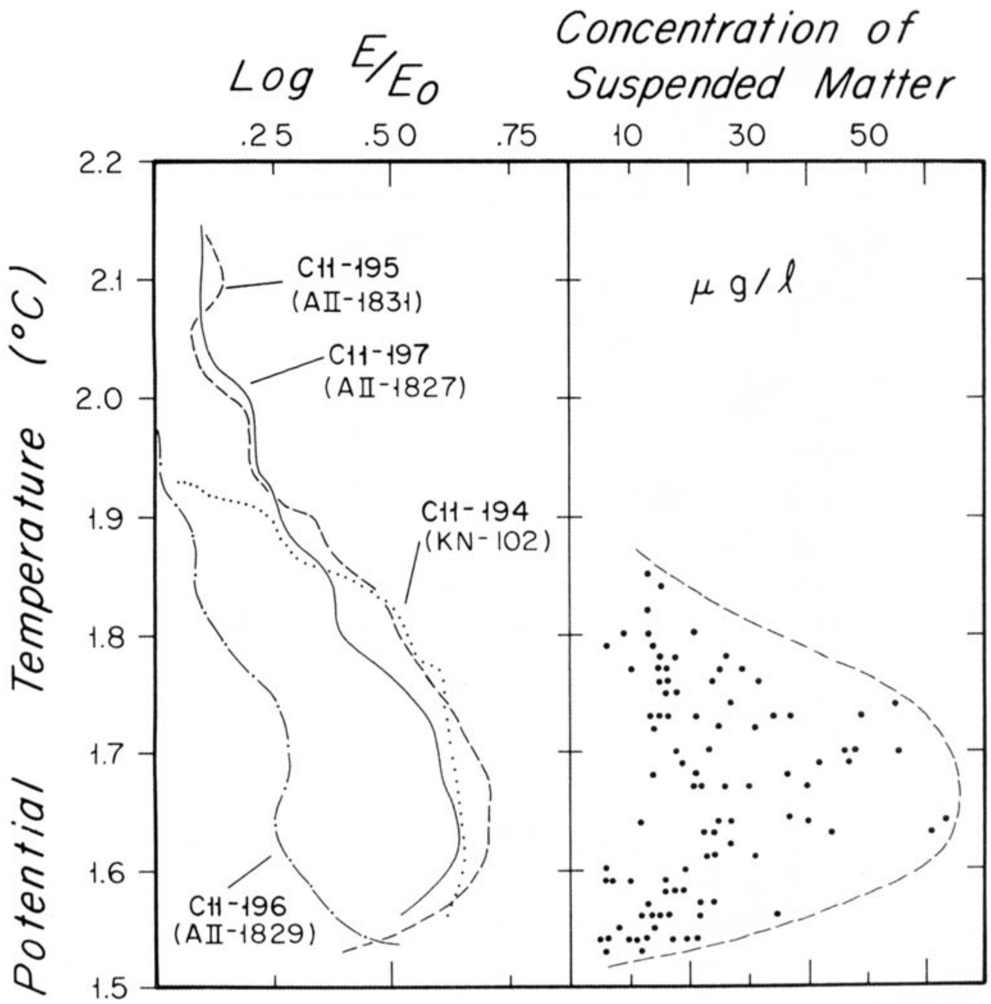


Fig. 12. Summary of light-scattering profiles made by the Lamont-Doherty nephelometer (left) and concentrations of suspended particulate matter measured by filtration of large-volume Niskin bottle samples (right) in the bottom nepheloid layer over the Greater Antilles Outer Ridge (from Tucholke 1975). Sampling locations are given in Figure 8. Data are plotted against potential temperature; temperatures below 1.8°C are Antarctic Bottom Water and the overlying water is North Atlantic Deep Water. Film exposure, E, in the light-scattering profiles is normalized against exposure in the clearest water, E_O; profiles are labeled by cruise and station number, and the labels in parentheses indicate cruise and station number of nearby hydrographic stations (within 22 km) that were used to provide potential temperature data. Note the robust near-bottom nepheloid layer indicated by three of the light-scattering profiles and by the suspended matter samples. The C11-196 light-scattering profile is from the center of Vema Gap. This profile shows a depletion of suspended matter in the bottom nepheloid layer; it falls outside the core of both the WBUC flow around the Greater Antilles Outer Ridge and the westerly AABW flow in the northern part of Vema Gap.

trough that subsequently developed into the present Puerto Rico Trench. Since that time the north slope of the trench and south slope of the eastern outer ridge have been isolated from any significant sediment source, and an average of less than 200 m of sediment has accumulated there over the past *c.* 40 Ma (Fig. 13).

Development of the Greater Antilles Outer Ridge

Current-controlled deposition that formed the core of the GAOR first appears above the Horizon A complex and thus post-dates the middle to late Eocene. Mountain & Miller (1992) found evidence on the southern Bermuda Rise that a pulse of strong, southern-source deep circulation occurred in late Paleocene time, but if these currents were active in the area of the GAOR their geological record appears to have been overwhelmed by the downslope sedimentation. A major oceanographic shift in the North Atlantic to a regime wherein sedimentation was influenced or controlled by deep circulation began in late Eocene to early Oligocene time (Tucholke & Mountain 1979). The onset of this regime is recorded in a widespread unconformity (Horizon A^U) that was eroded by abyssal currents along the continental margin of eastern North America and the base of the Bahama Banks. The unconformity can be observed truncating beds of the Horizon A complex under Caicos Outer Ridge (Fig. 4). Although there is no direct stratigraphic control on the age of the oldest GAOR sediments, it is reasonable to infer that the core of the outer ridge contains sediments eroded from the continental margin during this event.

Current-controlled deposition that initiated the GAOR probably was focussed beneath the eastern outer ridge by the crustal outer-high north of the Puerto Rico Trench, which diverted part of the WBUC into a flow around its northern margin (Fig. 14a). Interaction of this current with the numerous basement peaks protruding through the Horizon A complex most likely triggered deposition of local drifts, much like the isolated drift flanking the seamount in the southern Silver Abyssal Plain (Fig. 6) and the drifts presently on the far-eastern outer ridge (Fig. 2). As these drifts grew and merged, the increasing physiographic expression of the ridge would have forced the abyssal currents into a more organized system, with a distinct branch of the flow circulating around the drift (Fig. 14b). Along the Antilles margin south of the trench and in the area of the present northwestern outer ridge, downslope sedimentation characterized by seismically chaotic or laminated deposits dominated over current-controlled deposition.

The northwestward growth of the GAOR into the area of the present Hatteras Abyssal Plain is roughly constrained by interpretation of the seismic stratigraphy to have occurred by Miocene time (Fig. 14c) (Tucholke & Ewing 1974). Abyssal current intensity along the North American margin appears to have decreased during the Oligocene so that deposition rather than erosion began to predominate, and by early to middle Miocene time the cores of large sediment drifts such as the Blake Outer Ridge and Chesapeake Drift were forming there (Mountain & Tucholke 1985). Growth of the northwestern GAOR may be coincident with the initiation of these drifts.

The factors that caused this limb of the outer ridge to extend to the northwest remain unclear. One possibility is that diversion of the WBUC around the western end of the existing ridge core led

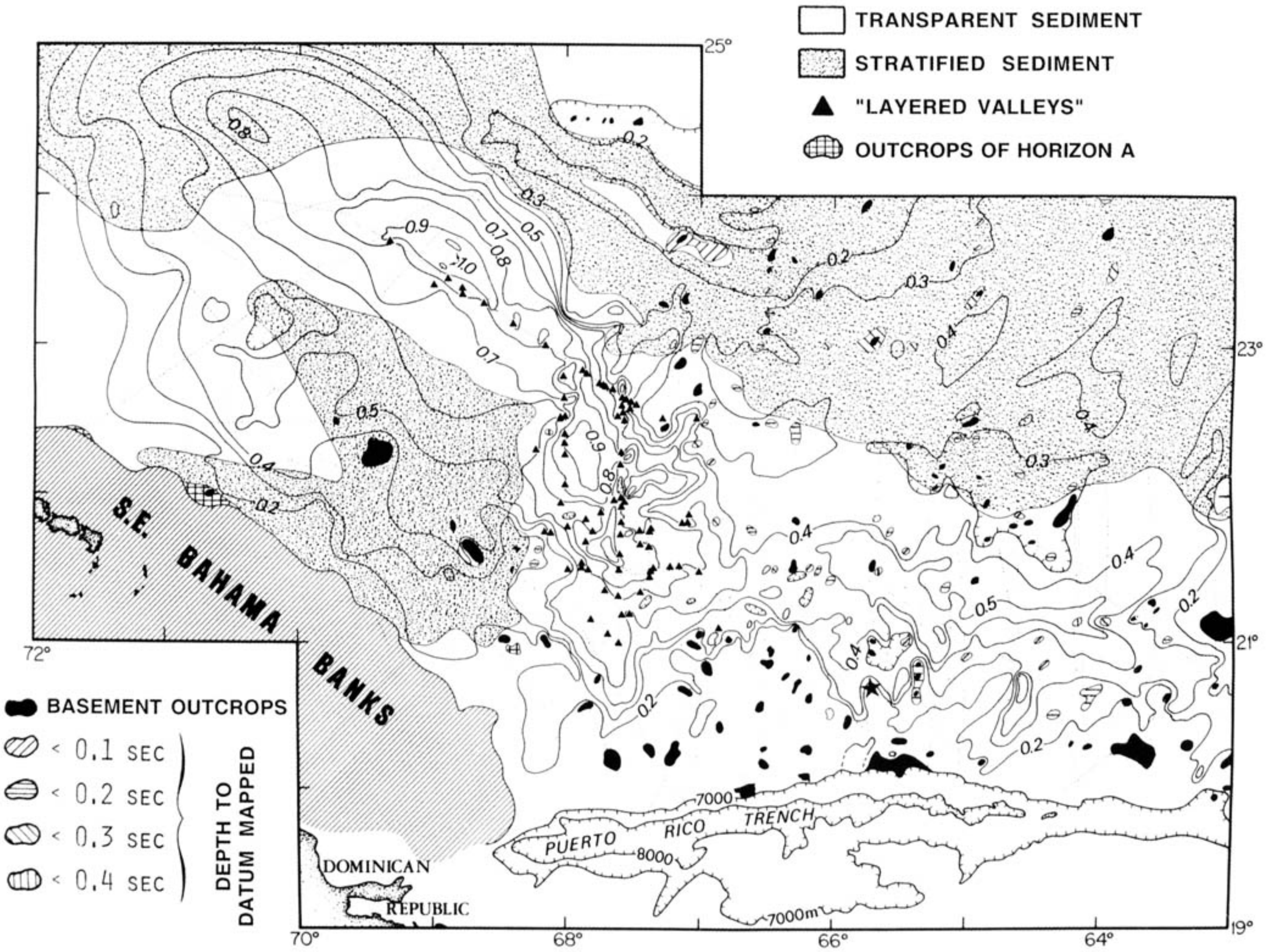


Fig. 13. Mapped sediment thickness above the stratified Horizon A complex (contours in seconds two-way travel time) and above basement peaks that interrupt Horizon A (see code at lower left). Control provided by seismic reflection profiles is shown by light dotted lines. The star shows the location of DSDP Site 28. Shaded areas show where sediments in the mapped interval are seismically stratified; these are mostly restricted to the abyssal plains. The southern limit of mapped thicknesses is the 7000 m contour along the north wall of the Puerto Rico Trench. The Horizon A complex crops out in three small areas at the base of the Bahama Banks and at the southern end of the Silver Abyssal Plain (crosshatch pattern) where abyssal currents eroded the complex and have prevented deposition since early Oligocene time. Note that sediment thickness patterns correlate closely with the physiographic form of the Greater Antilles Outer Ridge. Layered valleys within the transparent layer are restricted entirely to the western outer ridge. Figure from Tucholke & Ewing (1974).

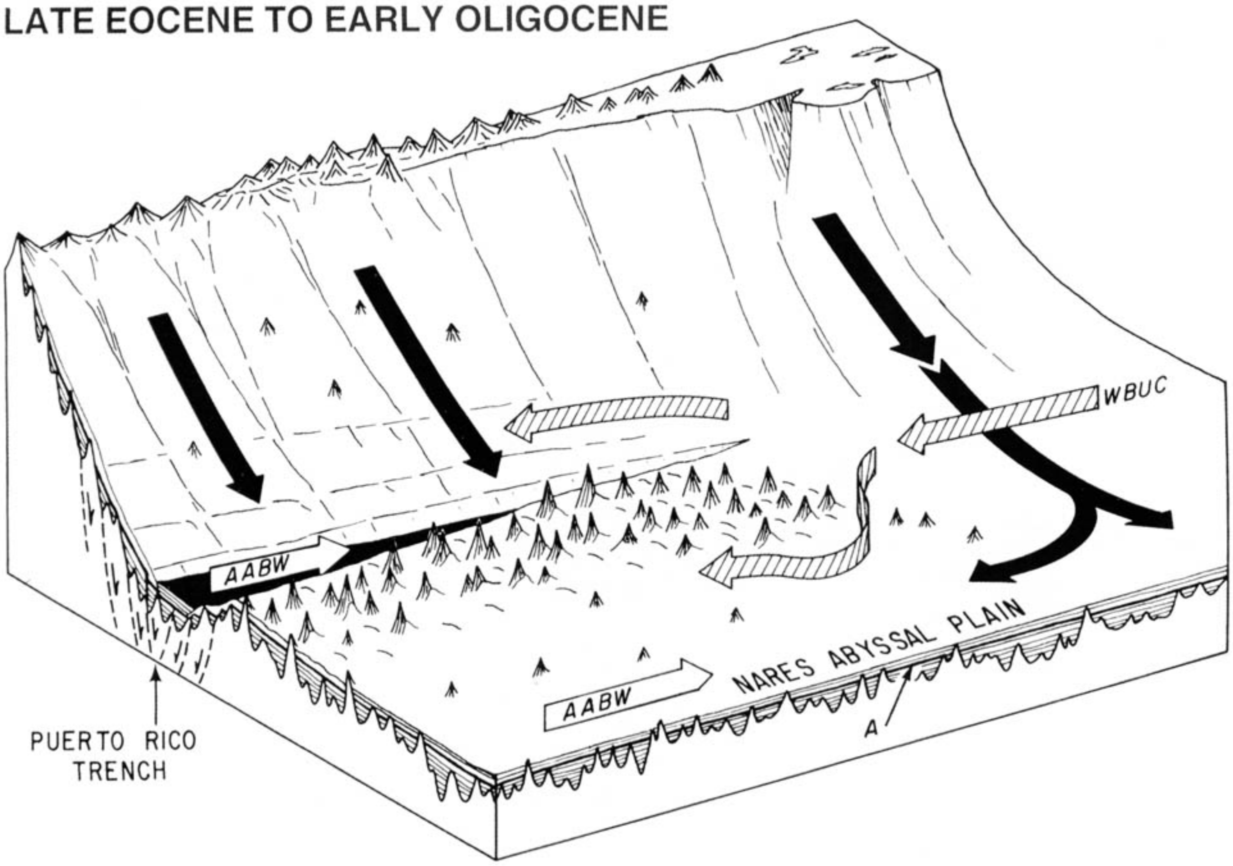
to a zone of current shear between northwest- and southeast-directed currents (Fig. 14b, c), and rapid deposition of suspended load beneath the shear zone formed the northwestern outer ridge (Fig. 15). In an alternate scenario, depositional patterns may have been affected by interaction of the WBUC and AABW entering the area from the southeast. Ice volume increased substantially in the middle Miocene (e.g. Miller *et al.* 1991), and it may have led to increased flux of AABW into the western North Atlantic. Amplified westward flow of AABW through Vema Gap would have opposed the eastward-flowing WBUC, and it could either have diverted the WBUC or created a shear zone against this current that triggered deposition to form the northwestern GAOR.

Discussion and conclusions

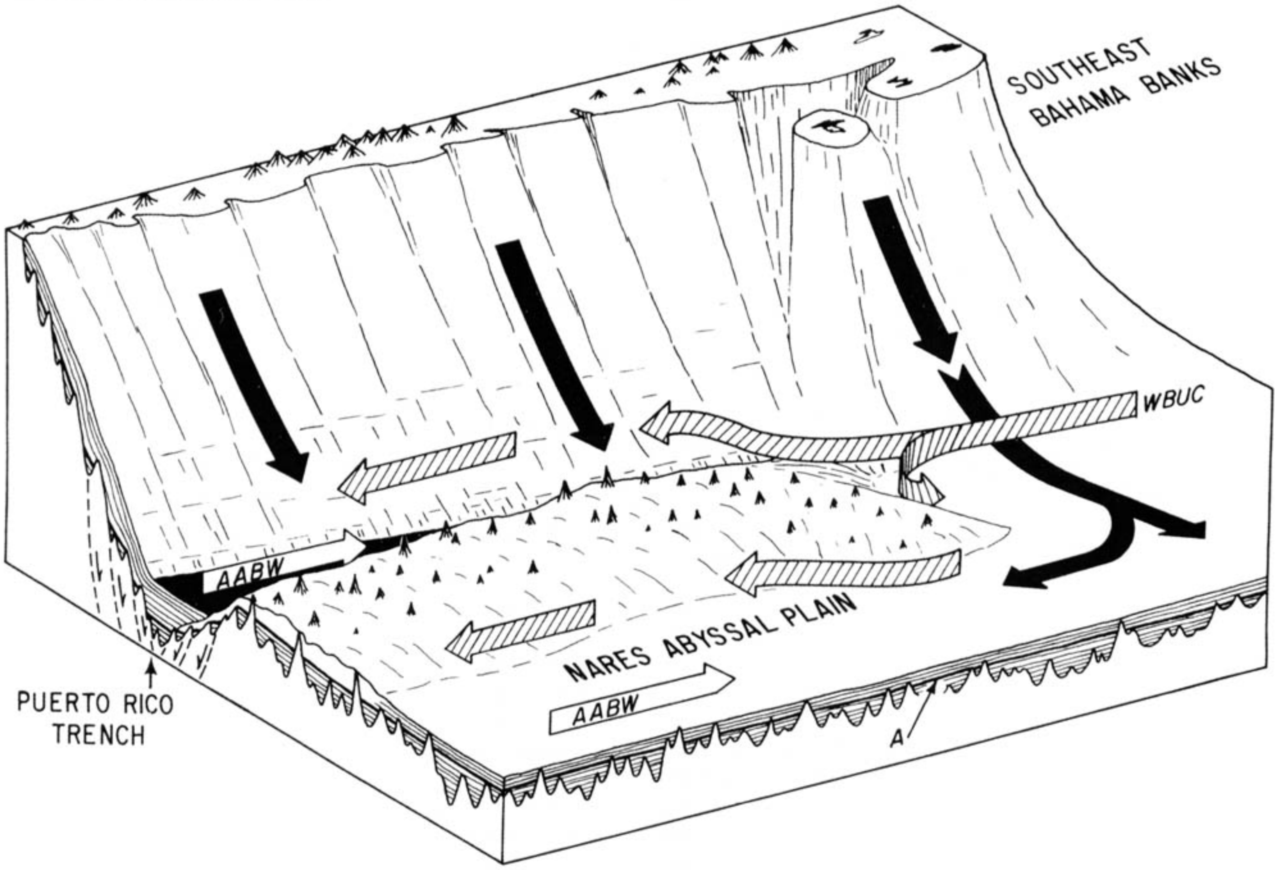
Most sedimentary drifts in continental-margin settings have direct or nearly direct downslope sources of sediment; bottom currents have reworked and transported these sediments to varying degrees, depending primarily on grain-size distribution and current intensity. The resulting drifts are complex aggregations of beds with mixed signatures of cross-slope and along-slope sedimentary processes. In contrast, the Greater Antilles Outer Ridge has been deposited entirely from suspended load carried in abyssal currents. Thus its characteristics can provide important insights into purely current-controlled sedimentary processes over long time and spatial scales.

The enrichment of chlorite in GAOR sediments (Fig. 10) provides strong evidence that a significant fraction of the sediment has been transported for great distances, up to 2000 km or more, from the North American continental margin north of Cape Hatteras. Hollister (1967) used the reddish colour of sediments derived from Permian–Carboniferous red beds in the Canadian Maritime Provinces as a tracer of northern-source sediments carried by bottom currents along the US continental rise, and the reddish brown and reddish gray clays on the GAOR (Fig. 9) may also reflect a continuation of this dispersal pattern. In the dominant, non-biogenic portion of GAOR sediment, grain size averages more than 80% clay (<2 μm), with the remainder consisting of very fine silt. These sediments were sampled only to 10–20 sub-bottom in piston cores but their seismic signature is the same as deeper, seismically transparent sediments that form the Oligocene(?)-Miocene core of the outer ridge, and it is likely that

A. LATE EOCENE TO EARLY OLIGOCENE



B. LATE OLIGOCENE



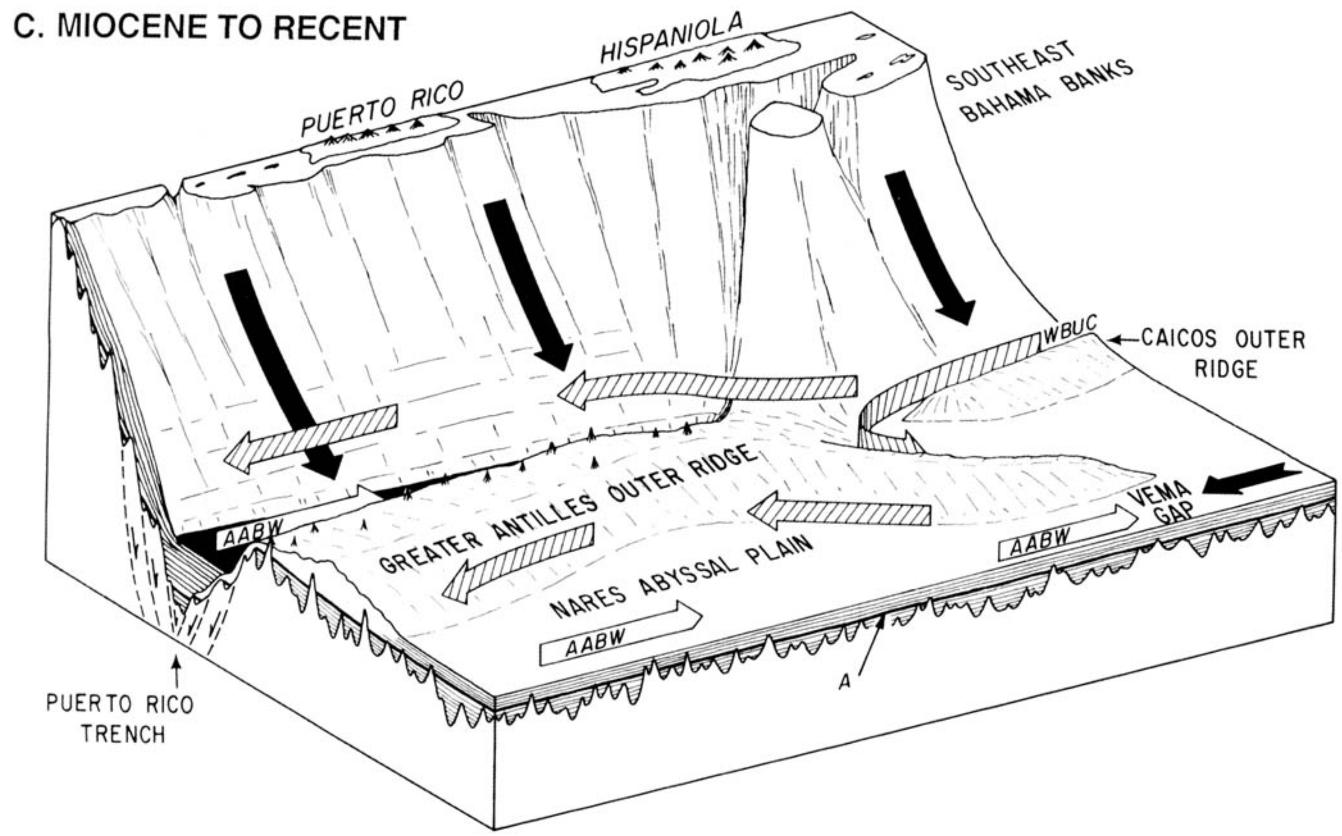


Fig. 14. Schematic summary interpreting the evolution of the Greater Antilles Outer Ridge (view to the southwest, covering the approximate area of Figure 1). (**a**) Late Eocene to early Oligocene: The developing Puerto Rico Trench cut off downslope sedimentation (black arrows) from the Greater Antilles and created a crustal outer-high that diverted part of the newly developed Western Boundary Undercurrent. Current-controlled deposition along the irregular topography of this bulge formed the core of the eastern outer ridge. Downslope gravity flows from the Bahama Banks continued to deposit stratified sediments in the area of the western outer ridge and on the surrounding abyssal plains. (**b**) Late Oligocene: Growth of the GAOR may have diverted WBUC flow enough that a shear zone developed between opposing currents at the western end of the ridge, stimulating ridge growth northwestward into the abyssal plain. (**c**) Miocene to Recent: By this time the western extension of the GAOR was well established, and ridge-crest sediments accumulated rapidly between opposing flows that followed the ridge flanks. The Caicos Outer Ridge also was deposited along the margin of the Bahama Banks, blocking downslope sediment supply to the Hatteras and Nares abyssal plains and diverting it to the Silver Abyssal Plain. Figure adapted from Tucholke & Ewing (1974).

most of the ridge has similar grain-size characteristics. From all these considerations, we infer that on a time scale of at least *c.* 20 Ma. the Western Boundary Undercurrent has been competent to transport very fine silt and clay-size sediments for thousands of kilometres. Composition and grain-size distribution in modern particulate-matter samples from bottom water over the GAOR are very similar to those in the seafloor sediments, so present-day dynamic conditions of sedimentation appear to be similar to average conditions over the longer-term construction of the outer ridge.

From observations in bottom photographs, current-produced bedforms seem to be neither well nor widely developed in GAOR sediments. Because of their fine grain size the sediments have high cohesion once deposited, and they are not easily eroded by ambient currents that have maximum speeds of only 15–17 cm s^{-1}. The lack of significant bedload transport probably hinders the production of pronounced bedforms. The only distinct lenses of coarse (silt-size) sediment known on the outer ridge occur in 'layered valleys' between sediment waves. These appear to be deposited from small turbidity currents generated by failure of rapidly deposited sediments on the adjacent sediment waves. Thus, unlike the conditions at sedimentary drifts along continental margins, sediments are moved in gravity flows as a result of, rather than as a prelude to, current-controlled sedimentation. The large-scale abyssal sediment waves on the GAOR are widespread but they do not seem often to develop in regular wave trains. However, this observation is not robust because there is relatively sparse echosounding and seismic reflection coverage, and denser data sets (e.g. multibeam bathymetry) could well reveal extensive development of coherent sediment waves. In some places sediment waves clearly do show both regular patterns and a long history of growth, dating well back into the Miocene (Fig. 7).

Abyssal current directions around the GAOR closely parallel bathymetric contours (Fig. 11), within certain limits. Direct current measurements over periods of months reflect the significant influence that even small topographic gradients have in organizing the flow. Currents along the flanks of the GAOR at locations 2–4 (Fig. 11), for example, follow the local contours (with short-term excursions) even though the seafloor slope is only *c.* 0.5°–1.0°. At location 1 on the Nares Abyssal Plain, however, the seafloor slope is less than 0.05° and there is no consistent direction in measured currents. Current directions determined from bedforms, tool marks, and other sedimentary features in bottom photographs are the most consistently contour-parallel. As already noted, current erosion or molding of the cohesive outer ridge sediments is difficult, so short-term flow variability is unlikely to modify the bed significantly. The bedforms probably represent average flow over periods of at least months to perhaps many years, and they come closer to characterizing flow that has long-term geological effects than do direct current measurements.

In the area of the Greater Antilles Outer Ridge, the primary controls on position and growth of sedimentary drifts have been current interaction with varying seafloor topography (which controls current vectors) and suspended particulate load.

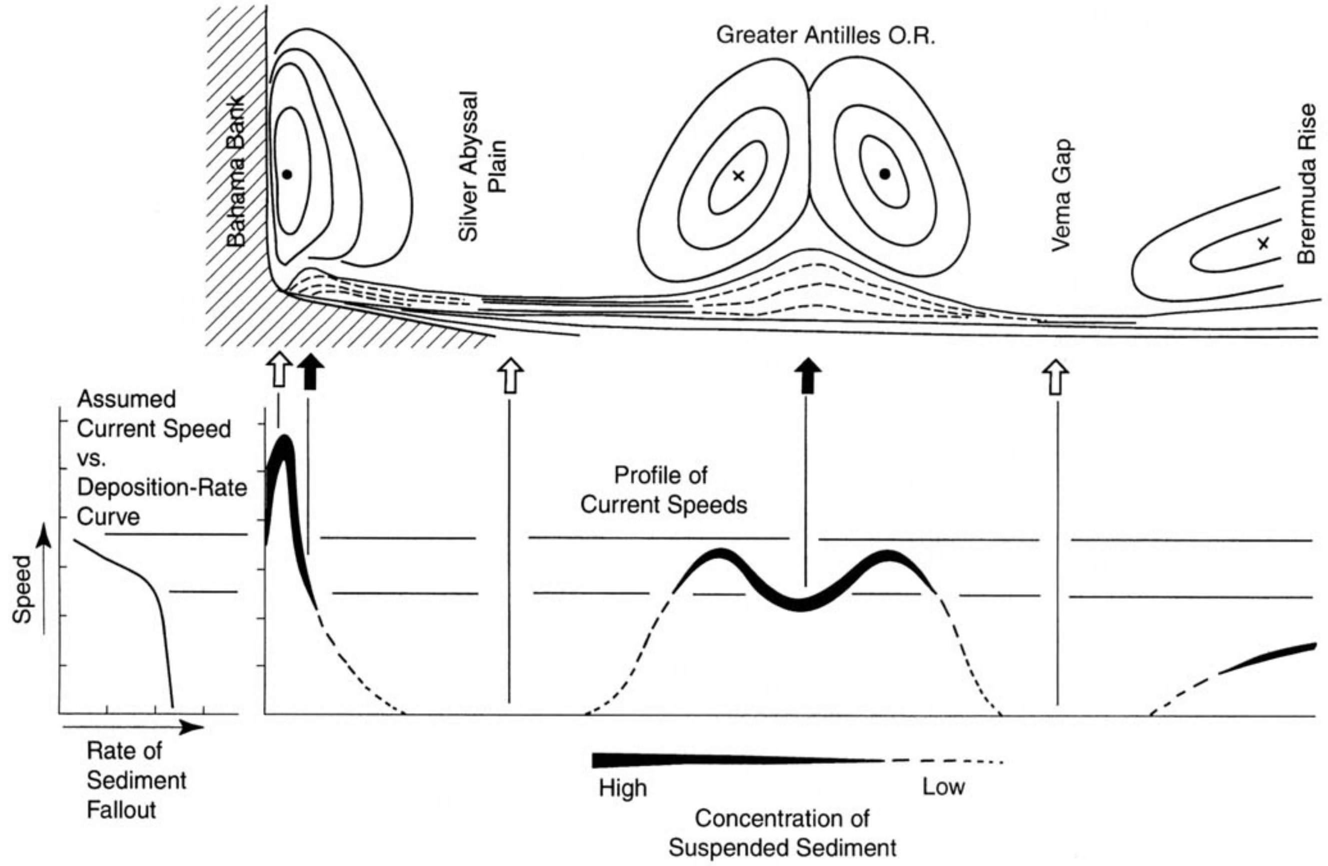


Fig. 15. Simple model for current-controlled deposition along a section extending northeast from the Bahama Banks to the southernmost Bermuda Rise, adapted from Tucholke & Ewing (1974) (compare with the seismic section in Figure 4). The top panel shows idealized flow of the WBUC along the Bahama Banks and around the Greater Antilles Outer Ridge, and flow of AABW in the northern part of Vema Gap (dots represent flows out of the page, X's are flows into the page). At bottom right is schematic current speed with superimposed concentrations of suspended matter. The current-speed versus deposition-rate curve at lower left assumes rapid sediment fallout over a small speed range, but the shape of the curve is not critical. Rapid sediment deposition from currents requires both significant suspended load and low current speeds. Thus, although suspended-matter concentration is high in the WBUC close to the Bahama Banks, high current speeds prevent deposition at the base of the banks (open arrow) while decreasing speeds away from the banks allow deposition on Caicos Outer Ridge (filled arrow). Over the GAOR, a combination of high suspended load and lower current speeds in the shear zone between opposing flows allows rapid deposition on the ridge crest (filled arrow); higher speeds with approximately the same suspended load attenuate deposition on the ridge flanks. Deposition from abyssal currents is minimal over the Silver Abyssal Plain and in Vema Gap where both current speeds and suspended load are low (open arrows).

Interaction of the WBUC with irregular topography formed the initial core of the GAOR on the outer high north of the Puerto Rico Trench probably in the Oligocene (Fig. 14). The deceleration and interactions of threads of currents over this confused topography most likely initiated deposition from a substantial suspended load. As the ridge grew, opposing NW- and SE-directed currents developed on its western end; lower current speeds in the shear zone between these flows allowed rapid deposition of suspended load to form the northwestern limb of the outer ridge as it exists today (Figs 14c & 15). To the southwest, in the WBUC along the Bahama Banks, suspended load may be high but currents are topographically intensified against the steep banks, so an erosional/non-depositional zone exists at the base of the banks inboard of the Caicos Outer Ridge. Shear zones with low current speeds between opposing flows exist over the Silver Abyssal Plain and in Vema Gap, but no coherent drift deposits have accumulated in these locations. This is probably explained by the fact that the shear zones are not stabilized by topography and thus are migratory, and by the absence of significant particulate suspended load away from the cores of the main currents.

My studies of current-controlled deposition in the region of the Greater Antilles Outer Ridge extend back to my PhD thesis research, undertaken under the tutelage of Charles D. Hollister. Charley was a constant source of enthusiasm, as well as personal and scientific inspiration, both in those early days and over the many intervening years of our continuing friendship. I hope that this brief synthesis reflects at least some small insight into the broad research questions of abyssal sedimentation that he inspired and promoted throughout his career. Geological and geophysical studies of the Greater Antilles Outer Ridge were funded by the US National Science Foundation and the Office of Naval Research. This overview was prepared with support from the Henry Bryant Bigelow Chair in Oceanography at Woods Hole Oceanographic Institution. Woods Hole Oceanographic Institution Contribution No. 10392.

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