FORUM

Carbonate-periplatform sedimentation by density flows: A mechanism for rapid off-bank and vertical transport of shallow-water fines: Comment and Reply

COMMENT

R. Jude Wilber
Associated Scientists at Woods Hole, Woods Hole, Massachusetts 02543
Jack Whitehead
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543
Robert B. Halley
U.S. Geological Survey, St. Petersburg, Florida 33705
John D. Milliman
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

Wilson and Roberts (1992) presented important new data on the flux of bank-top waters from the Florida-Bahamas carbonate platforms. The unique geographic location of the banks places them in the path of both tropical, oceanic low-pressure storms (hurricanes) and continental low-pressure storms featuring polar air outbreaks. Both have the potential to disturb bank-top conditions in a dramatic fashion.

We agree that "cold-condition" hyperpycnal cascades are important in the sediment dynamics of the open margins of Little and Great Bahama Banks, but not as a mud-flux mechanism. Rather, we believe that bank-margin cascades primarily erode and redistribute periplatform sediments deposited via hemipelagic means. We base this view on a wealth of sediment, seismic, and submersible data obtained on Bahamian slopes over the past two decades (see Hine and Mullins [1983] and Mullins and Cook [1986] for syntheses, and Boardman et al. [1986], Burns and Neumann [1987], and Slowey et al. [1989]). For Great Bahama Banks, it has been shown that the type, amount, and geometry of periplatform deposits is controlled primarily by the relative strength of long-slope currents (Wilber et al., 1990). In areas of weak currents (e.g., the Santaren Channel) a thick slope unit is marked by an erosional trough at the point of onlap. The trough is persistent along strike and consists of a series of discrete "plunge pools" carved into the onlapping muds. Individual pools are ~200 m long with as much as 50 m of relief between the trough floor and the seaward "dump bump" (Wilber et al., 1990, Fig. 3). Holocene high-stand shedding has been described for many other banks in the Bahamas and Caribbean (Hine and Steinmetz, 1984; Glaser and Droxler, 1991; Wilber and Corso, 1992), but bump-and-trough morphology is found *only* along western Little and Great Bahama Banks. We believe that the likely mechanism of slope *erosion* is found in cold-condition density flows.

Under extreme cold conditions (13 °C, 36.5 ‰), Great Bahama Banks bank-top water acquires a density of 1.02785 (σ_t = 27.85). The "compensation" depth (Wilson and Roberts, 1992) of this water in the adjacent seaways is >700 m, a depth greater than most of the Santaren Channel. On the basis of internal surge considerations outlined in Yih (1980), we find that cold-condition cascades may achieve a maximum down-slope velocity of 2.47 m/s or ~5 kn (Table 1). Further, the flow is bounded along its base by the slope and does not diverge from this surface as it descends. Thus, we believe that cold shedding is most easily envisioned as a high-energy scour event over much of the slope.

TABLE 1. VELOCITY OF BANK-MARGIN CASCADES: COLD VS. WARM CONDITIONS

Condition	T (°C)	S ($^0/00$)	ρ_0 (g/cm^3)	ρ_H (g/cm^3)	$\delta\rho$	H (m)	Z_c (m)	U (m/s)
Cold	13	36.5	1.02758	1.02500	0.00258	100	>700	2.47
Warm	30	40.0	1.02550	1.02550	0	150	150	0

Note: All calculations assume zero sediment load and no mixing during descent. Values determined by using $U = [2\,g\,H\,(\delta\rho/\rho_H)]^{1/2}$, where U = cascade velocity at depth H (depth of intrusion), g = acceleration of gravity (9.8 m/s^2), $\delta\rho = (\rho_0 - \rho_H)$, ρ_0 = seawater density at surface; ρ_H = seawater density at depth H. Z_c = compensation depth ($\delta\rho = 0$).

In support of this picture we offer the following. In summer 1989 we set out a line of weighted, cylindrical sediment traps at lat 23°20′N. Traps were placed in the trough, atop the bump, and at two sites down slope. Upon our return 15 months later (an interval that *included* the January 1990 cold snap), we found that three of the four sediment traps were knocked over and pointing due west. The deepest sediment trap (at 223 m) was upright and filled with a thick layer (~30 cm) of muddy sand. However, the lower rocky slope and trough were well scoured, mud free, and covered by a coarse lag deposit. The flow velocity necessary to tip over these traps is close to the maximum value calculated for cold-condition cascades.

In addition to cold flows, "warm-condition" cascades may also affect this margin. These may be generated during maximal solar heating during the late summer months. At 30 °C and 40‰, bank-top water acquires a density of 1.02550 (σ_t = 25.50). The compensation depth of this water is ~150 m where down-slope velocity equals zero (Table 1). The maximum down-slope flow velocity is only 1 m/s (2 kn) at 100 m. During one dive along western Great Bahama Banks, we encountered warm shedding at a depth of ~80 m. The slope water temperature rose ~1–2 °C, and the downward flux of water was sufficient to overcome the positive buoyancy of the submersible. On the basis of the submersible action and the downward streaming of elongate benthos (seawhips, etc.), we estimated flow at ~0.5 m/s. We escaped the flow by backing away from the slope ~20 m. Thus, we believe that warm shedding is much more pacific and lacks the energy for significant sediment reworking.

It is not clear to us that cold shedding is significant in either (1) the off-bank transport of sediment or (2) overcoming the effect of long-slope currents (Wilson and Roberts, 1992, p. 715). At least two facts argue against these contentions. First, the thickest periplatform sequences are always found in current-free conditions where it is clear that initial deposition was *not* in equilibrium with calculated cold-shedding dynamics. Second, in those areas of strong long-slope flow, the slope is sediment free and lithified. This suggests that *no* mechanism of deposition is able to compete with long-slope "sweeping" by geostrophic currents (Wilber et al., 1990).

Finally, Wilson and Roberts' contention (1992, p. 715) that some mechanism "must" accelerate the vertical flux of mud is not well supported by sediment data from the western Bahamas. It is

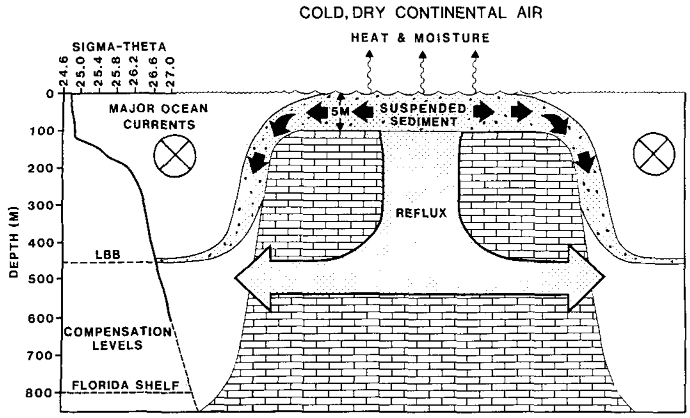

Figure 1. Schematic diagram corrected from Wilson and Roberts (1992, Fig. 5) showing off-bank density flows attached to slope. Slope separation is predicted at compensation levels. LBB = Little Bahama Bank. Sigma-theta profile: lat 26°55′N, long 76°75′W, February 28, 1990; sigma-theta = density − 1000, where density (kg/m^3) is from potential temperature (θ) and salinity in situ but with pressure effect reduced to zero (atmospheric); θ = temperature of water parcel brought to surface adiabatically.

doubtful that particle-flux data acquired from mid-channel sediment traps (Pilskaln et al., 1989) are directly applicable to the bank-edge environment. Indeed, it appears that much of the mud that leaves the banktop does so in some aggregated form (Wilber et al., 1990). We believe that the likely agents of off-bank *sand* transport are the strong westerly surges generated by hurricanes.

In summary, we agree with Wilson and Roberts (1992) that cold-condition density flows are an important and very high frequency mechanism of flux for bank-top waters in the Florida-Bahamas region. However, the main impact of such flows appears to be in altering the depositional geometry of periplatform units deposited via simple gravity settling (hemipelagic) mechanisms. The significance of bank-edge cascades in the long-term flux of water and material to the deep oceans *and* in megabank evolution is potentially great. We therefore strongly agree with Wilson and Roberts (1992) that direct data-collection experiments are needed to sort out the puzzle of carbonate platform density flows.

REFERENCES CITED

Boardman, M.R., Neumann, A.C., Baker, P.A., Dulin, L.A., Kenter, R.J., Hunter, G.E., and Kiefer, K.B., 1986, Banktop responses to Quaternary fluctuations in sea level recorded in periplatform sediments: Geology, v. 14, p. 28–31.

Burns, S.J., and Neumann, A.C., 1987, Pelagic sedimentation on an active gullied slope, Northwest Providence Channel, Bahamas: Marine Geology, v. 77, p. 277–286.

Glaser, K.S., and Droxler, A.W., 1991, High production and highstand shedding from deeply submerged carbonate banks, Northern Nicaragua Rise: Journal of Sedimentary Petrology, v. 61, p. 128–142.

Hine, A.C., and Mullins, H.T., 1983, Modern carbonate shelf-slope breaks: Society of Economic Paleontologists and Mineralogists Special Publication 33, p. 169–188.

Hine, A.C., and Steinmetz, J.C., 1984, Cay Sal Bank, Bahamas—A partially drowned carbonate platform: Marine Geology, v. 59, p. 135–164.

Mullins, H.T., and Cook, H.E., 1986, Carbonate apron models: Alternatives to the submarine fan model for paleoenvironmental analysis and hydrocarbon exploration: Sedimentary Geology, v. 48, p. 37–79.

Pilskaln, C.H., Neumann, A.C., and Bane, J.M., 1989, Periplatform carbonate flux in the northern Bahamas: Deep-Sea Research, v. 36, p. 1391–1406.

Slowey, N.S., Neumann, A.C., and Baldwin, K.E., 1989, Seismic expression of Quaternary climatic cycles in the peri-platform carbonate ooze of the northern Bahamas: Geological Society of America Bulletin, v. 101, p. 1563–1573.

Wilber, R.J., and Corso, W., 1992, Styles of carbonate platform response to Holocene sea-level rise in the Caribbean Basin: An overview: Geological Society of America Abstracts with Programs, v. 24, no. 1, p. 50.

Wilber, R.J., Milliman, J.D., and Halley, R.B., 1990, Accumulation of banktop sediment on the western slope of Great Bahama Bank: Rapid progradation of a carbonate megabank: Geology, v. 18, p. 970–974.

Wilson, P.A., and Roberts, H.R., 1992, Carbonate-platform sedimentation by density flows: A mechanism for rapid off-bank and vertical transport of shallow-water fines: Geology, v. 20, p. 713–716.

Yih, C-S., 1980, Stratified flows (second edition): New York, Academic Press, 414 p.

REPLY

Paul A. Wilson
Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, England
Harry H. Roberts
Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana 70803

Wilber et al. present exciting new field confirmation of our recent contentions that (1) hyperpycnal waters are routinely generated across the Bahama and Florida platforms in response to winter cold fronts and summer periods of intense evaporation, (2) these instabilities are reequilibrated by *density cascading* events involving sinking off-bank flows, (3) density cascading is an important shelf-break exchange process, and (4) in the case of cold fronts, exchange may also involve sediment flux (Wilson and Roberts, 1992, and unpublished; Wilson et al., unpublished). Whereas we (Wilson and Roberts, 1992) emphasized the significance of density cascading to off-bank and vertical transport of mud from the Bahama and Florida platforms, Wilber et al. prefer an erosional significance.

There is scope for general agreement. Elsewhere, we have argued that density cascades are capable of both depositional and erosional features (Wilson and Roberts, unpublished). In Figure 1 here we correct a drafting error (Fig. 5, Wilson and Roberts, 1992) to show that density flow is initially attached to the slope. However, assuming that the depth of compensation does not exceed depth at the base of the margin, flow should separate and spread laterally at this level (McCave, 1983). Wilber et al. present an alternative scenario in which the compensation level for down-slope flow exceeds depth at the base of slope. Under such circumstances "bump-and-trough" morphology is an intriguing consequence.

Wilber et al. give two arguments against density cascading as a mechanism for accelerating off-bank and vertical transport of platform mud: (1) periplatform deposition around Great Bahama Bank is primarily controlled by the strength of long-slope currents, and (2) bank-top mud is delivered to periplatform environments primarily by aggregation and settling. We consider these in turn.

The magnitude of ocean currents within the Straits of Florida vary with time, depth, and location on several scales (Lee et al., 1985). We do not doubt the ability of strong, well-focused bottom currents to redistribute periplatform deposits (Mullins et al., 1980). However, contourite redistribution is a side issue to the question of off-bank and vertical sediment flux. It is *surface* ocean currents that may limit vertical sediment flux by "long-bank sweeping." We expect density flows to be affected by geostrophic flow as they exit the bank, but we doubt the general applicability of Wilber et al.'s statement that "*no* mechanism of deposition is able to compete with long-slope 'sweeping'." Modern development of the southwest Florida shelf has been controlled by off-shelf transport and platform-margin progradation in the presence of strong (250 cm/s) surface geostrophic currents (Brooks and Holmes, 1990). Similarly, although geostrophic flow may have played a role in inhibiting leeward progradation of Great Bahama Banks (Ball et al., 1987), evidently erosion has been secondary to Neogene off-bank sediment transport and platform-margin progradation (Eberli and Ginsburg, 1987a, 1987b).

Settling velocities of particles finer than 62 μm are so slow as to be insignificant to their arrival at the sea floor (Honjo, 1986). Some mechanism *must* accelerate the vertical flux of bank-top mud. We reiterate that calculated (McCave, 1975) and measured (Shanks and Trent, 1980) sinking rates for the largest aggregates (>1 mm "marine snow") are 50–100 m/day. Wilber et al. accept the importance of density flows for the flux of bank-top waters to adjacent oceans. These same waters are laden with suspended sediments following cold fronts (Wilson and Roberts, 1992). It is therefore difficult for us to reject the potential of density flows (estimated downslope velocities on the same order as surface currents: ~250 cm/s; Wilber et al., Comment above) in favor of a process (aggregated settling) with maximum rates of sinking that are two to three orders of magnitude slower.

We thank Wilber et al. for their supporting field evidence and constructive comments on erosional consequences of density cascading, but we remain convinced that density flows are also mechanisms to accelerate off-bank and vertical flux of platform mud. Deep geostrophic currents undoubtedly redistribute bank-top mud, but it is first necessary that fines be delivered to depth in the presence of more vigorous surface currents. We restate the case for density cascading as a delivery agent. This discussion emphasizes the need for field and laboratory experiments as well as transect drilling of platform margins in order to determine the physical processes involved in Cenozoic platform coalescence.

REFERENCES CITED

Ball, M.M., Dillon, W.P., and Wilber, R.J., 1987, Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank: Comment: Geology, v. 15, p. 1081.

Brooks, G.R., and Holmes, C.W., 1990, Modern configuration of the southwest Florida carbonate slope: Development by shelf margin progradation: Marine Geology, v. 94, p. 301–315.

Eberli, G.P., and Ginsburg, R.N., 1987a, Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank: Geology, v. 15, p. 75–79.

Eberli, G.P., and Ginsburg, R.N., 1987b, Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank: Geology, v. 15, p. 1082.

Honjo, S., 1986, Oceanic particles and pelagic sedimentation in the western North Atlantic Ocean, *in* Vogt, P.R., and Tucholke, B.E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, Geology of North America, volume M, p. 469–478.

Lee, T.N., Schott, F.A., and Zantopp, R., 1985, Florida Current: Low frequency variability as observed with moored current meters during April 1982 to June 1983: Science, v. 227, p. 298–302.

McCave, I.N., 1975, Vertical flux of particles in the ocean: Deep-Sea Research, v. 22, p. 491–502.

McCave, I.N., 1983, Particulate size spectra and origin of nepheloid layers of the Nova Scotian continental rise: Journal of Geophysical Research, v. 88, p. 7647–7666.

Mullins, H.T., Neumann, A.C., Wilber, R.J., Hine, A.C., and Chinburg, S.J., 1980, Carbonate sediment drifts in northern Straits of Florida: American Association of Petroleum Geologists Bulletin, v. 64, p. 1701–1717.

Shanks, A.L., and Trent, J.D., 1980, Marine snow: Sinking rates and potential role in vertical flux: Deep-Sea Research, v. 27, p. 137–143.

Wilson, P.A., and Roberts, H.H., 1992, Carbonate-periplatform sedimentation by density flows: A mechanism for rapid off-bank and vertical transport of shallow-water fines: Geology, v. 20, p. 713–716.