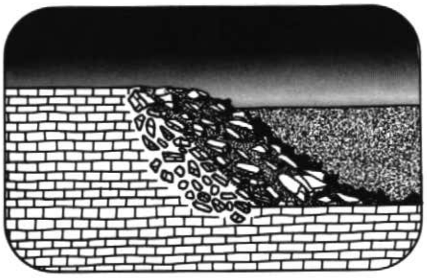


Facies Models 13. Carbonate Slopes

I.A. McIlreath
Petro-Canada, 650 Guinness House
727-7th Avenue S.W.
Calgary, Alberta T2P 0Z6

N.P. James
Department of Geology
Memorial University of Newfoundland
St. John's, Newfoundland A1B 3X5

Introduction

To any geologist who has seen them in the field the sediments that comprise the slope facies of many carbonate complexes are often the most staggering and long remembered of all. The sheer size of the enormous limestone blocks chaotically intercalated with delicately laminated lime mudstones tests our understanding of sediment genesis and deposition as almost no other deposits.

While the deposits themselves are intriguing they are also useful as the only remaining clues as to the nature and composition of a now dolomitized or tectonically obliterated platform margin. Furthermore, the very presence of this debris is an excellent indicator of a nearby carbonate platform or reef complex and this principle has been successfully used to locate reefs in the subsurface. The lime sands of these deposits, where intercalated with organic-rich basinal sediments, can be reservoirs.

We cannot interpret these deposits with the same level of confidence as shallow water carbonate sediments because: 1) modern slope deposits are not easily accessible for field study, although the limited use of small research submersibles and seismology is slowly changing this; 2) ancient slope deposits commonly occur in orogenic belts, where facies and tectonic relationships are so complicated that these deposits are often mistaken for tectonic breccias or mélanges; 3) slope sediments in the subsurface generally have not been serious exploration targets as long as adjacent platform margins remained the primary objective; 4) slope sediments are formed in a series of environments that transect major pressure, temperature and oxygen-level boundaries in the ocean and the precise effects of these physicochemical parameters on the sediments are poorly known.

As a result our present facies models are based on the rock record with additions from the modern. In addition, our understanding of sediment emplacement is based upon mechanisms determined for siliciclastic deposits. It has been easy to apply this comparative approach because many similarities do exist, but there are also differences which have been ignored for too long.

In the second article in this facies models series, Walker (1976) outlined the attributes of a turbidite model and then integrated all associated siliciclastic lithofacies that encompass the slope-to-basin transition into an overall, larger scale, submarine fan model. Similarly our approach in this article will be to outline the major aspects of the slope facies in carbonate sedimentary sequences, first by examining the major sediment types and their modes of emplacement, and second by relating these to general facies models, which are very much dependent upon the nature of the adjacent margin.

Carbonate Slope Sedimentation

The slope facies is a transitional one between the rapid and active production of calcium carbonate in shallow water and the slow gentle rain of fine-grained pelagic sediments in the basin. The platform-to-basin transition may in places be abrupt, in the form of a steep cliff, but more commonly is a gently inclined slope decreasing in grade with depth and merging imperceptibly into basinal deposits at some distances, which may be 100s of km from the actual margin. Because the environment as a whole is an incline, short periods of gravity-induced catastrophic sedimentation alternate with long periods of relatively quiet pelagic sedimentation, or to paraphrase Ager (1973, p. 100), "long periods of boredom alternating with short periods of terror".

Pelagic Carbonates. Pelagic carbonates are those sediments deposited in the open sea and derived from the skeletons of planktonic microorganisms which inhabit the overlying water column. Such deposits include ooze and chalk and consist primarily of the skeletons of various nannofossil groups, especially coccoliths, the tests of planktonic and sometimes benthic foraminifers. Macrofossils such as pteropods, pelecypods, echinoderms and, in older units, ammonites are present as accessory components. An excellent summary of such deposits can be found in Hsu and Jenkyns (1974) and Scholle (1977).

True pelagic carbonates are apparently not known from the early Paleozoic and are first recognized from rocks of Upper Silurian age (Tucker, 1974). Planktonic foraminifers and coccoliths appear to have evolved in the Jurassic and during post-Jurassic time pelagic carbonate has increased to the point that in the last 100 Ma it comprises about 67 per cent of world-wide carbonate deposition (Hay *et al.*, 1976).

Most chalks accumulate at a rate of between one and 30 cm per year. The sedimentary structures and colours depend upon the degree of circulation and oxygenation. Dark colours and preserved laminations reflect stagnation; lighter colours, more burrows and fewer preserved sedimentary structures reflect stronger bottom circulation.

The water depth of pelagic carbonate deposition ranges from less than 100 m to greater than 4500 m. The limiting factors for such accumulations are the relative rates of sedimentation of carbonate versus non-carbonate components, physical erosion and chemical dissolution. Chemical dissolution is particularly important in carbonate slope facies because the environment passes, with depth, through several important increasing pressure and decreasing temperature boundaries. Aragonite components, such as pteropods and benthic foraminifers, may be selectively removed by dissolution in water as shallow as 500 m (the aragonite compensation depth) while calcite components are completely dissolved at the carbonate compensation depth, between 4,000 and 5,000 m in today's oceans. Much less is known about the removal or recrystallization of Mg-calcite. This progressive removal by dissolutión results in a residual sediment composed largely of siliceous skeletons, red hemipelagic clays and wind-blown silt. Dissolution also takes place in the oxygen minimum layer, that zone just below the thermocline in the modern ocean where, due to the increased metabolism of aerobic organisms and the lack of oxygen replacement, the oxygen level is often reduced to less than 0.2 ml/1. The higher levels of CO^2 associated with the oxygen deficiency lead to an increase in the $CaCO^3$ solubility. Where this zone impinges on the sea floor sedimentary carbonate is removed and the resulting sediment is enriched in organic matter, contains more opaline silica and where the oxygen values are too low even for burrowing organisms, the sediment is dark and laminated.

In some areas of the modern ocean the production of siliceous plankton (silicioflagellates, diatoms and radiolaria) exceeds that of calcareous nanno-and microplankton. During the Paleozoic, when pelagic carbonate was reduced or absent, siliceous sediment was much more widespread in deep-water areas.

Hemipelagic Slope Sediments. Sediments that make up the fine-grained pelagic component of most slope deposits come not only from the water column but from the adjacent platform as well (Wilson, 1969). While the contribution at any one time from the water column is more or less constant, that portion derived from the platform is episodic. Most often storms stir up the wide, shallow, mud-floored areas of the shelf and the milk-white water streams out across the shelf margin to settle in deep water. A less voluminous but more regular transfer process exists at such near-vertical shelf-to-deep-oceanic-basin transitions as St. Croix, Virgin Islands where warm sediment-rich shelf waters 'float' over the cooler basinal waters by tidal exchange. These fine-grained, shallow-water derived slope sediments have been called 'peri-platform ooze' by Schlager and James (1978) because they occur as an apron around the platform and because they are significantly different in their mineralogy and composition from the wholly pelagic sediments of the open sea.

In the Precambrian and Paleozoic most pelagic slope carbonates may well have been almost wholly peri-platform ooze.

The resultant hemipelagic slope deposits are monotonous, uniform dark grey, fine-grained lime mudstones, generally thin-bedded with flat planar contacts and internal micro-laminations (Fig. 1). Mudstone beds are often separated by partings into very thin beds of similar mudstone or beds of shale, forming characteristic 'rhythmites' or 'ribbon limestones'. The original depositional textures and fabrics are often modified by sedimentary boudinage, while differential compaction and/or cementation frequently transforms the evenly-bedded sediments into a nodular limestone. The irregular nodules may, in some cases, be so packed together to form a jig-saw puzzle resembling an *in situ* breccia.

Peri-platform Talus. Directly seaward of the shallow water reefs or lime-sand shoals that form a platform margin, there is commonly a debris apron of limestone blocks (Fig. 2), skeletons of reef building metazoa, lime sand and muds. These accumulations are the result of rock-fall and sand-streams from shallow water and, as illustrated in Figure 3, are very common along the seaward margins of modern reef complexes (James and Ginsburg, in press; Land and Moore, 1977). The blocks themselves may be multigeneration in composition because the reefs, sand shoals and other deposits at the platform margin are characteristically susceptible to early lithification, either by submarine cementation, or if there are slight fluctuations in sea level, by complex subaerial diagenesis. In addition, parts of the talus wedge are commonly cemented on the sea floor (James and Ginsburg, in press; Land and Moore, 1977). The

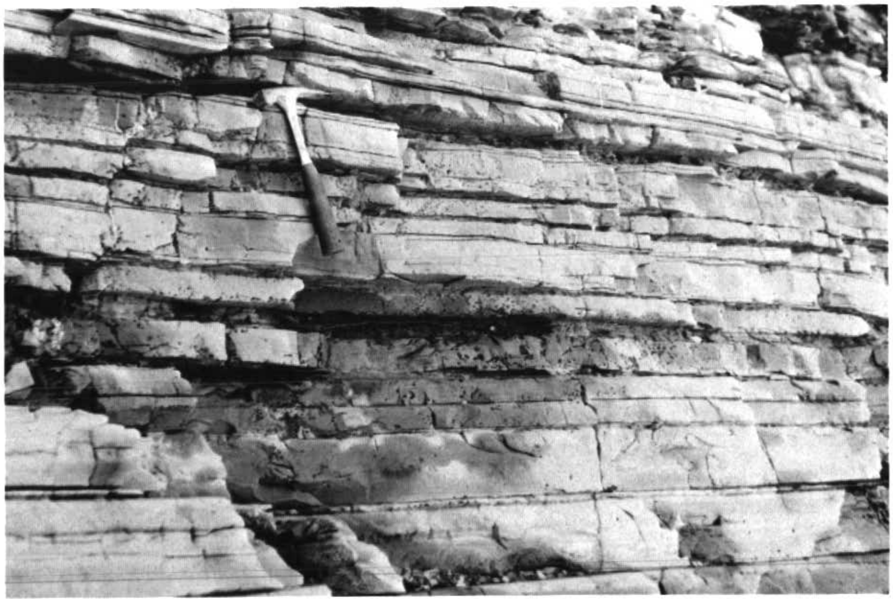


Figure 1
Peri-platform ooze; evenly-bedded, grey lime mudstone with thin interbeds of argillaceous lime mudstone, Cooks Brook Formation (Middle Cambrian, Humber Arm, Western Newfoundland.

lithified portions of these limestones become hard and brittle, and so are particularly susceptible to fracturing and fragmentation.

Large passes through a reef (see James, 1978) also act as conduits, funnelling back-reef sediments into this zone so that, along strike, areas of chaotic breccia may alternate with fans of lime sand. The latter sediment is also commonly cemented, forming numerous hardgrounds.

Examination of sediment dispersal seaward of the platform in areas with low to intermediate slopes (up to 30 degrees) indicates that this talus does not travel any significant distance away from the margin by day-to-day processes.

Lime Breccias. These deposits, which have been called debris flows, submarine mass flows, mass breccia flows, breccia and megabreccia beds, rudite sheets, or olistostromes (in the non-tectonic sense) are certainly the most impressive parts of the slope sequence. They originate in two very different areas, high up on the slope in shallow water or from lower down the slope profile.

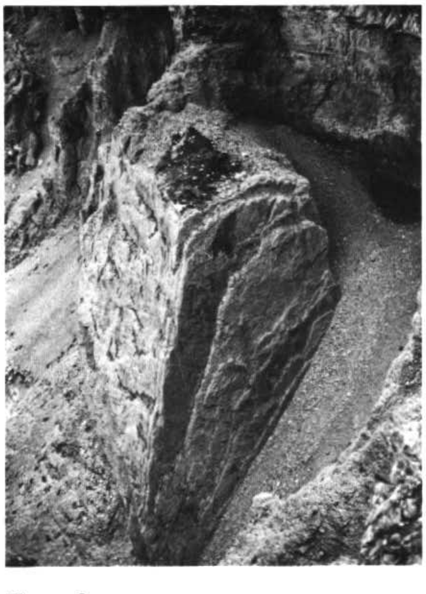


Figure 2

Peri-platform talus; a block of shallow-water reef limestone (approximately 30m high) enclosed in thin-bedded, dark grey, peri-platform lime mudstones. Block occurs approximately 250m down slope from the toe of a near-vertical, 200m high platform margin. Note vertical orientation of bedding within the block, Cathedral Formation (Middle Cambrian, north face Mt. Stephen, British Columbia.

A. Breccias Derived from Shallow Water. These breccias are generally exposed in discontinuous to laterally extensive sheets, channels with lenticular cross sections or irregular masses. They stand out as resistant masses of light-coloured carbonate against a background of dark-coloured, well-bedded limestone and shale (Figs. 4 and 5). They are characterized by blocks of all sizes and shapes, but often equidimensional and somewhat rounded. Some of the blocks are so enormous that they have been mistaken for bioherms (see Mountjoy *et al.,* 1972). One exceptional clast in the Cow Head Group (Cambro-Ordovician) at Lower Head, Newfoundland is 0.2 km x 50 m in size, with surrounding blocks often 30 x 15 m in dimension (Kindle and Whittington, 1958). The breccias commonly have a matrix of lime mud, lime sand or argillaceous lime mud.

The deposits are bedded, with a planar to undulating basal contact accentuated by differential compaction and an irregular to hummocky upper contact. The nature of the bedding contacts often cannot be determined accurately because the bedding planes are stylolitic, and so any original bedding-plane features are often destroyed. Davies (1977) made the interesting observation that the common occurrence of crinoids, bryozoa and ammonites at the upper surface of Permo-Pennsylvanian deposits on Ellesmere Island may represent an indigenous fauna inhabiting the 'reef-like' upper surface of the deposit.

The polymict nature of the clasts reflects the complexity of the source area; the platform margin consisting of partly lithified reefs and/or lime-sand shoals, down slope (yet still shallow) reef mounds, or peri-platform talus. Well-sorted and well-bedded lime sands which can be differentially submarine cemented (Fig. 6), individual colonies of reef builders, multigeneration reef rock, limestones with subaerial karst features, tidal flat lithologies and even cemented talus that has been refractured to give breccia clasts within breccia, are all to be expected.

The fabrics of such coarse clastic deposits have been discussed by Walker (1976) and they range from mainly chaotic to imbricated to horizontal to wave form and are rarely graded or even reverse graded. They range from clast-supported to most commonly matrix-supported, with the matrix ranging from shale to argillace-

Figure 3

Peri-platform talus; looking across the steeply dipping fore-reef slope at a depth of 130m seaward of the Belize barrier reef complex. The slope is composed of blocks of limestone, plates of coral and lime sand composed of the plates of the green alga Halimeda; *the small block at the center (arrow) is about one metre high.*

Figure 4
Lime breccias; light grey, shallow-water reef-derived limestone breccias occurring in a 'channel' – a *(approximately 8m thick), sheets* – b *(approximately 2m thick), and irregular masses* – c *(up to 12m thick), enclosed in thin-bedded, dark grey, peri-platform lime mudstones, Cathedral Formation (Middle Cambrian), southface Mt. Field, British Columbia.*

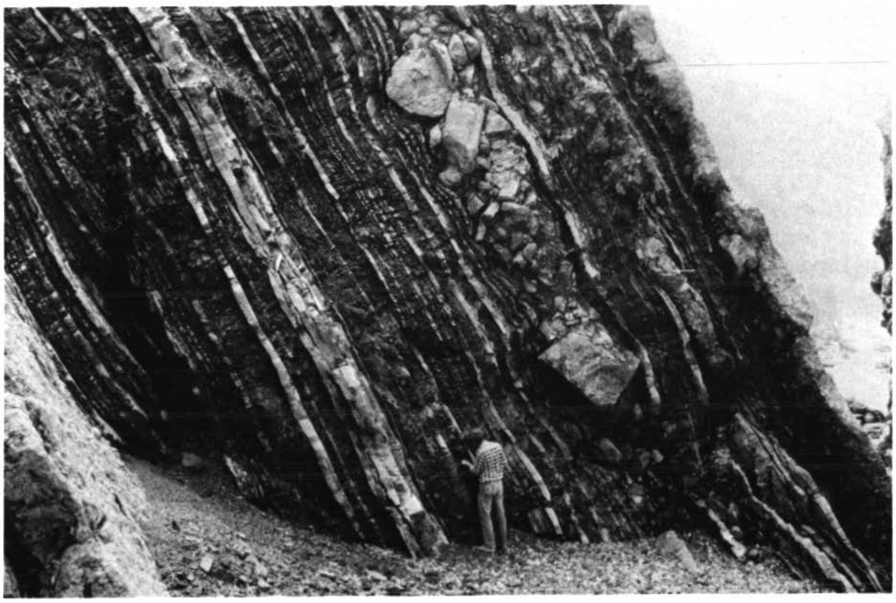


Figure 5
A sequence illustrating two different types of carbonate slope deposits; debris flows with large limestone clasts (right) and thin-bedded, graded calcarenites (the thin, grey limestone beds), interbedded with black fissile shale. This overturned sequence (top at lower left) of Middle Ordovician age occurs at Cape Cormorant, Port-au-Port Peninsula, Western Newfoundland.

ous lime mud to lime mudstone with occasional lime sand. As Hopkins (1977) points out, however, what is often taken to be lime mud in outcrop turns out to be peloid lime sand in thin section, so that sand-sized matrix may be more common than supposed.

The exact mechanisms by which these sediments are transported are not yet clear. Submarine debris flows (Hampton, 1972) are sediment gravity flows in which granular solids such as boulders, pebbles and sand are more or less "floated" during transport by the yield strength of the matrix composed of interstitial fluid and fine sediment. Buoyancy of the fluid matrix also contributes to the support. Since not all such deposits have a clay mineral matrix the transport mechanism is thought to be a combination of debris flow and grain flow (Middleton and Hampton, 1973). A major problem in this regard is that almost all experimental work to date has been done on clay-water mixtures; none of the experiments has been carried out on sediments with a clay-lime or lime mud matrix.

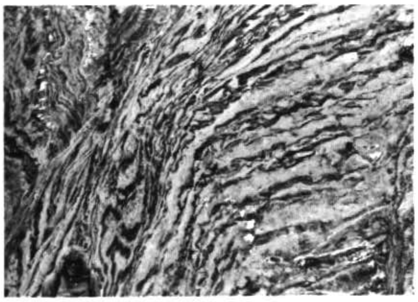
B. Breccias Derived from the Slope. The evenly-bedded calcilutites or lime muds of the slope facies are often prone to downslope creep. Individual beds can be seen to neck or wedge out, or whole intervals will move downslope within a series of slump folds (Fig. 7). Dislocation and movement of large masses of slope material downslope leads to the formation of breccias or submarine glide masses composed of numerous tabular clasts of slope limestone that have been bent or fractured, that are poorly-sorted and that exhibit random to subparallel orientations, often resembling shallow-water 'flat pebble conglomerates' (Fig. 8). Enormous blocks of bedded slope sediments, often internally folded, are caught up in the breccias.

The source of these breccias is thought to be the large 'intraformational truncation surfaces' (Fig. 9) or "cut-and-fill structures" (Wilson, 1969) which are sharp concave-up discontinuity surfaces that truncate underlying beds and are overlain by a downslope thickening wedge of sediment with an angular relationship on the truncated beds. In these deposits, reduction of shear stress occurs by displacement of coherent masses along discrete shear planes and not usually by deformation within the mass as occurs in slumps.

The tabular clasts of slope material clearly indicate that the slope sediments were partly consolidated very early, probably by submarine cementation. Cementation may have been

Figure 6
Thinly-bedded, nodular foreslope sequence comprising cemented nodules in compacted calcarenite (N) and a laterally continuous bed of cemented calcarenite (S). These calcarenites form the predominant foreslope facies below the Miette and Ancient Wall buildups (Upper Devonian), Alberta. Photo courtesy of J.C. Hopkins.

Figure 8
Slope-derived breccia; clasts of partly lithified peri-platform ooze (see Fig. 1) *that have been eroded and transported as a clast-supported breccia, Cooks Brook Formation (Middle Cambrian), Humber Arm, Western Newfoundland.*



similar to that in shallow-water with lithified and unlithified layers reflecting times of slow and rapid sedimentation respectively. If cementation took place below the thermocline, dissolution of aragonite and possible precipitation of calcite may have caused the same effect in layers of different original composition. Alternatively, if the lime mudstone is interlaminated with shale, cementation of the carbonate may have taken place while the shale remained soft.

Deposits of the two end members, one originating high on the slope and the other down on the proper slope are sometimes found intermixed in extensive breccia masses (Fig. 10). Such deposits are similar to what Schlager and Schlager (1973) term marl-flaser breccia, characterized by a chaotic fabric of plastically deformed, dark grey, argillaceous lime-mudstone lithoclasts separating irregular lenses of subangular limestone and other lithoclasts, with the deformed marls forming the flaser fabric. There are thought to be shallow-water derived breccia flows that incorporated lime mudstone clasts from the floor of the slope environment as they moved basinward and they may grade downslope, as do many other breccias, into turbidites.

Graded Calcarenites. A large proportion of any slope sequence is commonly size-graded beds of clastic textured limestone, mainly of sand size, interpreted to be the carbonate equivalent of siliciclastic turbidites (Fig. 5). They are envisaged to be deposited from turbidity currents that formed by the sudden surge-type release of dense fluid rather than from a steady state flow such as described recently by Harms (1974). These

Figure 7
Extensive syn-sedimentary distortion of bedding developed by creep in thin to very thin-bedded, upper basinal slope, peri-platform lime mudstones, Eldon Formation (Middle Cambrian), Wapta Mountain, British Columbia.

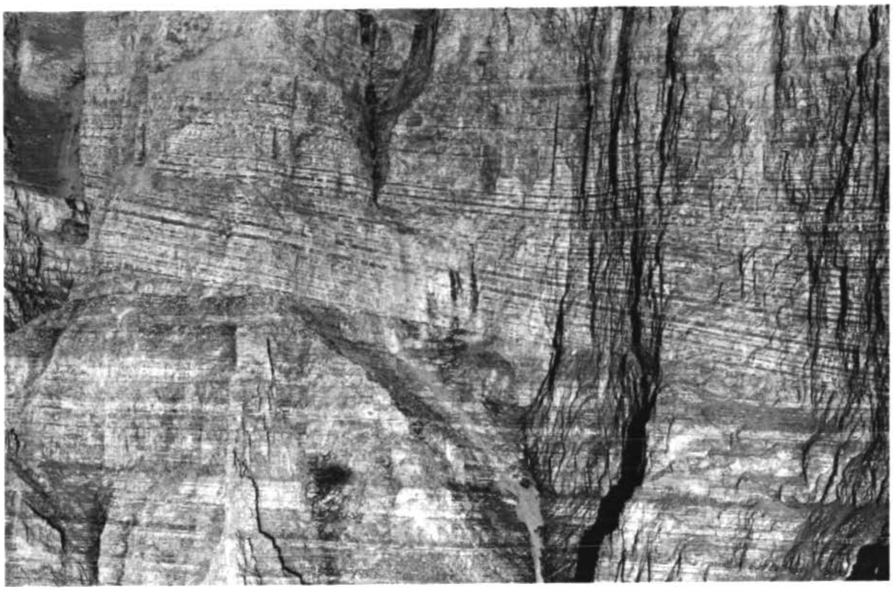


Figure 9
Large intraformational truncation surface in argillaceous and cherty limestones of the Hare Fiord Formation (Permo-Pennsylvanian), north side of Svartfjeld Peninsula, Ellesmere Island. Note smooth, curved concave-up (listric) geometry of the truncation surface and the lack of macro-scale deformation of beds below or above truncation surface. Shadow at lower left center is of heliocopter: width of view 150m. Photo courtesy of G.R. Davies.

Figure 11
A bed of light grey calcarenite comprised of a graded lower portion, planar laminated middle unit, and the upper portion having climbing ripples (A, B and C Bouma subdivisions respectively), capping a lime breccia, Sekwi Formation (Lower Cambrian), Cariboo Pass, Mackenzie Mountains. Photo courtesy of F.F. Krause.

Figure 10
A large deformed clast of well-bedded peri-platform ooze that was eroded, transported and redeposited as part of a debris flow, Cow Head Group (Middle Ordovician), Cow Head, Western Newfoundland.

deposits have also been called allodapic limestones (Meischner, 1964). Such sediments are well-bedded and characteristically have sharp planar bases that can be coplanar with, or locally scour and truncate underlying slope beds. Sole marks and load structures are usually absent although in some cases they may be obliterated because of stylolitization and solution along bedding contacts. Calcareous turbidites can exhibit all five of the typical ABCDE divisions of the Bouma sequence but most commonly it is the A, and sometimes the B and C divisions that characterize the deposits (Fig. 11). The particles in the basal parts of division A are often cobble size and larger and the more common grain types are lithoclasts, skeletal debris and ooids, the petrology of which indicates a shallow water origin.

The most obvious sources for these units are the unstable accumulations of lime sand and gravel that build up near the platform margin and are occasionally set into motion. It is also possible that they are the distal parts of carbonate debris flows. Davies (1977) has suggested a third origin, the indigenous fauna, especially pelmatozoans, that live on the slopes and produce abundant skeletal material that may be easily remobilized.

Post-Paleozoic graded calcarenites derived from sediments further down the slope profile can be virtually indistinguishable compositionally from pelagic limestone. These calcarenites are generally rich in pelagic components such as coccoliths and foraminifers but may also contain lesser amounts of pteropods, sponge spicules, radiolarians, and coarser-grained skeletal debris (especially pelmatozoans). The sediments are size-sorted and may be mixed with clastic terrigenous or volcaniclastic sediment if they have travelled great distances. Although the sedimentary structures such as horizontal laminations, convolutions, occasional channels, flute and groove casts and trace fossils may be present, the A and B divisions of the Bouma sequence are commonly missing and they generally start with the C or D divisions.

Non-graded Calcarenites. Massive to cross-bedded and ripple-marked calcarenites are an enigmatic type of deposit found in many slope sequences. These deposits are fine- to coarse-grained wackestones to grainstones with occasional large clasts or fossils. Individual beds have sharp bases and vary in geometry from lenticular to irregular masses. The fabric may be random or grains may be aligned parallel to the paleoslope.

The grains in these deposits are variable, ranging in composition from shallow-water derived particles to pelagic grains.

At present we envisage these deposits as resulting from one of three depositional mechanisms, liquified flow, grain flow, or reworking of pre-existing sediments by bottom currents. Perhaps the massive deposits having an apparent lack of sedimentary structures are nothing more than the product of downslope mass movement of well-sorted lime sands produced at a rapid rate near the platform margin.

Sedimentary structures in the cross-bedded deposits indicate some sort of bottom currents, often running parallel to the slope (contour currents). Well-sorted, rippled lime sands, sometimes with large scale bed forms, and composed of ooid sand occur in the deeper parts of the slopes around the margins of the Tongue of the Ocean, Bahamas (NJP, pers. obs.) and are also common on the slopes along the western parts of the Bahama Banks (Mullins and Neumann, in press) where currents flow along and parallel to the slope at speeds of 50 cm/sec and more (although such currents are high and not characteristic of today's oceans). These currents may rework pre-existing pelagic slope deposits, leaving only the larger foraminifers and pteropods together with lithoclasts of cemented pelagics to form a deep-water grainstone. They may also winnow the upper parts of turbidites, removing the finer layers and leaving a sequence composed only of shallow-water clasts, and divisions A and B of the Bouma sequence, capped by a cross-bedded lime sand.

Such clean, well-sorted sands are commonly sites of submarine cementation and hardground formation. In such areas precipitation of cement may lead to displacive expansion of grain-to-grain distance, resulting in fracturing and the formation of *in situ* breccias.

Facies Models

With the information presently available we cannot integrate the spectrum of carbonate slope deposits into one simple model as Walker (1976) has done for siliciclastic deposits. Rather, the style of carbonate slope sedimentation is equally a function of the abruptness of the margin to basin transition, and the nature of the shallow portion of the margin. Where the margin itself is a facies transition with a gradual slope profile, then the sequence of slope deposits is very much different from the sequence where the margin is abrupt. We have differentiated between these two types of margins and called them depositional and by-pass margins respectively (Figs. 12 to 15).

The nature of the slope sediments in each case depends on whether the shallow-water margin is formed (1) by reefs, of metazoan, calcareous algal or stromatolitic origin, and occurring either at the edge or slightly downslope below the zone of the most wave movement, or (2) by lime-sand shoals, of pelmatozoan, algal or oolitic origin.

It should be noted that none of the models are mutually exclusive and within a buildup or platform margin all four may be present at any one time, or in the case of a buildup, it may even be possible to have all four occur simultaneously in different places along the buildup margin.

Depositional Margins. The slopes are generally gentle and decrease basinward to merge with the flat basin floor.

A. Shallow-water reef. The zone of peri-platform talus is relatively narrow but the full spectrum of allochthonous deposits is present downslope (Fig. 12). Because most of the allochthonous materials comes from the reef or talus pile many of the allochthonous deposits generated high on the slope are deposited far down on the slope or in the basin. Consequently that zone seaward of the peri-platform talus is often composed of hemipelagic limestones and is by-passed by the mass movements. This type of depositional slope occurs most frequently around reef complexes and basinward of platform-margin barrier reef systems along paleotopographic highs, structurally positive elements or hingelines in fairly stable cratonic or miogeosynclinal basins. Examples of this style of slope deposit occur in the Cambrian of Western Canada (McIlreath, 1977a); and the Devonian of the Canning Basin, Australia (Conaghan *et al.*, 1976).

B. Shallow-water lime sands. The slope flanking this style of margin is generally a calcarenite wedge or proximal-to-distal turbidite plain (Fig. 13). These slopes probably represent a depositional equilibrium in that sedimentation controls the slope angle and is active all along the profile. Turbidites and grain flows are the predominant transport mechanisms with debris sheets and breccias rare. Some minor debris sheets composed of cemented lime-sand clasts or other slope-derived lithologies may be present. Hardgrounds and incipient brecciation are common.

Examples of this style of slope deposit includes the Pennsylvanian Dimple Limestone, Texas (Thomson and Thomasson, 1969); Silurian of California and Nevada (Ross, 1965); and the Devonian Fairholme reef complexes of Western Canada (Hopkins, 1977).

By-pass Margins. In these situations the margin is atop a cliff or submarine escarpment so that sediments are transported directly from shallow to deep water, bypassing much of the slope along a wide front or through channels and canyons. The cliffs may result from faulting, large fluctuations

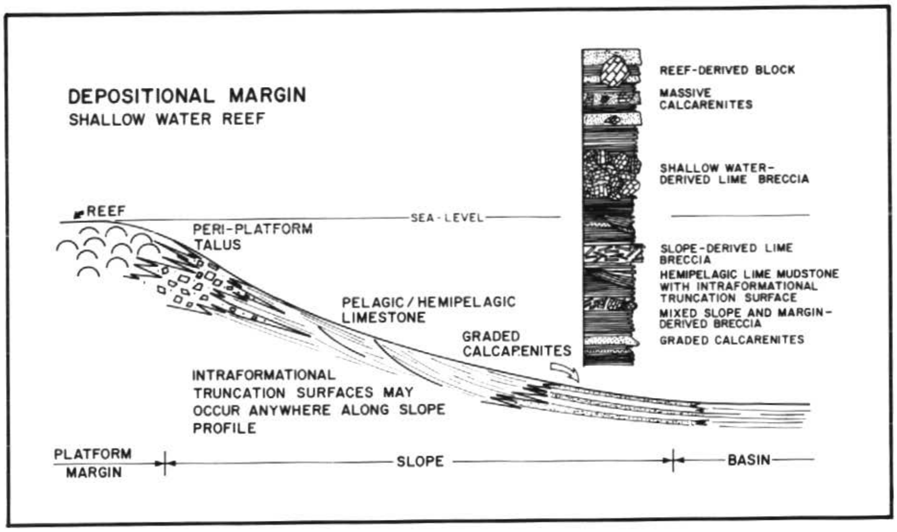


Figure 12
Schematic model for a shallow-water, reef dominated, depositional carbonate margin and illustration of a hypothetical sequence of deposits within the adjacent basin slope.

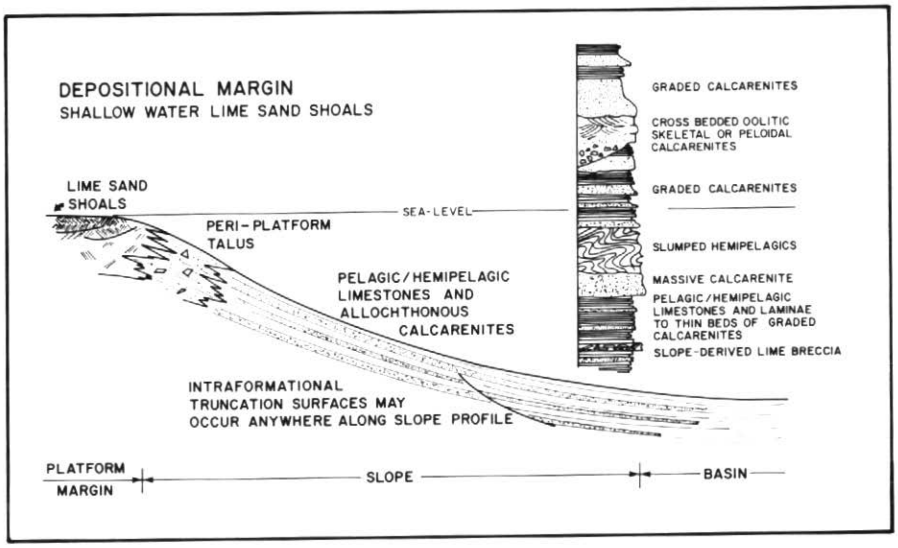


Figure 13
Schematic model for a depositional carbonate margin dominated by shallow-water lime sands and illustration of a hypothetical sequence of adjacent basinal slope deposits.

in sea-level or just rapid upbuilding of the platform as compared to the basinal deposits. This style of margin is particularly common along block-faulted oceanic margins or at the structural hingeline where a basin is subsiding faster than the adjacent platform.

A. Shallow-water reef. Since the reef crowns the escarpment, the most characteristic and spectacular style of accumulation is the wedge of peri-platform talus (Fig. 14). This wedge of material may be enormous, especially if the area is subject to tectonics, with the main transport mechanisms being a combination of rock-fall, sand-streams and gravity-induced downslope mass movement. If the cliff is dissected by channels or canyons, the peri-platform talus may interdigitate along strike with carbonate submarine fans similar to those described for siliciclastic deposits (Evans and Kendall, 1977). Slumps, creep and sliding are more active in the deposit than on the adjacent slope due to the variations in lithification. The talus wedge grades downslope into a relatively narrow zone of lime sands and then into pelagic calcilutites to form a debris apron.

This is the style of many modern slope deposits in Belize (Ginsburg and James, 1973); Puerto Rico (Conolly and Ewing, 1967); Jamaica (Goreau and Land, 1974); the Bahamas (Mullins and Newmann, in press); and the Pacific Atolls (Emergy *et al.*, 1954). The most spectacular fossil example is the Cretaceous of Mexico (Enos, 1977).

B. Lime sand shoals. If the shallow-water margin facies is lime sand, then the peri-platform talus will be predominantly lime sand intercalated with calcilutites (Fig. 15) and having fewer limestone blocks than in the previous model, unless there have been substantial movements in sea-level exposing the margin to subaerial diagenesis. Once again away from the escarpment the lime sands grade relatively quickly into slope or basinal pelagic lime muds. There are minor contributions from turbidites.

A fossil example of such a debris apron of calcarenite is the Cambrian Boundary Limestone (McIlreath, 1977b).

The Models as a Norm. In these models we have not consciously placed the slope lithologies in any particular sequence because we feel that the sequence on such a broad scale represents more the complex interactions of sea-level and tectonics at the shallow rim than any secondary sedimentary process on the slope. As a result unusual features are likely to record not so much the style of sedimentation on the slope, as the style of sedimentation and tectonics at the shallow margin.

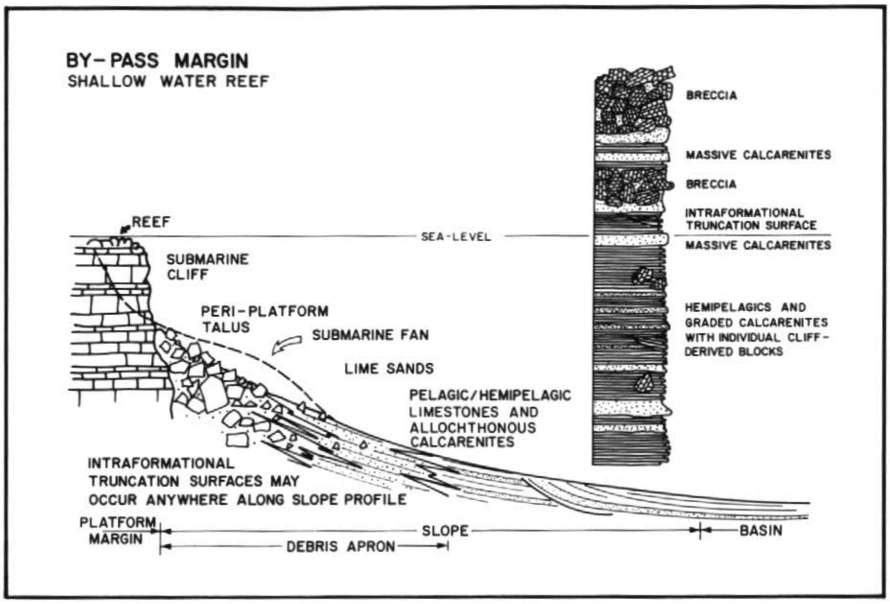


Figure 14
Schematic model for a shallow-water, reef dominated, by-pass type of carbonate margin and illustration of a hypothetical sequence of deposits within the adjacent basin slope.

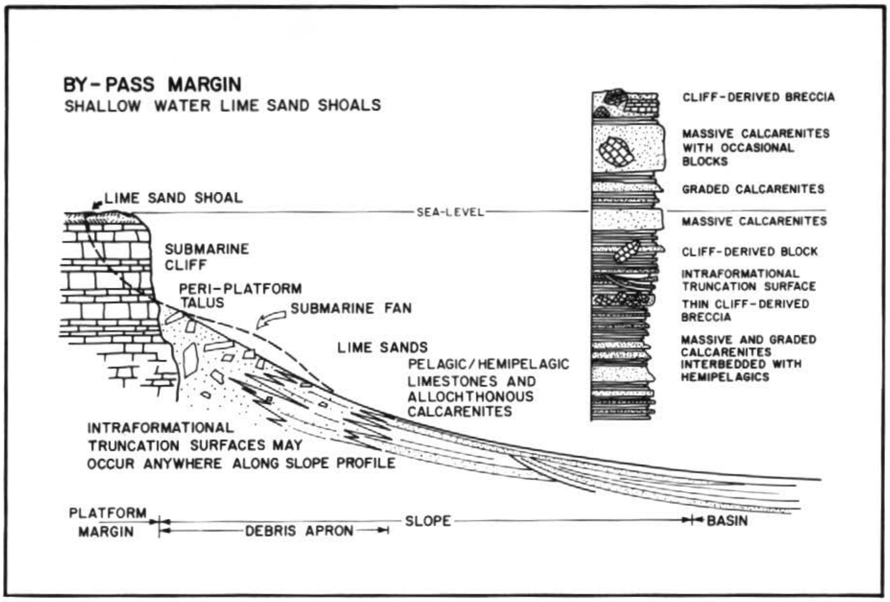


Figure 15
Schematic model for a by-pass type of carbonate margin dominated by shallow-water lime sands and illustration of a hypothetical sequence of adjacent basinal slope deposits.

The Models as a Framework and Guide for Description. The differences in carbonate deposition through time are, in large part, a function of the appearance and disappearance of different types of carbonate-secreting organisms and thus affect the use of these facies models as a framework in two ways: (1) the shallow-water benthic organisms that build massive reefs and so cause relief at the platform margin, as well as contributing major amounts of sediment to the slope, are present only at specific times in geologic history; (2) the pelagic calcareous zooplankton and phytoplankton are insignificant in the early Paleozoic, minor in the middle and late Paleozoic, and prolific in the Mesozoic and Tertiary. As a result, the hemipelagic slope deposition is almost entirely peri-platform ooze in the Precambrian and early Paleozoic and perhaps one-half peri-platform ooze and one-half true pelagic carbonate in the Mesozoic and Tertiary. Interruptions in the fallout of peri-platform ooze in the Paleozoic sometimes resulted in shale interbeds, whereas in the Mesozoic and Tertiary interbeds are thinner but are wholly pelagic carbonate.

The Models as a Predictor for New Situations. Based on a few observations and bearing in mind the age of the deposits as well as their tectonic setting, one can extrapolate and formulate three critical conclusions: (1) examination of the overall sequence indicates the relative position on the slope and possible nearness of the platform; (2) the lithology of the lime-sand beds and relative calcarenite to hemipelagic ratio gives some idea as to the nature of the slope facies, i.e., depositional versus by-pass; and (3) the composition of the clasts indicates the nature of the margin, which is often obliterated or inaccessible.

The Models as a Basis for Hydrodynamic Interpretation. The interpretation of carbonate sediment gravity flows has, to date, been based primarily on an analogy with siliciclastic deposits which have similar sedimentary characteristics. One of the important differences between carbonate and siliciclastic sediment gravity flows, however, is that a dispersal model for the hypothetical evolution of a single flow of carbonate platform-derived debris into deep water has not yet been constructed. In contrast to the relatively unconsolidated sediments on continental shelves, carbonate sediments in similar environments tend to be stabilized by organisms and/or well-lithified. This results in distinctively different slope deposits being produced by a variety of gravity-driven transport processes rather than different types of deposits evolving from the same flow. It should be noted, however, that the concept of a singular flow spawning a series of deposits may apply where slide failure occurs in the lower portion of the slope, remobilizing and transporting these mixed deposits even further basinward.

Summary

Carbonate slope sediments have, in the past, often been either ignored or interpreted as tectonic in origin. Their identification as deposits, separate from tectonically formed mélanges has come largely from a detailed analysis of not only the chaotic deposits but the fine-grained interbeds as well. Our understanding is increasing as more deposits are documented and the first timid steps are being taken beyond the reef into deeper water by submersibles. This latter aspect of carbonate sedimentology is still very much in its infancy.

Refinements of the models presented in this paper must come from two directions, experimentation and observations from modern carbonate slope environments. The hydrodynamic parameters for gravity-induced mass movements involving only carbonate materials must be carefully documented and contrasted with the results from siliciclastic materials. A combination of detailed observations from submersibles, and high resolution seismic and bottom sampling is needed to inventory the spectrum of sediments and structures that make up carbonate slope environments in the modern ocean.

Acknowledgements

Many of the ideas presented here have come about as a result of stimulating discussions with John Harper and Bob Stevens. Hank Mullins and Conrad Neumann kindly gave us a preprint of their paper on Carbonate Slopes in the Bahamas to sharpen our discussion. John Hopkins, Dave Morrow and Federico Krause critically read the manuscript. Gary Allwood drafted all the figures.

References

1. Basic References on Carbonate Basin Slope Facies

Cook, H.E. and P. Enos, eds., 1977, Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, 336p.

Hsu, K.J. and H.C. Jenkyns, eds., 1974, Pelagic sediments: on land and under the sea: Internatl. Assoc. Sedimentologists Spec. Publ. 1, 448p.

Mountjoy, E.W., H.E. Cook, L.C. Pray, and P.N. McDaniel, 1972, Allochthonous carbonate debris flows – worldwide indicators of reef complexes, banks or shelf margins: Proc. 24th Interntl. Geol. Congress, Sect. 6, p. 172-189.

Scholle, P.A., 1977, Deposition, diagenesis and hydrocarbon potential of "deeper-water" limestones: Amer. Assoc. Petrol. Geol. Continuing Education Course Notes, Series No. 7, 25p.

Wilson, J.L., 1969, Microfacies and sedimentary structures in "deeper-water" lime mudstones: *in* G.M. Friedman, ed., Depositional environments in carbonate rocks: Soc. Econ. Paleont. Mineral. Spec. Publ. 14, p. 4-19.

2. Examples of Ancient Carbonate Basin Slopes

The following papers contain examples of ancient carbonate basin slopes, with a strong bias towards examples in Canada. However as with reefs, the location of the country in temperate to boreal latitudes during much of the Mesozoic and, unfortunately, the Cenozoic results in Canadian examples being mainly Paleozoic in age.

Conaghan, P.J., E.W. Mountjoy, D.R. Edgecombe, J.A. Talent, and D.E. Owen, 1976, Nubrigyn algal reefs (Devonian), eastern Australia: allochthonous blocks and megabreccias: Geol. Soc. Amer. Bull., v. 87, p. 515-530.

Cook, H.E., P.N. McDaniel, E.W. Mountjoy, and L.C. Pray, 1972, Allochthonous carbonate debris flows at Devonian bank ("reef") margins Alberta, Canada: Can. Petrol. Geol. Bull., v. 20, p. 439-497.

Davies, G.R., 1977, Turbidites, debris sheets and truncation structures in upper Paleozoic deep water carbonates of the Sverdrup Basin, Arctic Archipelago: *in* H.E. Cook and P. Enos, eds., Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, p. 221-249.

Enos, P., 1977, Tamabra limestone of the Poza Rice trend, Cretaceous, Mexico: *in* H.E. Cook and P. Enos, eds., Deep-water carbonate environments: Soc. Econ. Paleont.,Mineral. Spec. Publ. 25, p. 273-314.

Hopkins, J.C., 1977, Production of foreshore breccia by differential submarine cementation and downslope displacement of carbonate sands, Miette and Ancient Wall buildups, Devonian, Canada: *in* H.C. Cook and P. Enos eds., Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, p. 155-170.

Hubert, J.F., R.K. Suchecki, and R.K M. Callahan, 1977, Cow Head breccia: sedimentology of the Cambro-Ordovician continental margin, Newfoundland: *in* H.E. Cook and P. Enos, eds., Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, p. 125-154.

Kindle, C.H. and H.B. Whittington, 1958, Stratigraphy of the Cow Head Region, Western Newfoundland: Geol. Soc. Amer. Bull., v. 69, p. 315-342.

Mackenzie, W.S., 1970, Allochthonous reef-debris limestone turbidties, Powell Creek, Northwest Territories: Can. Petrol. Geol. Bull., v. 18, p. 474-492.

McIlreath, I.A., 1977a, Stratigraphic and sedimentary relationships at the western edge of the Middle Cambrian Carbonate Facies Belt, Field, British Columbia: Ph.D. dissertation, Univ. of Calgary, Calgary, Alberta, 259p.

McIlreath, I.A., 1977b, Accumulation of a Middle Cambrian, deep-water, basinal limestone adjacent to a vertical, submarine carbonate escarpment, Southern Rocky Mountains, Canada: *in* H.E. Cook and P. Enos, eds., Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, p. 113-124.

Morrow, D.W., 1978, The Prairie Creek Embayment and associated slope, shelf and basin deposits: Geol. Surv. Can. Paper 78-IA, p. 361-370.

Ross, D.C., 1965, Geology of the Independence Quadrangle, Inyo County, California: U.S. Geol. Surv. Bull. 1181-0, 64p.

Srivastava, P.C., C.W. Stearn and E.W. Mountjoy, 1972, A Devonian megabreccia at the margin of the Ancient Wall carbonate complex, Alberta: Can. Petrol. Geol. Bull., v. 20, p. 412-438.

Thomson, A.F. and M.R. Thomasson, 1969, Shallow to deep water facies development in the Dimple Limestone (Lower Pennsylvanian), Marathon Region, Texas: *in* G.M. Friedman, ed., Depositional environments in carbonate rocks: Soc. Econ. Paleontol. Mineral. Spec. Publ. 14, p. 57-78.

Tyrrell, Jr. W.W., 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill-Capitan-Lamar), Capitan Reef Complex, West Texas and New Mexico: *in* G.M. Friedman, eds., Depositional environments in carbonate rocks: Soc. Econ. Paleontol. Mineral. Spec. Publ. 14, p. 80-97.

Unfortunately a number of excellent papers on Mississippian and Permian basin slope carbonates occurring in New Mexico and Texas exist in difficult-to-obtain guidebooks of local societies. For example, the "Guidebook to the Mississippian Shelf-edge and Basin Facies Carbonates, Sacramento Mountains and Southern New Mexico Region", published by the Dallas Geological Society (1975).

3. Examples of Modern Carbonate Basin Slopes

Andrews, J.E., 1970, Structure and sedimentary development of the outer channel of the Great Bahama Canyon: Geol. Soc. Amer. Bull., v. 81, p. 217-226

Andrews, J.E., F.P. Shepard and R.J. Hurley, 1970, Great Bahama Canyon: Geol. Soc. Amer. Bull., v. 81, p. 1061-1078.

Bushby, R.F., 1969, Ocean surveying from manned submersibles: Marine Technol. Soc. Jour., v. 3, p. 11-24.

Conolly, J.R. and M. Ewing, 1967, Sedimentation in the Puerto Rico Trench: Jour. Sed. Petrology, v. 37, p. 44-59.

Emery, K.O., J.I. Tracey, Jr. and H.S. Ladd, 1954, Geology of Bikini and nearby atolls: U.S. Geol. Surv. Paper 260-A, p. 1-262.

Ginsburg, R.N. and N.P. James, 1973, British Honduras by submarine: Geotimes, v. 18, p. 23-24.

Goreau, T.F. and L.S. Land, 1974, Fore-reef morphology and depositional processes, North Jamaica: *in* L.F. Laporte, ed., Reefs in time and space: Soc. Econ. Paleontol. Mineral. Spec. Publ. 18, p. 77-89.

James, N.P. and R.N. Ginsburg, (in press), The deep seaward margin of Belize barrier and atoll reefs: Internatl. Assoc. Sedimentologists, Spec. Publ. 3.

Land, L.S. and C.H. Moore, 1977, Deep forereef and upper island slope, North Jamaica: *in* S.H. Frost, M.P. Weiss and J.B. Saunders, eds., Reefs and related carbonates: ecology and sedimentology: Amer. Assoc. Petrol. Geol. Studies in Geology, no. 4, p. 53-67.

Moore, C.H., Graham, E.A. and L.S. Land, 1976, Sediment transport and dispersal across the deep fore-reef and island slope (-55m to -305m), Discovery Bay, Jamaica: Jour. Sed. Petrology, v. 46, p. 174-187.

Mullins, H. and A.C. Neumann, in press, Carbonate slopes along open seas and seaways in the Northern Bahamas: *in* O. Pilkey and R. Doyle, eds., Slopes: Soc. Econ. Paleont. Mineral. Spec. Publication.

Paulus, F.J., 1972, The geology of site 98 and the Bahama Platform: Initial reports of the deep sea drilling project, v. 11, p. 877, Natl. Sci. Found., Washington, D.C.

4. Additional References Cited in Text

Ager, D.V., 1973, The nature of the stratigraphical record: New York, J. Wiley and Sons Inc., 114p.

Evans, I. and C.G. St. C. Kendall, 1977, An interpretation of the depositional setting of some deep-water Jurassic carbonates of the central High Atlas Mountains, Morocco: *in* H.E. Cook and P. Enos, eds., Deep-water carbonate environments: Soc. Econ. Paleont. Mineral. Spec. Publ. 25, p. 249-261.

Hampton, M.A., 1972, The role of subaqueous debris flow in generating turbidity currents: Jour. Sed. Petrology, v. 42, p. 775-793.

Harms, J.C., 1974, Brushy Canyon Formation, Texas: A deep-water density current deposit: Geol. Soc. Amer. Bull., v. 85, p. 1763-1784.

Hay, W.W., J.R. Southam and M.R. Noel, 1976, Carbonate mass balance – cycling and deposition on shelves and in deep sea (Abst.): Amer. Assoc. Petrol. Geol. Bull., v. 60, p. 678.

James, N.P., 1978, Facies models 10. Reefs: Geosci. Canada, v. 5, p. 16-26.

Meischner, K.D., 1964, Allodapische Kalke, Turbidite in riff-nahen Sedimentations-Becken: *in* A.H. Bouma and A. Brouwer, eds., Turbidites: Elsevier, p. 156-191.

Middleton, G.V. and M.A. Hampton, 1973, Sediment gravity flows; mechanics of flow and deposition: *in* Turbidites and deep-water sedimentation: Soc. Econ. Paleontol. Mineral., p. 1-38.

Schlager, W. and M. Schlager, 1973, Clastic sediments associated with radiolarites (Tauglboden-Schichten, Upper Jurassic, eastern Alps): Sedimentology, v. 20, p. 65-89.

Schlager, W., and N.P. James, 1978, Low-magnesian calcite limestones forming at the deep-sea floor, Tongue of the Ocean, Bahamas: Sedimentology (in press).

Tucker, M.E., 1974, Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte (Southern France) and Cephalopodenkalk (Germany): *in* K.J. Hsu and H.C. Jenkyns, eds., Pelagic sediments: on land and under the sea: Internatl. Assoc. Sedimentologists Spec. Publ. 1, p. 71-92.

Walker, R.G., 1976, Facies models-2, Turbidites and associated coarse clastic deposits: Geosci. Canada, v. 3, p. 25-36.

MS received September 5, 1978