Layering - What Does It Mean?

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Abstract

‘Layering. What does it mean?’ Robert Ginsburg made this passing comment in the mid-1960s when the author was looking at a core sequence from Biscayne Bay, Florida. The core was a burrowed carbonate wackestone with a Hurricane Betsy storm layer at the top. It was a timely question as ‘Layering – What does it mean?’ has been asked many times since then. A few important answers have emerged – but there are still some serious challenges ahead. Understanding layering is more than just looking at the layers. It includes an appreciation of grain size, sorting and abrasion, influences of bioturbation and subsequent diagenesis. Together, these provide the critical tools to reconstruct paleoenvironmental setting, define depositional processes and determine the spectrum of energy levels operating in the system.

Keywords: layering, texture, burrowing, diagenesis, Ginsburg

Primary Stratification

The question of layering was actively pursued with Robert Ginsburg, Laurie Hardie and others on the tidal flats on Andros Island in the Bahamas. These studies documented that laminated carbonates formed on the tidal flat supratidal channel levees because of winter storm flooding events. Layering thickened on the lower levee backslope approaching the pond, but grazing and infaunal bioturbation quickly destroyed deposited layers (Hardie, 1977). This was a revelation that not all laminated carbonates were deep basinal. This work caused a bandwagon of reinterpretation of laminated carbonates. Many laminated carbonates interpreted as deep basinal were now realized to be shallow tidal flat (and of course, some that were in fact deep basinal were misinterpreted to be tidal flat).

The specific form of the laminae produced (flat, crinkly and such) was the result of cyanobacterial mats growing on the surface (Figure 1), and the distribution of the different mat types was a function of 'Exposure Index' (the inverse of the frequency of flooding; Hardie, 1977) or, as later documented on Caicos, the frequency of sedimentation events (Wanless *et al.*, 1988b).

Working on Caicos, and with the help of Hurricane Kate in 1985, Wanless *et al.* (1988b) learned that some carbonate tidal flats tend to be built of centimetre-thick bedding not millimetre laminae. These are flats that are not much influenced by winter-storm events but rely on hurricanes to build their sequence. Centimetre-thick bedding occurs on the inner marsh on Andros where the cyanobacterial mats were punctuated by thicker sediment layers from hurricanes, but not reached by winter storms. Based on field observations, channelled carbonate flats subjected to winter storms build laminated

levees, and flats or portions of flats affected only by larger hurricane events produce centimetre-thick bedding.

Grain Size

This centimetre-thick supratidal bedding described above presented a problem because it was now recognized that hurricanes produce centimetre-thick stratification in both normally subtidal and normally supratidal environments. These can be differentiated by grain size. The sediment swept across a tidal flat by Hurricane Kate was that which could be carried in suspension. In contrast, the offshore storm layer contained a total mix of coarse to fine grain sizes moved around the offshore bottom by the storm (Wanless *et al.*, 1988b). Bagnold (1966), working on desert sands in Africa, and McCave (1970, 1971), working on sands at the bottom of the North Sea, showed that grains finer than 200 μm tend to move in suspension (Figure 2). Specifically, when there is enough energy to move particles finer than about 200 μm , there is enough turbulence to put them in suspension. So even in hurricanes surges, except within about 100 m of the shore, the tidal flat layers are nearly entirely composed of less than 200 μm , suspension-transported sand. Risi *et al.* (1995) found that this was true for the 1-10 cm thick layer swept 10 km inland through the broad mangrove swamp of southwest Florida during Hurricane Andrew, a Category 5 storm in 1992.

Beaches display this principle well. Sand finer than 200 μm will not stay on a beach, because, whenever the sand moves (by water or wind), it will move in suspension and be carried from the beach. The minimum grain size of nearly all beaches is near 200 μm . In areas with higher persistent energy, the bedload boundary (what remains on the

beach) will shift to the coarser grain size as indicated in Figure 1. The rapid erosion of many beach renourishment projects is the result of ignoring this fundamental behaviour of sands.

Grain size explains a lot about the origin of stratification in the modern and ancient, whether one is looking at the centimetre-thick sand and shale beds in the Cambrian Bright Angel Shale in the Grand Canyon, water-density-driven canal sedimentation in Marco Island, Florida, or the sediments washing off to the flanks of Great Bahama Bank during storms. Rapid sediment dispersal of suspension-transported sands can, with sufficient sediment supply, totally overwhelm bedload transport and is thus a dominating influence on texture of event stratification on epeiric seas and broad carbonate platforms and their margins.

Grain size analysis by sieving is not always a sufficient approach when analyzing modern carbonates. Carbonate grains are commonly hollow, porous, and/or platy and their sieved grain size may not be a good measure of the grains' behaviour. Settling analysis, the settling of grains through a column of water, is a better measure of grain size. Ooids and abraded mollusc fragments are solid carbonate, equant, and have about the same density as quartz, so sieve analysis will give a good assessment. However, crinoid columnals, other echinodermal plates, foraminiferal tests, bryozoan fragments, the plates of the calcareous alga, *Halimeda*, and fecal pellet grain aggregates are very porous and will settle together with quartz grains $\frac{1}{2}$ to $\frac{1}{4}$ their size (carbonates - Braithwaite, 1973; Wanless, *et al.*, 1981; siliciclastics – Haven & Morales-Alamo, 1968). Sieving is, therefore, a poor measure of their behaviour.

Applying this to ancient limestones is challenging as the original porosity within grains is not always apparent. The first time a modern crinoid fragment is handled is a shock. The grains are very porous and seem to weigh nothing in comparison with the massive crinoidal limestones in which they are commonly preserved in the Paleozoic.

The point bar-tempestite-turbidite-tsunamiite dilemma

Great strides have been made in understanding the meaning of layering in turbidites (Bouma, 1962; Enos, 1969; Kuenen, 1948, 1950; Walton, 1967), tempestites (Ager, 1974; Aigner, 1985), and fluvial point bar sequences (Jackson, 1976). These processes – turbidity currents, storm transport and river flood transport – actually produce very similar products which are still easily confused and not rigorously characterized. Most researchers seem best able to define what these layers represent when they look at associated facies and fauna – the pelagic E unit of the turbidite, the shelf to lagoonal fauna and trace fossils of tempestites, and the terrestrial signature in flood plains capping meandering river sequences. In fact, copious literature is devoted to characterizing the details of these environments and deposits, but very little in defining criteria to distinguish them based on the physical sedimentary structures. It would first be helpful to dispose of the terms tempestite and turbidite as they essentially force the observer into one camp or another in the description phase. The tempestites in particular are probably still a lumping of stratification from several different types of storm transport processes, including local re-suspension and re-deposition, strong lateral cross shelf transport induced by density of sediment-laden water (Aigner & Reineck, 1982), and deposition on subtidal storm deltas (Aigner, 1985). Siliciclastic and carbonate sedimentologists have

characterized storm deposition quite differently, mostly reflecting different energy settings and different preserved components. Siliciclastic storm units are thought of as made of hummocky and swaley stratification of sand (Harmes *et al.*, 1975; Dott & Bourgeois, 1982). In carbonates, undulating sand stratification is only a part of the sequence, and is complemented by basal skeletal shell concentrations and capping muds and post-event faunal processes and community remains (Aigner, 1985).

Tsunami deposits must now be added to this list. There is perhaps hope for differentiating tsunami deposits as they are commonly a series of 2-6 very closely spaced, but distinct events, although not all tsunami deposits show multiple units (Dawson & Shi, 2000). In addition, it is important to acknowledge that tsunami deposits can vary from thin layers of mud or sand that extend kilometres inland, or more localized giant boulders (i.e. Grand Cayman).

Reineck & Wunderlich (1968) helped to differentiate sequences built of repetitive sand and mud alternations by tides from a stacking by less frequent storm events. In sands, In sands, flaser bedding – repeated, commonly reversing, ripple stratification separated by thin, partly eroded mud drapes – represent alternations of frequent, repetitive transport and quiet water settle out, commonly tidal in origin. More widely temporally-spaced event stratification commonly tends to be an alternation of sand layers interbedded with slightly thicker and more continuous mud layers, and the sand layers are characteristically more planar to hummocky stratified with a thin ripple top (Figure 3). For skeletal gravels, storm deposition is generally characterized by a loose and chaotically packed, flat to undulating layer. Some of the skeletal material is deposited articulated and most exhibits little abrasion unless the deposit has been repeatedly

reworked. Tidally reworked skeletal gravels are generally abraded and grains, if elongate, may organize into a fitted-fabric edgewise conglomerate (Figure 4).

Bioturbation of layering

Sometimes layering does not leave a very good record of its occurrence. This does not mean that physical sedimentation is not important in the more bioturbated sequences. Referring to a burrowed rock from the Grand Canyon Cambrian, colleague Francis Pettijohn responded to a question of how deposition occurred since layering could no longer be seen by stating: “The rock is burrowed not layered.” This is missing the point but was a common concept in the 1960s and early 1970s, especially in carbonates.

In 1975, Warzeski, working on Caesar’s Creek Bank, the large carbonate tidal bank building out into the reef tract outside southern Biscayne Bay, showed that over half of the bank’s sediment was derived from within Biscayne Bay (see Wanless *et al.*, 1995). He concluded this even though the sequence was bioturbated because the finer-grained skeletal constituents in the sediment sequence, were from organisms that lived only within Biscayne Bay and not in the outer reef tract. In other words, the sediment had been transported there and deposited as layers by storms, then subsequently bioturbated. This may seem obvious now, but it wasn’t then. During his studies Warzeski also found a 10-15 cm-thick layer of muddy carbonate sediment just below the surface across most of Caesar’s Creek Bank (over 4 km²). Using historical aerial photographs, he concluded that this was from the 1935 Great Labor Day Hurricane. Since recognizing that layer in the mid-1970’s, it has slowly disappeared through bioturbation.

Risi mapped the distribution and fate of the storm surge layer from Hurricane Andrew in 1992 along the southwest coast of Florida (Risi *et al.*, 1995; Risi, 1998). This 1-10 cm thick layer washed 10 km in through the broad mangrove swamp along 10 km of the coast in less than 45 minutes. Except right at the coast, the grains were less than 200 μm and only gradually became finer inland (like the Hurricane Kate layer across the Caicos tidal flat, this Andrew layer was mostly a fine grainstone, as most of the mud washed off as the surge moved back to the sea). Fortunately the layer had a few percent quartz grains in it. Within a year, mangrove rootlets from the surviving mangroves began to grow up into the overlying layer. This root bioturbation, combined with dissolution of the carbonate particles by tannic and humic acids has essentially obliterated this dramatic layer in only about 10 years. Fine quartz sand is disseminated throughout this mangrove peat sequence along the southwest coast of Florida. This is all that remains of the story of repetitive major hurricane sedimentation events there.

Layering is better preserved where individual depositional units are thicker, coarser grained, or happen frequently. Shepard (1960) recorded preserved layering in the central Texas lagoons only in association with river or tidal deltas, which served as a focus of more frequent or thicker sedimentation events. Perlmutter (1982) found preserved layering in the 10,000 Islands of south Florida mainly where hurricane flood surges through tidal channels formed broad, low deltas in the interior lagoons.

Many carbonate sedimentologists have focused on the enormous role of biological processes in forming carbonate sequences, and early on it seems that physical processes were played down except in the more energetic settings, such as ooid sand shoals. Ball (1967) did point out that the Safety Valve muddy tidal bar belt along the seaward side of

Biscayne Bay (south Florida) was the low energy setting to which sediment could be transported, deposited and accumulate. But in reading *Carbonate Sediments and Their Diagenesis* (Bathurst, 1975), the mud banks in Florida Bay were portrayed as a biological wonderland in which carbonate sediment was produced by calcareous green algae, trapped by the sea grasses and grew carbonate banks. In fact these banks, which grow into the intertidal zone, are layered, physically deposited features in which the layers are a product of energy events, predominantly winter storms (Wanless & Tagett, 1989). They are actively migrating in central Florida Bay, building on the south and west flanks at rates of 1-2 cm per year or more (Boscence, 1989).

Sea-level-driven pulses of sedimentation

Most Holocene and Pleistocene dune ridges in the Bahamas are predominantly built of physically layered strata, whereas nearly all Modern coastal dune ridges today are mostly all stabilized by vegetation, being root bioturbated, and do not appear to be producing layered sequences, the sand as it gradually accumulates is bioturbated by root processes. There seem to be two answers to this dilemma, both right. First, some of these ridges are formed during and just following major storm events as large volumes of sediment are scoured and recycled. Some Pleistocene ridges in the Bahamas have low angle beach laminae with beach fenestrae (bubble casts) extending up an individual layer a vertical distance of more than 6 m, a representation of storm wave run up.

Second, coastal and shallow marine environments have pulses of growth. In the Berry Islands and elsewhere in the Bahamas, islands record rapid pulses of growth during times of rising sea level as large volumes of coastal and shelf sediment became exposed

and unstable. Waves and currents rapidly erode and recycle this sediment bankward producing pulses of island or dune-ridge growth. These thick layered sequences are then followed by a time of vegetative stabilization, bioturbation of the upper portion, and minor trapping of sand that is blown or washed in. Something similar is happening along sections of the southwest Florida coast today. Probably with the help of 23 cm relative rise of sea level during the past 70 years, the marl (firm carbonate mud) and organic peat coast is rapidly eroding (200-400 m since the earliest 1928 aerial photographs) and large volumes of sediment are being re-distributed (see Vlaswinkel & Wanless, this volume). Natural and cut tidal channels are feeding a larger tidal prism and thus bringing increased volumes of sediment laden tidal water into coastal lakes and estuaries. Rapidly forming flood tidal mud deltas are filling these lakes and bays at rates of 1-20 cm per year. Organic content of these carbonate sediments is up to 40 % (in contrast to 2-10 % in most of the Florida Bay mud banks). There is a burrowing infauna and aggressive ibis (deep prodding) wading bird community across most of the deltas. Nevertheless layering is commonly preserved as distinct mud and organic laminae from daily and winter storm flood tide sedimentation and millimetre to centimetre fine-sand and mud layers from historical hurricanes. This rapid pulse of coastal sedimentation in response to small sea-level changes and coastal instability may be more common in building a stratigraphic record than presently appreciated.

Subsurface Deposition

Sedimentation events are commonly best preserved when they are not deposited on the sediment surface but rather below, which seems like a paradox. Storm sediment

infillings of deep excavating burrow networks of mud shrimp were documented following Hurricane Kate in 1985 (Wanless *et al.*, 1988a). These infillings ('tubular tempestites') tend to be coarse, poorly sorted mixes of grains moving near the bottom during storms. The finer material left as a surface layer at the end of the event will quickly be obliterated by bioturbation. These coarse, storm-generated, burrow infillings preserve a record of storm-event sedimentation and have forced reassessment of the depth of sedimentary environments such as Paleozoic mud mounds (Tedesco & Wanless 1989). These coarse storm infills demonstrate that these mounds were well above storm wave base.

Diagenesis and Layering

Selective diagenesis (cementation, recrystallization, dolomitization and pressure dissolution) commonly accentuates subtle differences in primary layers that would not otherwise stand out. In the Pleistocene Miami Limestone for example, the finer oolitic layers become better cemented than the coarser layers during early meteoric diagenesis. Although a minor grain-size difference (350 vs 300 μm), the different textured layers become very distinct and may take different pathways during later recrystallization and pressure dissolution.

In the Cambro-Ordovician, shallow marine 'ribbon limestones' have an alternation of limestone and dolomitic limestone beds, from millimetres to centimetres in thickness. These layers are commonly displayed on the weathered outcrop as alternation of grey and tan (Figure 5). Wanless (1979, 1982) offered evidence that this bedding is the result of selective pervasive pressure dissolution of the finer-grained beds with the

dolomite forming as a 'reactate' byproduct mineral during dissolution. Again, what may have begun as small textural differences may become pronouncedly different in form, composition and altered thickness with diagenesis.

Pressure dissolution commonly accentuates small initial differences or forms along the boundary between two bed types (Logan & Semeniuk, 1976; Wanless, 1979, 1981), but it can also create layering and fabric where there was none originally. Structural geologists commonly recognize that 'spaced solution cleavage' is a fabric that forms by pressure dissolution in rocks in response to tectonic stresses. Cleavage is commonly at an angle to primary stratification because compressive tectonic stress directions are usually not vertical. The fabrics produced, spaced solution cleavage, pencil cleavage and flattened nodular lenses, however, are very similar to that seen in some limestones in which pressure dissolution formed in response to burial stress. Structural geologists recognize that different rocks will produce different tectonic cleavage with different spacings, fabrics and forms. Sedimentologists should recognize that burial stresses, which will produce dissolution surfaces parallel to primary bedding, can sometimes produce spaced false stratification and nodular fabrics where there originally were none.

Discussion

This paper has presented examples of our improved knowledge of what layering means from the experience of the author and students and colleagues with whose work the author is intimately familiar. Other scientists and groups have also made significant contributions in advancing our understanding of layering.

Since Ginsburg first asked “Layering, what does it mean” over 40 years ago, significant progress has been made. Pursuit of this question has helped sedimentologists figure out how modern environments work and reconstruct the environments and dynamics of ancient layered sediments now frozen in stone. However, communicating this information to other disciplines may not have been so effective. For example, coastal engineers and beach managers are commonly still putting sand that is mostly less than 200 μm on beaches, wasting taxpayers money and degrading offshore marine habitats and waters. Sedimentologists need to do a better job of communicating.

In finding these answers many new questions have emerged, questions for the next generation of sedimentologists to enjoy. The new generation can start by carefully questioning our interpretations and then consider the following important problems. Tackle the complicated question of differentiating the several types of layering that presently are grouped under that heading of tempestites or hummocky stratification through careful work in the modern and ancient. Seek improved criteria for differentiating the fluvial-tempestite-turbidite-tsunamiite group of very similar fining-upwards sequences (as Jackson [1976] showed, there is very significant variability within these sedimentary deposits). Be prepared to use textural characteristics and biological structures in reconstructing physical processes, as that is commonly all that is available. And recognize that diagenesis and pressure dissolution can accentuate, modify, and even fabricate layering. Although much of the pressure dissolution research was done 25 years ago, that does not mean it is out of date.

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Figure Captions

Figure 1. With less frequent sedimentation events on carbonate tidal flats, the tufted cyanobacteria, *Scytonema* has an increasing influence on layering form. (A) Frequent

sedimentation events permit only the beginning of tufts to form and the layering takes on a crinkly appearance. (B) With more time between sedimentation events tufts become more pronounced and disrupt layer continuity. (C) In areas removed from significant sedimentation events for years, a pronounced tufted cushion mat forms and adsorbs minor sedimentation events. Millimeter or thicker sediment layers (light) smother and kill the mat which will take 0.5-1 years to recolonize. The decayed tufted mat and its contained sediment form the thicker, darker layers in the sequence. Andros Island tidal flats, Bahamas.

Figure 2. Entrainment diagram for quartz sands. When there is sufficient wave or current energy to move grains finer than 200 microns, then there is also enough turbulence to transport them in suspension (τ =shear stress; ρ_s =density of grain; ρ =density of fluid; and D =grain diameter). Modified from McCave 1970.

Figure 3. Storm layers of fine sand interbedded with lesser energy green shale. Fine sand layers are either planar layered with a ripple cap (foreground) or ripple lenses (middle). Middle Cambrian Bright Angel Shale from Pipe Springs, Grand Canyon, Arizona, USA. This is a shallow marine epeiric sea environment over 200 km from the cratonic margin.

Figure 4. Oyster deposits from the seaward portion of the Savannah River, Georgia, USA, in an area exposed to both reversing tidal currents and incoming storm waves. (A) view down onto a loose chaotically oriented oyster gravel ridge thrown up by a storm event. (B) View down onto surface of a tightly fitted edgewise conglomerate of oyster shell in an intertidal area persistently subjected to strong flood and ebb tidal currents.

Figure 5. Examples of layering modified by pervasive pressure dissolution. In both, light layers are limestone and darker layers are finely crystalline dolomite and insoluble grains. (A) A limestone layer containing quartz sand pinches out but the insoluble quartz continues as a traceable band showing that this limestone layer was originally much more extensive but has been lost by pressure dissolution. Cambrian Conococheague Limestone, western Maryland, USA; originally grainy limestone layers with quartz (storm layers) and fine carbonate mud (now dolomitic) from lesser events; deposited in shallow marine waters. (B) Skeletal and intraclastic limestone layer, containing radiolarians and fine quartz sand thins through a zone of pervasive pressure dissolution but the insoluble grains continue as a markedly thinned layer. Ordovician distal slope limestone and shale, Picadilly, Port au Port, Newfoundland, Canada. Other light layers were also originally thicker distal turbidite layers but have been completely thinned by pressure dissolution.