Geoscience Canada

Facies Models 8. Shallowing-Upward Sequences in Carbonates

Noel P. James

Volume 4, Number 3, September 1977

URI: https://id.erudit.org/iderudit/geocan4_3art02

See table of contents

Publisher(s)

The Geological Association of Canada

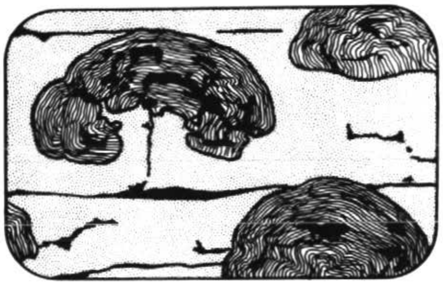
ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

James, N. P. (1977). Facies Models 8. Shallowing-Upward Sequences in Carbonates. *Geoscience Canada*, *4*(3), 126–136.



Facies Models 8. Shallowing-Upward Sequences in Carbonates

Noel P. James
Department of Geology
Memorial University of Newfoundland
St. John's, Newfoundland A1C 5S7

Introduction

Perhaps the most commonly encountered carbonate deposits are laterally persistant, evenly bedded limestones and dolomites of apparent shallow water origin, as demonstrated by abundant fossil mud cracks and stromatolites. These deposits, which occur most commonly on the continents and in relatively undeformed portions of mountain belts, are not only important sources of paleontological and sedimentological information, but are also common host rocks for hydrocarbons and metallic ores (particularly lead and zinc). As such, it is critical that we be able to determine, as precisely as possible, the environment in which each of the interbedded sediments was deposited.

A quantum jump in our understanding of these deposits occurred when modern carbonate tidal flats were examined in detail, notably by Robert Ginsburg and his colleagues in Florida and the Bahamas about 20 years ago. It was quickly realized that there were a host of sedimentary structures and textures on these flats that would allow a much more precise definition of environments of deposition than was possible before: these findings were quickly applied to fossil sequences (Fischer, 1964; Laporte, 1967; Aitken, 1966; Roehl, 1967). This application in turn generated two different lines of investigation: 1) description of other areas of modern tidal flat deposition, in particular the southern shore of the Persian Gulf where evaporites are common and Shark Bay, Western Australia, where a great variety of modern stromatolites are forming; and 2) documentation of different styles of tidal flat deposits in the geologic record.

Despite the great number of studies which record carbonate sequences with evidence of period exposure, there has not been, to date, a synthesis of the various sequences. In siliciclastic deposits, it is commonly the sequence of rock types that defines the environment of deposition. In carbonate stratigraphy, however, the actual sequence is of less importance, possibly because sedimentary environments commonly can be defined accurately on the basis of grain type, fossil fauna and structures.

The Model

Carbonate sediments characteristically accumulate at rates much greater than the rate of subsidence of the shelf or platform upon which they are deposited. This is because carbonate sediments are produced mainly in the environment of deposition - especially in shallow water where conditions for the biological and physiochemical fixation of carbonate are optimum. As a result, carbonate accumulations repeatedly build up to sea level and above, resulting in a characteristic sequence of deposits, in which each unit is deposited in progressively shallower water. This shallowing-upward sequence also may commonly is repeated many times in a succession of shallow water deposits (Fig. 1).

Readers will recognize that such a shallowing upward sequence also may be termed a 'regressive sequence'. This term has led to much confusion in the past, because it has been used to describe deposits associated with a high rate of sediment production and accumulation under relatively static sea level - sea bottom conditions. So I have abandoned the term 'regressive' altogether in favor of a rock-descriptive term, albeit interpretive, the shallowing-upward sequence, which others have called shoaling-upward (even though all such deposits are not shoals).

1) The model as a norm. The ideal carbonate shallowing-upward sequence comprises four units,

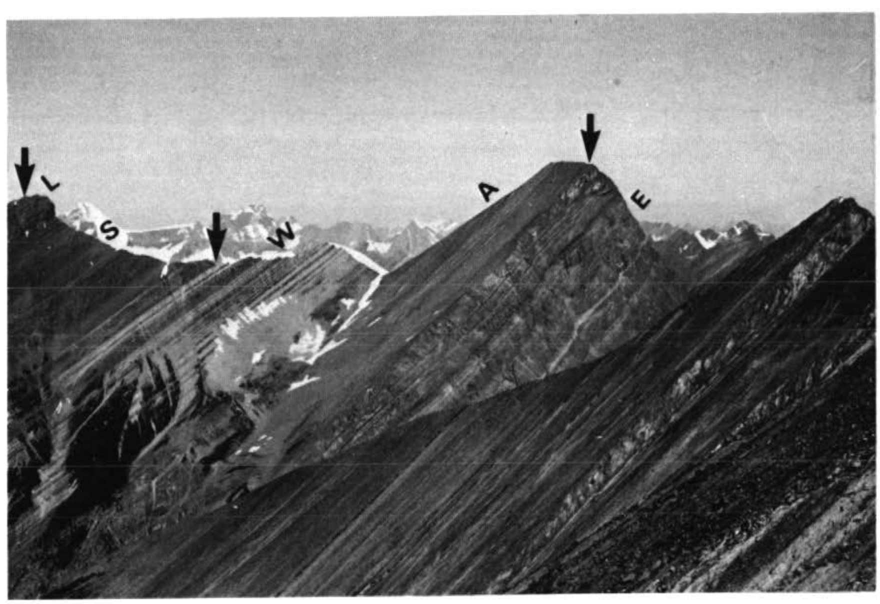


Figure 1
Bedded carbonates ranging in age from Middle to Late Cambrian near Fortress Lake, B.C.; Arrows mark the top of large-scale shallowing-upward sequences (L - Lyell FM., S - Sullivan Fm., W - Waterfoul Fm., A - Arctomys Fm., E - Eldon and Pica Fms.). Striping of the Waterfoul Fm. is caused by repetitive smaller scale shallowing-upward sequences between subtidal-intertidal limestones (dark) and supratidal dolomites (light). Photo courtesy J. D. Aitken.

illustrated in Figure 2. The basal unit, which is generally thin, records the initial transgression over pre-existing deposits and so is commonly a high energy deposit. The bulk of the sequence which may be of diverse lithologies consists of normal marine carbonate, as discussed below. The upper part of the sequence consists of two units: the intertidal unit within the normal range of tides; the other a supratidal unit, deposited in the area covered only by abnormal, windblown or storm tides. Each of these units exhibits the characteristic criteria of subaerial exposure.

The thread that binds all such sequences together is the presence of the distinctive intertidal unit, which, once recognized, allows one to interpret the surrounding lithologies in some kind of logical sequence (Fig. 3).

2) The model as a predictor. First-order variation on the basic model revolves around the two main types of intertidal environment: 1) quiet, low-energy situations, commonly referred to as tidal flats, and 2) agitated, high-energy situations, or quite simply, beaches. Second-order variation involves the kind of subtidal units below and of supratidal units above; the subtidal reflects the type of marine environment adjacent to the tidal flat and the supratidal reflects the adjacent terrestrial environment, in particular the climate (Fig. 4).

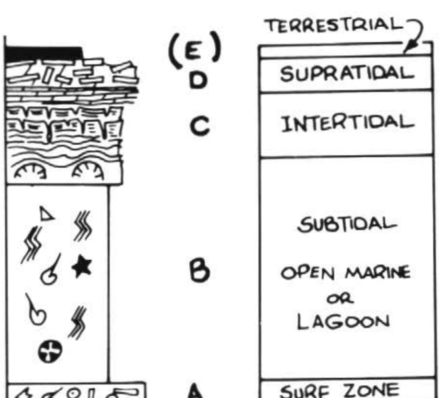


Figure 2
Five divisions of the shallowing-upward model for carbonates; A - lithoclast rich lime conglomerate or sand, B - fossiliferous limestone, C - stromatolitic, mud-cracked cryptalgal limestone or dolomite, D - well laminated dolomite or limestone, flat-pebble breccia, E - shale or calcrete, bracketed to emphasize that the unit is often missing - see text. Symbols used throughout are from Ginsburg (1975).

For purposes of discussion I will begin with those sequences that contain low-energy intertidal units (tidal-flats) because they exhibit the greatest variety of distinctive features and consequently are well documented, both in modern and ancient settings. To place the observed features in context we should first examine modern carbonate tidal flats.

Sequences with a Low-Energy Intertidal Unit

Modern Tidal Flats

The main elements of a modern carbonate tidal flat system as exemplified by the narrow shelf and embayments of Shark Bay, Western Australia, the southern coast of the Persian Gulf and the wide platform of the Bahama Banks are shown in Figure 5. A characteristic of most modern examples is that they occur in protected locations: protected that is from the open ocean waves and swells, yet still affected by tides and severe storms. This unique setting is commonly afforded by the presence of a semi-protective barrier composed of lime sand shoals, locally associated with reefs and/or islands. The barrier commonly is dissected by tidal channels through which flow high velocity tidal currents. A shallow muddy lagoon lies in the lee of this barrier. The lagoon may be enormous as in the case of the Bahamas, relatively narrow and elongate as in the Persian Gulf, or very small as in the pocket embayments of Shark Bay. In such an arrangement, tidal flats are present as: 1) small flats atop and on the lee side of the emergent sand shoals of the barrier, and 2) large flats along the shoreline of the shallow lagoon (Fig. 5). Thus tidal flats occur in association with two separate carbonate accumulations, high energy sand bodies and low energy lime muds. A third type of association which is less common in modern situations is the association with reefs, especially the interior of large reef complexes.

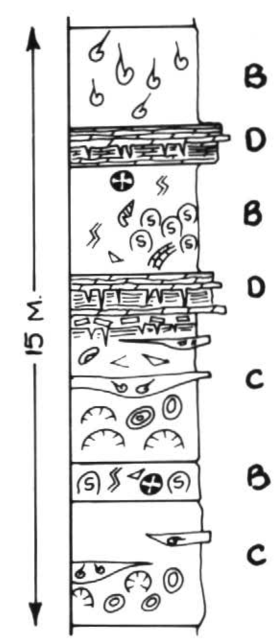


Figure 3
Actual sequence of several shallowing-upward sequences from the Manlius Fm., New York State (From Laporte, 1975).

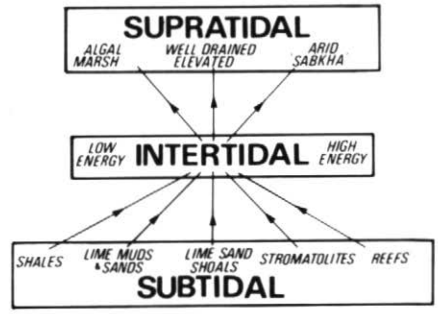


Figure 4
A flow diagram indicating the various possible environmental transitions present in a carbonate shallowing-upward sequence.

Intertidal environments. The intertidal zone, especially along rocky coasts and beaches is commonly a gradual transition from sea to land without much noticeable variation. On wide gradually sloping tidal flats, this zone can be the familiar gradual transition or a complex area of many subenvironments. At one end of the spectrum the flats have few, very shallow, short tidal creeks (Fig. 6). At the other end of the spectrum the flats are dissected by many tidal creeks flanked by levees. Slight depressions between the creeks are occupied by tidal ponds (which fill and partially empty during each rise and fall of the tide), and the whole complex is fronted by small beach ridges or erosional steps (Fig. 6). Perhaps in this case it would be better to refer to the whole zone as the "pond and

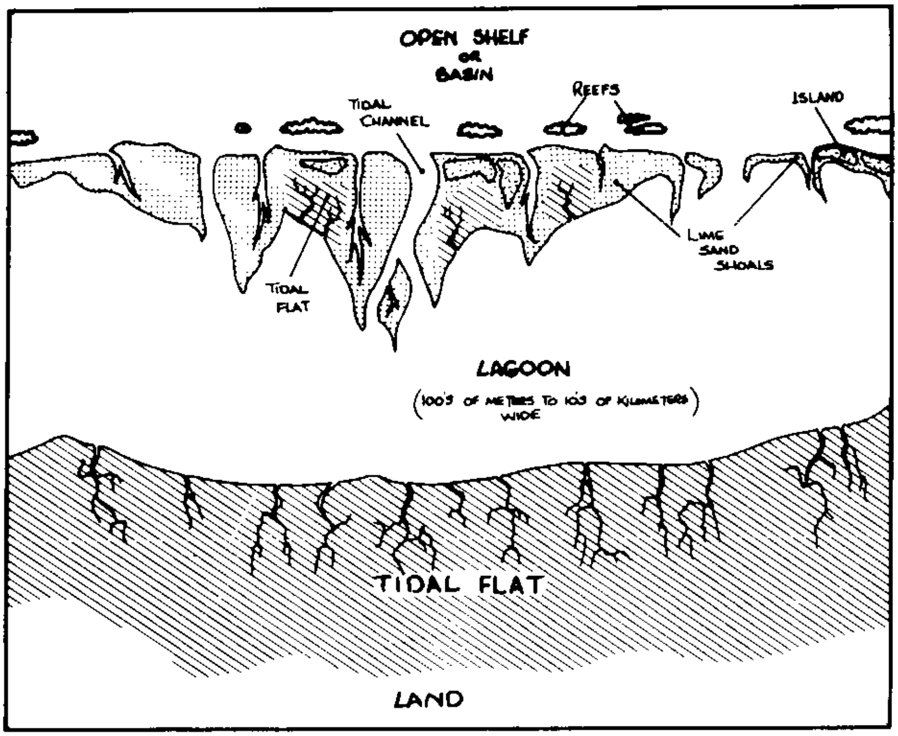


Figure 5
Plan view of the geometry of a modern tidal flat complex. Note that tidal flats can be present both adjacent to the land or in the lee of lime sand shoals.

creek belt" because some of the areas are dry most of the time (levees and beaches) whereas others are continuously submerged (ponds and creeks). These complications have led some workers (e.g., Ginsburg and Hardie, 1975) to despair of conventional terms and instead to relate different zones to the per cent of time that they are exposed rather than to their position.

On some tidal flats, in the Bahamas for example where there are many tidal creeks and noticeable relief between levee and tidal pond (about 1 m), the true intertidal zone which lies between the two may comprise only 60 to 70 per cent of the intertidal environment. In other areas such as the Persian Gulf, where there are fewer creeks and less relief, almost the whole flat is truly intertidal. The important point to grasp is that numerous environments may exist in very close proximity, not only perpendicular to the shoreline but parallel to it as well, so that in the geologic record rapid, local lithological variations are to be expected, both vertically and laterally, rather than a smooth succession of progressively shallower environments.

The tidal flat wedge is built up of fine grained sediments brought onto the flats from the adjacent offshore marine zone

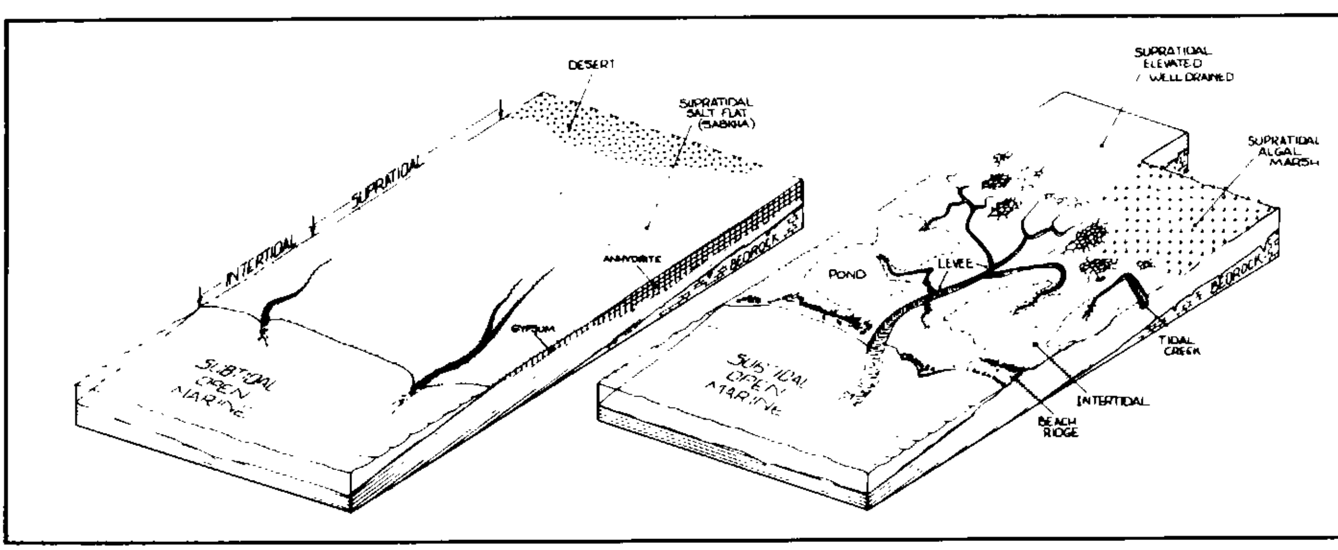


Figure 6
Block diagrams showing the major morphological elements of a tidal flat: left - a hypersaline tidal flat with few channels and bordering a very arid desert (similar to the modern Persian Gulf), right - a normal marine tidal flat with many channels and ponds and bordering an elevated well-drained area of low swamp algal marsh in a humid climate (similar to the modern Bahamas).

by storms rather than by daily tides. Large storms such as hurricanes which flood the flat with sheets of water white with suspended sediment are particularly effective. Shinn, Lloyd and Ginsburg (1969) have suggested that *the tidal flat is a river delta turned wrong-side out* with the sea as the "river" supplying sediment to the channeled flats as the "delta".

Sediments of the intertidal zone are characterized by three distinctive features, not found elsewhere: 1) algal mats, 2) irregular to even laminations (cryptalgal laminites), with fenestral porosity, and 3) desiccation features.

The algal mats, gelatinous to leathery sheets of blue-green algae growing on top of the sediment surface are widely regarded as the signature of intertidal deposition; they may occur throughout the intertidal zone but their precise distribution is controlled by climate and the presence or absence of other organisms. The upper limit is controlled by climate; in arid areas they cannot grow above the high intertidal into the supratidal zone, whereas in areas of high rainfall where the supratidal zone is moist or flooded for days at a time, mats are prolific. The lower limit is more variable and appears to be controlled by the presence of gastropods that eat algae. In areas of normal salinity, mats are prevented from developing below the middle intertidal zone because they are browsed by gastropods; in areas of hypersalinity (deadly for gastropods), mats grow down into the subtidal zone. In addition algal mats will colonize only a temporarily or permanently stable bottom, and will not grow on shifting sand.

Although the algal mats may themselves vanish with time, evidence of their presence during deposition remains because of the peculiar pores that they help to create, generally referred to as 'laminoid fenestrae'. These are irregular, elongate to mostly sub-horizontal sheet-like cavities (loferites or birds-eyes of some workers) with no obvious support and much larger than can be explained by grain packing. They are simply due to the fact that the mats are covered with sediment and eventually rot away as they are buried, leaving voids as well as holes due to entrapped gas and shrinkage.

Another structure recording the presence of blue-green algal mats are the finely laminated carbonates (Fig. 7), ranging from stratiform and slightly crenulated to the familiar arched domes of stomatolites. These have been called cryptalgal (hidden, algal) laminations by Aitken (1967) in reference to the fact that the influence of algae in the rock-forming process is more commonly inferred than observed.

Lower intertidal zone. Much of the subtidal character remains evident in sediments from this part of the environment, and the deposits are commonly well burrowed and bioturbated. In hypersaline areas, however, the surface of the sediment is veneered with a thick algal mat, frequently broken into desiccation polygons. Beneath the mat grains are blackened due to reducing conditions and altered by boring algae to peloids of lime mud.

Tidal ponds and the creeks that drain them on hypersaline tidal flats support the most prolific growth of algal mats anywhere on the flat. The algal mat flourishes in water depths greater than those in the immediate offshore area because of relatively elevated salinites in the ponds. On tidal flats where the salinity is closer to normal, marine tidal ponds are populated by a restricted but prolific fauna of foraminifers and gastropods and the gastropods prevent the growth of algal mats. Similarly, if tidal creeks are common in such areas, the channels are devoid of mats but do contain concentrations of the pond fauna, which may accumulate as bars of skeletal lime sand. As the channels migrate these skeletal sands commonly form a basal lag deposit.

Middle and upper intertidal zone. Sediments here are commonly light-grey to light-brown (oxidizing conditions), have good fenestral porosity (the variable growth of algal mats), are graded (episodic storm deposition) and are broken into desiccation polygons (prolonged exposure). There is generally good growth of algal mats throughout: in the lower parts thick leathery mats are separated into desiccation polygons a few cms to a metre in a diameter with cracks filled by lime mud in the lower parts (Fig. 8); in the central parts, thinner, leathery mats have surfaces that are puffed up into blisters and convoluted into crenulated forms; and in the upper parts, shriveled, crinkled and split mats are found. Bedding generally is irregular especially in the upper zones with mats alternating with graded storm layers.

In some settings sediment in the upper intertidal zone dries out to form chips of lime mud while in others the

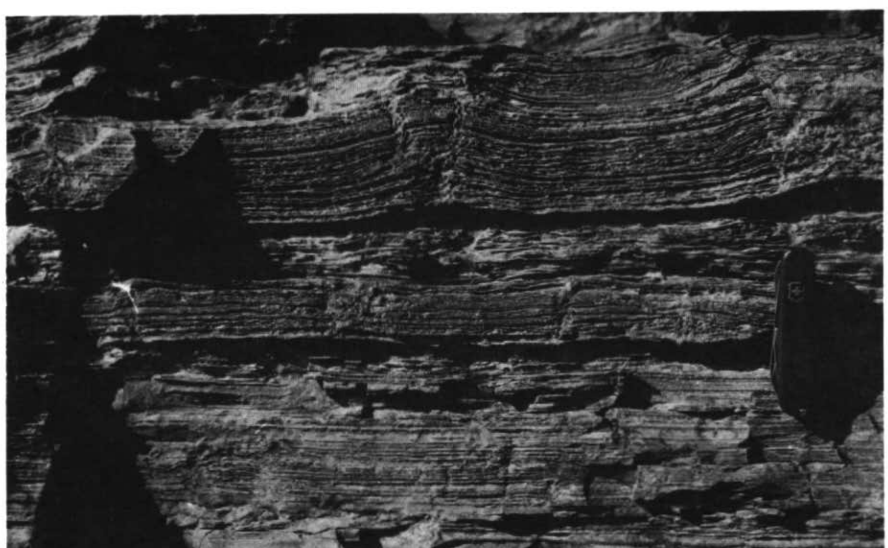


Figure 7
Cryptalgal laminites that have been mud-cracked. The intertidal unit of a shallowing-upward sequence in the Petit Jardin Fm. (Upper Cambrian) on the south shore of the Port-au-Port Peninsula, Nfld. (Photo courtesy R. Levesque).

sediment below the mats is lithified to a depth of as much as 10 cms.

Although sediments commonly are laminated throughout the intertidal environment, they are also riddled with small-scale tubules produced by insects and worms, larger tubes produced by crabs and other crustaceans. Sediments also may be penetrated by the prolific shallow roots systems of salt tolerant plants.

Supratidal environment. In all situations (including channel levees) this area is characterized by long periods of exposure. This is reflected by the lithification of storm deposited sediments in the form of surface crusts, several cms thick, and which in turn are fractured into irregular polygons. These polygons may be pushed up by the force of crystallization (or by plant roots) to form 'teepees', or dislodged completely to form pavements of flat-pebble breccia. Clasts are commonly cemented on modern tidal flats by cryptocrystalline aragonite or calcite, and characteristically contain considerable (25 to 50%) fine crystalline dolomite.

If the creek levees in the intertidal zone have built up above normal high tide level, they consist of hard, finely to very finely laminated sediment, extremely regular, and composed of alternating layers of sediment and thin algal mats with excellent fenestral porosity.

The landward parts of the supratidal zone may grade into various terrestrial environments, the end members of which are: 1) areas of elevated, pre-existing bedrock and no sedimentation in which the surface of the rock is characterized by intensive subaerial diagenesis, and the development of caliche (calcrete crusts); 2) areas of contemporaneous sedimentation which grade between: a) low-lying environments in regions of high rainfall, occupied by algal marshes, b) low-lying environments in arid, desert regions, characterized by evaporite formation, and c) well drained zones, often slightly elevated and with little deposition.

Algal marshes, flooded by fresh water during the rainy season are an ideal environment for the growth of algal mats and these mats are periodically buried by layers of sediment swept in during particularly intense storms: thus the preserved record is one of thick algal mats alternating with storm layers. With progressive aridity the supratidal zone dries out. If the chlorinity of the groundwaters remains constantly above 39°/oo, cementation, particularly by aragonite, is common. Cementation is most common if there is minor but consistent input of fresh water from inland to dilute the hypersaline groundwaters somewhat. If the chlorinity of the groundwaters remains constantly above 65°/oo then authigenic evaporites precipitate within the sediment below ground level. In this setting (called a supratidal sabkha, or salt flat in the Middle East) dolomitization is also common in the subsurface, saline brine pools occur at the surface and terrigenous wind-blown sand is common in the sediment

In relatively well-drained zones the supratidal environment is a deflation surface, occasionally cut by the upper reaches of tidal creeks, sometimes damp from rising capillary waters and covered by a thin film of algal mat. Scoured and rippled sediment is common and clasts are sometimes encrusted with algae to form oncolites.

Figure 8
A bedding plane of mud-cracked polygons with the edges of each polygon curled up, likely because the algal mats in the polygons shrivelled upon exposure and drying out; Near the top of a shallowing-upward sequence in the East Arm Fm. (Upper Cambrian), Bonne Bay, Nfld.

Common Sequences with a Low-Energy Intertidal Unit

a) *Muddy and grainy sequences.* These sequences developed either by progadation of the wide continental tidal flat or by shoaling of the lime sand bodies that formed the barrier offshore (Fig. 9). The climate in the region of deposition was generally too wet or the groundwater table too low or diluted by fresh water to permit precipitation of evaporites.

The muddy sequences, those in which skeletal lime muds or muddy lime sands are the main subtidal unit, are well developed today in well-drained areas of Shark Bay where salinities are too high to permit browsing of the algal mats by gastropods, and in the tidal creek and pond belt of the Bahamas. These sequences are generally regarded as the 'classic' tidal flat sequences. The basal unit, if present, records the initial incursion of the sea onto land and as such is commonly coarse-grained, composed of clasts, etc., all diagnostic of surf-zone deposition. The subtidal unit is characteristically a bioturbated lime wackestone to packstone with a normal and diverse marine fauna, commonly containing stromatolites in deposits older than middle Paleozoic. In Precambrian and lower Paleozoic deposits the characteristic tidal flat features such as desiccation polygons,

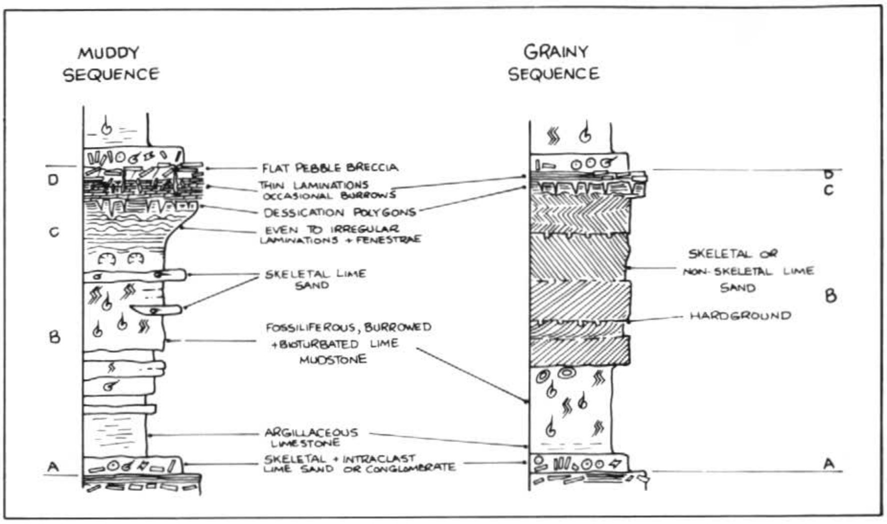


Figure 9
Two hypothetical sequences with a low energy, tidal flat unit developed on a low energy subtidal unit (left) and a high energy lime sand unit (right).

Figure 10
Shallowing-upward sequences comprising lower intertidal-subtidal limestones (L) overlain by supratidal dolomites (D - Cryptalgal laminites, sandy in part) in the Lyell Fm. at Takakkaw Falls, Yoho National Park, B.C. (photo courtesy J. D. Aitken).

well-laminated sediments and fenestrae will occur at the base of the intertidal zone (Figs. 10, 11). In deposits younger than middle-Paleozoic, the prolific browsing and burrowing activity in the lower intertidal zone (unless the water mass was hypersaline) have homogenized the sediment, so that the signature of intertidal deposition is recorded only within the mid and upper intertidal sediments.

If the tidal flat were extensively channelled, the migration of channels back and forth may also have destroyed some of the subtidal character, forming instead a partial fining-upward sequence (much like that of a river), with a basal skeletal lime sand.

Where fenestrae are present they show a zonation: horizontal to laminated in the lower intertidal environments (smooth mat), irregular and in some cases vertical in the middle and upper intertidal environments (pustular, shriveled and crinkled mats). Desiccation polygons are most common near the top, apparently coincident with cementation. The supratidal zone is characterized by very evenly laminated deposits or flat pebble breccias.

Readers interested in the finer details of such sequences are referred to studies by Laporte (1967) and Fischer (1964), the latter outlining and documenting a similar facies sequence but in reverse order, forming a deepening-upward sequence.

The same style of shoaling sequence also may be present off-shore from the low-energy tidal flat, on the lime-sand shoals. Here low energy tidal flats developed in the lee of the leading edge of the shoal once beach ridges were developed or currents had swept sand together to form islands. This will be reflected in the sequence as a sudden change from obvious high energy deposition to low energy intertidal deposition. The subtidal unit is generally well-sorted, oolitic, pelletoidal or skeletal lime sand (pelmatozoans are particularly common in the Paleozoic), with a few containing oncolites. Bedding is characteristically planar, with herringbone cross-laminations, large at the base and becoming smaller upwards, and individual bedding planes are commonly covered with small-scale ripples. Early cementation is characteristic, and so deposits contain many intraclasts of cemented lime sand, and bored surfaces. Once the shoals, or parts of the shoals are inactive they may be burrrowed and much of the original cross-bedding may be destroyed.

The intertidal to supratidal units are similar to those described above, but are generally relatively thin. If the shoal is exposed for a long time caliche and soil profiles commonly develop, reflected by brown irregular laminations, breccias, and thin shale zones.

b) *Stromatolite and reef sequences.* One common variation on the model is the development of shoaling-upward sequences in association with abundant stromatolites in the lower Paleozoic/Precambrian and with reefs in the Phanerozoic in general.

In Shark Bay, Western Australia, where all environments are hypersaline and so stromatolites abound, the interrelationship between stromatolite morphology and environment has only recently been documented (Hoffman, 1976). In the intertidal zone columnar to club-shaped forms, up to one metre high are found rimming headlands. In relatively high energy, exposed environments the relief of the columns is proportional to the intensity of wave action. These grade laterally away from the headlands to the lower energy bights where the stromatolites are more prolate and elongate, oriented normal to the shoreline. In tidal pools digitate columnar structures abound.

These growth forms are the result of active sediment movement; algal mats only grow on stabilized substrate, thus columns are nucleated upon pieces of rock, etc.; growth is localized there and does not occur on the surrounding shifting sands. Early lithification of the numerous superimposed layers of mat and sediment turns the structures into resistant limestone. Moving sand continuously scours the bases of the stromatolites. The mounds of pillars are largest in subtidal or lower intertidal environments and decrease in synoptic relief upwards, finally merging with stratiform mats in upper intertidal zones, above the zone of active sediment movement.

The resulting model sequence, summarized in Figure 12, is integrated from the Shark Bay example and the summary sequence of 200 or more shoaling sequences present in the Rocknest Formation of middle Precambrian age near Great Slave Lake (Hoffman, 1976). In the intertidal zone deposits reflect higher energy than normal, indicating a more exposed shoreline. These sediments underlie and surround the domal to columnar stromatolites, which in turn grade up into more stratiform stromatolites, and finally into very evenly bedded structures. The supratidal unit of this sequence will be characterized by both desiccation polygons and flat-pebble breccias as well as occurrences of delicate branching stromatolites, forming in supratidal ponds. Care should be taken in delineating this sequence because stromatolites that are similar to those in the intertidal zone also occur in the subtidal (Playford and Cockbain, 1976).

Shallowing-upward sequences are also common as the last stage of sedimentation in large bioherms, as numerous successions within the large back-reef or lagoonal areas of reef complexes, and as 'caps' on widespread biostromes. In this type of sequence the shoaling upward is first reflected in the subtidal unit itself, generally as a transition from large massive hemispherical colonial metazoans of the reef facies, to the more delicate, stick-like forms that are common in the shallow protected locations. These stick-like skeletons may be swept together on beaches at the edge of the tidal flat. As a result, the intertidal unit commonly contains a conglomerate within it, or at the base. The upper part of the sequence is otherwise similar to the others described. For a more detailed description of "reefy" sequences see the two studies by Havard and Oldershaw (1976) and Read (1973).

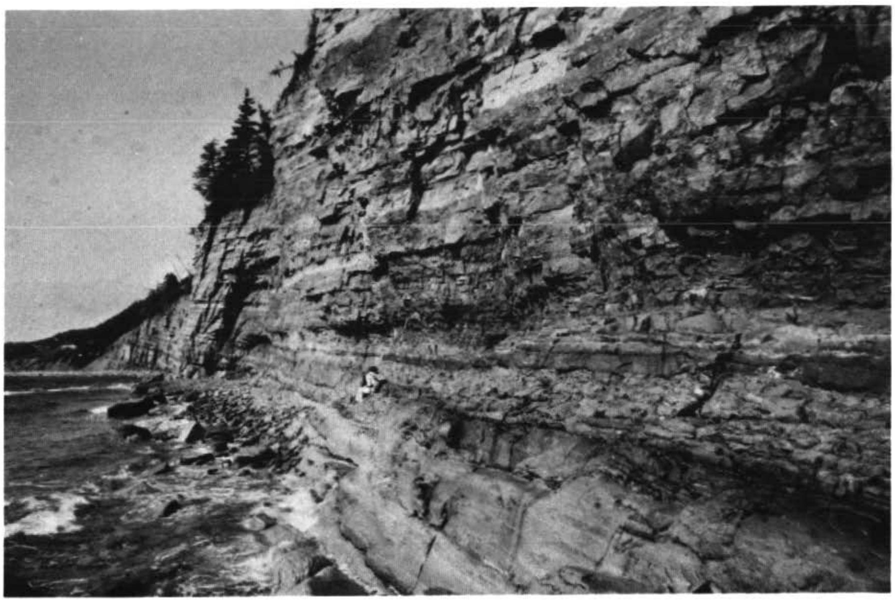


Figure 11
Numerous shallowing-upward sequences comprising thick subtidal oolite lime sands and thin intertidal-supratidal cryptalgal laminites with fenestrate porosity; Petite Jardin Fm., Port-au-Port Peninsula, Nfld.

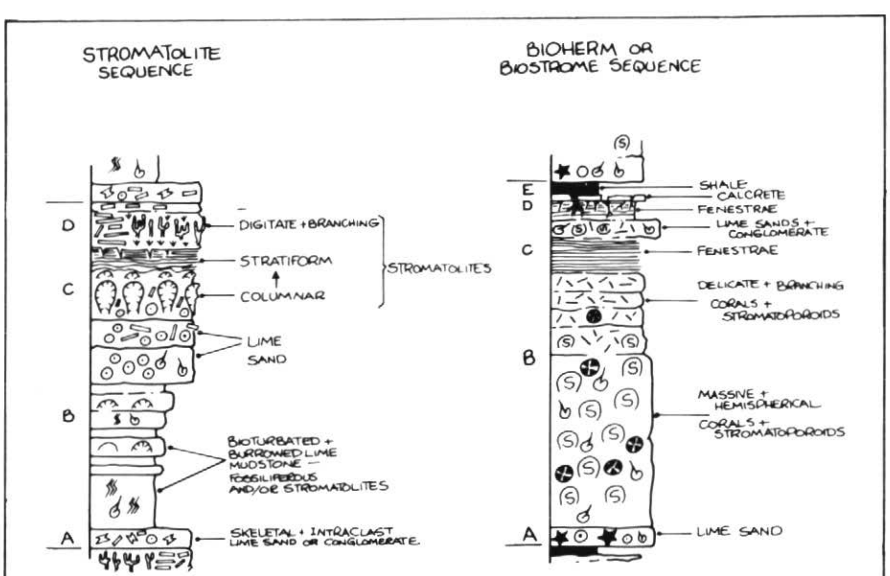


Figure 12
Two hypothetical sequences with a low energy intertidal unit developed in conjunction with stromatolites (left) and on top of a skeletal metazoan bioherm or biostrome (right).

c) *Carbonate-evaporite sequences.* The other major variation on the model proposed at the beginning of this article is at the opposite end of the environmental spectrum, in the supratidal zone, in this case emergent in a very arid environment and flushed by hypersaline groundwaters. The hypersalinity of the groundwaters and attendant high evaporation results in the formation of *authigenic* evaporites which in turn raises the Mg^{++}/Ca^{++} ratio of the groundwaters and induces dolomitization of the sediment. The processes occur within the sediment, above the water table in the intertidal zone and both above as well as below the water table in the supratidal zone. If the water compositions are barely within the field of gypsum precipitation, and there are fluctuations due to brackish flow of groundwater from the mainland, evaporites will occur in the form of isolated masses or crystals in the upper part of the sequence. If the groundwater compositions are continuously well within the field of gypsum precipitation, growth of evaporite minerals takes place as a mush of gypsum crystals in the intertidal zone or as layers of anhydrite nodules, as complex masses with a characteristic chickenwire texture, and as layers contorted into enterolithic (intestine-like) shapes (Fig. 13). The important point, which is often ignored, is the growth of the evaporites *within* the sediment, as a diagenetic overprint on depositional facies of various environments. As evaporite growth is porphyroblastic, the host sediment commonly is displaced to intercrystalline areas and earlier fabrics are destroyed. Accompanying dolomitization commonly is intense, with sediments of the intertidal and much of the subtidal zones affected.

Evaporites, however, are very soluble when exposed to percolating meteoric waters of low salinity and have a tendency to vanish from the record. Dissolution of the evaporites affects the sequence in several ways, but the most important is the formation of collapse breccias (Fig. 14). This collapse occurs when the evaporites dissolve leaving no support for the overlying sediments, which subside into the void created by evaporite removal. Thus the top of the sequence is a breccia of marine limestone from the overlying sequence with a mixture of terrigenous sand if a

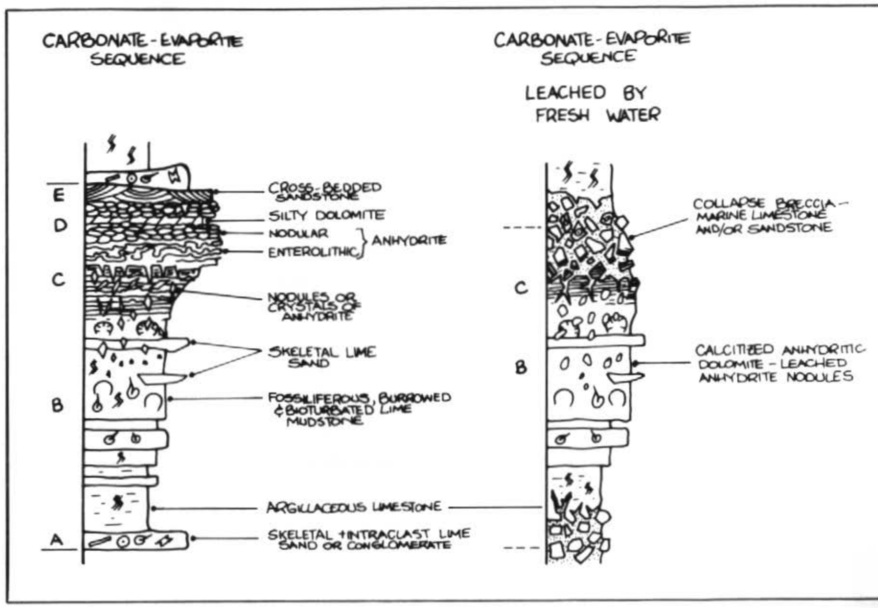


Figure 13
Two hypothetical sequences with a low-energy intertidal unit and a supratidal unit developed under arid conditions; on the right the evaporites have been dissolved by percolating fresh waters.

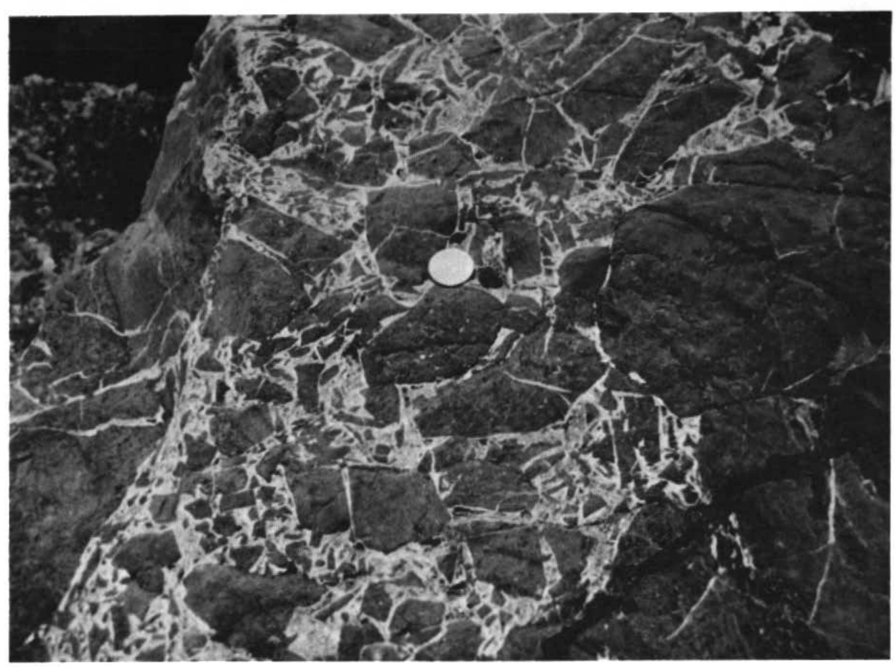


Figure 14
A collapse breccia of subtidal lime mudstone clasts in white calcite; caused by the solution of anhydrite at the top of a shallowing-upward sequence in the Shunda Fm. (Mississippian) at Cadomin, Alberta (photo courtesy R. W. Macqueen).

terrigenous facies capped the original sequence (Fig. 13). Isolated anhydrite crystals in lower parts of the sequence may be leached out, forming vugs which may be subsequently filled with quartz or chalcedony (usually length-slow). The dolomite, at least in the upper part, is commonly altered to calcite, in the reverse of the dolomitization process (so-called "dedolomitization").

Sequences with a High Energy Intertidal Unit

In contrast to the low-energy intertidal (the tidal flat) the higher energy beach zone is not commonly recognized in the rock record. This may be partly because it resembles many subtidal grainstone deposits and so is not obviously distinctive. Also, it is relatively narrow compared to the tidal flat, and has a lower preservation potential, and finally, the beach deposits lack the distinctive sedimentary features of the tidal flat. These very reasons illustrate the value of the concept of a shoaling-upward sequence as a guide. Once the potential for such a sequence is recognized in the geologic record, then one can concentrate on the search for subtle features that characterize beach deposition, which otherwise might go unnoticed.

Modern carbonate beaches. The beach is characterized by two zones: 1) *the lower foreshore*, that zone unusually below the zone of wave swash, and 2) *the upper foreshore*, the zone of wave swash. Sediments of the lower foreshore are coarse grained, poorly sorted, have a matrix of lime mud (if it is available), and are characterized by small and large-scale festoon cross-bedding, oriented parallel to the shoreline and generally attributed to longshore drift. The upper foreshore comprises thick-bedded, internally laminated, very well-sorted lime sands and gravels in planar cross-bedded accretionary beds that dip gently seaward (generally less than 15 degrees). Sediments in the upper foreshore zone may have many open-space structures, the equivalent of the fenestrae of muddy intertidal sediment, called keystone vugs (Dunham, 1969) or microcaverns (Purser, 1972). These are due to gas escape and in the geological record are partly to completely filled with cement.

As on the tidal flat, periodic exposure of beach deposits leads to cementation and partial subaerial diagenesis. The textures thus created are difficult to recognize in the field but are important keys to recognizing the beach environment. The two most important of these diagenetic phenomena are beachrock and calcrete.

Beachrock is composed of seaward-dipping beds of lime sand and gravel that are generally cross-laminated and occur in the lower intertidal to middle intertidal environment. It is formed by the precipitation of carbonate cement out of seawater or mixed seawater and rainwater. The beds of limestone may be up to one metre thick, are commonly jointed at right angles to the beach and are encrusted and/or bored by numerous intertidal organisms. Lithification disappears seaward and rarely extends higher than the intertidal zone. The partly cemented beds may be broken up and redeposited as conglomerates, made up of cemented sand clasts. In the upper parts of the intertidal zone cementation takes place in intergranular voids partly filled with air; the cements, as a result, are often stalactitic (more extensively developed on the undersides of grains).

If exposed for long periods of time and if located in an environment where there is at least periodic rainfall, the lime sands will begin to undergo subaerial diagenesis (see Bathurst, 1975, for an extended discussion of subaerial diagenesis). In addition the upper metre or so of such subaerially exposed deposits develop calcrete or caliche horizons which have many features that closely resemble those produced by laminar to laterally-linked stromatolites and oncolites. These features are discussed in detail by James (1972) and Read (1976).

The supratidal unit in these sequences may be any of the ones described above, although calcrete (caliche) is very common. Beaches may act as small barriers protecting supratidal ponds and flats so that the cap in such sequences will be thin beds of lime mud (often dolomitized) with all of the associated supratidal features. One variation not found elsewhere occurs where the high energy surf zone of the overlying sequence erodes the top of the sequence down to the cemented portions, resulting in truncation layers or hardgrounds that separate sequences.

Shallowing upward sequence with a high-energy intertidal unit. The lower two units of this type of sequence are similar to those described in the preceding sections on sequences with low-energy intertidal units (Fig. 15). In this sequence, however, characteristic subtidal carbonates grade upward into coarse-grained lime sands with all the characteristics of the lower and upper foreshore described above (Fig. 9). The supratidal unit, in the form of a thin shale (soil), may be present, but more commonly the supratidal is represented not by a deposit but by intensive diagenesis of the upper unit (cementation, dissolution, calcrete formation and microkarst). This is in many ways similar to the diagenetic overprint of other facies by supratidal evaporite formation.

Summary

In the past there has been a natural tendency to use obvious sedimentary structures (e.g., mud cracks, stromatolites) to infer that parts of a carbonate sedimentary sequence had been periodically exposed. Individual structures, however, often have counterparts in other sedimentary environments (e.g., syneresis cracks, subtidal stromatolites) resulting, in many cases, in questionable paleoenvironmental interpretations. With all the data now available on carbonate strandline deposition we can frequently use what have become

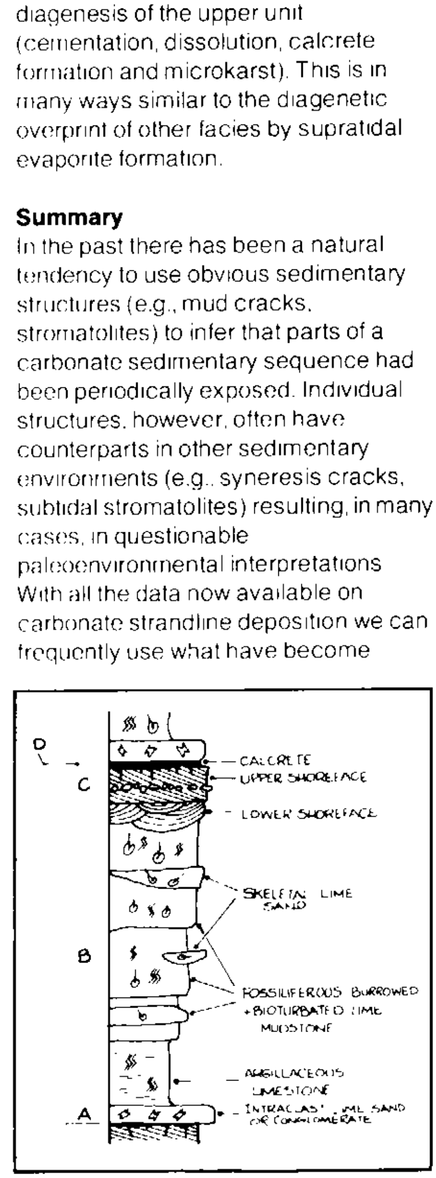


Figure 15

A hypothetical sequence with a high-energy intertidal unit, a beach, developed, in this case, adjacent to a low energy subtidal environment.

natural associations of sedimentary features in a vertical succession and define, with precision, specific strandline facies and their interrelationships.

While this is true for low-energy shoreline sequences, it is much less so for high-energy shoreline sequences. To bring all aspects of this type of facies model to comparable levels of understanding much more data is needed on exposed or high-energy intertidal environments, not from the modern, but from the rock record. In addition, the time is ripe to test whether or not the diagenetic features which result from periodic subaerial exposure (cementation, microkarst, calcrete) can be commonly recognized in ancient sequences.

Acknowledgements
Roger Macqueen, Bob Stevens and David Kobluk kindly criticized early versions of this manuscript and kept me honest.

References

Basic References on Shallowing-Upward Carbonate Sequences

Ginsburg, R. N., ed., 1975, Tidal Deposits: Springer-Verlag, 428 p.
The best all around, up-to-date reference on siliclastic and carbonate tidal deposits.

Merriam, D. F., ed., 1964, Symposium on Cyclic Sedimentation: State Geol. Survey Kansas Bull., 2 vols., 636 p.
40 papers many of which are still basic references, on cyclic sedimentary sequences.

Lucia, F. J., 1972, Recognition of evaporite-carbonate shoreline sedimentation, *in* K. J. Rigby, and K. Hamblin, eds., Recognition of Ancient Sedimentary Environment: Soc. Econ. Paleontol. Mineral. Spec. Publ. 16, p. 160-192.
A well-written summary with many samples.

Hoffman, P., 1973, Recent and Ancient Algal Stromatolites. Seventy years of Pedagogic cross-pollination: *in* R. N. Ginsburg, Evolving Concepts in Sedimentology: Johns Hopkins Press, p. 178-191.
A very readable essay on the evolution of our understanding of stromatolites and related sediments.

Irwin, M. L., 1965, General theory of epeiric clear water sedimentation: Amer. Assoc. Petrol. Geol. Bull., v. 49, p. 445-459.
The first integrated synthesis of shallow water carbonate sequences and their meaning.

Shaw, A. B., 1965, Time in Stratigraphy: McGraw-Hill, p. 1-71.
A pedantic, but thought-provoking analysis of epeiric sea carbonate sedimentation.

Fischer, A. G., 1964, The Lofer cyclotherms of the Alpine Triassic, *in* D. F. Merriam, ed., Symposium on Cyclic Sedimentation: State Geol. Survey Kansas Bull. 169, v. 1, p. 107-149.
A regressive sequence of shallow water carbonates, superbly documented and illustrated.

Laporte, L., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State: Amer. Assoc. Petrol. Geol. Bull., v. 51, p. 73-101.
An extremely clear, well-written analysis of a shallowing-upward sequence.

Bosellini, A. and L. A. Hardie, 1973, Depositional theme of a marginal evaporite: Sedimentology, v. 20, p. 5-27.
An analysis which concentrates on the sedimentology of, not evaporites in, a series of shallowing-upward sequences.

Modern Carbonate Tidal Flats

Bathurst, R. G. C., 1975, Carbonate Sediments and Their Diagenesis: Developments in Sedimentology No. 12, Elsevier, p. 178-209, 217-230, 517-543.

Shinn, E. A., R. M. Lloyd, and R. N. Ginsburg, 1969, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: Jour. Sed. Petrology, v. 39, p. 1202-1228.

Garrett, P., 1970, Phanerozoic stromatolites: non-competitive ecological restriction by grazing and burrowing animals: Science, v. 169, p. 171-173.

Logan, B. W., G. R. Davies, J. F. Read, and D. Cebulski, 1970, Carbonate sedimentation and environments, Shark Bay, Western Australia: Amer. Assoc. Petrol. Geol. Memoir 13, 223 p.

Logan, B. W. *et al.*, 1974, Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia: Amer. Assoc. Petrol. Geol. Memoir 22, 358 p.

Hoffman, P., 1976, Stomatolite morphogenesis in Shark Bay, Western Australia: *in* M. R. Walter, Stomatolites, Elsevier, p. 261-273.

Kinsman, D. J. J., 1966, Gypsum and anhydrite of Recent Age, Trucial Coast, Persian Gulf: Second Symposium on Salt, Northern Ohio Geol. Soc. Cleveland, p. 1302-1326.

Kendall, C. St. G. C. and P. A. d'E. Skipwith, 1968, Recent Algal mats of a Persian Gulf Lagoon: Jour. Sed. Petrology, v. 38, p. 1040-1058.

Kendall, C. St. G. C. and P. A. d'E. Skipwith, 1969, Holocene shallow-water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, Southwest Persian Gulf: Amer. Assoc. Petrol. Geol. Bull., v. 53, p. 841-869.

Purser, B. H., ed., 1973, The Persian Gulf: Springer-Verlag, 471 p.

Modern Carbonate Sand Bodies

Imbrie, J. and H. Buchanan, 1965, Sedimentary structures in modern carbonate sands of the Bahamas: *in* Primary Sedimentary Structures and Their Hydrodynamic Interpretation: Soc. Econ. Paleontol. Mineral., Spec. Publ. 12, p. 149-173.

Ball, M. M., 1967, Carbonate sand bodies of Florida and the Bahamas: Jour. Sed. Petrology, v. 37, p. 556-591.

Canadian Examples: Low-Energy Intertidal

The papers listed below are studies in Canada or nearby USA in which sequences or partial sequences have been well documented. I have omitted papers that simply mention that the rocks are deposited in very shallow environments.

1. Predominantly muddy or shaley sequences

Aitken J D 1966. Middle Cambrian to Middle Ordovician cyclic sedimentation, Southern Rocky Mountains of Alberta Can Petrol Geol Bull. v 14, p 405-441

Macqueen, R W and E W Bamber, 1968. Stratigraphy and facies relationships of the Upper Mississippian Mount Head Formation, Rocky Mountains and Foothills, Southwestern Alberta Can Petrol Geol. Bull., v 16 p 225-287

Roehl P O, 1967. Stony Mountain (Ordovician) and Interlake (Silurian) Facies analogs of recent low-energy marine and subaerial carbonates. Bahamas Amer Assoc. Petrol Geol Bull. v 51, p 1979-2032

Mukherji, K K, 1969, Supratidal carbonate rocks in the Black River (Middle Ordovician) Group of Southwestern Ontario, Canada Jour Sed Petrol. v 39, p 1530-1545.

Kobluk D R, S G Pemberton M S Karolyi and M J Risk 1977. The Silurian-Devonian disconformity in southern Ontario Can Bull Petrol Geol. in press

Trettin H P, 1975. Investigations of Lower Paleozoic geology, Fore Basin, Northeastern Melville Peninsula, and parts of Northeastern and Central Baffin Island Geol Survey Canada Bull 251, 177 p

2. Reef or Stromatolite-rich Sequences

Hoffman P, 1976. Environmental diversity of middle Precambrian stromatolites *in* M R Walter, Stromatolites Elsevier, p 599-613

Donaldson J. A., 1966. Marion Lake map area, Quebec-Newfoundland Geol Survey Canada Memoir 338, 85 p

Havard, C and A Oldershaw, 1976. Early diagenesis in back-reef sedimentary cycles, Snipe Lake, reef complex, Alberta Can Petrol Geol Bull. v 24, p 27-70

Mountjoy, E W 1975. Intertidal and supratidal deposits within isolated Upper Devonian Buildups: Alberta *in* R N Ginsburg, ed. Tidal Deposits Springer-Verlag, p 387-397

3. Carbonate-Evaporite Sequences

Wilson, J L, 1967, Carbonate-evaporite cycles in lower Duperow Formation of Williston Basin Can Petrol Geol Bull. v 15, p 230-312

Schenk, P E, 1969, Carbonate-sulfate-redbed facies and cyclic sedimentation of the Windsorian Stage (Middle Carboniferous), Maritime Provinces Can Jour Earth Sci., v. 6, p 1037-1066

Fuller J G C M and J W. Porter, 1969, Evaporite Formations with petroleum reservoirs in Devonian and Mississippian of Alberta Saskatchewan and North Dakota Amer Assoc Petrol Geol. Bull., v 53, p 909-927

Shearman, D J and J G Fuller, 1969, Anhydrite diagenesis, calcitization, and organic laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan Can Petrol Geol Bull. v 17, p 496-525

For an alternate interpretation see N C Wardlaw, and G E Reinson, 1971, Amer Assoc Petrol Geol Bull., v 55, p 1759-1787

Mossop, G D, 1973. Lower Ordovician evaporites of the Baumann Fiord Formation, Ellesmere Island *in* Rept of Activities, Part A, Geol Survey Canada Paper 73-1, p. 264-267.

Mossop G D., 1973, Anhydrite carbonate cycles of the Ordovician Baumann Fiord Formation Ellesmere Island, Arctic Canada A Geologic History Univ London Ph D Thesis 231 p

Canadian Examples: High-Energy Intertidal

There appears to be no well described beach sequence in carbonate successions in Canada, so I have included two foreign examples

Purser B H, 1972, Subdivision et interprétation des sequences carbonates Mém Bur Rech Géol Min. v 77, p 679-698

Inden R F 1974, Lithofacies and depositional model for a Trinity Cretaceous sequence *in* B F Perkins, ed Geoscience and Man, vol VIII Aspects of Trinity Geology, Louisiana State Univ, p 37-53.

Other References

Jones, B and O A Dixon, 1976, Storm deposits of the Read Bay Formation (Upper Silurian) Somerset Island, Arctic Canada (an application of Markov Chain analysis) Jour Sed Petrology, v. 46, p 393-402

Cumming, L M, 1975, Ordovician strata of the Hudson Bay Lowlands Geol Survey Canada Paper 74-28

Monger, J W H, 1975, Upper Paleozoic rocks of the Atlin Terrane, Northwestern British Columbia and South-Central Yukon Geol Survey Canada Paper 74-47

Kluyver, H M, 1975, Stratigraphy of the Ordovician St George Group in the Port-aux-Choix area, Western Newfoundland Can Jour Earth Sci, v. 12, p 589-594

References Cited in Text

Aitken J D, 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta Jour Sed Petrology, v 37, p 1163 1178

Dunham, R J, 1969, Early vadose silt in Townsend mound (reef), New Mexico *in* G M Friedman ed, Depositional Environments in carbonate rocks a symposium Soc Econ Paleontol Mineral, Spec Publ 14, p 139-181

Playford P E and A E Cockbain, 1976, Modern algal stomatolites at Hamelin Pool, a hypersaline barred basin in Shark Bay, Western Australia *in* M R. Walter, ed. Stromatolites, Developments in Sedimentology Elsevier 389 413

Read, J F 1973, Carbonate cycles, Pillara Formation (Devonian) Canning Basin, Western Australia Can Petrol Geol Bull. v 21 p 38 51

MS received May 3, 1977