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SEDIMENTARY ENVIRONMENTS, DEPOSITIONAL SYSTEMS, AND STRATIGRAPHIC CYCLES

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From its earliest beginnings, the study of sedimentary geology has been concerned with classifying depositional environments and with the means for recognizing strata deposited in different natural environments. Perhaps the first exciting distinction of this kind was between marine beds, in which fossil sea shells and the like occur, and non-marine beds from which such exotica as the remains of dinosaurs and extinct mammals can be collected. Such comparatively primitive criteria and simple distinctions are now largely part of the history of geology, although some comparably elementary indicators, such as the presence or absence of redbeds or coals, still find daily use.

More sophisticated approaches to the analysis of sedimentary environments have come in part from the stimulus of intellectual curiosity, but the major thrust of conceptual advances stems from practical interests. Most facets of economic geology benefit from better understanding of sedimentary environments. The distribution of producible petroleum and natural gas correlates in detail with specific environmental assemblages. Even more directly related genetically to the immediately enclosing strata are solid commodities such as coal, sand and gravel, and the various evaporites, although the latter can migrate diapirically. Aspects of groundwater geology, the study of several kinds of metallic ore deposits, and many facets of the fields called engineering geology and environmental geology all depend upon adequate knowledge of sedimentary environments.

Sedimentary Environments

In recent decades, under the imperatives of practical necessity, data on modern sedimentary environments have accumulated into a staggering mass of empirical information. Improved instrumentation, especially as related to the flowering of oceanographic research, has played a key role in this process. In recent years, the deceptively subtle culmination of all this work has taken shape in the form of a fundamental synthesis embodying a fresh outlook on the generation of characteristic stratigraphic sequences.

The early emphasis in studies of environmental parameters was properly upon simply defining conditions typical of specific natural environments. Water depth and salinity, current strength and persistence, temperature and Eh-pH relations are examples of pertinent factors. Conceptually, it is thus possible to conceive of *sedimentary environments* at given instants in time in terms of particular combinations of such parameters. The limitations of this approach are severe, however, owing to the dynamic behavior of real depositional systems. Individual sedimentary environments are not immutable, but instead are variable resultants of a complex of competing natural processes.

Depositional Systems

The concept of *depositional systems*, as such, depends upon perception of the intricate interplay of different sedimentary processes, and upon the resulting appreciation that different depositional environments inherently shift in position and character as the depositional system encompassing them evolves through time. The general functioning of some depositional systems, such as those of meandering rivers, has been known for so long as to be part of the traditional folklore of geology. On the other hand, the very existence of some other depositional systems, such as those of subsea turbidite fans, was wholly unsuspected only a few decades ago. Regardless of the antiquity of our knowledge about a given sedimentary phenomenon, systematic treatment in the context of an explicit model for systemic evolution is of recent vintage. A prominent case in point is the elaborate body of knowledge developed in recent years for deltaic systems.

One of the most powerful fruits of the concept of integrated depositional systems stems from the realization that correct models for behavior allows the prediction of the succession of sedimentary environments to be expected at a given place. To the extent that these successive environments are recorded by the deposition of sediment, analysis of the depositional system thus predicts the nature of the stratigraphic record.

In general, the evolution of depositional systems is reflected by the migration of sedimentary environments. Examples are the migration of channel meanders on a river floodplain, progradation of a tidal flat or beach-barrier sand ridge, and construction of a fan or delta complex by channel-switching. Such environmental migrations may be unitary or repetitive in various cases whose specific development depends in part upon inherent properties of the depositional system and in part upon external influences such as tectonics and eustasy.

Sedimentary Cycles

The diagnostic sedimentary sequence deposited by the characteristic succession of migratory environments typical of a given depositional system can be viewed as a unit *stratigraphic cycle*, which may be singular or repeated. The unit stratigraphic cycle is thus the record in space of the succession of sedimentary environments that prevail through time at a particular place within the influence of a controlling depositional system.

The concept of stratigraphic cycles is potentially universal, for no depositional process is indefinitely static. It would be folly to suppose, however, that any rigid set of invariant stratigraphic cycles could account for all the variability imposed upon depositional systems by numerous influences difficult to predict. A certain flexibility in thinking is thus vital, and concepts of stratigraphic cycles must be viewed as contained within some useful limits about a nominal norm, rather than as definitions of fixed progressions. It is also important to remember that sedimentary environments and processes operative locally need not be equally represented by strata in the unit cycle, and indeed that some processes and environments are recorded not by strata at all, but by hiatus or unconformity.

With these reservations, the concept of stratigraphic cycles as the product of processes operative within migratory environments linked rationally in space and time within an overall depositional system becomes a powerful tool for stratigraphic analysis. The approach emphasizes genetic relationships within stratigraphic successions, and downplays or surmounts the purely descriptive formal nomenclature of stratigraphy. Used properly, the methodology also serves as a vehicle to achieve the necessary fusion of lithostratigraphy and biostratigraphy including the hybrid viewpoints of paleogeography and paleoecology.

Facies and Sequence

A sedimentary cycle visible in vertical stratigraphic section forms because lateral migration of sedimentary environments builds horizontal layers. The stratigraphic record of a set of migratory sedimentary environments that are adjacent to one another within a coherent depositional system is a succession of superimposed horizons. Each layer is laterally continuous and yet each is a facies of the others. In a literal sense, equence and facies within a stratigraphic cycle are identical and have independent meanings only in terms of specific places or specific times.

Evolution of recent thought about sedimentary nvironments, depositional systems, and stratigraphic cycles hus leads directly to a detailed restatement of Johannes Valther's Law of Correlation of Facies. From the translation y Gerard V. Middleton, the key passage of Walther's roposition is the following: "The various deposits of the same depositional environment), and similarly the sum of the rocks f different (depositional environments), are formed beside ach other in space, though in a cross-section we see them ying on top of each other . . . . It is a statement of ar-reaching significance that only those facies . . . . can be uperimposed primarily which can be observed beside each ther at the present time." With his apparently deliberate llusion to the present as the main key to the past, Walther ven anticipated the actualistic flavor of current research on odern depositional systems as the key to understanding tratigraphic cycles laid down in the past.

raphic Columns

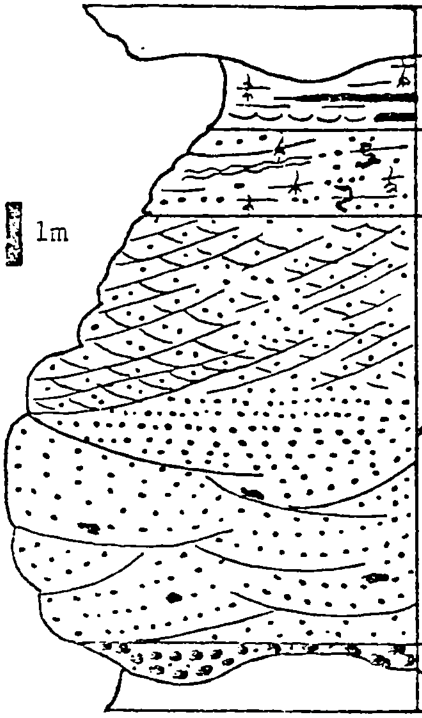
As a sampling of the success achieved thus far in defining ey stratigraphic cycles of practical use, a series of graphic olumns is appended. For each, annotations attached to egments of each unit cycle briefly relate process of formation o resulting lithology. At least two levels of scale and omplexity are represented to call attention to the fact that a ectrum or hierarchy of depositional models is likely to be ne ultimate outgrowth of systemic analysis.

One set of cycles represented are those generated by migrations of single, discrete paleogeographic features. These cycles have thicknesses that directly reflect the vertical scales of the individual paleogeographic features, and are not thick enough to induce important isostatic adjustments. All the examples shown are well-described in the literature. They are designated here as meander-belt fluvial fining-upwards cycle (fig. 0-1) with thickness governed by depth of paleochannel, progradational clastic beach-barrier strand-line cycle (fig. 0-2) with thickness governed by height of paleobeach face, and two kinds of progradational tidal-flat cycles with thicknesses governed by paleotidal range: clastic intertidal cycle (fig. 0-3) and carbonate-evaporite algal-sabkha intertidal cycle (fig. 0-4). Other stratigraphic cycles of comparable scale that could have been illustrated, but only on the basis of less extensive documentation, include successions formed by braided streambeds on land and by sublittoral sand bars in shelf seas.

Three examples of unit cycles developed on a larger scale are also included. These thick cycles may include several kinds of the thinner cycles developed on a smaller scale, and are in that sense compound entities. The overall migrations of sedimentary environments represented by the large-scale cycles are thus complex resultants of discrete migrations of individual paleogeographic features on a smaller scale. The thickness of the larger cycles is commonly great enough to promote isostatic adjustments sufficient to spoil simple correlations between thicknesses of cycles and vertical dimensions of related paleogeographic features. Examples shown include the constructional-destructional deltaic succession (fig. 0-5), perhaps the most classic variety of cyclothem; the progradational deep-sea fan succession (fig. 0-6), for which much less detail is available as yet; and the carbonate reef-bank succession (fig. 0-7), the kind of assemblage most directly influenced by organic processes.

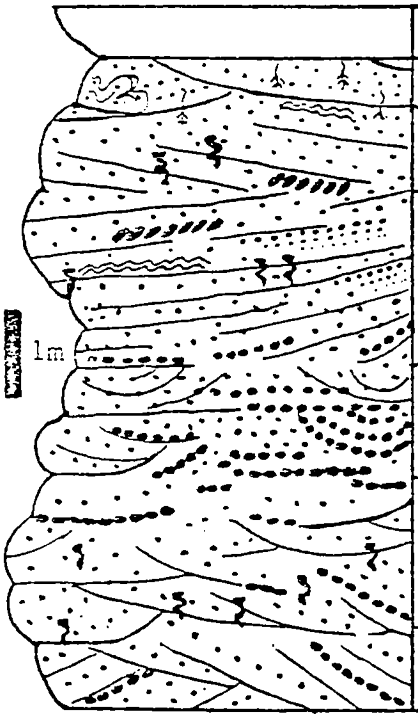
assuming no unconformities

Following the graphic columns are selective compilations of references on processes, sediments, and cycles related to salient depositional systems. Papers listed are those in which clarity of thought, excellence of illustrations, thoroughness of summary, or the like are impressive. The compilation is not intended to be exhaustive or even authoritative, but to lead the interested reader as quickly as possible into the intricacies of modern research and thinking in each case.



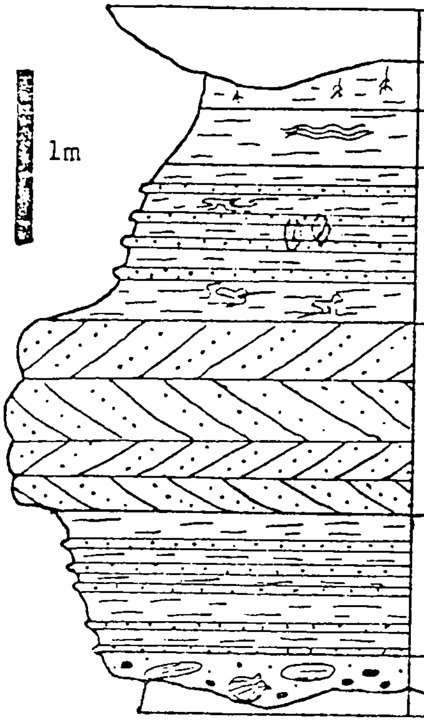
STRUCTURES/TEXTURES	ENVIRONMENT
Siltst. & mudst.: poorly-bedded; mud-cracked, rooted; peaty horizons.	Overbank flood basin
Sandst. & siltst.: ripples, flaser str, root-mottling; sheet-like geometries.	Levee/crevasse splay
Sandstone: fine-grained, ripple-laminated.	Upper point bar
Sandstone: fine-to med.-grained; flat-bedded, laminated.	
Sandstone: med.-grained, cross-bedded; common trough sets & transverse sets on slip-off face; armored mud balls.	Lower point bar
Cgl. & crse. ss.: scour-fill.	Channel lag

Fig. 0-1 Ideal meander-belt fluvial fining-upwards sequence (see references D4, D5, D10); thickness is related directly to channel depth and cyclicity is caused by channel migration.



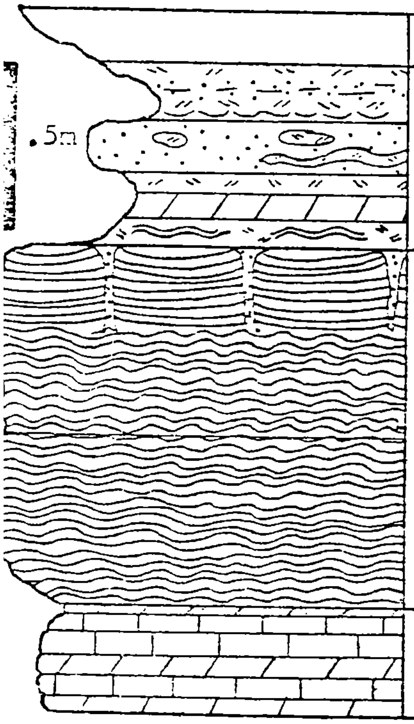
STRUCTURES/TEXTURES	ENVIRONMENT
Ss.: fine-gr., landward dir. tabular & trough cross-beds.	Dunes
Ss.: med.-gr., inland dips; burrowed.	Backshore
Ss.: med.-coarse, seaward dipping horiz. laminations; seaward imbric. discoidal pebbles; inversely graded heavy mineral laminations.	Berm Foreshore: swash zone (inner planar)
Ss. & cgl.: landward dir. trough sets (upper), planar beds, seaward dir. trough sets (lower).	Foreshore: combined lo. swash (in. rough), surf (out. planar), & build-up (o. rou.) zos.
Sandstone: med.-gr., landward dir. trough sets.	Nearshore: build-up zone (outer rough)
Ss.: med.-gr., landward dir. tabular cross-beds; burrowed.	Offshore (asymmetrical ripple facies)

Fig. 0-2 Ideal progradational clastic beach sequence for fair-weather conditions on non-barred high-energy shoreline (see reference G8); thickness is related to beach height but cyclicity is dependent upon tectonic or eustatic fluctuations in relative sea level.



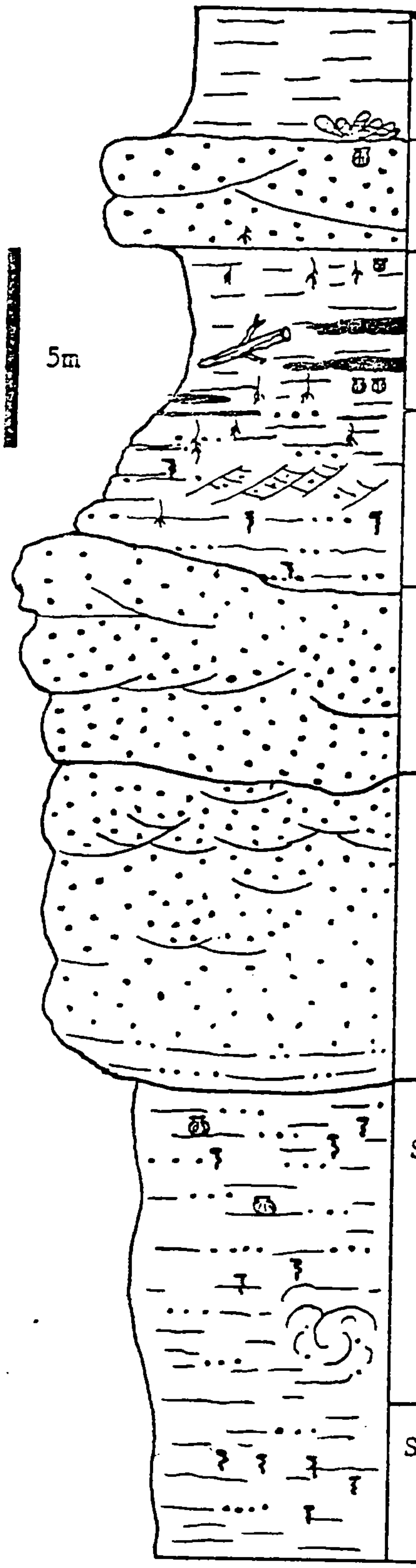
STRUCTURES/TEXTURES	ENVIRONMENT
Mudst.: org.-rich, rooted.	Salt marsh
Mudst.: bioturbated, algal mats, mudcr.	High water High mud flat
Ss. & mudst.: load & liquif. structure, flaser bedding; sand decreases up.; burrowing molluscs.	Mid flat
Sandstone: herringbone cross-bedding, current & interference ripples.	Lower sand flat
Sandstone & mudstone: flaser bedding.	Low water Subtidal
Cgl.: lutite clasts & shells.	Tidal channel lag

Fig. 0-3 Ideal clastic intertidal sequence (see references E3, E7); thickness is governed by tidal range, and cyclicity may develop either by migration of tidal channels, or through tectonic or eustatic fluctuations in relative sea level.



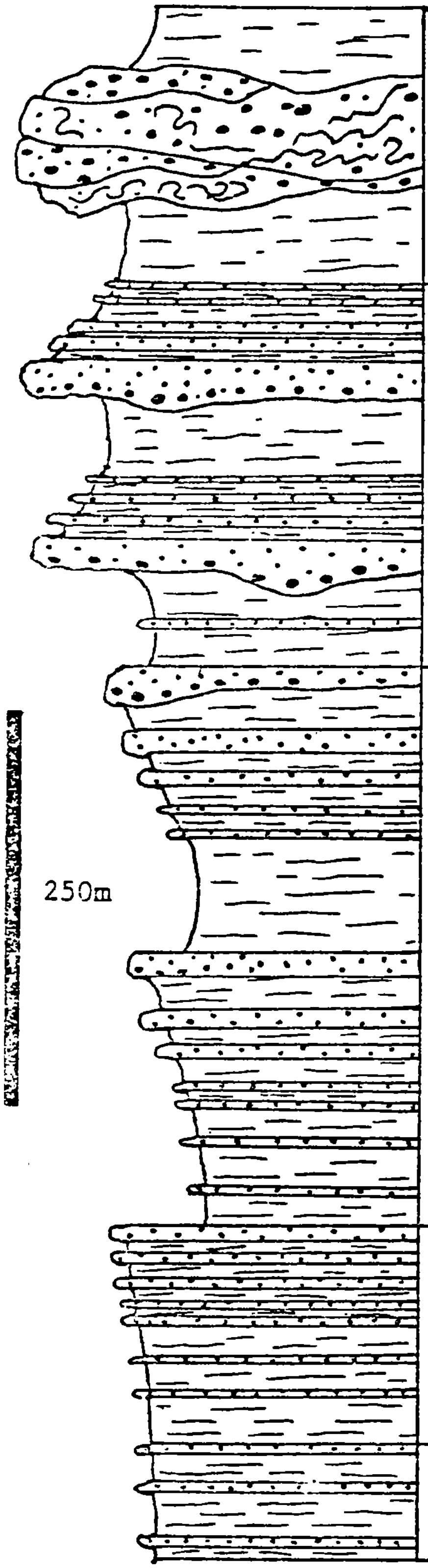
STRUCTURES/TEXTURES	ENVIRONMENT
Dolomite & evaporites: bedded & nodular; eolianites, mudcracks, stromatolites, chaotic & birdseye struct.	Sabkha
Dolomite: stromatolites, polygonally cracked at top & filled with eolian clastics; edgewise conglomerates.	Mean high water Algal flat
Carbonate wackestones & packstones: skel. grains, pellets; bioturbated.	Mean low water Lagoon

ig. 0-4 Ideal algal flat sabkha intertidal sequence (see references F3, F5); thickness is governed by paleotidal range, provided grazing subtidal organisms trim deeper edge of algal mat; cyclicity is dependent upon tectonic or eustatic fluctuations in relative sea level; primary features are commonly destroyed or disrupted by solution, diagenesis, or diapirism.



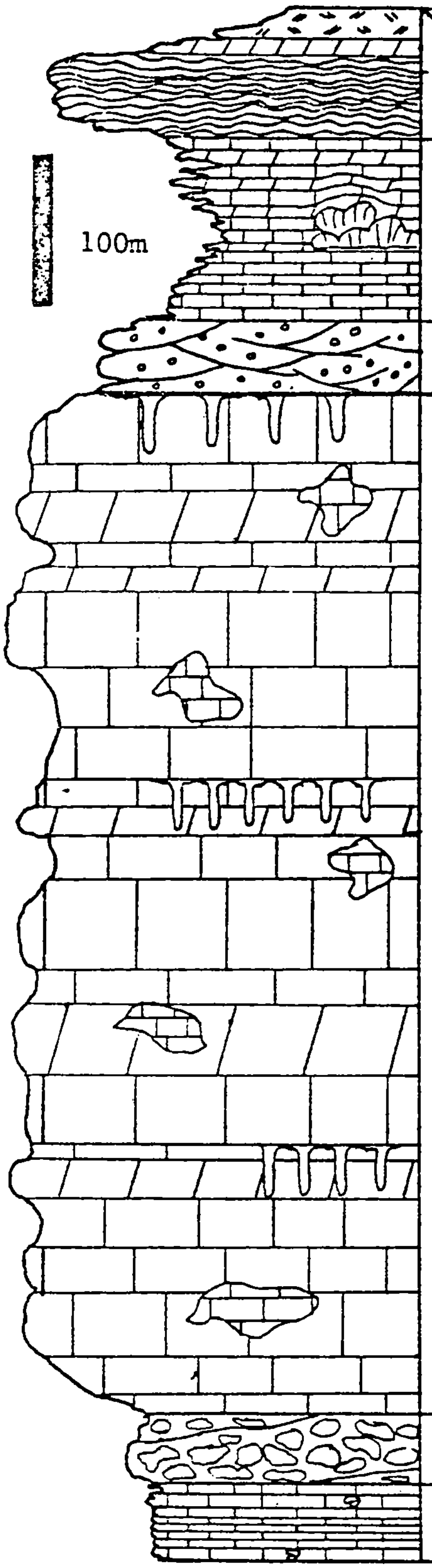
STRUCTURES/TEXTURES		ENVIRONMENT
Mudst.: marine; poss. oyster reefs.	Destructional	Peri-delta marine
Ss.: typical dune & beach features; coarsening upward; shell debris.		Chenier
Mudstone: structureless, burrowed, rooted; peaty layers, logs, shells.	Delta constructional phase	Swamp & marsh
Silty sandstone & silty clay: ripple-laminated; organic-rich, burrowed.		Natural levee
Ss.: fine-to med.-grained, well-sorted, ripple-laminated, cross-bedded; scour & fill, contorted bedding, channel geometries.		Distributary channel
Sandstone & siltstone: better sorting & coarsening upward, wave & current rippled, multi-directional cross-beds; plant debris laminae; gas heave structures; bar geometries.		Distributary channel mouth bar
Shaley siltstone: parallel & cross-laminated (upper part); shells, plants, shale clasts common; soft-sediment deformation structures.		Delta front
Silty shale: parallel & lenticular silt laminae common, thinning seaward; abundant fauna & burrowing.		Prodelta

Fig. 0-5 Ideal constructional-destructional deltaic succession (see references H13, H14); scale is arbitrary; repetitions may occur in response either to delta-switching, or to tectonic or eustatic fluctuations in relative sea level.



STRUCTURES/TEXTURES	ENVIRONMENT
Cgl., pebbly ss., olistostromal masses: irregular, massive, channeled sequences encased in mudstone.	Inner fan
Sandstone & mudstone: complete & base cut-out turbidites, pebbly sandstone, & sandstone with dish structures, amalgamated sandstone, in thinning upward sequences; channeling.	Middle fan (thinning upward related to channel switching)
Sandstone & mudstone: complete & base cut-out turbidites, pebbly sandstone, & sandstone with dish str., some channeling, in upper part; base cut-out turbidites in lower part; thickening upward sequences.	Depositional lobes of outer fan (thickening upward related to aggradation of lobes)
Sandstone & claystone: base cut-out turbidites, increasing upward in frequency & thickness.	Outer fan (upward frequency increase related to fan progradation)
Claystone & occasional base cut-out turbidites.	Basin plain

Fig. 0-6 Ideal progradational deep-sea fan succession (see references J11, J12); diagram is highly schematic; thinning-upwards and thickening-upwards turbidite packets within the succession are related to fan-channel migration; where major sedimentary progradation occurs along the flank of a deep marine basin, such a fan succession may merge upward into deltaic deposits (see fig. 0-5).



STRUCTURES/TEXTURES	ENVIRONMENT
Stromatolitic dolomite & evaporites.	Algal flat/sabkha
Micrite, wackestone, packstone: pellet & skeletal debris; dolomitization common; local 'round' hexacoral reefs.	Lagoon +/- patch reefs
Oolite: well-sorted, in dune forms; skeletal debris.	Intrareef/backreef
Boundstone (biolithite): may be algal, coralline, crinoidal, etc.; hexacoral reefs show rib and furrow structure (exaggerated here); large primary & solution voids (also exaggerated), which may be filled with later sediment; dolomitization common; subaerial exposure results in pisolitic horizons; non-reef building organisms common.	Organic reef
Breccia: angular reef rubble.	Forereef talus apron
Micrite: dark carbonate, commonly in turbidites; pelagic organisms.	Basin

Fig. 0-7 Ideal progradational reef-bank succession (see references 13, 19); scale is arbitrary; full development is dependent upon suitable paleolatitude and paleoclimate in areas without pronounced clastic sedimentation; repetitions may occur in response to tectonic or eustatic fluctuations in relative sea level; pronounced diagenetic modifications of primary features are common.

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