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GEOLOGICAL SURVEY

Platform margin and deep water carbonates:

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PART 1. INTRODUCTORY PERSPECTIVES, BASIC CARBONATE PRINCIPLES, AND STRATIGRAPHIC AND DEPOSITIONAL MODELS

INTRODUCTION

The increased need to find new energy resources in deep marine frontier environments has clearly intensified the importance and interest in deep water carbonate settings and how these settings interrelate to adjacent shoal water platform margins. Coarse-grained mass-flow deposits beyond the shelf break in terrigenous clastic environments have been known for many years to form major petroleum reservoirs (Barbat, 1958), and it is likely that similar deep-water clastic facies will continue to be future exploration targets (Hedberg, 1970; Curran et al, 1971; Gardett, 1971; Nagel and Parker, 1971; Schlanger and Combs, 1975; Walker, 1978; Wilde et al, 1978; Howell and Normark, 1982). With the concept of plate tectonics, seismic stratigraphy, advances in seismic-reflection technology and cycles of relative sea level change, a more sophisticated approach to understanding the developments of deeper water environments has emerged (Cook and Enos, 1977a, b; Doyle and Pilkey, 1979; Stanley and Moore, 1983). Consequently, this understanding has placed more emphasis on the geological history and petroleum potential of slope and basin margin settings (for example, Hedberg, 1970; Burk and Drake, 1974; Weeks, 1974; Bouma et al, 1976; Thompson, 1976; Wang and McKelvey, 1976; Bloomer, 1977; Schlee et al, 1977; Mattick et al, 1978; Krueger and North, 1983).

Well-documented examples of petroleum reservoirs in carbonate slope and basinal settings are fewer in number than their terrigenous clastic counterparts. However, discoveries of major petroleum accumulations in upper Paleozoic-lower Cenozoic slope facies have stimulated interest in deep water carbonates (Cook et al, 1972; Enos, 1977a, in press; Viniegra-O, 1981; Cook, 1983, in prep. b). It is likely that more deep-water carbonate reservoirs will be discovered as exploration and research continue in this domain (Cook et al, 1972; Cook, 1979a; Cook and Enos, 1977b; Enos, 1977a, b, in press; Scholle, 1977; Flores, 1978; Mullins et al, 1978; Mullins and Neumann, 1979; Santiago, 1980; Cook and Egbert, 1981a; Viniegra-O, 1981; Cook, 1983; Cook and Mullins, 1983; Enos and Moore, 1983; Mullins and Cook, in prep.).

The ultimate purpose of this short course is to improve approaches and ideas related to petroleum and mineral exploration in platform margin and deeper water carbonate environments. To this end emphasis is placed on understanding depositional environments, their contained facies, and diagenetic patterns. Better geologic interpretation of these three elements in carbonate sedimentology and facies analysis are usually critical in petroleum exploration. These elements are also receiving wider importance in base metal exploration as many mineral deposits in carbonates are controlled by primary depositional patterns and not simply due to tectonics and/or proximity to igneous intrusions (Callahan, 1977).

One of the necessary steps in carbonate exploration lies in predicting the location of porous and permeable zones likely to be commercial reservoirs. Because depositional facies and facies patterns often control depositional porosity trends and strongly influence post depositional diagenetic patterns in carbonates it follows that the correct recognition of environments and knowledge of depositional trends and sequences in these environments can provide important advantages in designing exploration and production strategies.

To achieve these goals focus in this volume will be on 1) The nature, origin and interrelationships of facies transitions through platform margins, slope, apron, fan, and basin-plain environments, 2) biofacies characteristics and their influences on carbonate facies characteristics in the modern and ancient, 3) depositional and diagenetic facies and facies associations and their relation to carbonate ramp, rimmed shelf, debris sheet, apron, and fan models, and 4) potential source rocks, reservoirs, and traps in both platform margin and deep-water carbonate sequences.

BASIC CARBONATE PRINCIPLES

A basic tenant that is implicit throughout this volume is that the better we understand the origin of rocks the more likely we will be to understand their depositional and diagenetic patterns, and accordingly be better equiped to make well founded stratigraphic predictions.

The following principles or precepts of carbonate sedimentology and stratigraphy can be thought of as guidelines by which a carbonate geologist attempts to decipher the data base at hand and to generate ideas, models, and exploration approaches. This data base may consist of only a handful of drill cuttings or it may include a diverse array of electric logs, seismic data, cores, and even beautifully exposed mountains of carbonate rocks. The intangible data base is, of course, the experience, perspective, and imagination of the person interpreting these data.

These principles have evolved from studies of modern carbonate environments as well as ancient carbonate sequences throughout the geologic column. Included in Wilson (1975) and Wilson et al (1983) is a great deal of wisdom encapsulated within a relatively few pages. The discussion below draws on these two references as well as the author's own experience and observations in different parts of the world.

Depositional Environments

Much of what we know about carbonate depositional environments originated from studies of modern sediments particularly during the 1950's and 1960's, in Florida, the Bahamas (Figs. 1-1, 1-2), Belize, the Persian Gulf, and the Pacific Atolls (ex: Newell et al, 1953; Newell and Rigby, 1957; Purdy, 1963; Ginsburg and Shinn, 1964; Schlanger, 1964;

Purser, 1973). The application of these modern studies to help in the interpretation of ancient depositional environments and their contained facies patterns was forcefully presented by Newell et al (1953) in their classic study of the Permian Reef Complex of west Texas. Subsequently a number of studies on ancient carbonate sequences have amplified modern observations, have better established the parameters most likely to be preserved in the ancient record, have demonstrated the geologically long ranging characteristics of many environments, and have made significant inroads in establishing the nature and origin of deep water carbonate environments (ex: Pray and Murray, 1965; Friedman, 1969; Laporte, 1967, 1974; Wilson, 1975; Cook and Enos, 1977b; Reading, 1978; Cook, 1979; Doyle and Pilkey, 1979; Toomey, 1981; James and Mountjoy, 1983; Cook and Mullins, 1983; Enos and Moore, 1983; Scholle et al, 1983a, b).

There are five basic depositional environments in carbonate systems: 1) an inner shelf or shelf lagoon which is associated with tidal flats; 2) a middle shelf; 3) an outer shelf; 4) a slope; and 5) a basin (Figs. 1-3 - 1-10. Each of these five settings can be divided into one or more subenvironments (i.e. see the beautifully illustrated carbonate environments in Scholle et al, 1983a). It is well to keep in mind that the scale of most environments can vary dramatically depending on whether the carbonates formed on a broad continental margin 100's of kilometers wide or on isolated platforms whose widths may only have been a few 10's of kilometers or less (Fig. 1-11).

Most carbonate sediment that forms in a shelf environment is the product of shallow, warm, clear marine waters at low latitudes. The outer shelf environment which often is referred to as the shelf-edge, reef margin, bank margin, skeletal margin, etc., is commonly a high energy, well-circulated zone on the shelf. Middle shelf settings are subject to sea water mostly of normal salinity, water depths from a few meters or less to one or two hundred meters, well oxygenated water, and water conditions commonly below wave base. The inner shelf is characterized by restricted marine to hypersaline marine conditions. Inner shelf environments include the shallow subtidal "shelf lagoon" setting of many authors as well as carbonates that formed on tidal flats under supratidal, intertidal, and shallow subtidal conditions. Slope and basin environments are normally below effective wave and storm base. Bottom waters in these deeper water environments can range from well-circulated and highly oxygenated to stagnant and anaerobic.

A fundamental difference between carbonate and terrigenous clastic provinces is that carbonate generation is essentially autochthonous. That is, whereas terrigenous clastic shelf sands may have originated 1000's of kilometers from their current site, carbonates usually formed close to where they are found. As stated by Laporte (1974) "intrabasinal factors control facies development". Less formally stated this can be called the principle of "What you see is what you get", i.e. the lithofacies and biofacies in a particular modern carbonate environment are being generated in that environment and, with only a few exceptions, these sediments will remain relatively close to their site of origin to become ancient carbonates. A notable exception to this principle is the fact that carbonate mass flows, such as debris flows or turbidity current flows, can be generated in outer shelf settings and these flows can transport large volumes of shoal-water carbonates into a deep-water basinal environment. In fact, the rigid application of the "What you see is what you get" principle has been responsible for misinterpreting deep water allochthonous carbonates as in situ shoal water carbonates (Cook, et al, 1972).

Carbonate Components

All carbonate rocks are composed of only four major components: these are 1) fossils or fossil fragments, 2) ooids and/or other coated grains, 3) carbonate mud as micrite, as pelloids, and as intraclasts, and 4) carbonate cement. These four components are made up of only four basic carbonate minerals - 1) aragonite, 2) calcite, 3) magnesian calcite, and 4) dolomite.

The composition of skeletal debris is highly variable depending on the taxonomic group (Fig. 1-12). Ooids are initially magnesian calcite or aragonite. Carbonate mud as in Florida Bay is made up of fine-grained aragonite needles whereas deep-water carbonate micrite can consist wholly of calcite coccoliths (Cook and Egbert, 1983). The fourth component, carbonate cement can consist of aragonite, magnesian calcite, and/or calcite.

Textural Considerations

A corollary to the principle of "What you see is what you get" is that because most carbonate grains accumulate where they are produced, the textures of many carbonate sediments are highly dependant upon the nature of the contributing organic or inorganic producers rather than on external processes as in terrigenous clastic systems. Thus, a carbonate sediment can originate with carbonate particles of a wide variety of shapes and sizes. If these constituents undergo relatively little net transport, as is commonly the case, special care must be taken in interpreting this texture. An example that well exemplifies this point is that in some middle shelf low energy settings large pebble sized, articulated crinoid columns can be admixed with abundant lime mud. The message here is that the presence or absence of interpreted original lime mud is considered a better guide to water energy than grain size or shape.

With the above and other concepts in mind Dunham (1962) designed a simple yet eloquent classification of carbonate rocks. His classification is simple to use, descriptive, yet his descriptive modifiers have powerful genetic overtones (Fig. 1-13). In this classification the focus is on the presence or absence of interpreted original lime mud, and whether or not the sediment is grain-supported or matrix-supported. Because carbonate mud can be generated in situ in both quiet water and high energy environments the presence of mud in a carbonate rock tells us something about the energy level or currents of removal at that site. Likewise rather than simply stating that a carbonate rock contains a certain percentage of grains the concept of a grain-support fabric implies emphatically that the rock is full of its particular assortment of grains. Also because the shapes of carbonate grains can vary from spherical oolites to platy algal fragments an oolite grainstone contains a higher percentage of grains than does a Halimeda algal grainstone - the common genetic denominators, however, are that both rocks are grain-supported and contain as many grains as the shape of the constituents will geometrically allow.

Facies, Facies Genesis and Distribution

As discussed above both organic and inorganic carbonate particles are produced essentially in situ, in a variety of shapes and sizes, and many facies types accumulate and remain where produced with relatively little net transport. During storms obviously some transport takes place in carbonate sand shoals and in outer shelf settings. Maximum transport occurs in deeper water environments where mass transport processes are common.

Facies genesis is a function of many variables. Some of the variables that appear to exert the strongest control, however, include tectonic setting, water energy, light conditions, circulation, fluctuations in relative sea level, sediment dynamics at the outer shelf-slope margin, age of the carbonate province, and diagenesis. In spite of numerous variables, the basic types of facies that are formed in basin, slope, and shelf environments are surprisingly regular and their lateral distribution is reasonably predictable (Fig. 1-14). As Wilson (1975) points out concerning these nine facies belts "it is significant that this pattern is so persistent; it offers essentially a single model for prediction of geographic distribution of rock types. It thus becomes a tool in practical field mapping, in designation of rock units for correlation purposes, for depositional interpretations, and in the search for petroleum and for metallic ores such as lead, zinc, and silver, whose distribution may be facies controlled".

Not all the shallow water facies belts shown in figure 1-14 are necessarily developed in any one carbonate system. On the other hand since 1975 the deeper-water slope environments as well as platform margins have received increased study and a variety of new facies can now be documented for these settings (Cook and Mullins, 1983; Halley et al, 1983). Facies belts in platform margin and deep water settings can vary in width, being narrower and well defined where the shelf and slope is steep and rapid seaward progradation is evident. Conversely on low gradient stable shelves and slopes the facies belts can be quite wide and rather diffuse.

Rates of Sedimentation

An important point that must be included in any examination and interpretation of carbonate sequences is a paradox that carbonate geologists have noticed for years. Wilson (1975, p. 15, 16, 18) stated it well by noting that carbonate sedimentation can be extremely rapid with growth rates of Holocene shallow-water carbonates and reefs being at least one order of magnitude higher than net accumulation rates of ancient carbonate sequences (Table 1-1). Wilson (1975, p. 16) goes on to say that "when conditions remain favorable, carbonate production can keep up with almost any amount of tectonic subsidence or eustatic sea level rise". Thus, even though carbonate deposition is rapid it is easily inhibited and therefore through geologic time it must have been sporadic. An excellent paper by Schlager (1981) presents new data that supports the earlier ideas of Wilson (1975) as well as offering suggestions as to why drowned platforms are common in the geologic record, even though "there should be no drowning of platforms at all" (Schlager, 1981, p. 198).

The paradox of drowned reefs and carbonate platforms can be put in perspective by examining the data in figures 1-15, 1-16, and Table 1-2. In essence what these data show are: (1) modern carbonates have average potential growth and/or sedimentation rates of about 1,000 Bubnoffs (i.e. 1 Bubnoff equals 1 micron (um)/year, or 1 mm/thousand years, or 1 m/million years), (2) relative sea level rise due to subsidence of new oceanic crust is 250 Bubnoffs, (3) long-term basin subsidence rates are about 10-100 Bubnoffs, (4) sea level rise due to seafloor spreading is <10 Bubnoffs, (5) early Holocene glacio-eustacy sea level fluccuations were 500-8,000 Bubnoffs, (6) ancient carbonate sequences accumulated vertically at rates of about 30 to 150 Bubnoffs and rarely at 300-500 Bubnoffs, (7) ancient carbonate sequences that exhibit seaward progradation must have had potential growth and/or sedimentation rates far in excess of their vertical accumulation rates. For example horizontal seaward progradation of some Upper Devonian carbonate complexes in Alberta, Canada is estimated to have been about 750-1,000 Bubnoffs (750-1,000 m/my) which is significantly greater than its' estimated overall vertical accumulation rate of about 50-80 Bubnoffs (50-80 m/my) (Cook, unpublished data).

The above seven points strongly suggest that the growth potential of many drowned carbonate platforms was in excess of their net accumulation rates. Relative sea level rises (10-250 Bubnoffs) caused by long term geologic processes do not appear to be great enough to drown healthy carbonate platforms that exhibit the capability of seaward progradation on the order of 1,000 Bubnoffs.

Schlager (1981) suggests that "causes of platform downing include (1) reduction of benthic growth due to environmental stress, such as (a) global salinity drops due to fresh-water injections or excessive evaporite deposition or (b) regional deterioration during drift to higher latitudes; or (2) rapid pulses of relative sea level, such as regional downfaulting or global rises due to desiccation of small ocean basins, submarine volcanic outpourings, or glacio-eustacy".

Stratigraphic Sequences

The above sedimentologic principles have been discussed mainly in a two-dimensional context. The third-dimension, that of time, is what leads to the development of stratigraphic sequences. Carbonate platform margins can evolve through time and space in several ways (Fig. 1-17).

The depositional style or combination of styles that a platform margin exhibits is a function of numerous variables some of which include relative sea level changes, sedimentation rates, type of facies at the platform margin, age, and tectonic activity. Stratigraphic sequences are discussed in detail in this chapter under "Stratigraphic Models".

Diagenetic Considerations

Diagenesis is commonly considered to include all processes and events that a sediment undergoes after deposition, but before metamorphism. This definition is rather confining especially in situations where biotic constituents such as coral heads can undergo significant amounts of bioerosion. In these cases bioerosion could be considered a diagenetic process. Also, in deeper water carbonate environments it is important to understand the modifications that can occur to biogenic particles before they reach the sediment-water interface. This is useful in order to gain a clearer perspective of what sediment features are inherited versus those changes that are of a depositional origin (Cook and Egbert, 1983).

Carbonate sediments and rocks have a high susceptibility to change, that is, they have a high diagenetic potential. In its simplest form, the diagenetic potential of a carbonate sediment or rock is a measure of its geochemical-textural-constituent maturity. Schlanger and Douglas (1974) introduced this concept for deep-sea carbonates but it is an equally useful concept for shallower water carbonates.

Diagenetic processes include, but are not limited to, gravitational compaction, geochemical compaction, mineral stability transformations such as the transformation of aragonite and magnesian calcite to calcite, solution (dissolution), pressure-solution, cementation, organic rotting, bioerosion, crystal rearrangement (neomorphism), dolomitization, and fracturing.

In petroleum and minerals exploration and production, major emphasis is placed on better understanding diagenetic environments and the geologic processes in these environments that lead to porosity modifications. Major processes that lead to a decrease in porosity include cementation and compaction (both gravitational and geochemical). Processes that can enhance porosity consist of dissolution, dolomitization, and fracturing. As shown in figure 1-18 the dominant trend from modern carbonate sediments to ancient carbonates is toward an overall reduction in porosity. Thus, the mark of a potential carbonate reservoir is one in which the pore-reducing processes were either nonexistant or arrested at some stage, and/or porosity enchancing factors came into existance or were dominant.

The reader is encouraged to read the excellent paper by Choquette and Pray (1970) on porosity in sedimentary carbonates. They compare the porosity in carbonate versus terrigenous clastic rocks, make a clear distinction between fabric-selective porosity and non-fabric selective porosity and discuss major surface and burial zones in which porosity is created or modified (Figs. 1-19 - 1-21).

Figures 1-22 - 1-34 are included in this chapter to illustrate the basic diagenetic environments as presently conceived for carbonate systems, the processes that are active in these environments, petrographic criteria for recognizing the different cement types that form in various diagenetic realms, and the relationship between burial depth and possible porosity enhancing and reducing processes.

STRATIGRAPHIC MODELS

As used in this chapter stratigraphic models are an attempt to explain the vertical facies changes (i.e. the stratigraphic sequences) that occur at the platform margin-to-slope transition. Two recent publications (Playford, 1980; James and Mountjoy, 1983) illustrate the basic ways in which platforms can evolve through time in response to varying rates of relative sea level change, basin subsidence, sedimentation rates, and tectonic activity. Relative sea level rise or fall is herein used to refer to the net effect of sea level movement and subsidence.

Playford (1980) depicts six situations (Figs. 1-35 - 1-37):

1. Upright - carbonate growth and/or sedimentation essentially keeps pace with relative sea-level rise.
2. Advancing - carbonate platform margin advances (progrades) seaward out over deeper water facies.
3. Retreating - carbonate platform margin retreats (retrogrades) back over shallower-water facies.
4. Back-stepping - platform margin retreats sharply, in steps, to a position in the platform interior over shallower-water facies.
5. Drowned/Pinnacle - special situations where platforms are completely drowned and local isolated pinnacle reefs form (steep-sided spires of reef in which the ratio of breadth to height is less than 2:1).
6. Combination - four types of platform margins occur in figure 1-37. A retreating margin in the Givetian, an upright margin in the early Frasnian followed by a drowning and/or back-stepping in the late Frasnian, and finally an advancing platform margin in the Famennian.

James and Mountjoy (1983) present similar models (Figs. 1-38 - 1-40):

1. Stationary - same as Playford's (1980) Upright.
2. Offlap - same as Playfords's (1980) Advancing.
3. Onlap - same as Playford's (1980) Retreating. They include their stepped onlap mode as a type of Onlap (Fig. 1-39).
4. Drowned - drowning or inundation is similar to Playford's (1980) Drowned examples.
5. Emergent - subaerial exposure of shallow water parts of platform, erosion.

6. Combination - they cite Playford (1980) as an example of combination margins (Fig. 1-37).

It is useful at this point to briefly summarize some of the terms in the carbonate literature that are used interchangeably when referring to the different types of platform margin stratigraphic models:

1. Upright and stationary stratigraphic sequences develop during a relative rise of sea level. Both terms refer to platform margins that remained essentially in the same paleogeographic position through time.

2. Advancing, offlapping, prograding, and regressive refer to seaward movement of platform margin facies over deeper water facies. These sequences can develop during both relative sea level rises and falls. The genetic term "regressive" is not recommended for use as it implies that a seaward prograding sequence (i.e. a shoaling upward sequence) only develops during a relative lowering of sea level.

3. Retreating, onlapping, retrograding, and transgressive all refer to platform sequences that record deepening upward facies changes such as platform margin facies being overlain conformably by slope facies. Retrogradational sequences develop during a relative rise in sea level.

Thus, relative changes in sea level can produce different results in platform margin sequences depending on the magnitude and rate of sea level changes, the paleobathymetric position of the shelf edge facies and rates of sedimentation on the shelf edge and inferior parts of the shelf. For example, a relative fall in sea level can cause subaerial solution in tidal flat environments whereas in deeper water shelf edge and basin margin settings the facies may prograde seaward attempting to seek former bathymetric conditions. Alternatively, during a relative rise in sea level the shelf edge can also prograde seaward if sedimentation is faster than sea level rise or retrograde landward if the relative rise in sea level is faster than sedimentation.

Figures 1-35A and 1-38B represent situations where the sedimentation rate is balanced by a relative rate of sea level rise and/or basin subsidence such that the shelf edge simply evolves vertically. Backstepping (Figs. 1-35B, 1-39) can occur when there is a rapid rise in relative sea level and/orfaulting such that a former shelf edge and shelf interior is drowned and a new shelf edge is only able to develop at a later time some distance in a landward direction. Retreating shelf margins (Figs. 1-35C, 1-39) may take place during a relative sea level rise where shelf edge sedimentation cannot quite keep pace with increasing water depths but the sea level rise is not rapid enough to drown the shoal water facies. Advancing shelf edges (Figs. 1-35D, 1-38B) occur during a relative rise or fall of sea level depending on rate of sea level change and rate of depositional processes at the shelf edge.

Figures 1-37 and 1-41 illustrate that two platform margins of the same age can respond differently to a relative rise in sea level.

During the Frasnian (Upper Devonian) the Miette and Ancient Wall isolated buildups in Alberta, Canada evolved in two ways. Initial accumulation was dominated by a retreating phase. Either relative sea level rates slowed and/or sedimentation rates increased as the upper half of these buildups rapidly prograded seaward (Cook, 1972; Cook et al, 1972). In contrast to these Canadian buildups, during the Frasnian, platform margins in the Canning Basin of western Australia developed in both an upright and back-stepping manner. Local tectonism in the Canning Basin (Playford, 1980), imprinted on what is considered to be a eustatic rise in sea level during the Frasnian, may account for the differences in these two platform margins.

Geologic age can clearly affect the manner in which a platform margin evolves insofar as the major biotic constituents changed and/or became more numerous through time (Figs. 1-42 - 1-44) (Heckel, 1974; James, 1983). Tectonic setting can affect the nature of a platform margin in several fundamental ways. A sudden rapid downfaulting may cause a significant rise in sea level that exceeds the sedimentation rate of the platform margin. In extreme cases the platform may be drowned or forced to back step (ex: Playford, 1980; Winterer and Bosellini, 1981; Bosellini, in press). Drifting continental plates may move into colder latitudes thereby causing a gradual yet irreversible deterioration of the carbonate generating constituents. Then when a modest sea level rise occurs the diminished growth potential of the platform is unable to keep pace and drowning occurs.

For any significant amount of vertical accumulation there must be regional subsidence of the platform and basin. An excellent example of long term subsidence coupled with eustatic sea level flucculations through time is seen in the Paleozoic continental margin carbonates in the Basin and Range Province of the western United States (Fig. 1-45). Here Cambrian through Devonian sedimentation produced over 5,000 meters of platform margin and deep water carbonates that collectively exhibit all the stratigraphic models discussed above (Cook and Taylor, 1975, 1977; Cook, 1979; Cook and Mullins, 1983; Cook and Taylor, 1983).

DEPOSITIONAL MODELS

Over the last twenty years detailed models for both modern and ancient carbonate systems have been developed. Coupled with these models there has been an improved understanding of the interrelationships, between plate tectonics, paleontological studies, carbonate sedimentology, relative changes in sea level, and the evolution of carbonate shelf edge, slope, and base-of-slope settings. All of these and other factors have led to significantly improved interpretation of carbonate systems as well as enhancing the ability to make subsurface stratigraphic predictions.

One of the primary reasons for studying modern carbonate environments and facies is to more fully and accurately interpret ancient rocks. Many modern environments provide us the direct observation and measurement of sedimentary processes. This is true in shallow water environments where direct observation is possible. In deeper water slope and basin environments submersibles are being used with more frequency as well as using ancient deep water sequences to assist in understanding deep water modern settings (Cook, 1979; Cook and Mullins, 1983).

Depositional models can be an aid in understanding and correctly interpreting lateral and vertical facies transitions and for assigning facies and facies associations to a certain depositional environment. Although there are only a relatively small number of basic depositional environments in carbonate systems there are sub-environments within each setting and numerous variables that have the potential to lend considerable variation to the sediments themselves. Some of the larger scale variables include the nature of the paleobathymetric profile of the depositional interface, the type of platform margin in terms of whether it is dominantly a reef or sand shoal and the effects on marine circulation behind the platform margin, tectonic setting, evolutionary patterns of organisms, climatic variations, sea level fluctuations, and influx of terrigenous clastics. Smaller scale influences include a myriad of inorganic and organic depositional and post depositional processes.

In using depositional and stratigraphic models for making environmental and facies interpretations one must remember that <u>models are basically summary statements</u> and as such one should expect to see details at the scale of an outcrop that reflect local variability. In spite of the many factors that can affect facies and facies patterns it is these very factors that commonly exert predictable controls on the location, geometry, and overall characteristics of depositional facies. Thus, the major facies sequences that characterize different depositional environments, from boulder-bearing deep water fan and apron deposits to supratidal muds (Figs. 1-4 - 1-10; 1-14), rarely were developed at random within a carbonate system--there is a reason for the distribution patterns of depositional facies.

Models can be an aid in guiding us to know what to look for, to give a modicum of predictability, and to allow the flexibility of modifying and updating models. A distinct danger is that of becoming too attached to a model--at this point one can lose objectivity and force new data to fit a particular model rather than modifying the model or seeking a new model to help explain the data.

There are a number of carbonate platform margin and deep water depositional models based upon examination of ancient sequences. All, for the most part, recognize or imply the concept of rimmed platform margins or non-rimmed platform margins (i.e. ramps). Table 1-3 defines some terms commonly used by carbonate geologists. Table 1-4 compares the four classifications of platform margin models discussed below. The models in table 1-4 have been developed mainly from ancient carbonates.

Platform Margin Models

Wilson (1975) by examining a large number of ancient settings recognized nine basic facies belts (Fig. 1-14) which can be found along three carbonate margin profiles (Fig. 1-46):

1. Type I. Downslope Mud Accumulations
2. Type II. Knoll Reef Ramps
3. Type III. Framework Reef Rims

These three profiles are based on level of incoming wave energy. As pointed out in Chapter 3 of this volume his Type III, being the steepest and reef-dominated, resembles most modern reef-rimmed margins. However, good modern analogues for Types I and II do not appear to be clearly available. Conversely, the modern non-rimmed margins of west Florida or Campeche Bank do not seem to comfortably fit in either type although a case could be made for Type II.

Wilson (1975, p. 361-363) cites several ancient examples of his three types of carbonate margins.

James and Mountjoy (1983) as well as McIlreath and James (1978) present a morphologic, process-based series of models (Figs. 1-47 - 1-51). The series of models by James and Mountjoy (1983) updates the earlier version of similar models by McIlreath and James (1978) by including a ramp model and including both shallow and deep basins adjacent to by-pass margins. These models are:

1. Ramp (non-rimmed shelf)
2. Depositional Margin (rimmed shelf)
   a. reef dominated
   b. sand shoal dominated
3. By-Pass Margin (rimmed shelf)
   a. reef dominated — both deep and
   b. sand shoal dominated — shallow basin varieties

The by-pass, reef-dominated model is similar to the modern reef-dominated rimmed model (windward, closed margins of the Bahama Banks). Also, the by-pass, shallow-water lime sand shoal model resembles the modern, sand shoal dominated rimmed margin (leeward, open margin of Bahama Banks). Finally, the ramp model of James and Mountjoy (1983) has some of the same features as the modern West Florida Margin.

A criticism of the models of McIlreath and James (1978) is their restriction of carbonate aprons and submarine fans to the by-pass margin models. As will be discussed in Part 2 of this volume carbonate aprons are also common in ancient depositional margin sequences. Also, documented examples of carbonate submarine fan facies are too rare to know whether or not they are restricted to any one platform margin type (Cook and Egbert, 1981a, b; Cook, 1982; Cook and Mullins, 1983). Thus, the assumption that carbonate fans are restricted to by-pass margins as shown in figures 1-49 and 1-50 is premature. The models of James and

Mountjoy (1983) apparently corrected this by eliminating the use of the terms "aprons" and "fans" in the revised version of depositional margin and by-pass margin models.

Reads' (1982) classification of platform margins (Figs. 1-52 - 1-55) is the most complete scheme yet to be published. It is similar to those mentioned above but he adds several additional variations for which there are ancient examples (ex: distally steepened ramp model). His scheme is:

1. Ramps (non-rimmed shelves)
    a. homoclinal
    b. distally steepened
2. Rimmed Shelves (shelf-edge reefs and/or sand shoals)
    a. depositional or accretionary
    b. by-pass margin escarpment type
    c. by-pass margin gullied slope
    d. erosional margin
3. Isolated Platforms (Bahama Type)
4. Drowned Platforms

Read (1982) gives ancient and modern examples of his models. He cites the Silurian-Devonian of the western United States as being an example of a homoclinal ramp. However, as discussed in Part 2 of this volume these Silurian-Devonian carbonate platform margins are not homoclinal ramps but are accretionary rimmed shelves with sand shoal and coral-rich shelf-edge facies (Cook and Taylor, 1983). Hine (pers. comm.) suggests that the ramp model of James and Mountjoy (1983) has some of the same features as the modern West Florida Margin. Alternatively, because parts of the west Florida slope exhibit major submarine slides and slumps perhaps the distally steepened ramp model of Read (1982) may better apply.

Although figure 1-11 is not a depositional model it makes an important distinction between the scale of platforms on continental margins and those formed within the continental interior. For example, the Basin and Range Province of the western United States is an excellent example of an area where carbonates formed on a broad Paleozoic passive continental margin whereas the Permian Basin of west Texas and the Devonian Basin of Alberta, Canada probably represent intracratonic carbonate basins.

Deep Water Models

The above platform margin models are best suited to explain and understand platform margin morphology and sediment types which are in close proximity to either side of the shelf edge. However, the deeper water slope, base-of-slope, and basinal parts of those models are too overgeneralized, misleading in some places, and lack some of the major predictive elements that reflect actual facies transitions in deep water carbonate sequences. Thus, there is a need for models that provide a similar sophistication and predictive quality for deep water carbonate environments that the submarine fan models do for terrigenous clastic systems (Cook, in prep. b; Mullins and Cook, in prep.).

A dominant attribute of carbonate slope and basin-margin settings is the major role that submarine mass-transport processes have in determining the overall character and stratigraphic sequences in these deeper water environments. Accordingly, depositional models for these environments need to focus on redeposited carbonates. There are basically four end-member models that have been developed from ancient sequences by Cook et al (1972), Cook and Egbert (1981a), Cook (1982), Mullins (1983), Cook and Mullins (1983), Cook (in prep. b), and Mullins and Cook (in prep.). These deep-water carbonate models are illustrated in figures 1-56 - 1-61 and include:

1. Debris Sheet
2. Carbonate Apron (Debris Apron)
   a. slope apron
   b. base-of-slope apron
3. Carbonate Submarine Fan

Debris sheets and aprons can occur adjacent to both depositional and by-pass rimmed shelves. Carbonate submarine fans may require special circumstances. As mentioned above it is not known at this time whether true carbonate fan facies can develop adjacent to both ramps and rimmed shelves.

The two carbonate apron models appear to be applicable to more basin-margin sequences than either the debris sheet or carbonate submarine fan models. Debris sheets are relatively rare but where they are well exposed such as in the Devonian of western Canada (Cook et al, 1972; Cook and Mullins, 1983) they are quite spectacular. A major debris sheet is well documented in modern carbonate sequences from Exuma Sound, Bahamas (Crevello, 1978; Crevello and Schlager, 1980). Carbonate aprons form the vast majority of the redeposited debris in a variety of ancient platform margins in many parts of the world (Cook and Mullins, 1983; Cook and Taylor, 1983) as well as much of the debris in the Bahamas (Schlager and Chermak, 1979; Mullins, 1983; Mullins and Cook, in prep.).

Two end-member types of carbonate aprons can be recognized in ancient sequences. The first is provisionally termed a <u>Slope Apron</u> (Fig. 1-57) because the apron begins at the platform margin and continues down the slope into the basin. Slope apron facies, for example, occur adjacent to some Upper Devonian carbonate complexes in Alberta, Canada (Cook et al, 1972). These carbonate complexes are especially interesting as they contain both episodic megabreccia debris sheets (Fig. 1-56) as well as slope apron facies. The other carbonate apron is termed the <u>Base-of-Slope Apron</u> as most of the platform margin derived sediment gravity flows are deposited at or near the base-of-slope with thinner-bedded debris and turbidity flows continuing seaward into the basin (Fig. 1-58). In situ lime muds on the slope exhibit variable degrees of submarine slumping and sliding. Base-of-slope carbonate aprons have also been recognized in the Bahamas (Mullins, 1983).

At this time there appears to be only two well documented carbonate submarine fans--one from Cambrian-Ordovician carbonates in the western United States (Cook and Egbert, 1981a, b; Cook and Mullins, 1983; Cook, in prep. b) and another in Jurassic rocks of Spain (Ruiz-Ortiz, 1983). There are no documented carbonate submarine fan facies in modern carbonate environments.

All of the above platform margin and deep water models include slope gradient and the presence of a rimmed (reefs and/or sand shoals on the margin) or non-rimmed margin (ramp) as key variables. However, the response of these depositional profiles and their products to organic evolution through time, long-term tectonic effects, relative sea-level fluctuations, and diagenetic processes is still a large area for model refinement and basic understanding.

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Table I-1. Comparison of modern rates of $CaCO_3$ sedimentation with depositional rates of some thick limestone sections (from Wilson, 1975)

Reference	Locality	Maximum thickness meters	Time years	Rate meters per 1000 years	Depositional environment
Enos (1974)	Florida reef tract	25	7000	3+	Reef and debris
Turmel-Swanson (1972)	Rodriguez bank	5	Less than 5000	1+	Open sea bank
Stockman et al. (1967)	Florida bay-Crane key	3	3000	1	Lagoon
Shinn et al. (1965)	Andros Island	1.5	2200	0.7	Tidal flats
Bathurst (1971), and Cloud (1962)		3	3800	0.8	
Illing et al. (1965)	Sabkha Faishak	4	4000	1	Sabkha
Kinsman (1969)	Trucial coast	2	4000–5000	0.5	Sabkha-intertidal
Brady (1971)	N.E. Yucatan	5	5000	1	Lagoonal average from bank thickness
Holocene Average rate of shallow water $CaCO_3$ production[a]				1.0	Lagoons, tidal flat, sebkhas, reefs
Goodell-Garman (1969)	Superior well, Andros Island	4600	120×10^6	0.035	Bank sediment
	Suniland field Florida	4000	120×10^6	0.03	Bank-shallow shelf
Coogan et al. (1972)	Golden Lane bank (Albian-Cenomanian)	1500	20×10^6	0.08	Bank sediment
Wilson, J.L.	Persian Gulf Mesozoic-Cenozoic-maximum	6000	200×10^6	0.03	Shallow marine and tidal flat
Ham, W.E.	Arbuckle Group (Lower Ordovician portion)	3000	100×10^6	<0.03	Tidal flat-lagoonal
Maximum rate of $CaCO_3$ production from ancient rocks				0.04	Variety of shallow sediments like those of Holocene

[a] These figures are maximum thickness of unconsolidated mud or reef growth over Late Pleistocene subaerially exposed and hardened sediment. They represent accumulation since the last sea level rise. (Post-Wisconsin glacial maximum).

TABLE 1-2. PROGRADING PLATFORMS IN THE GEOLOGIC RECORD AND THEIR RATES OF ACCUMULATION (from Schlager, 1981)

Time	Platform	Rate (μm/yr)	Source
Devonian (Givetian/Frasnian)	Canning Basin	30	Playford and Lowrie (1966)
Devonian-Mississippian (Kinderhookian-Meramecian)	Rocky Mountains	50–80	Rose (1976)
Mississippian (Meramecian-Chesterian)	Rocky Mountains	100–150	Rose (1976)
Pennsylvanian Permian	Sverdrup Basin (Nansen Fm.)	30–40	Davies (1977)
Permian (Guadalupian)	Delaware Basin (Capitan Fm.)	75	Harms (1974)
Triassic Late Anisian–Ladinian)	Northern Limestone Alps	100	Ott (1967)
(Early Carnian)	Dolomites (Picco di Vallandro)	300–500	Schlager and others, unpub. data
Late Jurassic	Southern Alps (Friuli Platform)	30–45	Winterer and Bosellini (1981)
Cretaceous (Late Albian–Cenomanian)	Tampico Embayment	60–90	Enos (1977, p. 279–286)

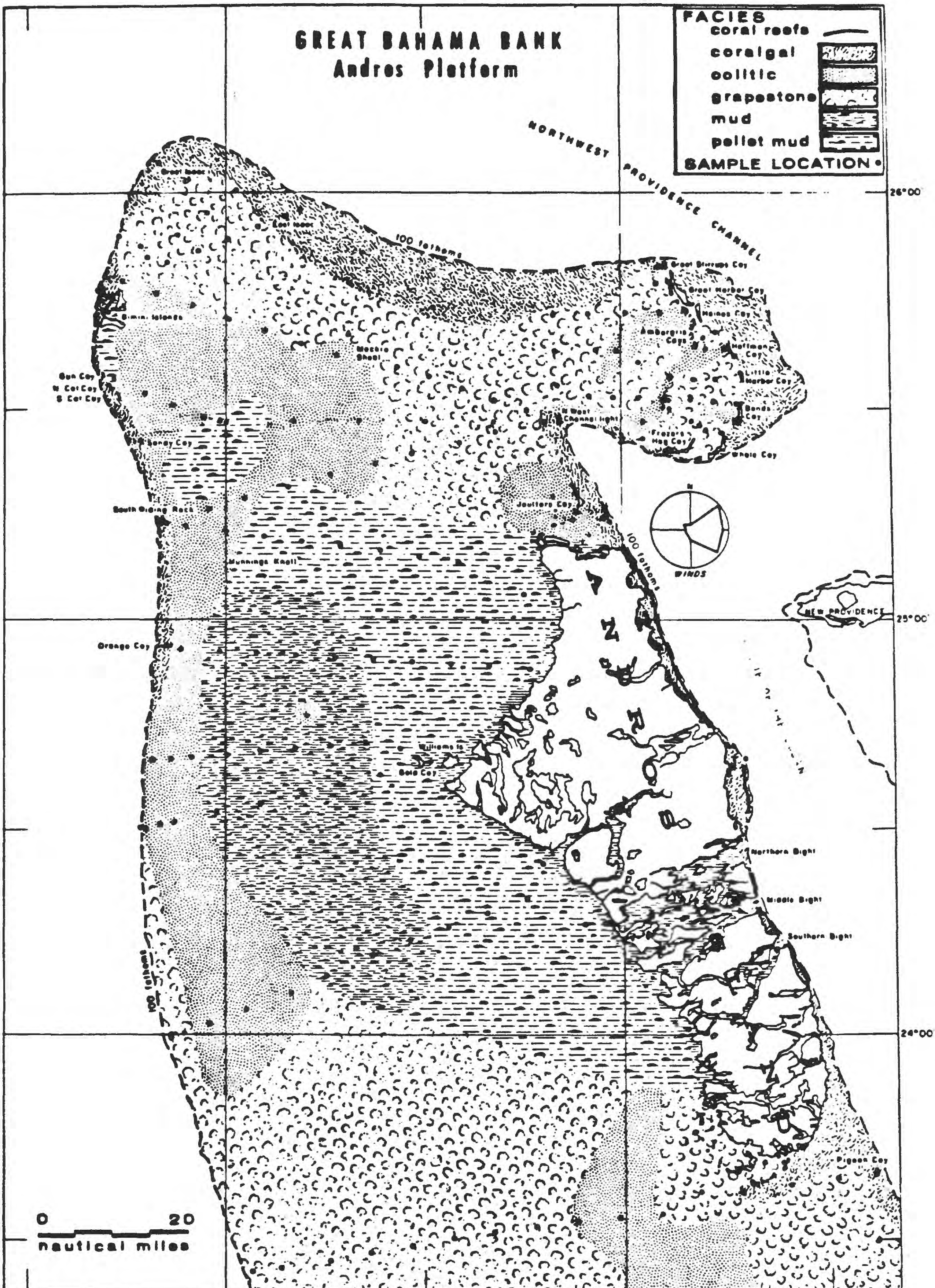
Note: Calculated from stratigraphic age bracket reported for the formation, applying absolute time spans indicated in the Phanerozoic time scale, 1964, Cohee (1978); accumulation rates are not corrected for compaction.

TABLE 1-3. Terminology commonly used by carbonate geologists (from Read, 1982)

WEBSTERS THIRD NEW INTERNATIONAL DICTIONARY	AHR (1973)	GINSBURG AND JAMES (1974)	WILSON (1975)	THIS PAPER
PLATFORM - (LITERALLY "FLAT FORM"). A HORIZONTAL FLAT SURFACE USUALLY HIGHER THAN THE ADJOINING AREA (AS OF FLOOR OR GROUND) OR A FLAT OR NEARLY FLAT AREA OF THE EARTHS SOLID SURFACE EITHER ABOVE OR BELOW THE SURFACE OF THE SEA THAT STANDS ABOVE ADJACENT AREAS ON AT LEAST ONE SIDE.	CARBONATE PLATFORM - A GENERAL TERM USED BY AHR (1973), WHICH INCLUDES SHELVES AND RAMPS		CARBONATE PLATFORM: HUGE CARBONATE BODIES BUILT UP WITH A MORE OR LESS HORIZONTAL TOP AND ABRUPT SHELF MARGINS WHERE "HIGH ENERGY" SEDIMENTS OCCUR. THIS 3 DIMENSIONAL USAGE OF PLATFORM (AND RAMP) CONTRASTS WITH COMMON ENGLISH USAGE OF THE TERMS TO REFER TO SURFACES (2 DIMENSIONAL FEATURES)	PLATFORM: THIS TERM IS USED IN THE SENSE OF AHR (1973) TO INCLUDE BOTH SHELVES AND RAMPS (OF AHR, 1973)
SHELF - A THIN FLAT USUALLY LONG AND NARROW PIECE OF WOOD OR OTHER MATERIAL FASTENED HORIZONTALLY AT A DISTANCE FROM THE FLOOR (AS ON A WALL OR FRAME) TO HOLD OBJECTS; OR SOMETHING RESEMBLING A SHELF IN FORM OR POSITION; OR THE SUBMERGED BORDER OF A CONTINENT OR OF AN ISLAND EXTENDING FROM THE SHORELINE TO THE DEPTH AT WHICH THE SEA-FLOOR BEGINS TO DESCEND STEEPLY TOWARD THE BOTTOM OF THE OCEAN BASIN.	SHELF - NEARLY FLAT PLATFORM WITH A CLEARLY DEFINED SHELF-SLOPE BREAK. MUDDY ROCKS ON THE INNER SHELF PASS DOWNDIP INTO BOUNDSTONES AND GRAINSTONES AT THE SHELF MARGIN. CONTINUOUS REEF TRENDS (RATHER THAN PATCH REEFS) PRESENT.	RIMMED SHELVES - THOSE IN WHICH A CONTINUOUS OR SEMICONTINUOUS RIM OR BARRIER ALONG THE SHELF MARGIN RESTRICTS CIRCULATION AND WAVE ACTION ON THE ADJACENT SHELF LAGOON.	SHELF: AN AREA ON TOP OF A RAMP OR PLATFORM. NOTE THAT WILSON'S USAGE OF THIS TERM REFERS TO A SURFACE (2 DIMENSIONAL) WHEREAS THE OTHER TERMS USED BY WILSON (1975) ARE 3-DIMENSIONAL AND REFER TO CARBONATE BODIES	RIMMED CARBONATE SHELF: A SHALLOW PLATFORM WHOSE OUTER EDGE HAS A SHALLOW RIM AND IS MARKED BY A PRONOUNCED INCREASE IN SLOPE (COMMONLY FEW DEGREES TO OVER 45°) INTO DEEP WATER. SHELF EDGE DOMINATED BY LIME SANDS, AND REEFS THAT MAY FORM CONTINUOUS TRENDS. ABUNDANT SEDIMENT GRAVITY FLOW DEPOSITS CONTAINING PLATFORM DERIVED MATERIAL (TURBIDITES, MEGABRECCIAS) DOWNSLOPE FROM THE SHELF EDGE. DIVIDED INTO DEPOSITIONAL (ACCRETIONARY) MARGINS, BYPASS MARGINS, EROSIONAL MARGINS
RAMP - A SLOPING FLOOR OR WALK LEADING FROM ONE LEVEL TO ANOTHER.	RAMP - A SLOPING TOPOGRAPHIC SURFACE ON WHICH FACIES ARE DEPOSITED WHILE SUBJECT TO OPEN OCEAN CONDITIONS FROM THE SURF ZONE TO DEPTH OF HUNDREDS OF FEET. GRAINY FACIES ARE DEPOSITED NEAR THE SURF ZONE AND THE ADJACENT MAINLAND, AND PASS DOWNDIP INTO MUDDY SEDIMENTS. CONTINUOUS REEF TRENDS ABSENT.		CARBONATE RAMPS: HUGE CARBONATE BODIES BUILT AWAY FROM POSITIVE AREAS AND DOWN GENTLE REGIONAL PALEOSLOPES. NO STRIKING BREAK IN SLOPE EXISTS, AND FACIES PATTERNS ARE APT TO BE WIDE AND IRREGULAR BELTS WITH THE HIGHEST ENERGY ZONE RELATIVELY CLOSE TO THE SHORE	CARBONATE RAMP: SHALLOW, GENTLY SLOPING PLATFORM (SLOPES TYPICALLY LESS THAN 1°) THAT LACKS A MARKED BREAK IN SLOPE. GRAINSTONES COMMONLY IN UPDIP POSITION, AND MAY ALSO BE ASSOCIATED WITH LOCAL BUILDUPS DOWNDIP. CONTINUOUS REEF TRENDS ABSENT; BUILDUPS TYPICALLY SEPARATE AND DISCRETE. DOWNSLOPE, SEDIMENT-GRAVITY FLOW DEPOSITS CONTAINING CLASTS OF SHALLOW PLATFORM ROCKS ABSENT, EXCEPT ADJACENT TO LOCAL BUILDUPS. DIVIDED INTO HOMOCLINAL AND DISTALLY STEEPENED RAMPS
			MAJOR OFFSHORE BANKS: COMPLEX CARBONATE BUILDUPS OF GREAT SIZE AND THICKNESS WELL OFFSHORE FROM THE COASTAL RAMPS OR PLATFORMS	ISOLATED PLATFORM: ISOLATED SHALLOW WATER PLATFORMS TENS TO HUNDREDS OF KILOMETERS WIDE, THAT ARE SURROUNDED BY DEEP WATER. COMMONLY STEEP SIDED. MARGINS MAY BE DIVIDED INTO ACCRETIONARY, BYPASS AND EROSIONAL.
		OPEN SHELVES - TYPICAL OF MOST SHELVES BORDERING CONTINENTS IN TODAYS OCEANS. LACK OF AN ELEVATED RIM ALLOWS TIDAL FLUSHING AND SWELL TO EXTEND ACROSS MOST OR ALL OF THE INNER SHELF. ,		DROWNED (OPEN) PLATFORM: WHERE SUBSIDENCE OR SEALEVEL RISE EXCEEDS UPBUILDING, PLATFORMS (RAMPS, SHELVES, ISOLATED PLATFORMS) MAY BE DROWNED. MARGIN FACIES ASSOCIATED WITH RAMPS, SHELVES OR ISOLATED PLATFORMS MAY DEVELOP ADJACENT TO POSITIVE ELEMENTS (FAULT BLOCKS, FOLIATED DOMES, ARCHES AND OROGENIC SHORELINES), AT CONSIDERABLE DISTANCE FROM THE EARLIER SEAWARD MARGIN.

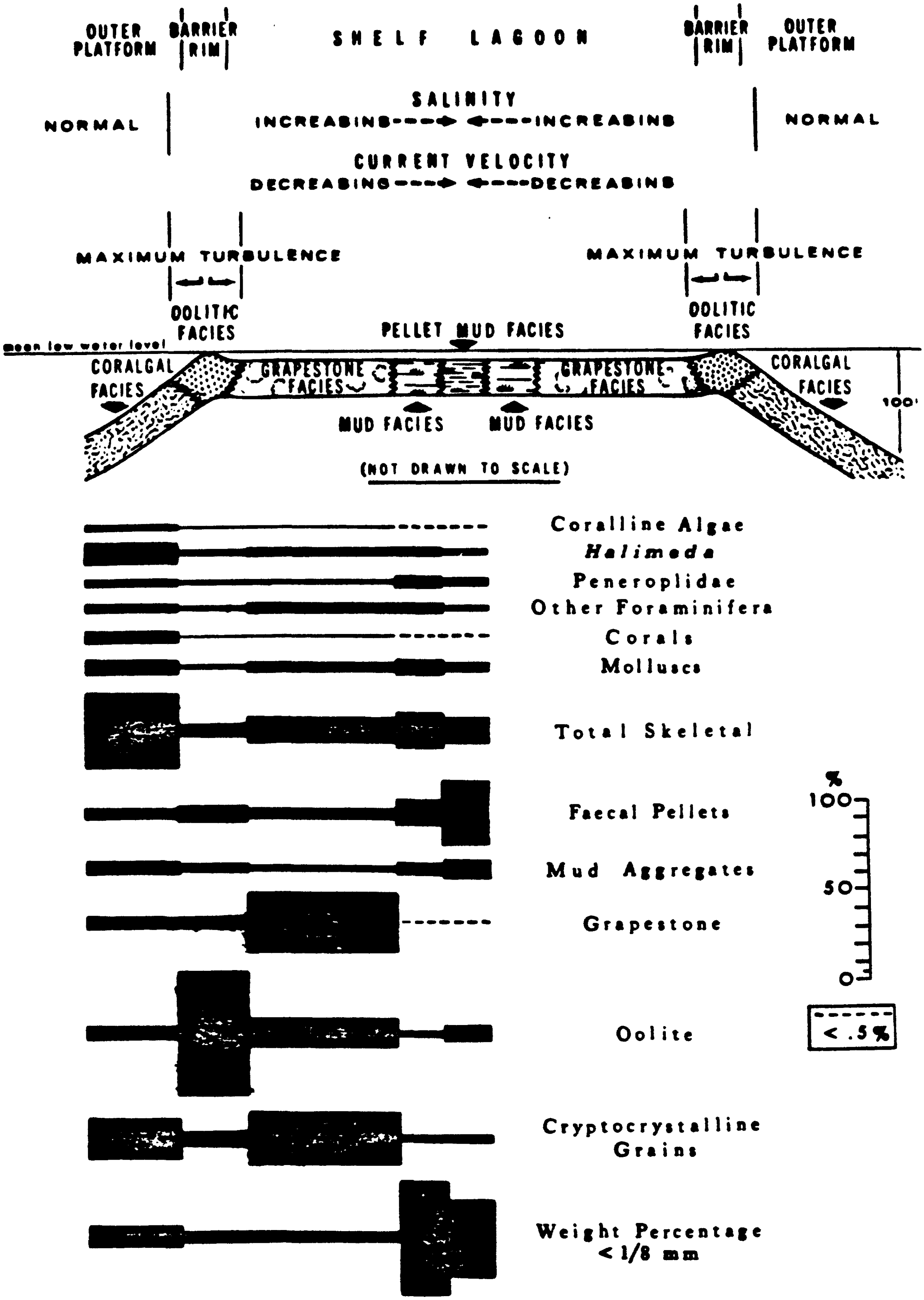
TABLE 1-4. COMPARISON OF PLATFORM MARGIN MODELS AND TERMINOLOGY

<table>
<tr><th></th><th>WILSON (1975)</th><th>MCILREATH & JAMES (1978)</th><th>READ (1982)</th><th>JAMES & MOUNTJOY (1983)</th></tr>
<tr><td rowspan="2">NON-RIMMED SHELVES</td><td>- NONE -</td><td>- NONE -</td><td>RAMP - HOMOCLINAL</td><td>RAMP</td></tr>
<tr><td>- NONE -</td><td>- NONE -</td><td>RAMP - DISTALLY STEEPENED</td><td>- NONE -</td></tr>
<tr><td rowspan="7">RIMMED SHELVES</td><td>TYPE I
DOWNSLOPE MUD ACCUMULATION</td><td>- NONE -</td><td>- NONE -</td><td>- NONE -</td></tr>
<tr><td>TYPE II
KNOLL REEF RAMP</td><td>DEPOSITIONAL MARGIN
(reef dominated)</td><td rowspan="2">RIMMED SHELF
ACCRETIONARY
(reef and/or sand shoal)</td><td rowspan="2">DEPOSITIONAL MARGIN
(reef and/or sand shoal)</td></tr>
<tr><td>- NONE -</td><td>DEPOSITIONAL MARGIN
(sand shoal dominated)</td></tr>
<tr><td>TYPE III
FRAMEWORK REEF RIMS</td><td>BYPASS MARGIN
(reef dominated)</td><td rowspan="2">BYPASS MARGIN
ESCARPMENT TYPE
(reef and/or sand shoal)</td><td rowspan="2">BYPASS MARGIN
(reef and/or sand shoal shallow basin)</td></tr>
<tr><td>- NONE -</td><td>BYPASS MARGIN
(sand shoal dominated)</td></tr>
<tr><td>- NONE -</td><td>- NONE -</td><td>BYPASS MARGIN
GULLIED SLOPE
(reef and/or sand shoal)</td><td>BYPASS MARGIN
(reef and/or sand shoal deep basin)</td></tr>
<tr><td>- NONE -</td><td>- NONE -</td><td>EROSIONAL MARGIN
(reef and/or sand shoal)</td><td>- NONE -</td></tr>
</table>



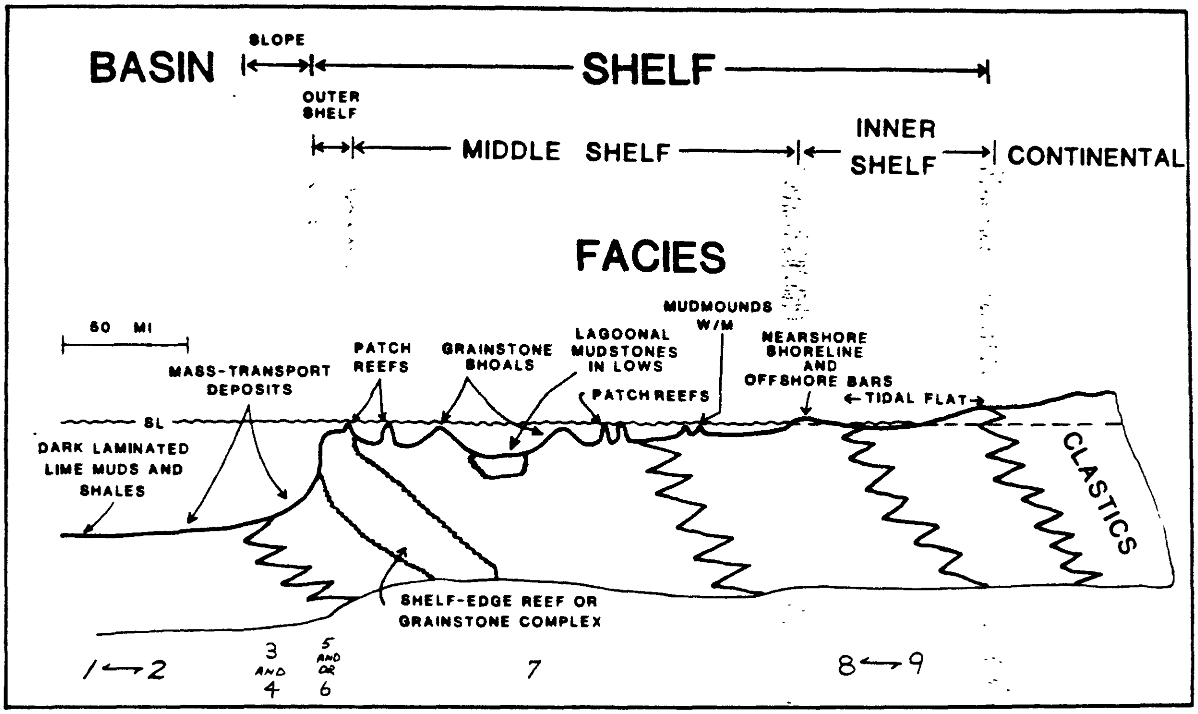
FACIES DISTRIBUTION ON THE ANDROS PLATFORM.
Figure 1-1. (After Purdy, 1963)

Distribution of Facies on an Idealized Bahamian Platform



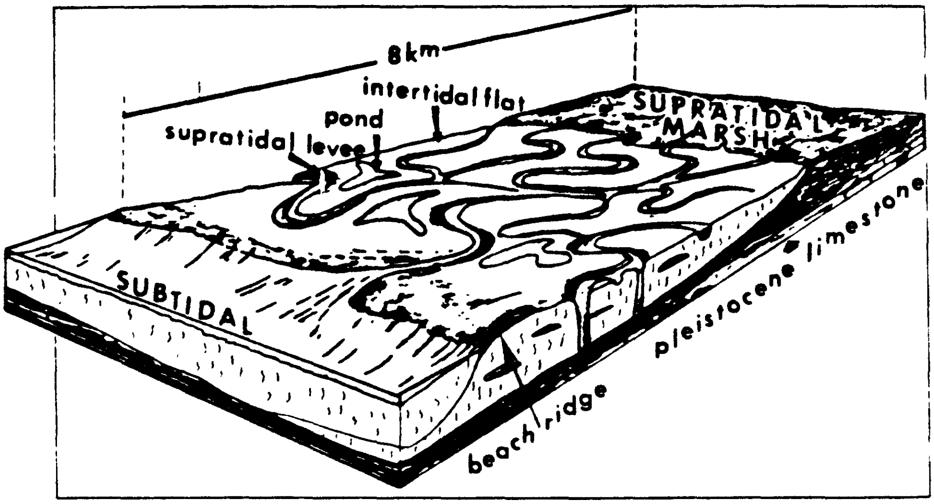
VARIATIONS IN MEAN CONSTITUENT PARTICLE COMPOSITION AND GRAIN SIZE OF BAHAMIAN FACIES ON AN IDEALIZED BAHAMIAN PLATFORM.

Figure 1-2. (After Purdy, 1963).



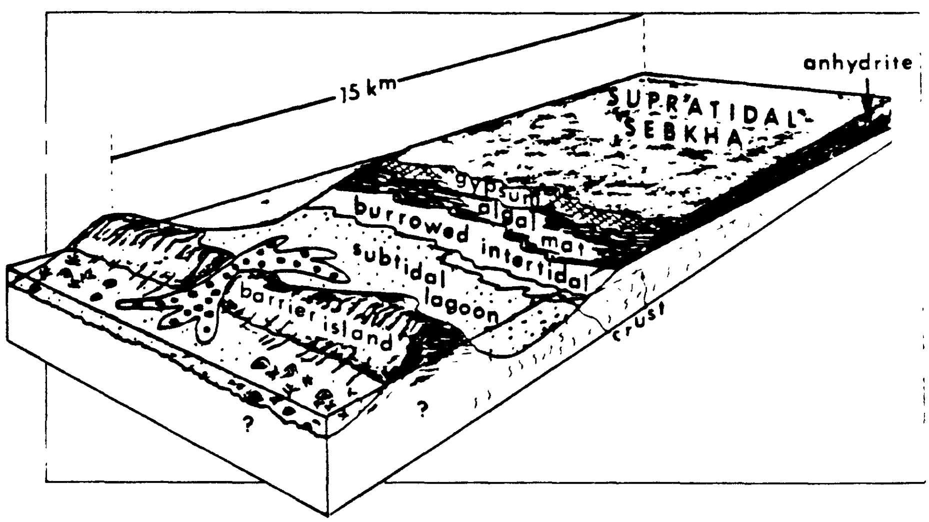
Profile of a rimmed carbonate shelf or drop-off model. Numbers at bottom of figure refer to Standard Facies Belts of Wilson (1975).

Figure 1-3. (modified from Wilson and Jordan, 1983)



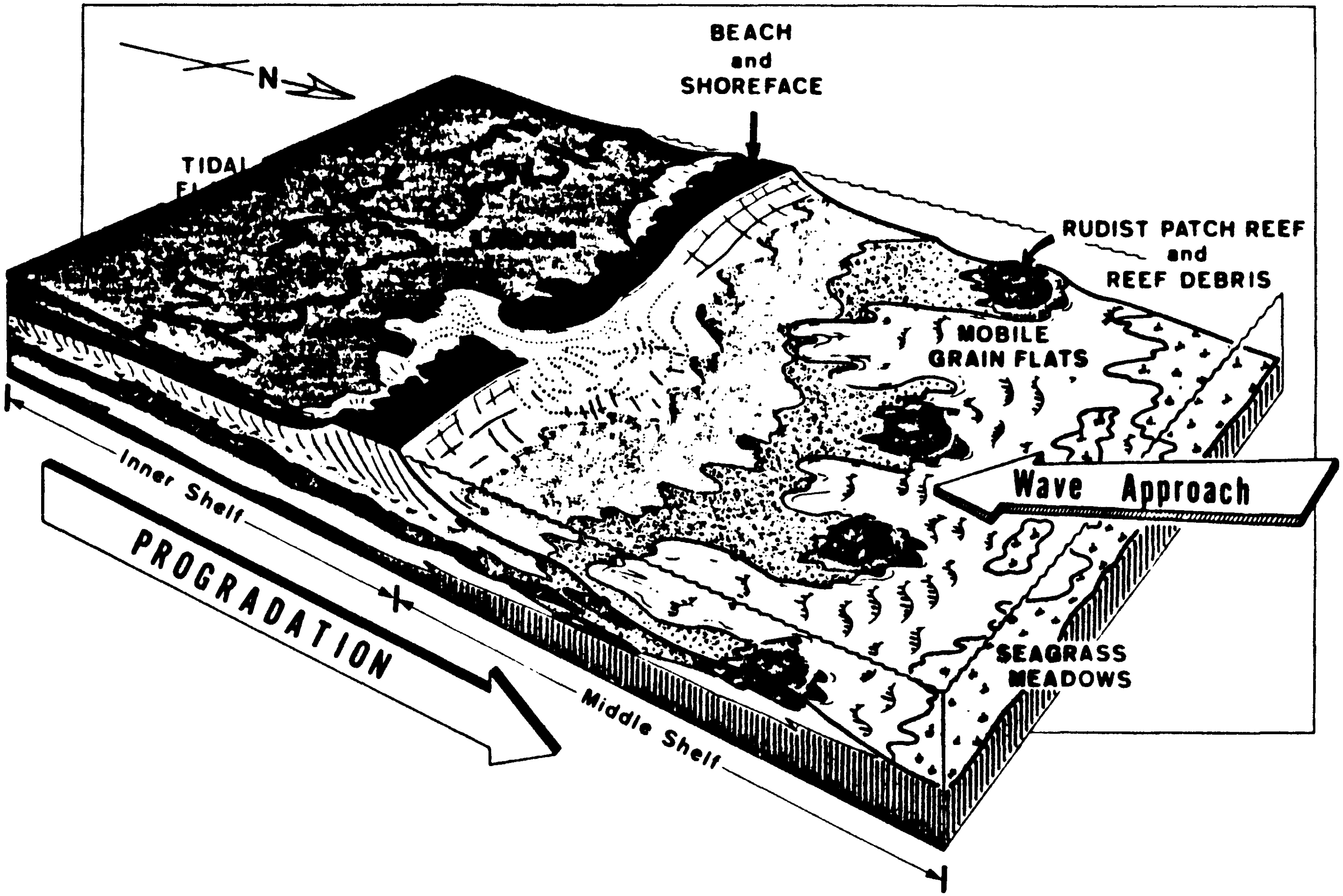
Block diagram schematically showing major facies on the Andros Island onlap (transgressive) tidal flat model.

Figure 1-4. (from Shinn, 1983)



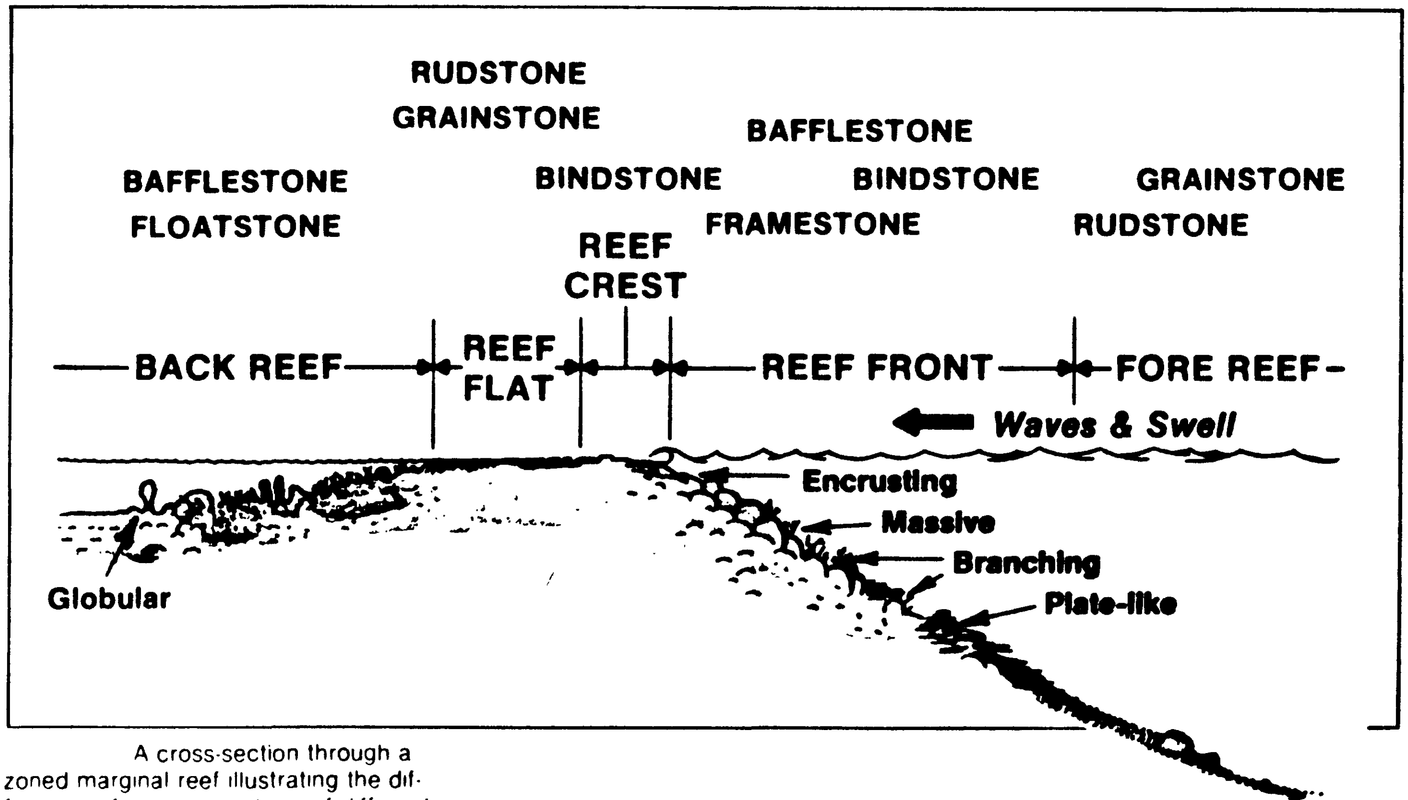
Block diagram schematically showing major facies on the Persian Gulf Trucial Coast offlap (regressive) tidal flat model

Figure 1-5. (from Shinn, 1983)



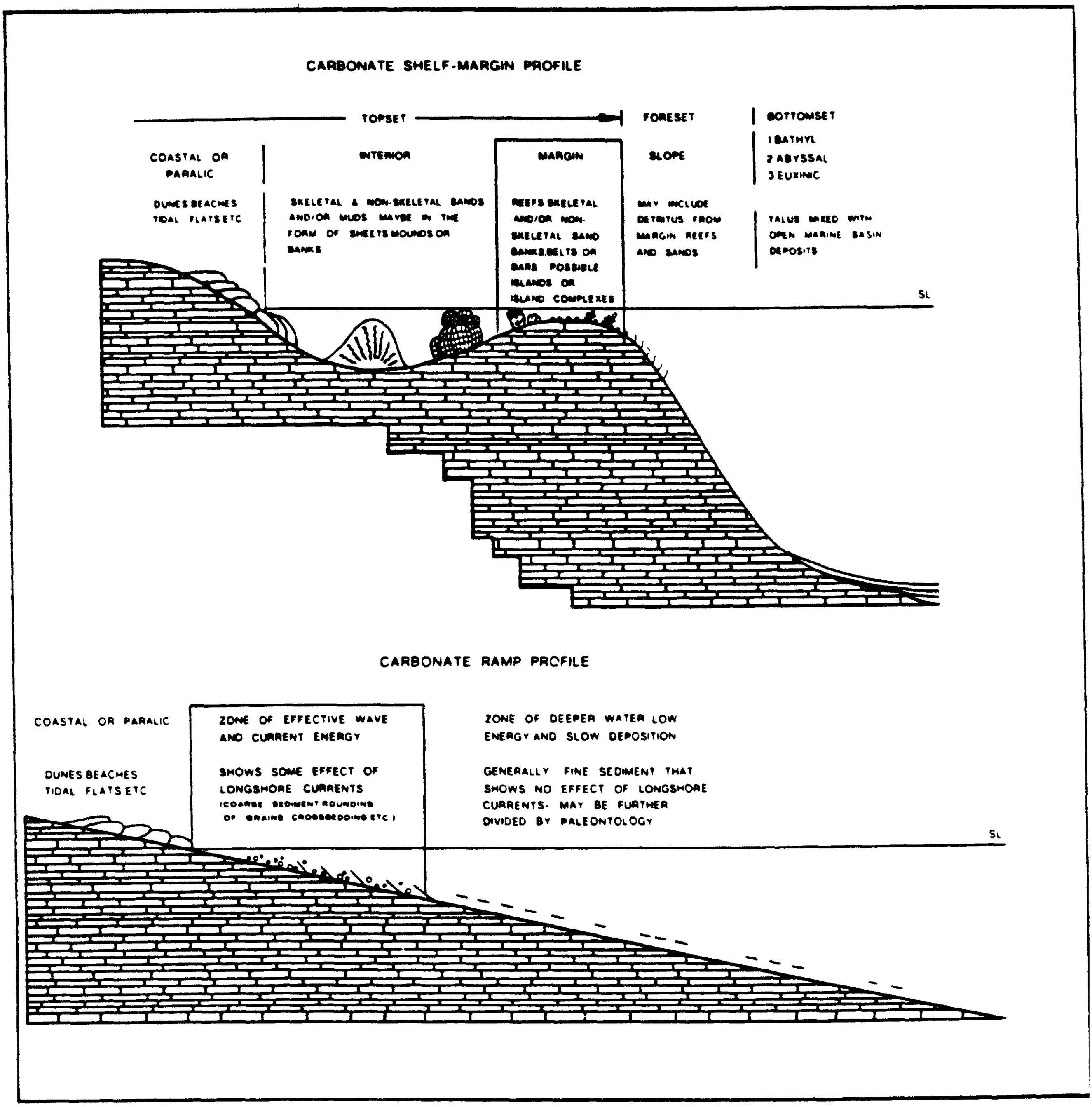
Depositional model of the Edwards Limestone (upper Fredericksburg and equivalent strata) in the area of Belton, Texas, showing progradational inner and middle shelf facies

Figure 1-6. (from Wilson and Jordon, 1983)



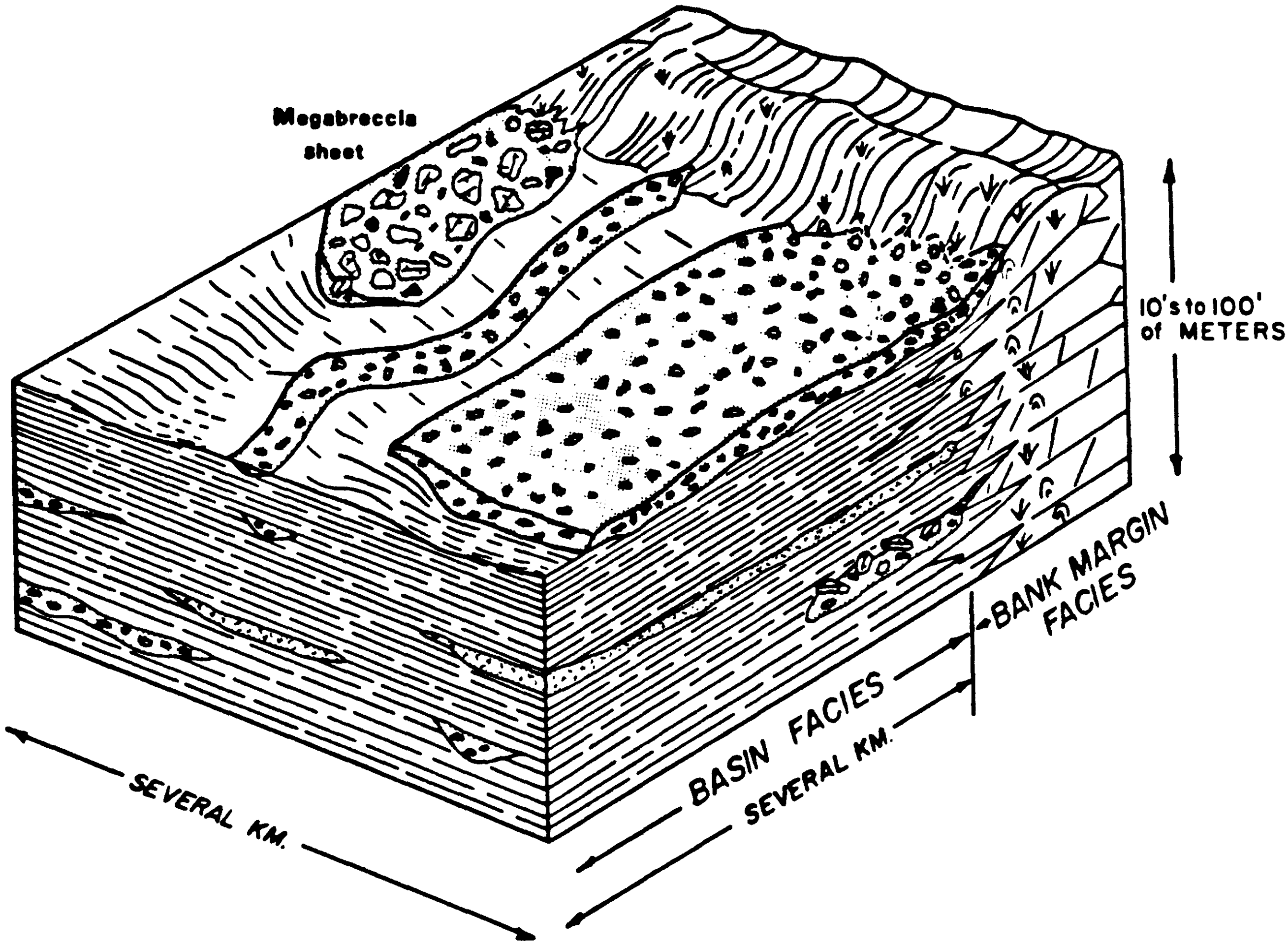
A cross-section through a zoned marginal reef illustrating the different reef zones, spectrum of different limestones produced in each zone, and environment of different reef-building organisms

Figure 1-7. (from James, 1983)



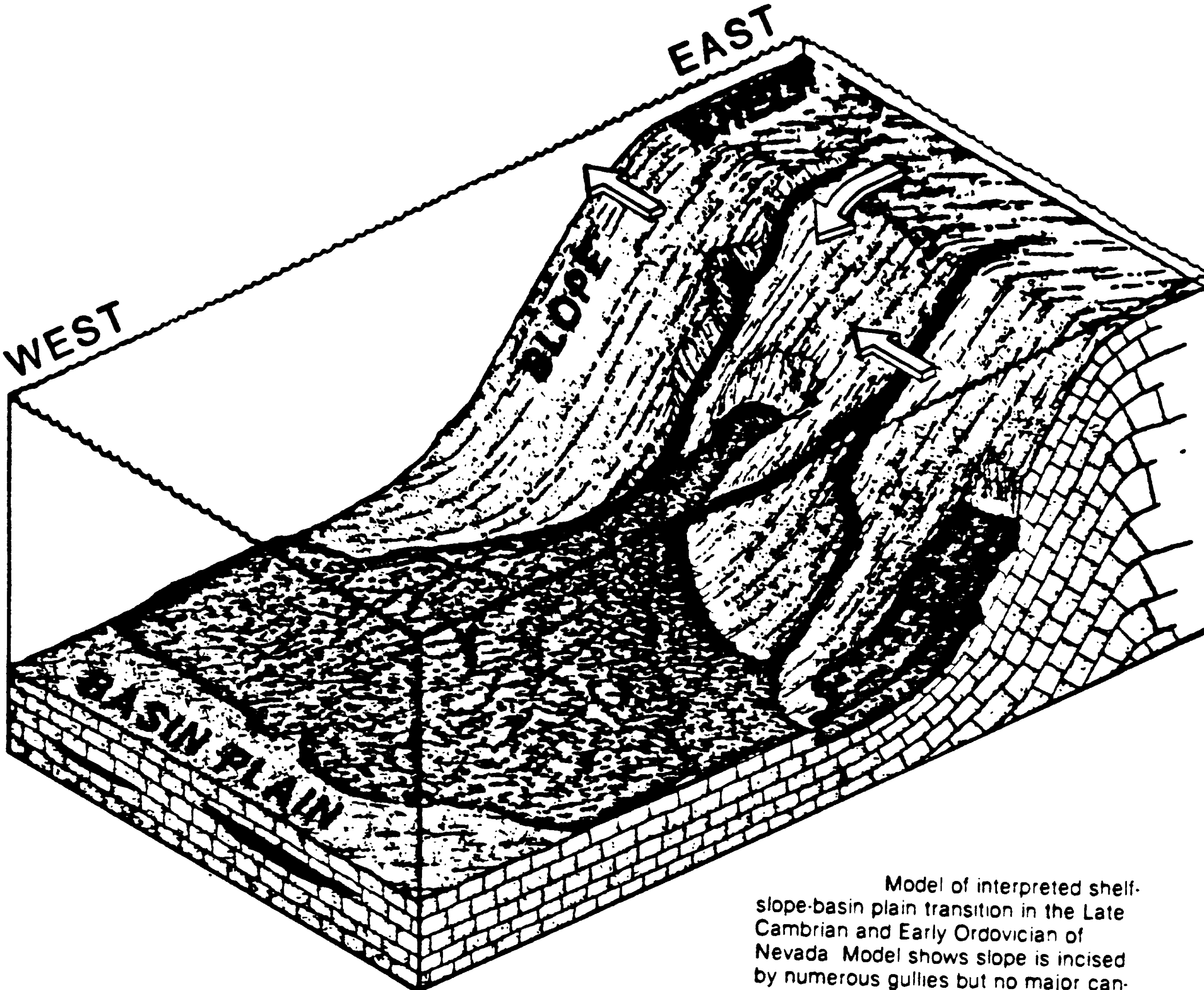
Bank-margin sands play an important part in geologic models, whether deposition occurred over a shelf-margin or a ramp profile.

Figure 1-8. (from Halley et.al., 1983)



Generalized representation of allochtonous debris deposits showing textures, shapes and relation to bank and basin facies.

Figure 1-9. (from Cook et.al., 1972)



Model of interpreted shelf-slope-basin plain transition in the Late Cambrian and Early Ordovician of Nevada. Model shows slope is incised by numerous gullies but no major canyons; carbonate submarine fan develops at base of slope and basin plain, fan sediment is a mixture of shoal-water shelf carbonates and deeper water slide generated debris, contour currents flow northerly along upper slope.

Figure 1-10. (from Cook and Egbert, 1981a, and Cook and Mullins, 1983)

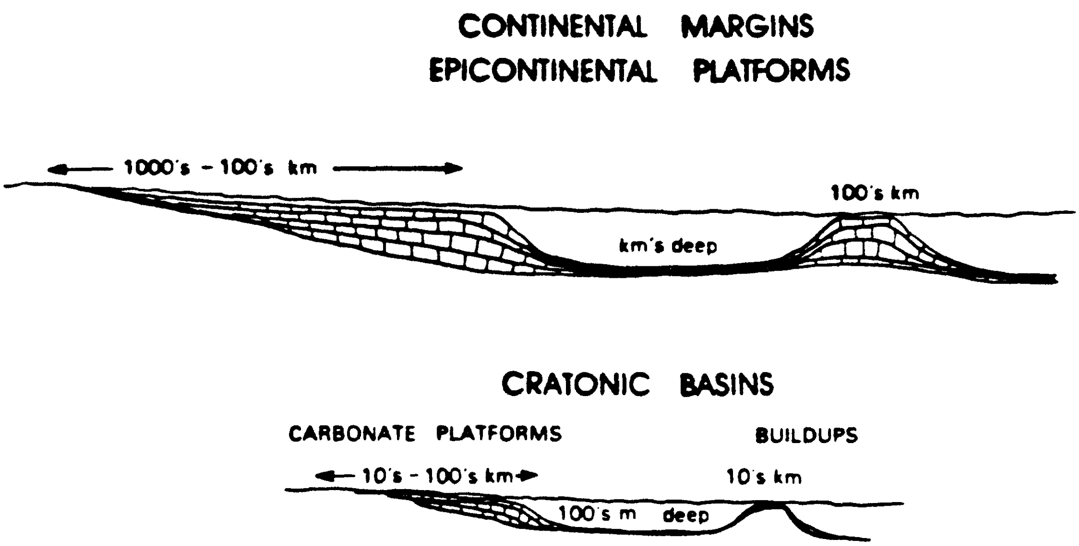


Diagram illustrating the difference in scale between continental margins or epicontinental platforms and isolated carbonate platforms in open ocean basins versus carbonate platforms and buildups developed in intracratonic basins.

Figure 1-11. (from James and Mountjoy, 1983)

SKELETAL COMPOSITIONS

TAXON	ARAG.	CALCITE %Mg 0 5 10 15 20 25 30 35	BOTH ARAGONITE AND CALCITE
CALCAREOUS ALGAE:			
RED		X——X	
GREEN	X		
COCCOLITHS		X	
FORAMINIFERA.			
BENTHONIC	O	X——X - - X	
PLANKTONIC		X–X	
SPONGES:	O	X—X	
COELENTERATES:			
STROMATOPORIDS (A)	X	X ?	
MILLEPOROIDS	X		
RUGOSE (A)		X•••	
TABULATE (A)		X ?	
SCLERACTINIAN	X		
ALCYONARIAN	O	X—X	
BRYOZOANS:	O	X—X	O
BRACHIOPODS:		X–X	
MOLLUSKS:			
CHITONS	X		
PELECYPODS	X	X–X	X
GASTROPODS	X	X–X	X
PTEROPODS	X		
CEPHALOPODS (MOST)	X		
BELEMNOIDS & APTYCHI (A)		X	
ANNELIDS (SERPULIDS):	X	X—X	X
ARTHROPODS:			
DECAPODS		X—X	
OSTRACODES		X—X	
BARNACLES		X–X	
TRILOBITES (A)		X	
ECHINODERMS		X——X	

X Common   O Rare   (A) Not based on modern forms

Figure 1-12. Skeletal compositions of major taxa (from Scholle, 1978).

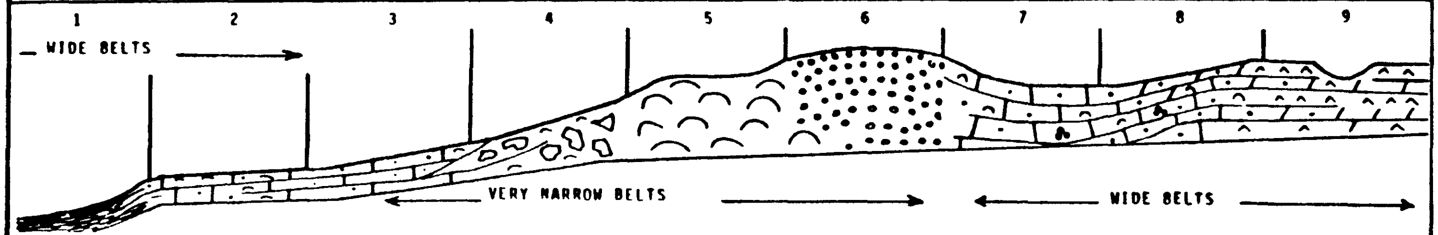
<table>
<tr><td colspan="5">Depositional Texture recognizable</td><td rowspan="6">Depositional texture not recognizable

Crystalline carbonate

(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
<tr><td colspan="4">Original components not bound together during depositions</td><td rowspan="4">Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</td></tr>
<tr><td colspan="3">Contains mud
(particles of clay and fine silt size)</td><td rowspan="3">Lacks mud and is grain-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackstone</td><td>Packstone</td><td>Grainstone</td><td>Boundstone</td></tr>
</table>

Classification of Carbonate rocks according to depositional texture

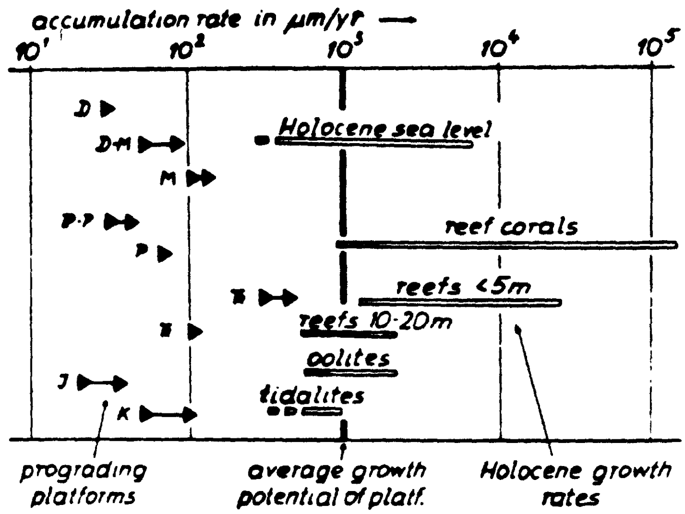
Figure 1-13. (from Dunham, 1962)



	1	2	3	4	5	6	7	8	9
FACIES PROFILE	BASIN	OPEN SEA SHELF	DEEP SHELF MARGIN	FORESLOPE	ORGANIC BUILD UP	WINNOWED EDGE SANDS	SHELF LAGOON OPEN CIRCULATION	RESTRICTED CIRCULATION SHELF AND TIDAL FLATS	EVAPORITES ON SABKHAS-SALINAS
2ND ORDER SEDIMENTARY BODIES			DEBRIS FLOWS AND TURBIDITES IN FINE LAMINATE STRATA. MOUNDS ON TOE OF SLOPE.	GIANT TALUS BLOCKS. INFILLED LARGE CAVITIES. DOWNSLOPE MOUNDS.	DOWNSLOPE MOUNDS. REEF KNOLLS. BOUNDSTONE PATCHES. FRINGING AND BARRIER FRAME-WORK REEF. SPUR AND GROOVE.	ISLANDS. DUNES. BARRIER BARS. PASSES AND CHANNELS.	TIDAL DELTAS. LAGOONAL PONDS. TYPICAL SHELF MOUNDS. COLUMNAR ALGAL MATS. CHANNELS AND TIDAL BARS OF LIME SAND.	TIDAL FLATS. CHANNELS NATURAL LEVEES. PONDS. ALGAL MAT BELTS.	ANHYDRITE DOMES. TEPEE STRUCTURES. LAMINATED CRUSTS OF GYPSUM. SALINAS (EVAPORATIVE PONDS) SABKHAS (EVAPORATIVE FLATS)
STANDARD MICROFACIES	1 SPICULITE 2 MICROBIO-CLASTIC CALCISILT 3 PELAGIC MICRITE RADIOLARITE SHALE	2 MICROBIOCLASTIC CALCISILT 8 WHOLE SHELLS IN MICRITE 9 BIOCLASTIC WACKESTONE 10 COATED GRAINS IN MICRITE	2 MICROBIOCLASTIC CALCISILT 3 PELAGIC MICRITE 4 BIOCLASTIC-LITHOCLASTIC MICROBRECCIA	4 BIOCLASTIC LITHOCLASTIC MICROBRECCIA. LITHOCLASTIC CONGLOMERATE. 5 BIOCLASTIC GRAINSTONE-PACKSTONE. FLOATSTONE. 6 REEF RUDSTONE.	7 BOUNDSTONE 11 COATED, WORN, BIOCLASTIC GRAINSTONE. 12 COQUINA (SHELL HASH)	11 COATED, WORN BIOCLASTIC GRAINSTONE 12 COQUINA (SHELL HASH) 13 ONKOIDAL BIOCLASTIC GRAINSTONE 14 LAG BRECCIA 15 OOLITE	8 WHOLE SHELLS IN MICRITE 9 BIOCLASTIC WACKESTONE 10 COATED GRAINS IN MICRITE 16 PELSPARITE 17 GRAPESTONE ONKOIDS IN MICRITE 18 FORAM, DASYCLADACEAN GRAINSTONE	16, 17, 18 19 FENESTRAL PELOIDAL LAMINATE MICRITE 24 RUDSTONE IN CHANNELS 21 SPONGIOSTROME MICRITE 23 NON LAMINATE PURE MICRITE 22 ONKOIDAL MICRITE	20 STROMATOLITIC MICRITE. 23 NON LAMINATE, PURE MICRITE NODULAR-PEARL ENTEROLITHIC ANHYDRITE. SELENITE BLADES IN MICRITE.

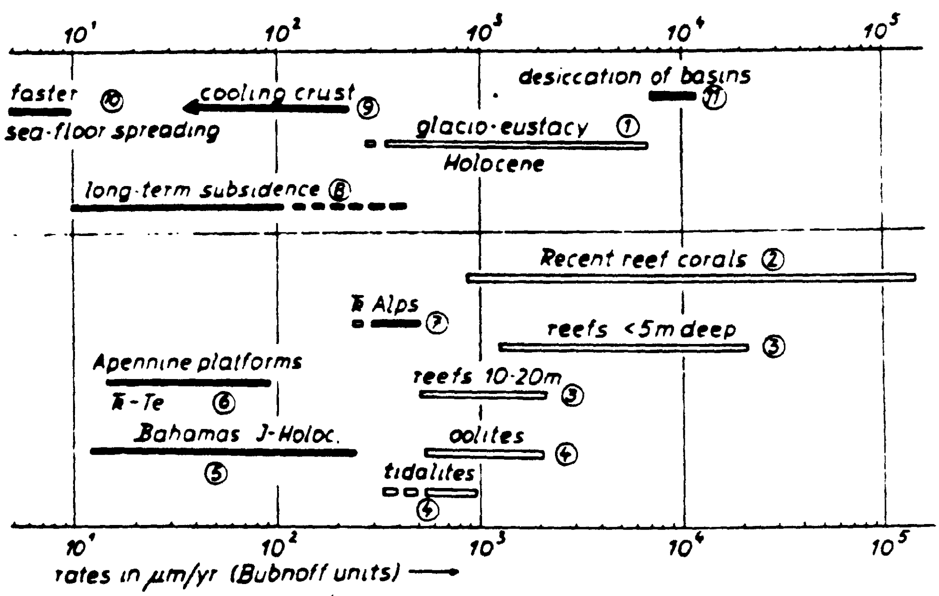
Synopsis of Standard Facies Belts reviewing second order bodies of sediment and standard microfacies associated with each belt.

Figure 1-14. (from Wilson, 1975)



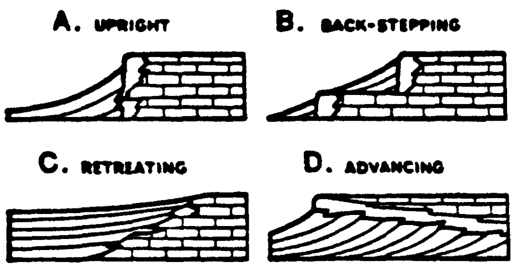
Average growth potential of carbonate platforms estimated from growth rates and accumulation rates during Holocene transgression (open bars) and from accumulation rates of prograding platforms in the geologic record (triangles). Average growth potential is probably in the 1,000-μm/yr range.

Figure 1-15. (from Schlager, 1981)



The paradox of platform drowning is illustrated by a comparison of rates of the relevant processes. Rates of relative rise of sea level produced by various processes in upper part of graph, rates of growth and sediment accumulation in lower part. Holocene rates = open bars; distant geologic past = black bars. Holocene accumulation matches or exceeds glacio-eustatic Holocene rise of sea level, all Holocene rates are one to several orders of magnitude faster than those of the geologic record.

Figure 1-16. (from Schlager)



Morphologic evolution of carbonate outer-shelf margins.

Figure 1-17. (modified from Playford, 1980)

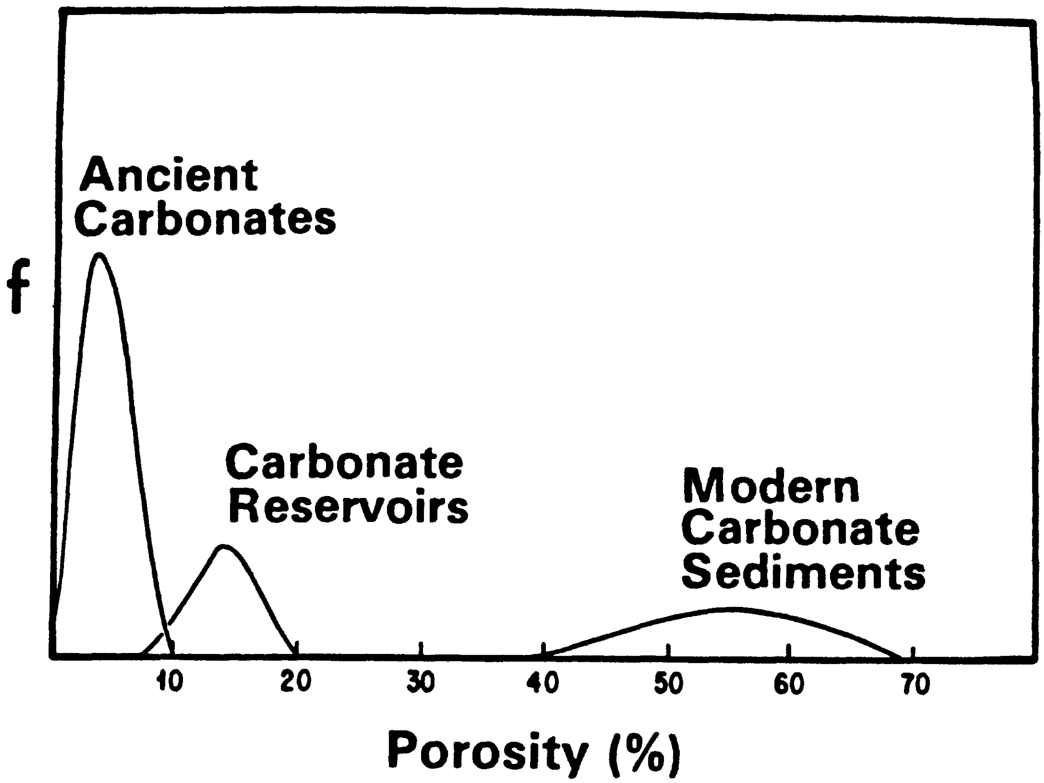


Figure 1-18. (after Pray and Choquette, 1966)

Comparison of Porosity in Sandstone and Carbonate Rocks

Aspect	*Sandstone*	*Carbonate*
Amount of primary porosity in sediments	Commonly 25-40%	Commonly 40-70%
Amount of ultimate porosity in rocks	Commonly half or more of initial porosity; 15-30% common	Commonly none or only small fraction of initial porosity, 5-15% common in reservoir facies
Type(s) of primary porosity	Almost exclusively interparticle	Interparticle commonly predominates, but intraparticle and other types are important
Type(s) of ultimate porosity	Almost exclusively primary interparticle	Widely varied because of post-depositional modifications
Sizes of pores	Diameter and throat sizes closely related to sedimentary particle size and sorting	Diameter and throat sizes commonly show little relation to sedimentary particle size or sorting
Shape of pores	Strong dependence on particle shape—a "negative" of particles	Greatly varied, ranges from strongly dependent "positive" or "negative" of particles to form completely independent of shapes of depositional or diagenetic components
Uniformity of size, shape, and distribution	Commonly fairly uniform within homogeneous body	Variable, ranging from fairly uniform to extremely heterogeneous, even within body made up of single rock type
Influence of diagenesis	Minor; usually minor reduction of primary porosity by compaction and cementation	Major; can create, obliterate, or completely modify porosity; cementation and solution important
Influence of fracturing	Generally not of major importance in reservoir properties	Of major importance in reservoir properties if present
Visual evaluation of porosity and permeability	Semiquantitative visual estimates commonly relatively easy	Variable, semiquantitative visual estimates range from easy to virtually impossible, instrument measurements of porosity, permeability and capillary pressure commonly needed
Adequacy of core analysis for reservoir evaluation	Core plugs of 1-in. diameter commonly adequate for "matrix" porosity	Core plugs commonly inadequate, even whole cores (~3-in. diameter) may be inadequate for large pores
Permeability-porosity interrelations	Relatively consistent, commonly dependent on particle size and sorting	Greatly varied, commonly independent of particle size and sorting

Figure 1-19. (from Choquette and Pray, 1970)

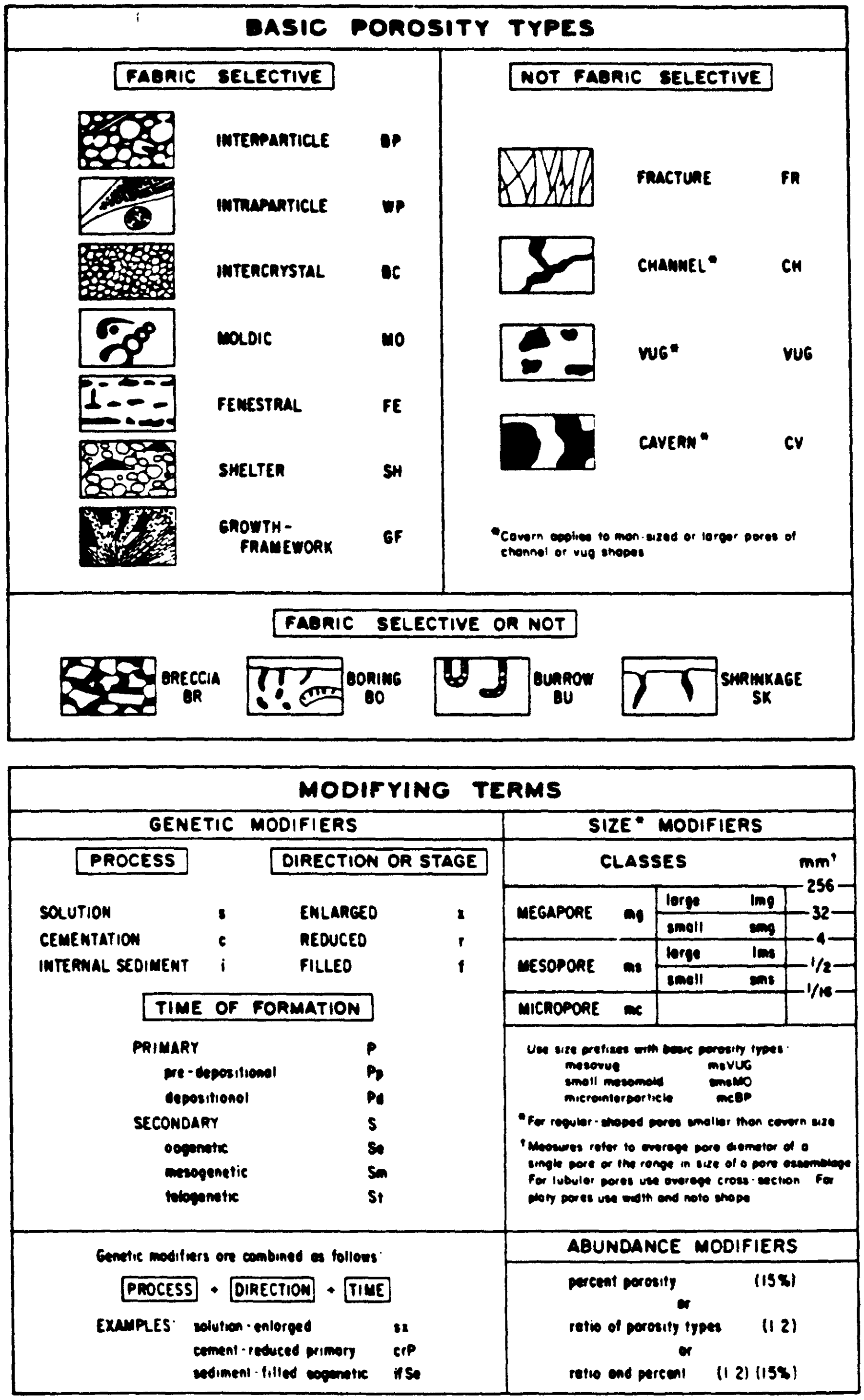
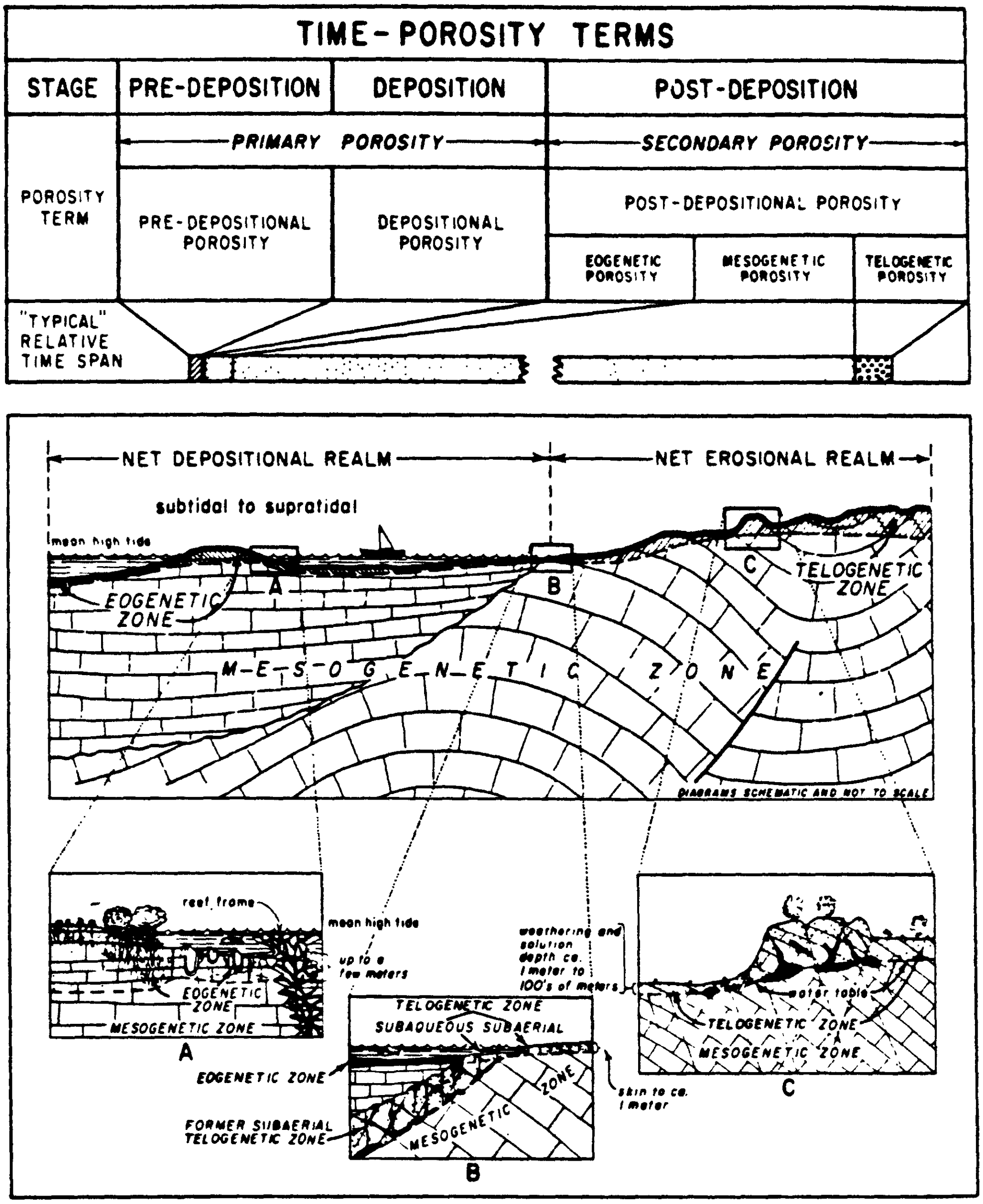


Figure 1-20. (from Choquette and Pray, 1970)



Time-porosity terms and zones of creation and modification of porosity in sedimentary carbonates. *Upper diagram:* Interrelation of major time-porosity terms. *Primary* porosity either originates at time of deposition (*depositional* porosity) or was present in particles before their final deposition (*predepositional* porosity). *Secondary* or *postdepositional* porosity originates after final deposition and is subdivided into *eogenetic*, *mesogenetic*, or *telogenetic* porosity depending on stage or burial zone in which it develops (see lower diagram). Bar diagram depicts our concept of "typical" relative durations of stages.

Lower diagram: Schematic representation of major surface and burial zones in which porosity is created or modified. Two major surface realms are those of net deposition and net erosion. Upper cross section and enlarged diagrams **A**, **B**, and **C** depict three major postdepositional zones. Eogenetic zone extends from surface of newly deposited carbonate to depths where processes genetically related to surface become ineffective. Telogenetic zone extends from erosion surface to depths at which major surface-related erosional processes become ineffective. Below a subaerial erosion surface, practical lower limit of telogenesis is at or near water table. Mesogenetic zone lies below major influences of processes operating at surface. The three terms also apply to time, processes, or features developed in respective zones.

Figure 1-21. (from Choquette and Pray, 1970)

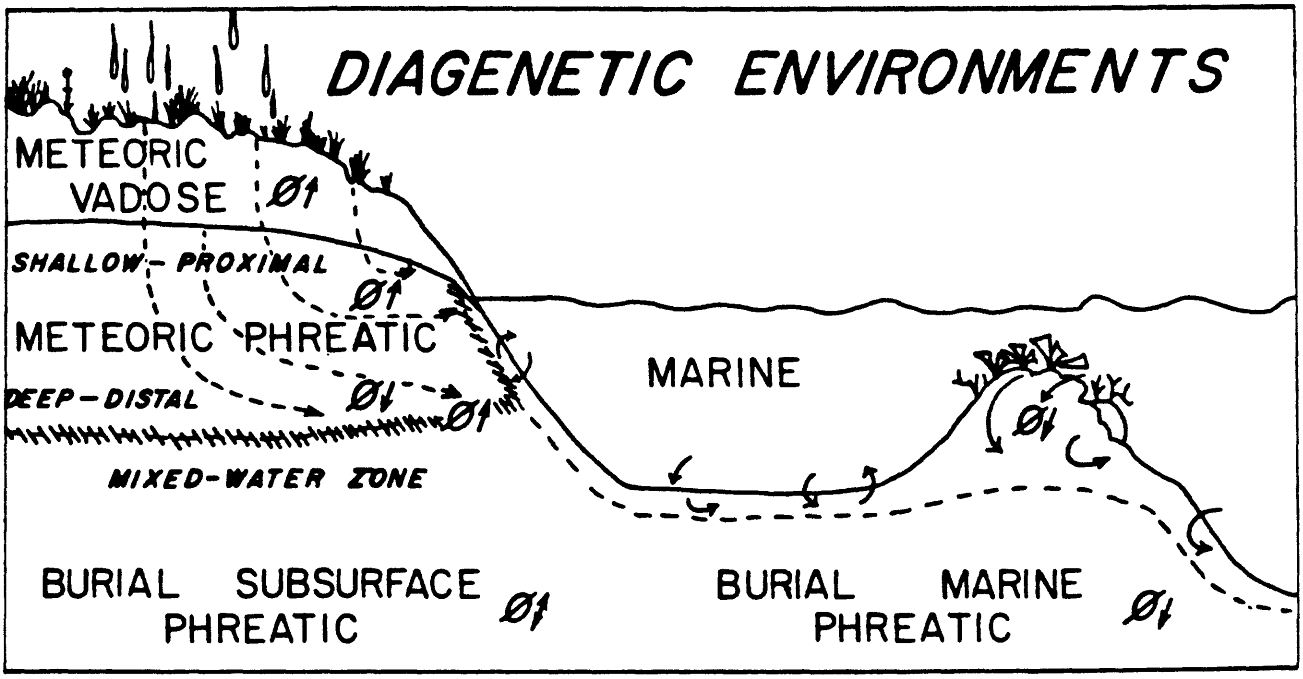
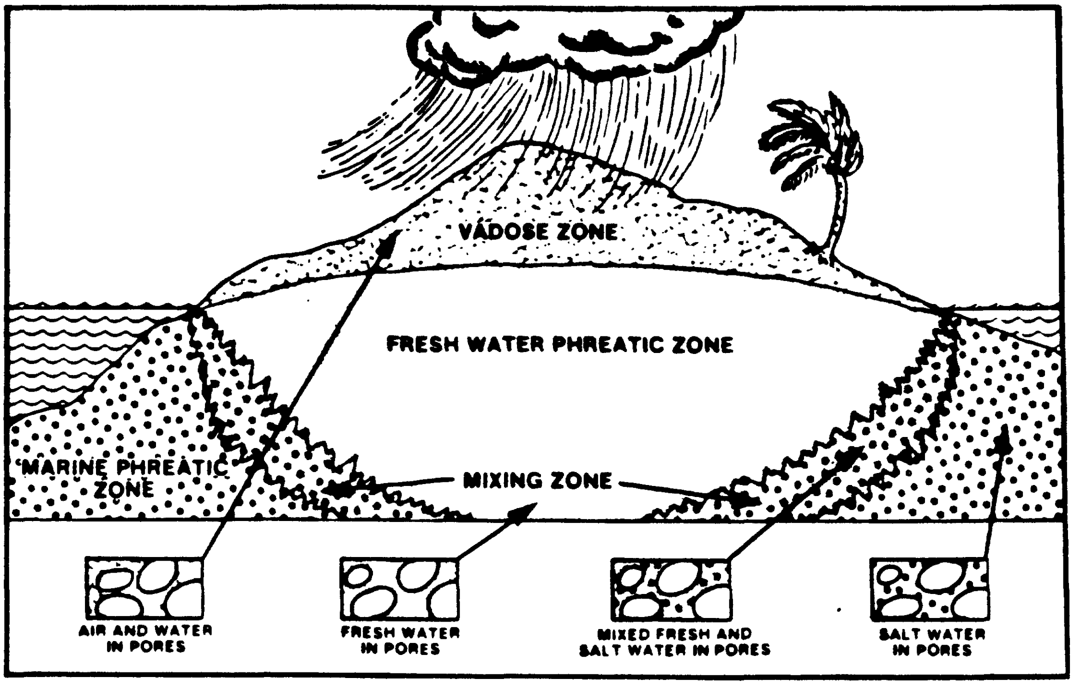
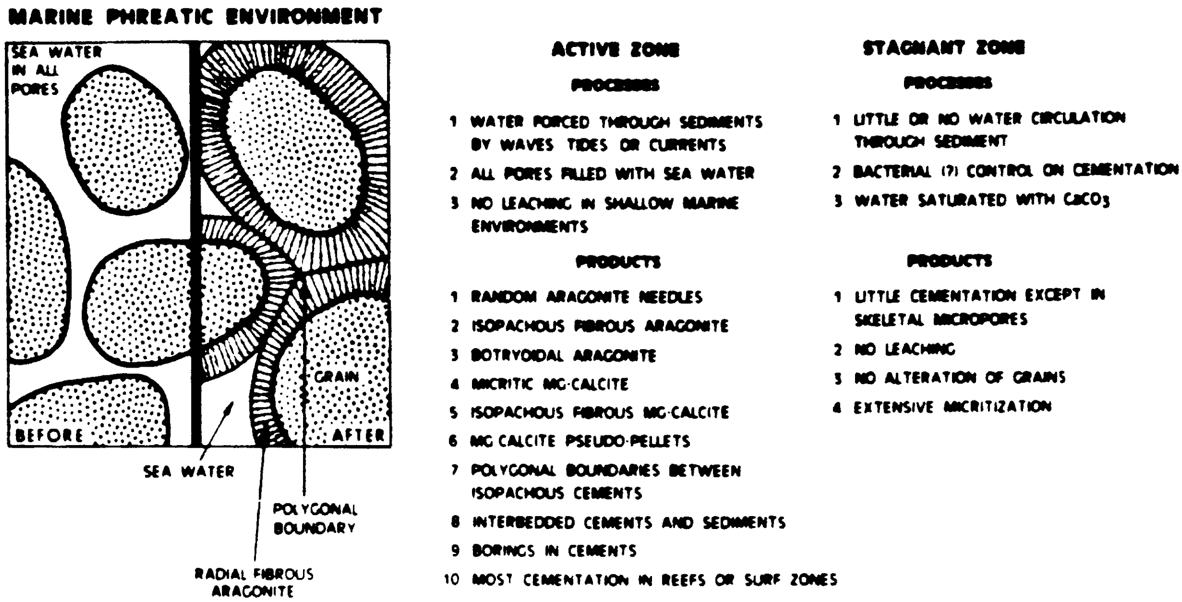


Figure 1-22. Diagenetic environments showing predicted porosity changes (from Wilson et.al., 1983).

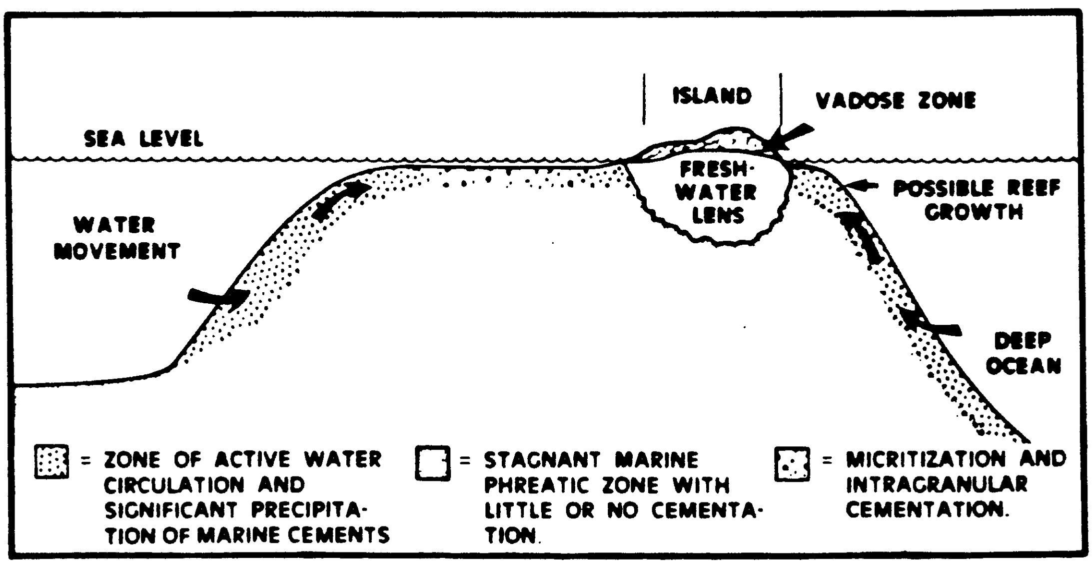


Cross section showing the distribution and relationships of major diagenetic environments in the shallow subsurface in an ideal permeable carbonate sand island. No scale is given but the vertical distance would typically represent tens of meters while the horizontal distance would be a few kilometers.

Figure 1-23. (from Longman, 1981)



Characteristics of the marine phreatic diagenetic environment.



Schematic cross section of a large carbonate bank showing the marine phreatic zone divided into areas with active water circulation (and thus cementation) and little water circulation (stagnant zones with little cementation). Modelled after the Great Bahamas Bank with vertical scale in hundreds of meters and horizontal scale in kilometers.

Figure 1-24. (from Longman, 1981)

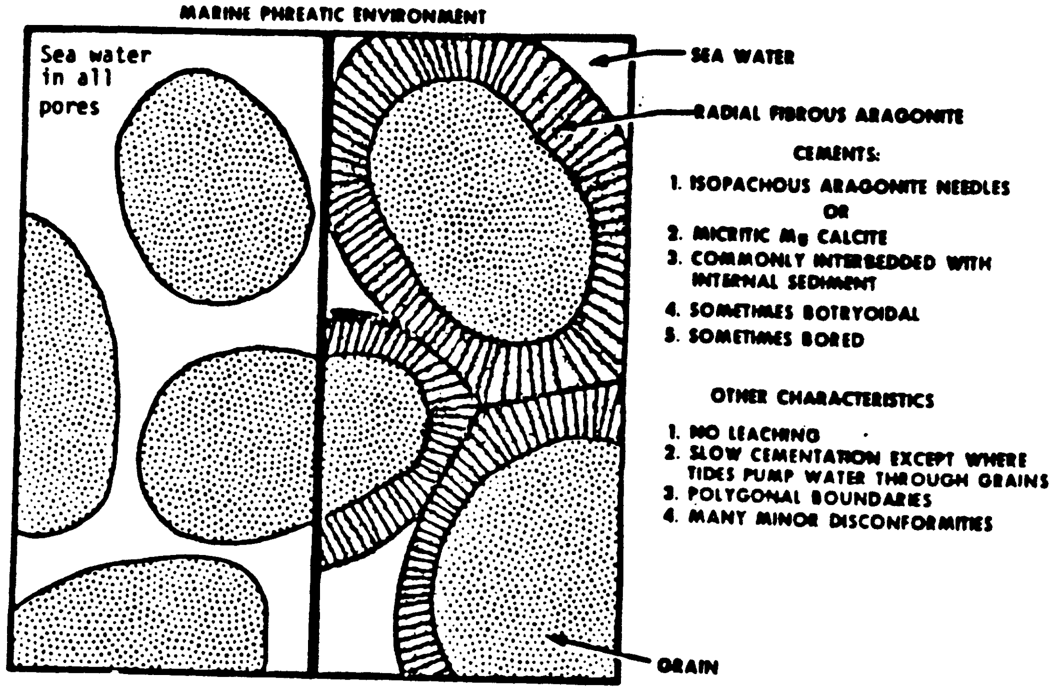
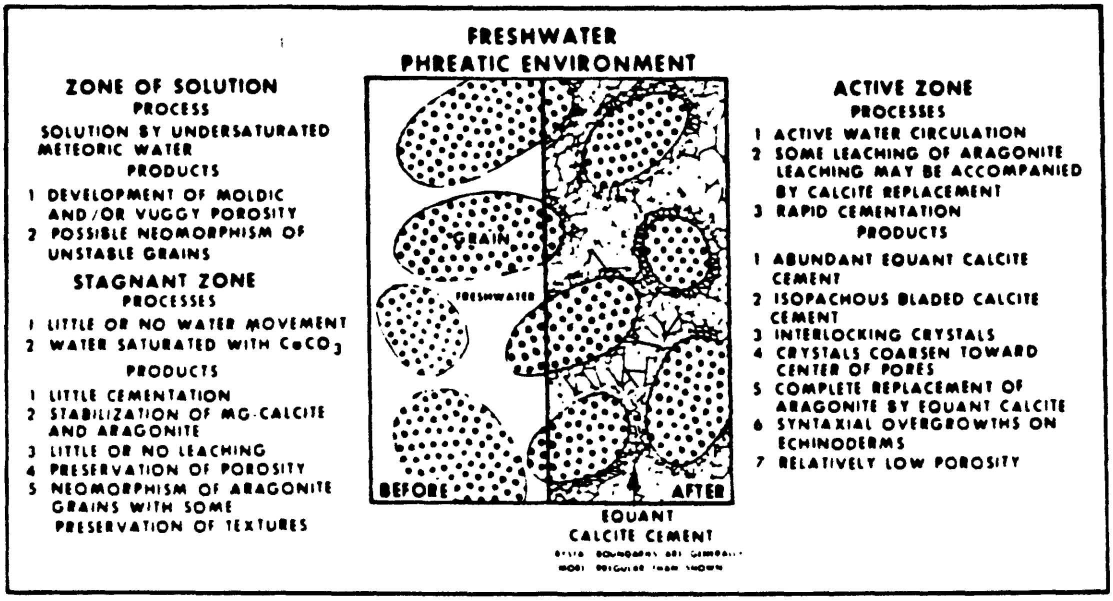
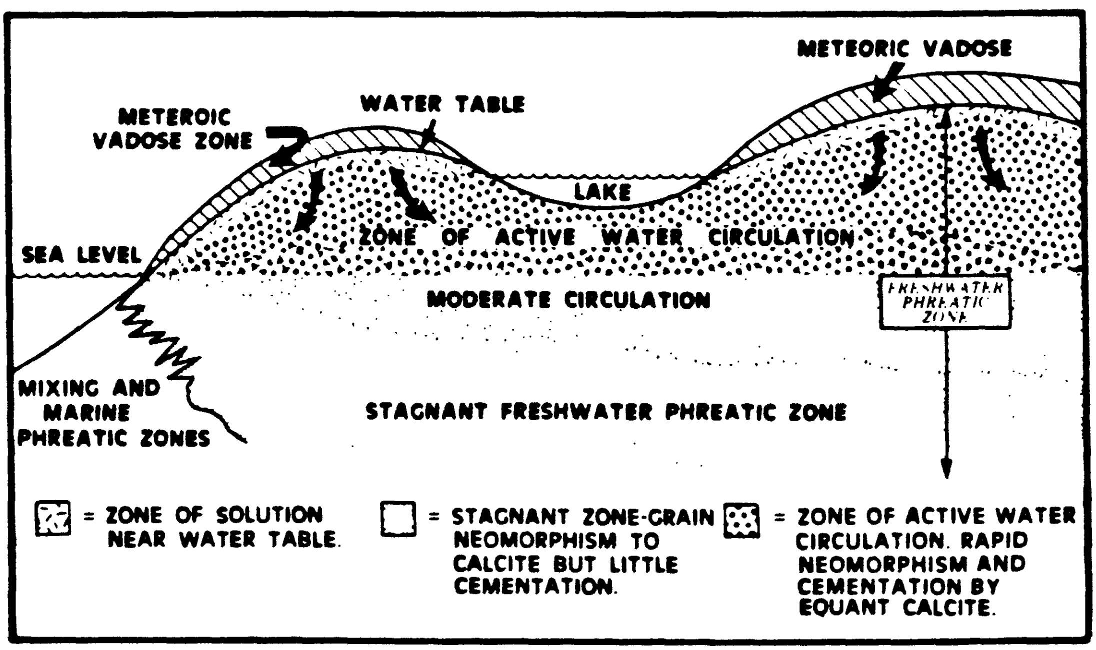


Figure 1-25. (from Longman, 1980)



Characteristics of the fresh water phreatic environment.



Schematic cross section of an idealized fresh water phreatic zone showing possible distribution of zone of solution, zone of active water circulation and cementation, and zone of stagnant water.

Figure 1-26. (from Longman, 1981)

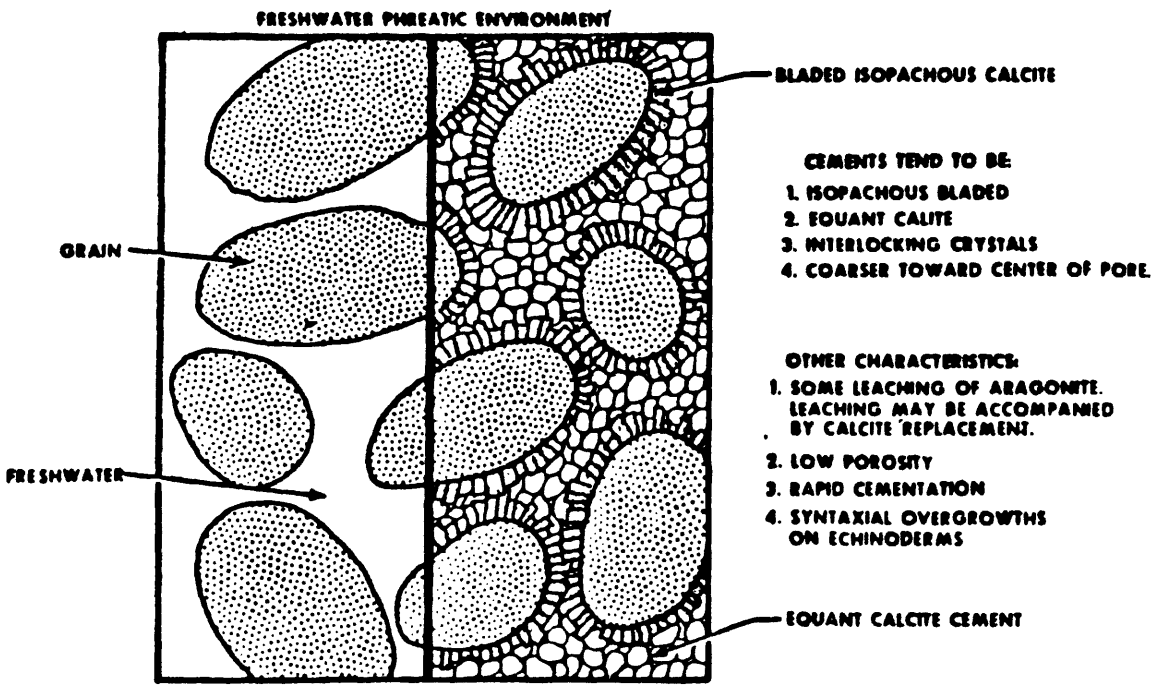


Figure 1-27. (from Longman, 1980)

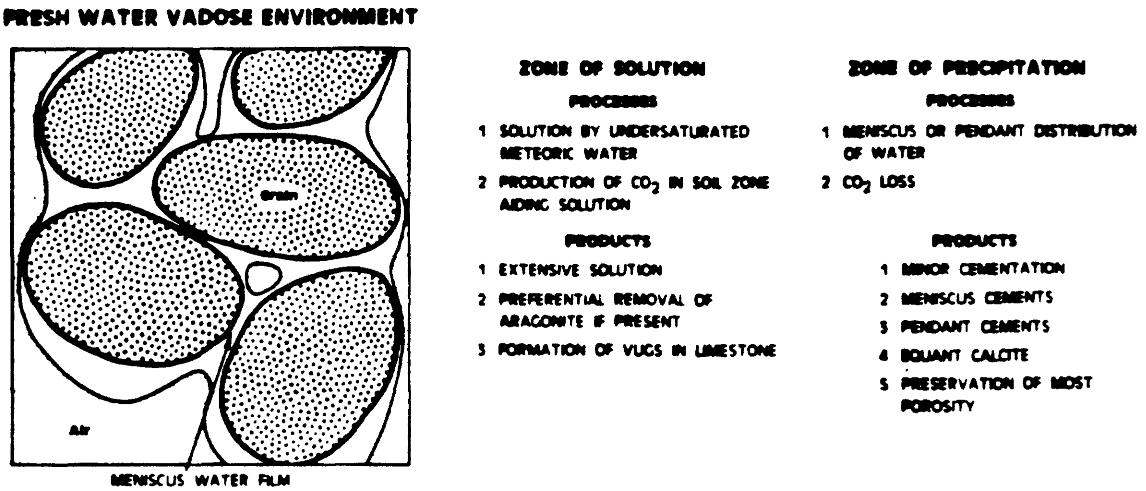
INCREASING SATURATION WITH $CaCO_3$

INCREASING DEPTH

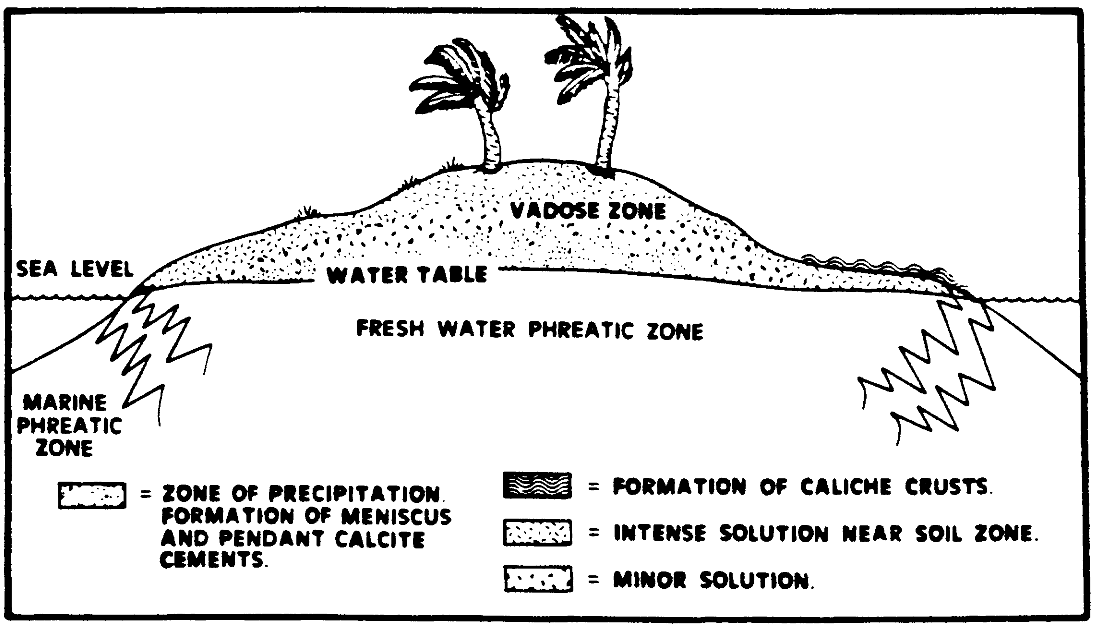
ZONE	CHARACTERISTICS
1. ZONE OF SOLUTION OF CALCITE AND ARAGONITE	FORMATION OF VUGGY AND MOLDIC POROSITY.
2. ZONE OF SOLUTION OF ARAGONITE	FORMATION OF MOLDIC POROSITY
3. ZONE OF ARAGONITE SOLUTION AND CALCITE PRECIPITATION	RAPID NEOMORPHISM OF ARAGONITE GRAINS TO EQUANT CALCITE CEMENTATION BY EQUANT CALCITE
4. ZONE OF NO SOLUTION PRECIPITATION OF CALCITE	RAPID CEMENTATION BY EQUANT CALCITE
5. STAGNANT ZONE, SATURATED WITH $CaCO_3$	LITTLE OR NO CEMENTATION SLOW NEOMORPHISM OF ARAGONITE GRAINS WITH PRESERVATION OF SOME STRUCTURES

Idealized zonation in the freshwater phreatic environment based on the assumption that saturation of water with respect to $CaCO_3$ increases as the water moves downward.

Figure 1-28. (from Longman, 1981)



Characteristics of the vadose diagenetic environment.



Idealized cross section of fresh water vadose zone showing probable distribution of areas of solution and precipitation.

Figure 1-29. (from Longman, 1981)

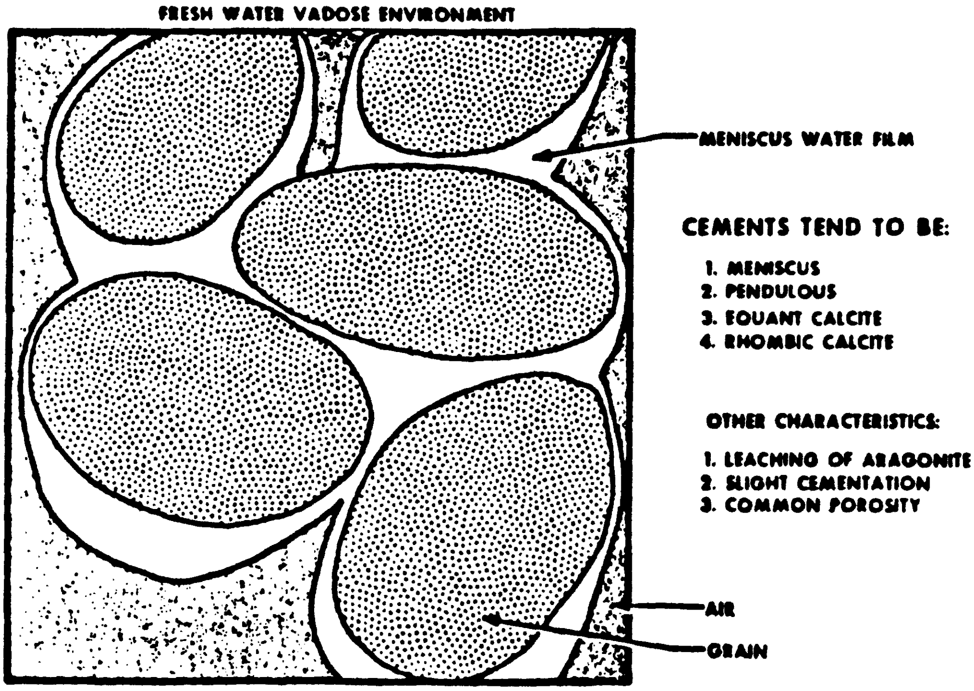
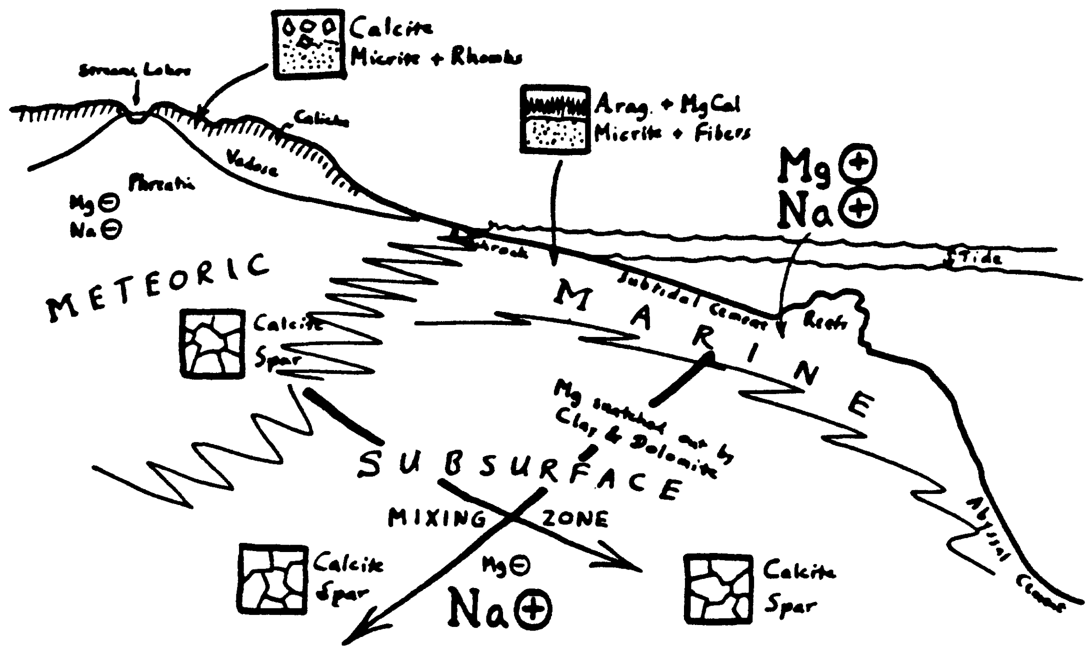
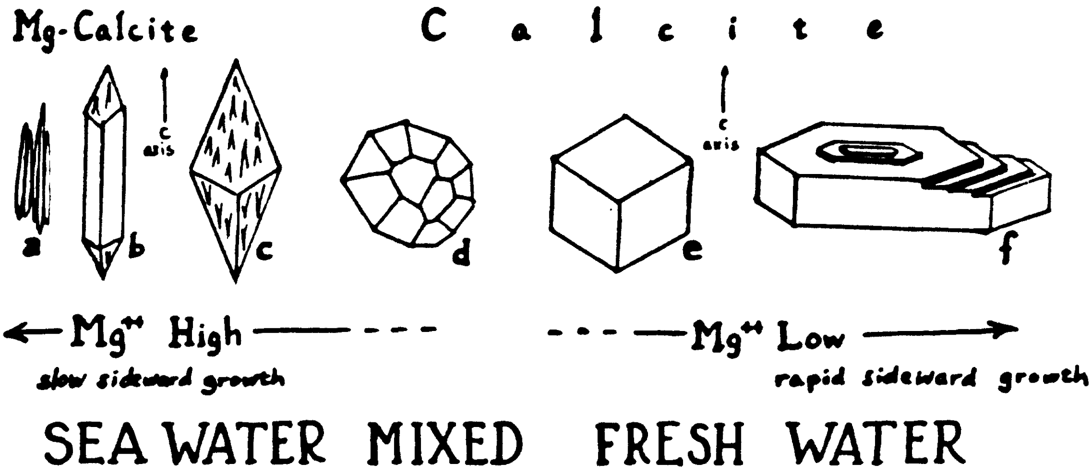


Figure 1-30. (from Longman, 1980)



Diagenetic realms and carbonate crystal morphology. Chemically, three main realms are present: (1) Na^{+} and Mg^{++} both high, as in marine cements (beachrock, subtidal cement, reef cement, etc). (2) Na^{+} high and Mg^{++} low, as in the subsurface zone, where Mg^{++} has been removed through trapping by clays and dolomite. This is often a mixing zone between connate waters of supernormal salinity and fresh meteoric water. (3) Na^{+} and Mg^{++} both low, in the meteoric zone. A major point of this diagram is the formation of equant sparry calcite mosaic in the *subsurface* zone, by "de-magnesiumization" of buried sea water, or by mingling with meteoric waters. Sparry calcite thus does *not* necessarily imply any subaerial exposure.

Figure 1-31. (from Folk, 1974)



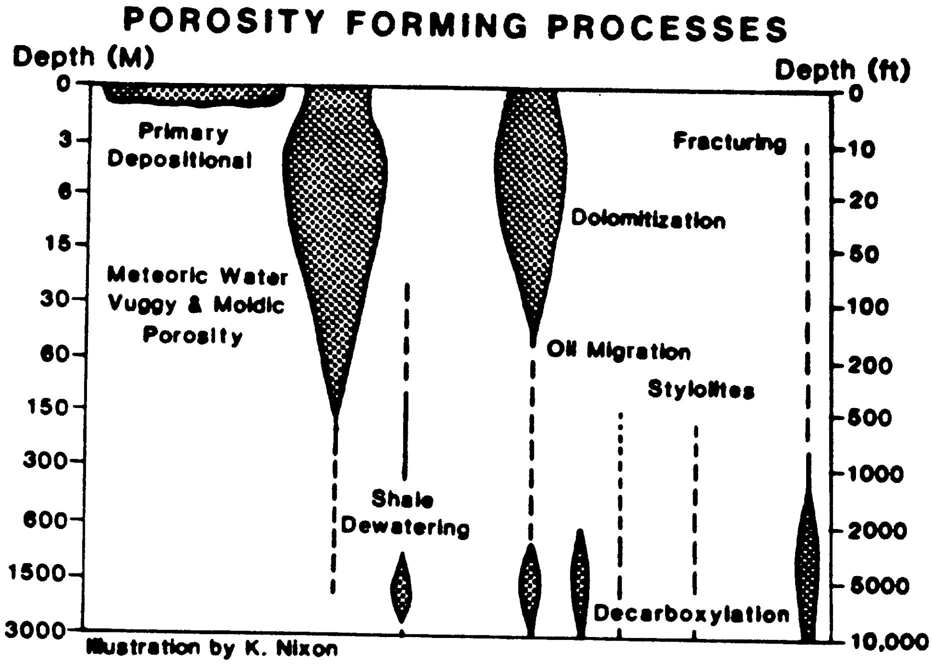
Crystal habit of $CaCO_3$ as controlled by Mg/Ca ratio. Where Mg is abundant it selectively poisons sideward growth so that fibrous crystals or elongate rhombs develop (these may represent bundles of coalescing fibers, as shown by the vertical flutings on the sides). Subsurface waters, often a mixture of sea water with fresh water, have a low Mg content and complex polyhedra form. In fresh waters either the elemental rhomb forms, or (if growth is very rapid and the Mg/Ca ratio very low), calcite may form mica-like books.

Figure 1-32. (from Folk, 1974)

—Ion Strength, Environment, and Carbonate Morphology

Chemistry		Environment	Crystal habit
Mg High	*Na High*	Hypersaline to Normal Marine, Beachrock, Sabkha, Submerged Reefs, etc.	Steep rhombs of Mg-Calcite with vertically-oriented flutings; Fibers of Mg-Calcite and Aragonite; growth rapid in c-direction; very slow laterally because of selective Mg-poisoning. Crystals limited in width to a few microns.
(Mg Low)	*Na High*	Mainly connate subsurface waters	Complex polyhedra and anhedra of calcite; lack of Mg allows unhampered growth and equant habit.
(Mg Low)	Na moderate to low	Meteoric phreatic, to deep subsurface mingling between meteoric and connate water	Complex polyhedra and anhedra of calcite; lack of Mg and slow crystallization allows equant crystals, often coarse.
(Mg Low)	(Na Low)	Meteoric vadose; caliche; streams and lakes	Simple unit rhombohedra of calcite
(Mg Low)	(Na Low)	Streams, Lakes, Caliche	Calcite micrite. Also, calcite sheets or hexagonal crystals with basal pinacoids; sheet-structure on edges visible due to very rapid lateral growth in the absence of Mg-poisoning.

Figure 1-33. (from Folk, 1974)



Relationship between depth and the major factors that increase porosity. Highly subjective.

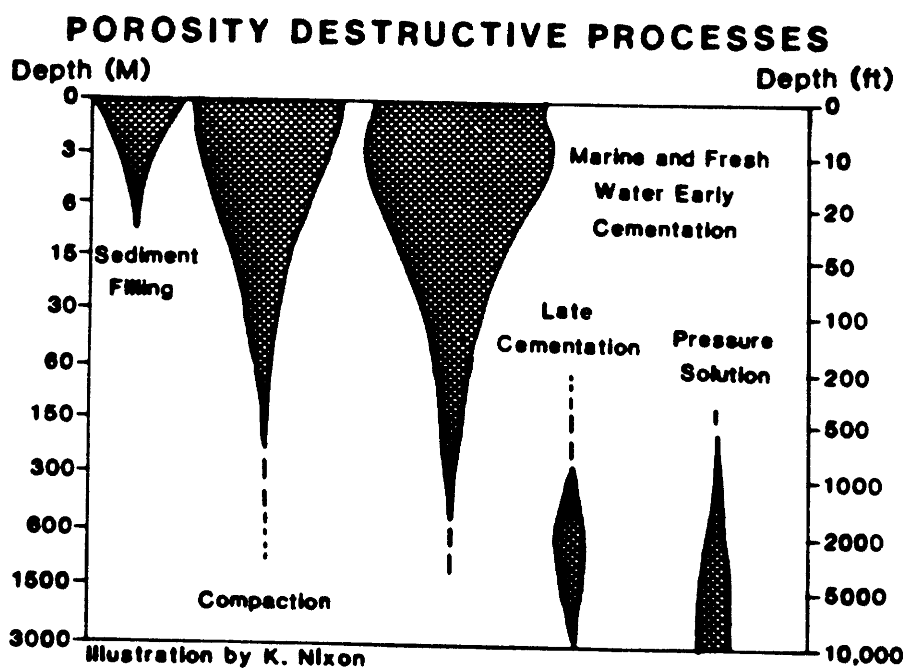
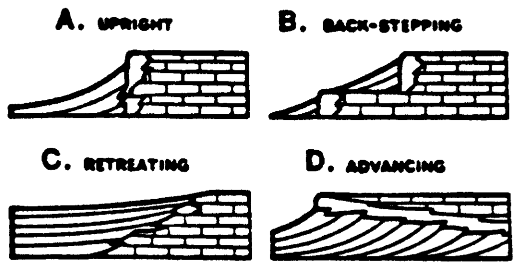


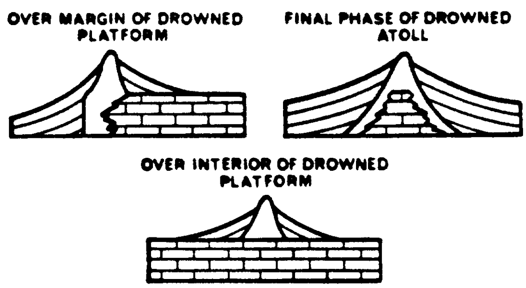
Diagram suggesting relationship between depth and the major factors that decrease porosity. Width of field is an indication of relative importance.

Figure 1-34. (from Longman, 1981)



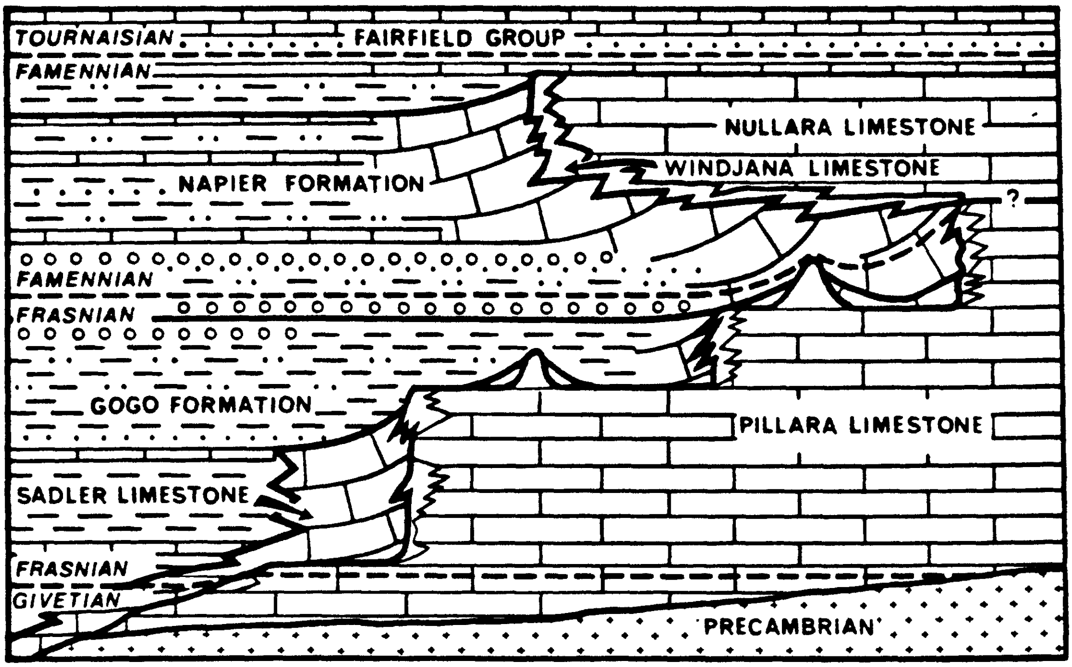
Morphologic evolution of carbonate outer-shelf margins

Figure 1-35. (modified from Playford, 1980)



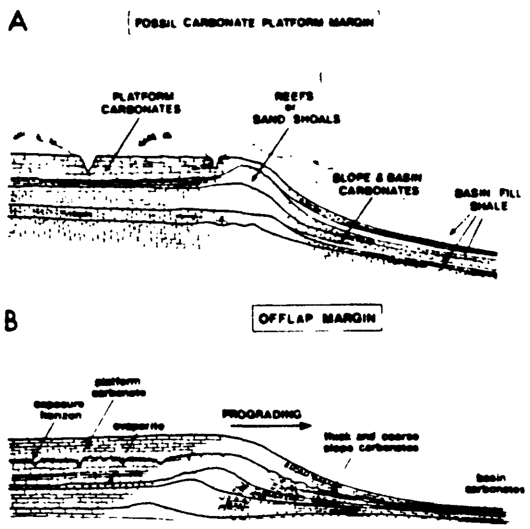
Sections illustrating development of pinnacle reefs in Canning basin.

Figure 1-36. (from Playford, 1980)



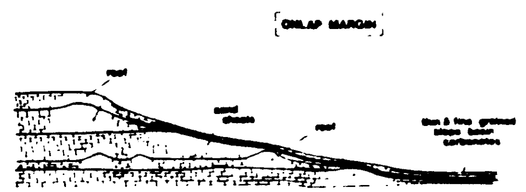
Diagrammatic cross section illustrating development of reef complexes through time and relations of stratigraphic units.

Figure 1-37. (from Playford, 1980)



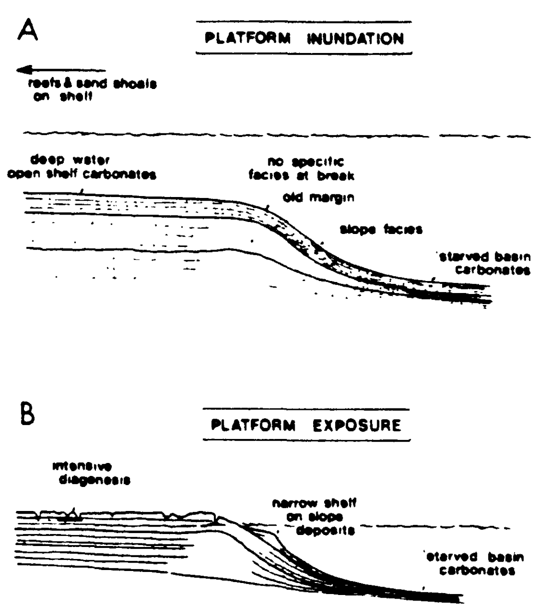
A. Sketch illustrating the main elements of a fossil carbonate platform margin In this example the shelf-slope break is in a *stationary* mode, remaining more or less in the same position as the platform grew. *B*. Diagram of a carbonate platform in which the rate of accretion has exceeded the relative rate of sealevel rise and the shelf-slope is in the *offlap* mode, prograding over older slope deposits.

Figure 1-38.



Sketch illustrating the response of the shelf-slope break to rapidly rising sealevel In this onlap mode, two situations are possible: if reefs occupy the break then the onlap occurs in a series of steps; if sand shoals are at the shelf-slope break, then a classic gradual onlap occurs.

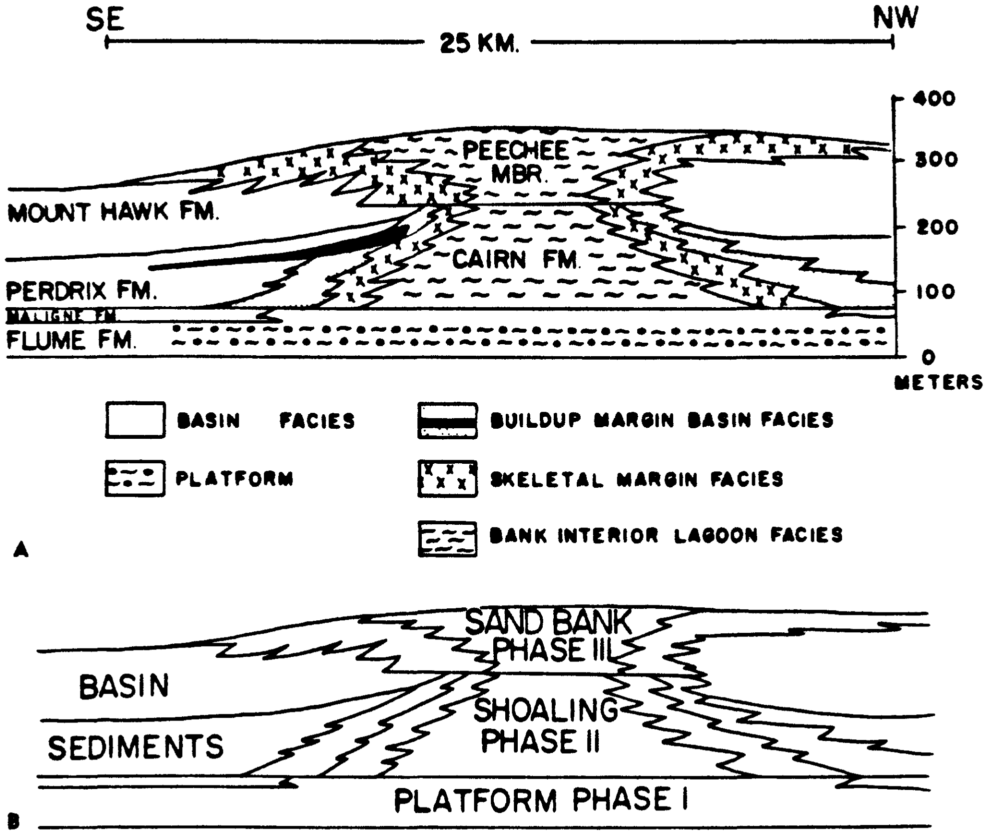
Figure 1-39.



A. Sketch illustrating the style of deposition at the shelf-slope break during complete inundation of a carbonate platform *B*. Diagram showing the effects of subaerial exposure of a carbonate platform.

Figure 1-40.

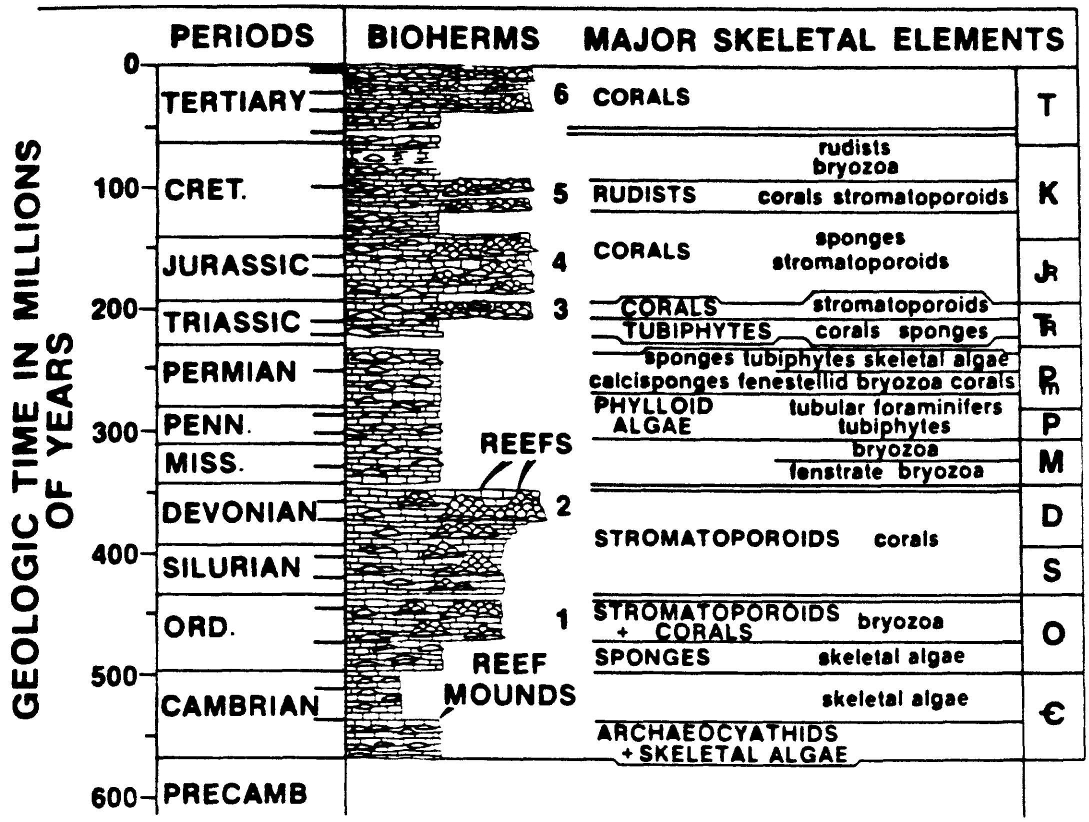
(from James and Mountjoy, 1983)



A. Generalized stratigraphic cross-section showing the stratigraphic and facies relationships at the Miette carbonate complex.

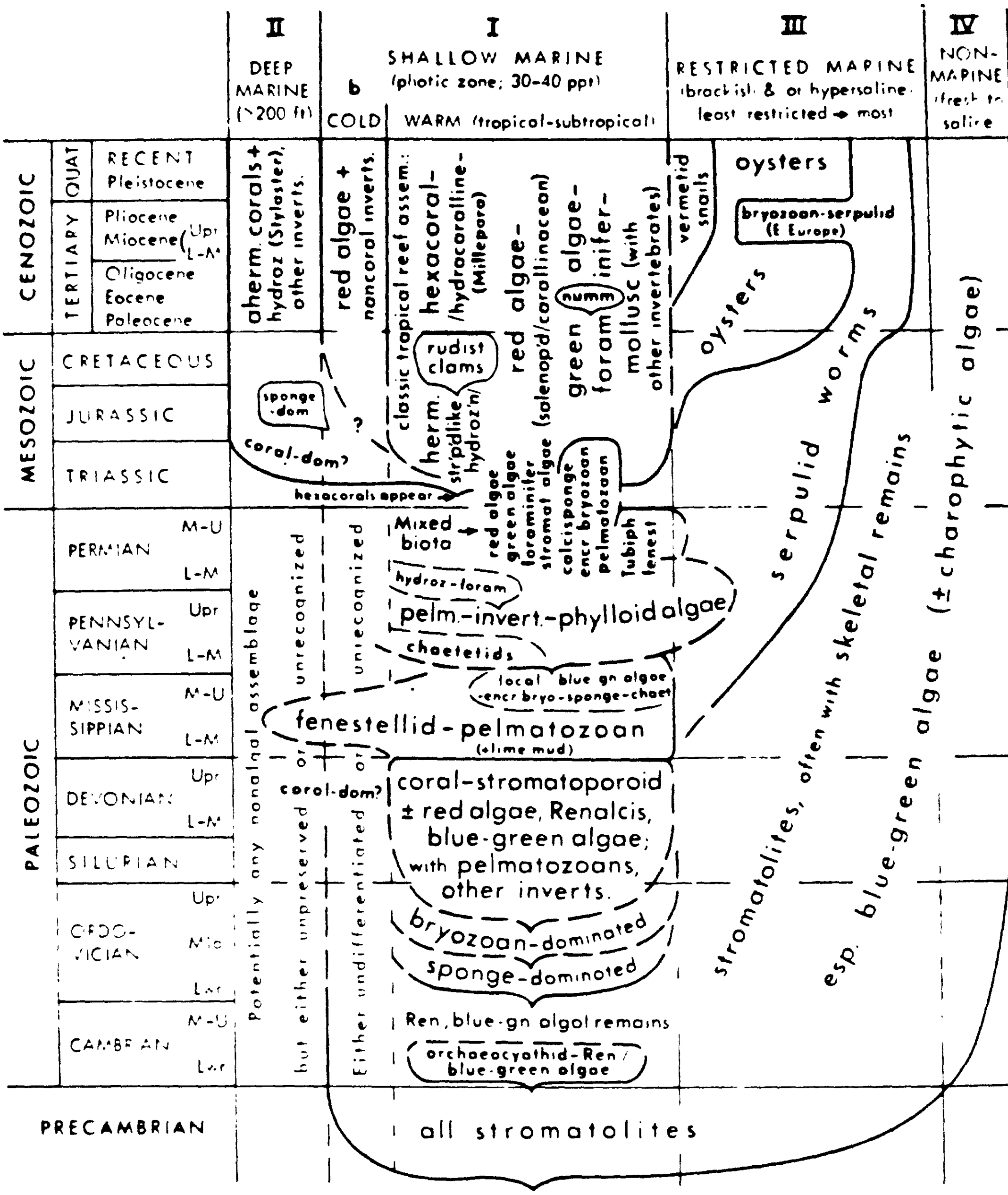
B. Generalized depositional phases of the Miette carbonate complex.

Figure 1-41. (from Cook et.al., 1972)



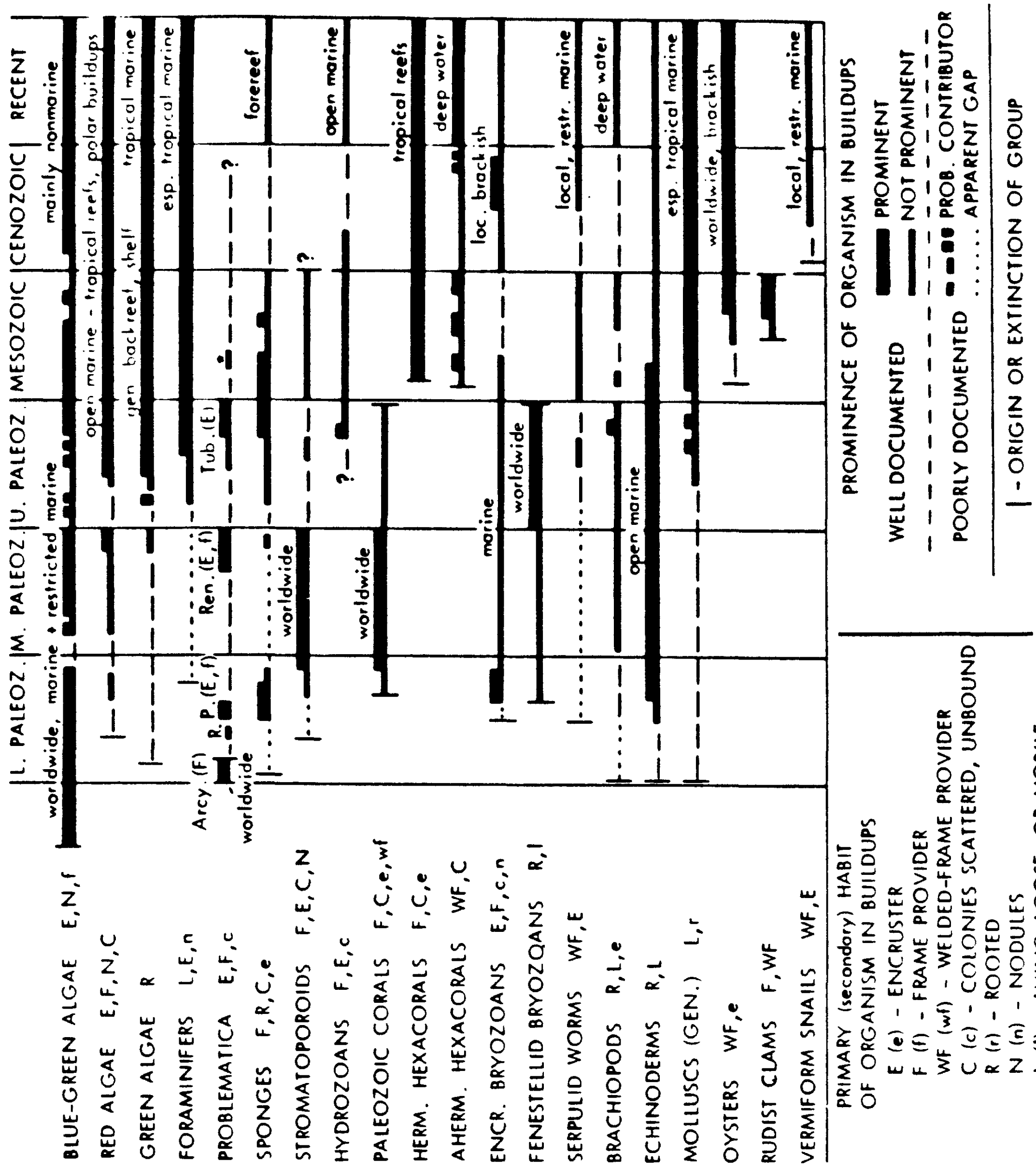
Idealized stratigraphic column representing the Phanerozoic and illustrating times when there appear to be no reefs or bioherms (gaps), times when there were only reef mounds, and times when there were both reefs and reef mounds and the organisms that built them.

Figure 1-42. (from James, 1983)



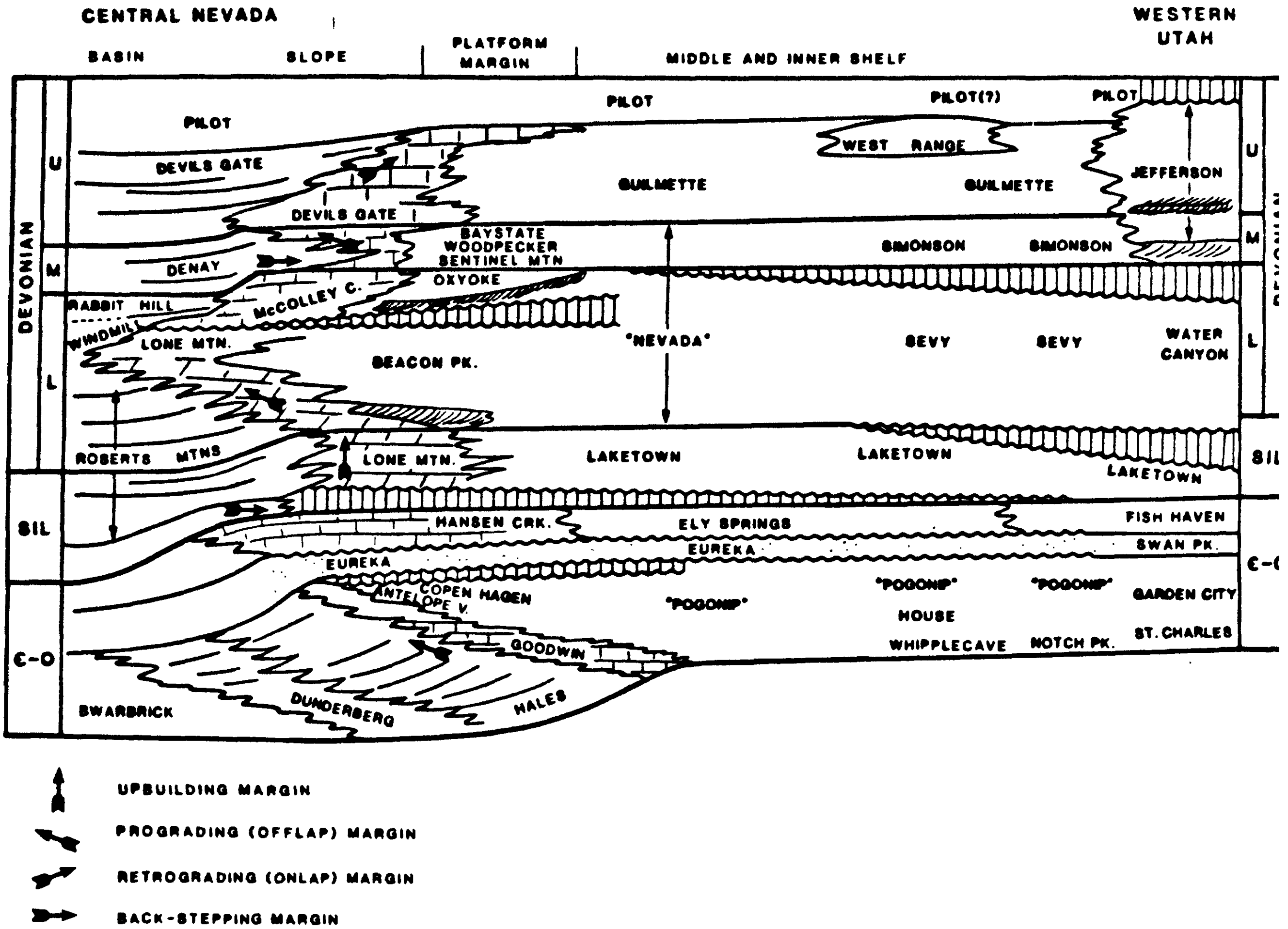
Geological history of major skeletal buildup assemblages in major environmental regimes. Because this scheme is based mainly on information from North America and Europe, modifications may be expected as more information from other areas become available.

Figure 1-43. (from Heckel, 1974)



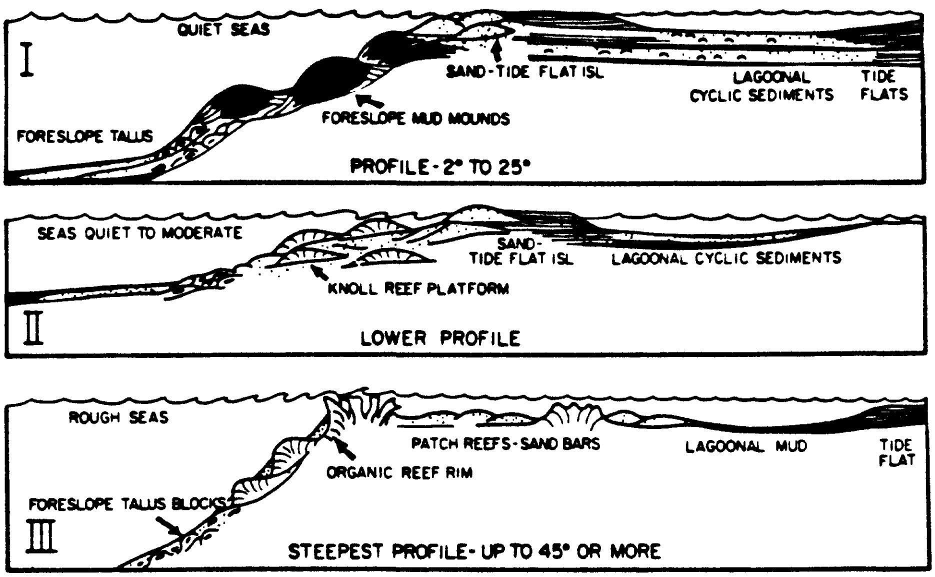
Geologic history of major skeletal contributors to carbonate buildups. Abbreviations not explained on figure: Arcy., Archaeocyathids; P., *Pulchrilamina*, R, Ren., *Renalcis* and related forms; Tub., *Tubiphytes*; *, other references to specific problematica. Ranges denoted "poorly documented" reflect only the literature readily available to me

Figure 1-44. (from Heckel, 1974)



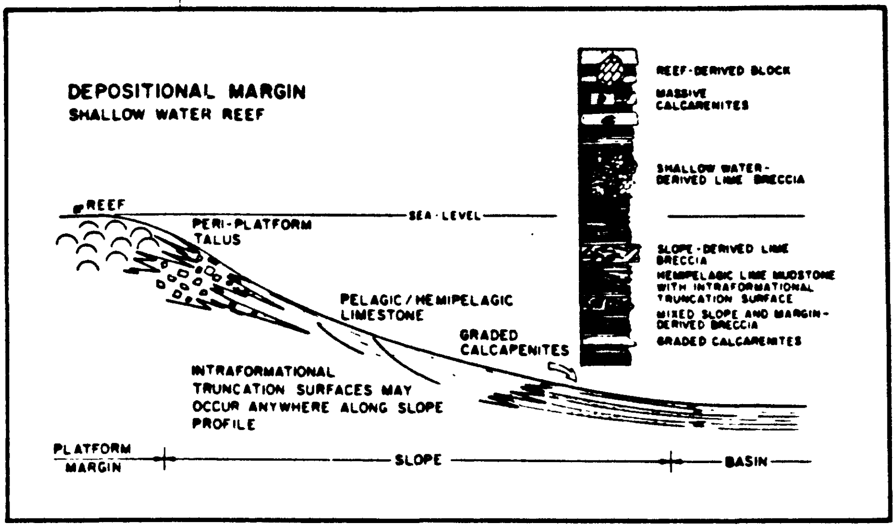
Pre-Antler orogeny depositional profile from western Utah to central Nevada showing formational terminology from Upper Cambrian through the Devonian. Unconformities are shown by vertical bars enclosing wavy horizontal windows of missing time. The total stratigraphic thickness shown at the platform margin is on the order of 10,000 to 15,000 feet, although the relative thicknesses of each System has been altered for diagramatic purposes. The distance across this continental margin from inner shelf settings to basin-margin settings is about 250 to 300 miles.

Figure 1-45. (modified from Cook and Taylor, 1983)



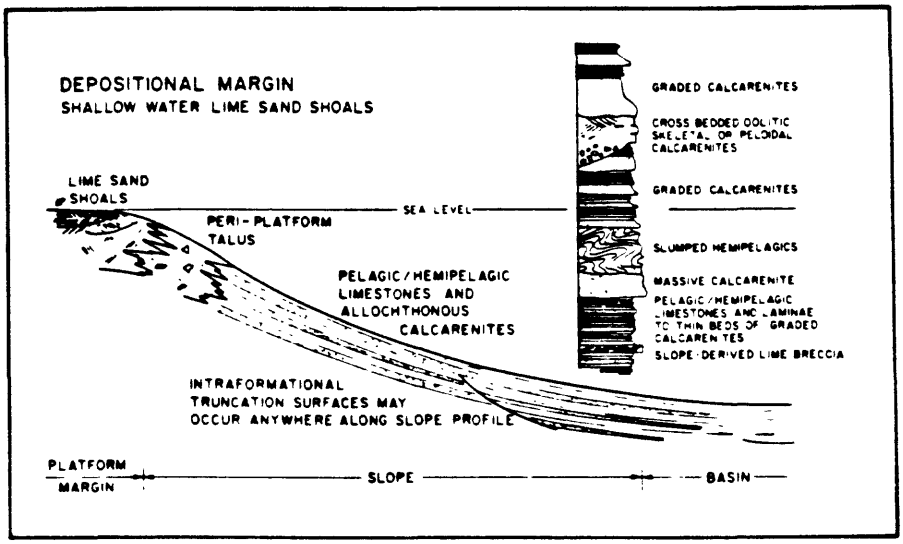
Three types of carbonate shelf margins: I, downslope lime-mud accumulation; II, knoll reef ramp or platform; III, organic reef rim.

Figure 1-46. (from Wilson, 1975)



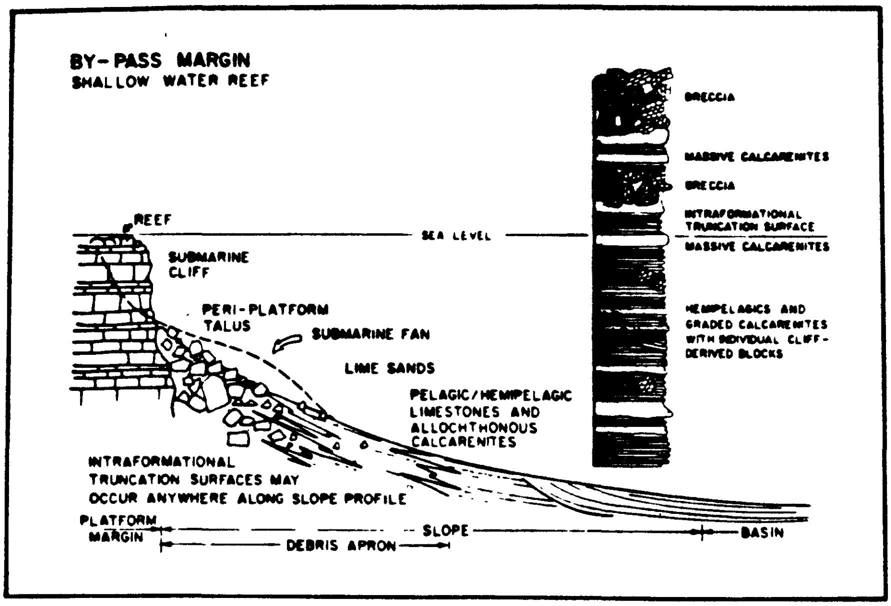
Schematic model for a shallow-water, reef dominated, depositional carbonate margin and illustration of a hypothetical sequence of deposits within the adjacent basin slope

Figure 1-47. (from McIlreath and James, 1978)



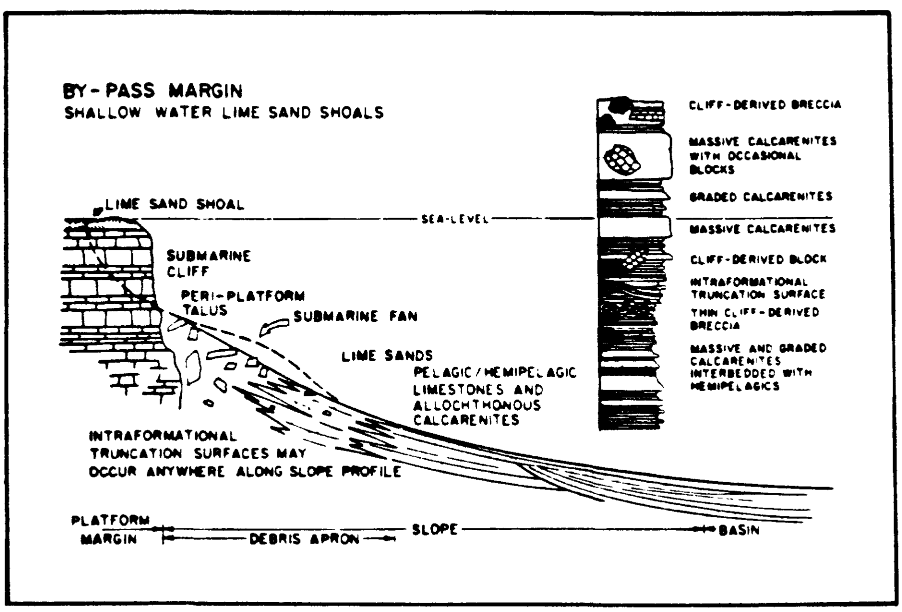
Schematic model for a depositional carbonate margin dominated by shallow-water lime sands and illustration of a hypothetical sequence of adjacent basinal slope deposits

Figure 1-48. (from McIlreath and James, 1978)



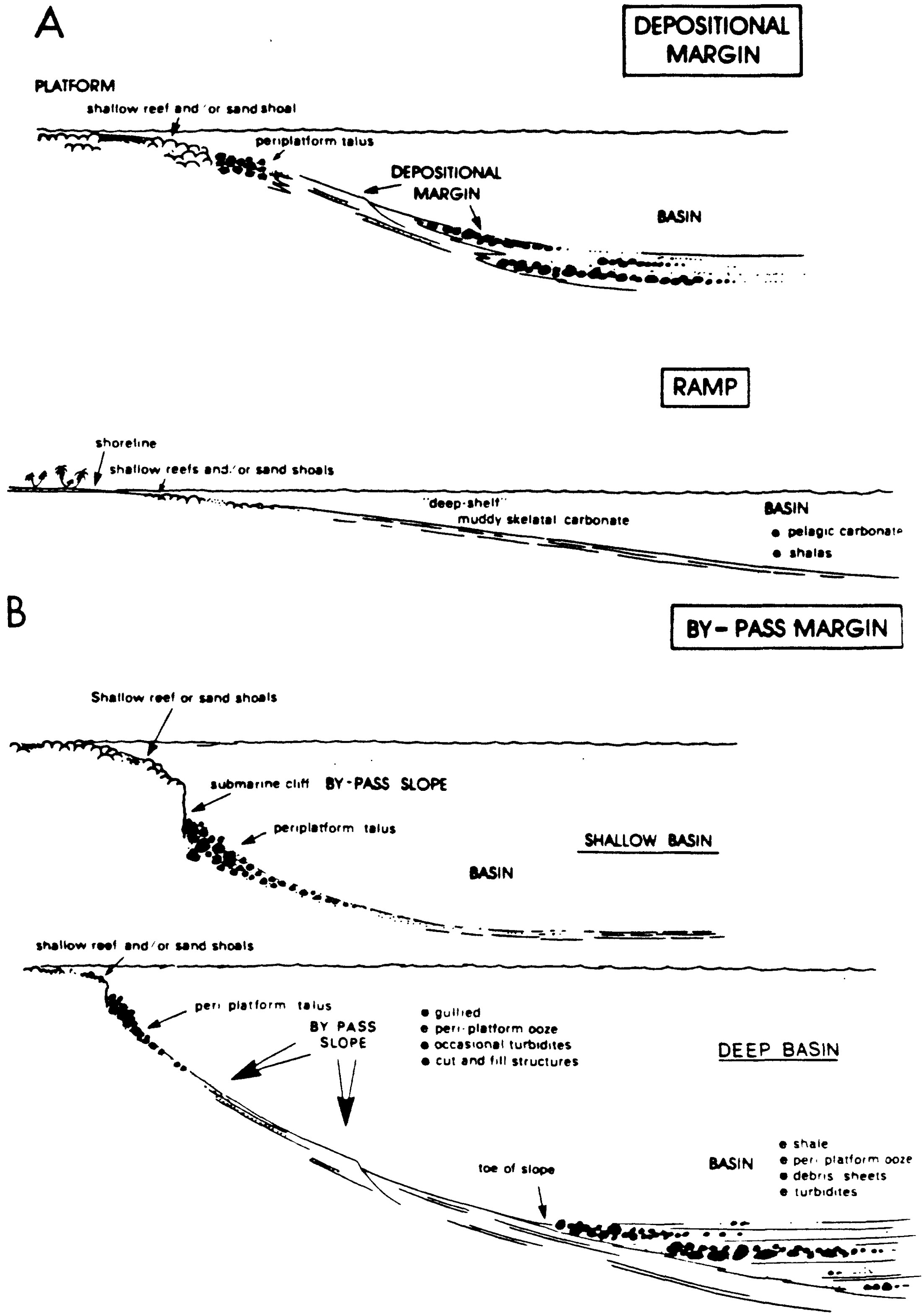
Schematic model for a shallow-water, reef dominated, by-pass type of carbonate margin and illustration of a hypothetical sequence of deposits within the adjacent basin slope

Figure 1-49. (from McIlreath and James, 1978)



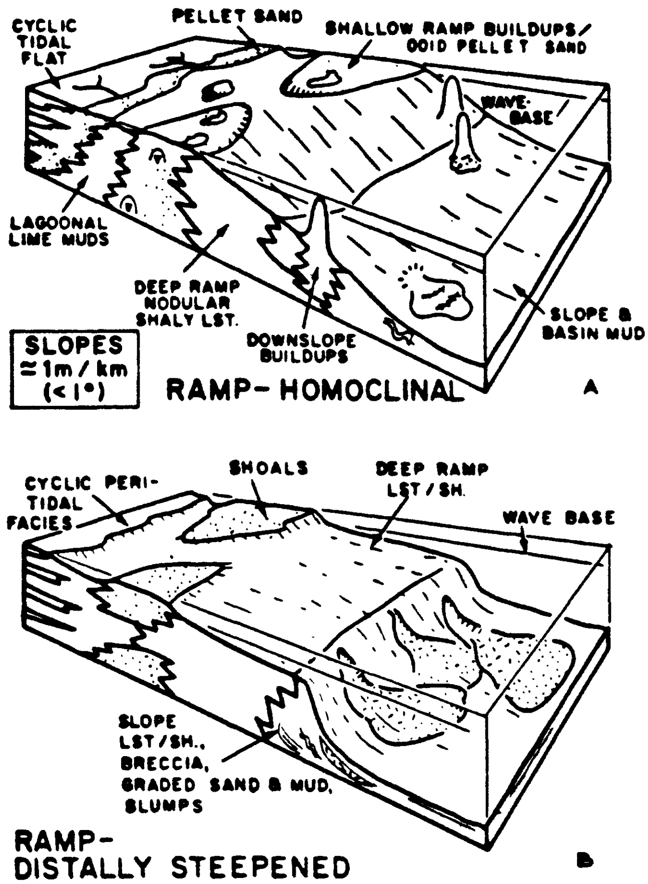
Schematic model for a by-pass type of carbonate margin dominated by shallow-water lime sands and illustration of a hypothetical sequence of adjacent basinal slope deposits.

Figure 1-50. (from McIlreath and James, 1978)



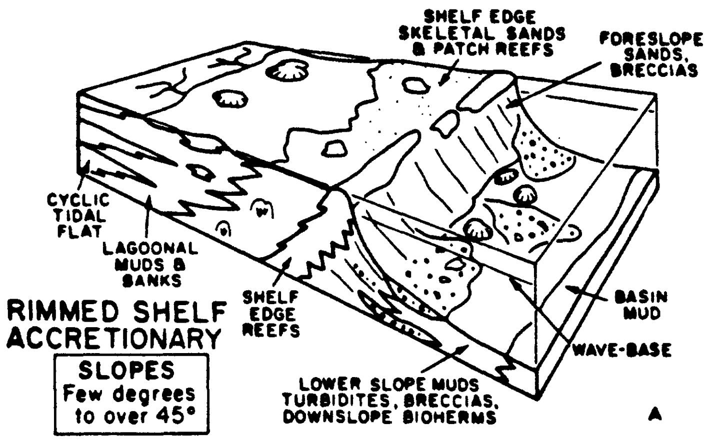
A. Sketch illustrating the morphology abd sediments on a depositional margin and a carbonate ramp. B. Sketch illustrating the morphology of and sediments on by-pass margins fronting shallow and deep basins.

Figure 1-51. (from James and Mountjoy, 1983)



A. Block diagram of homoclinal carbonate ramp. B. Block diagram of distally steepened ramp.

Figure 1-52. (from Read, 1982)



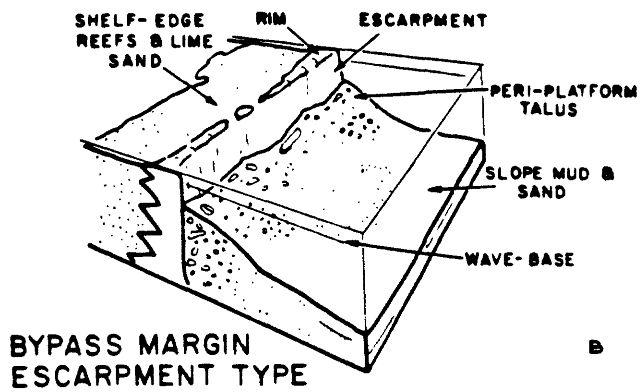
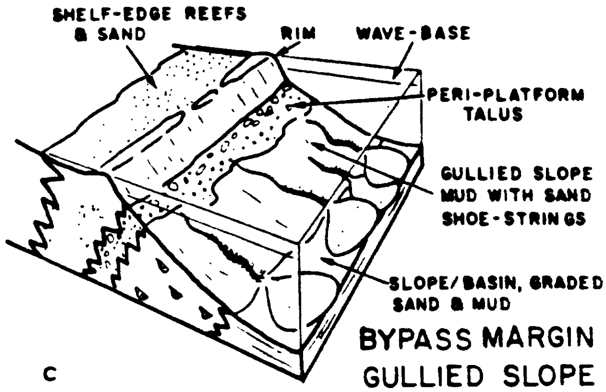


Figure 1-53. A. Block Diagram of rimmed carbonate shelf, accretionary type. B. Block diagram of rimmed shelf with bypass margi of escarpment type (from Read, 1982).



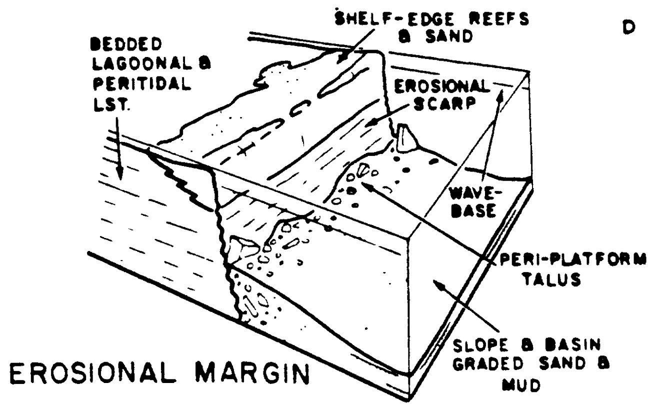
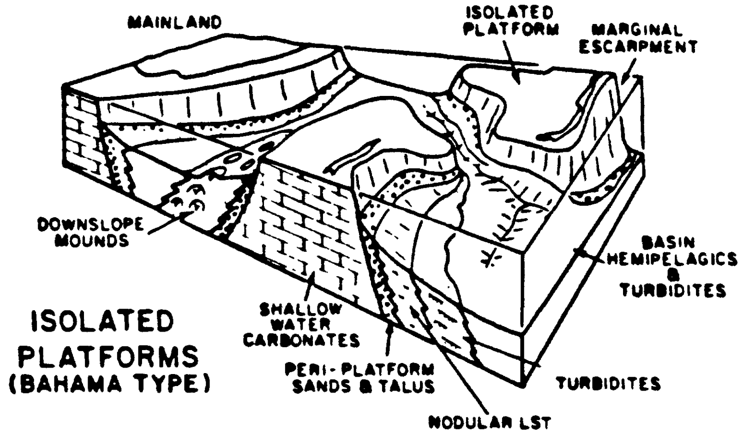
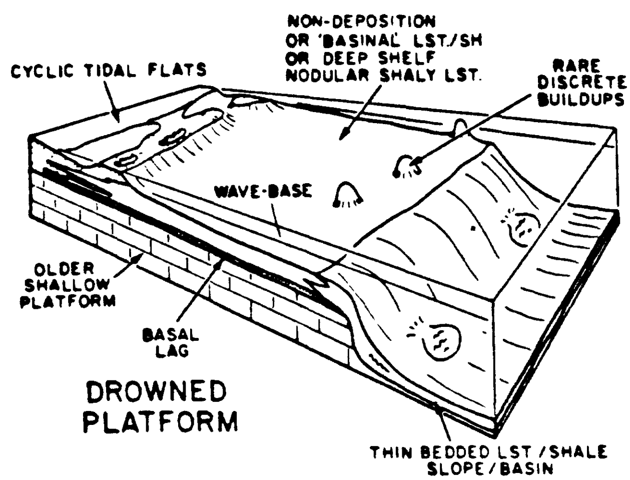


Figure 1-53. C. Block diagram of rimmed shelf with bypass margin of gullied slope type. D. Block diagram of rimmed shelf; erosional margin (from Read, 1982).



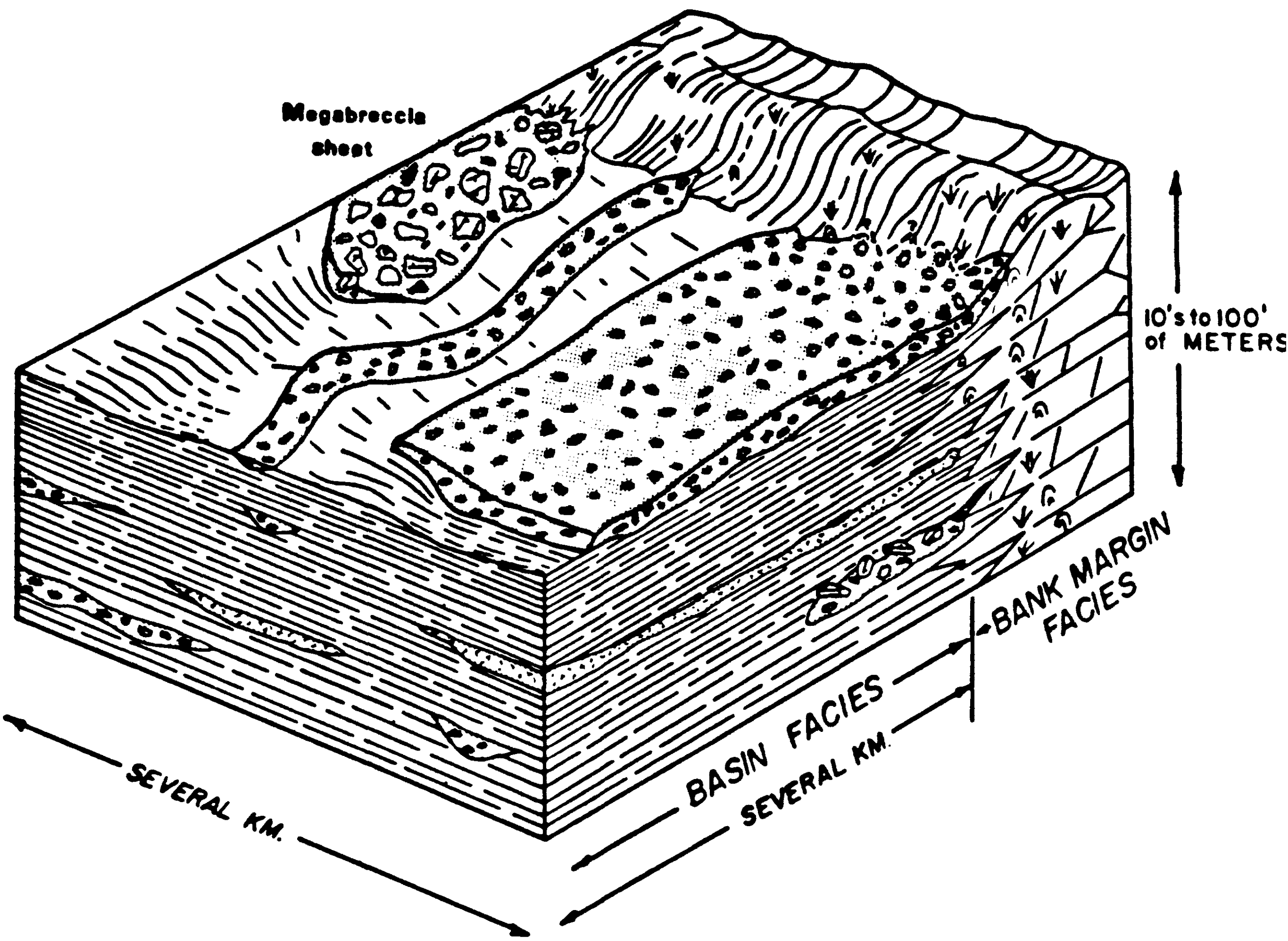
Block diagram of isolated platform.

Figure 1-54. (from Read, 1982)



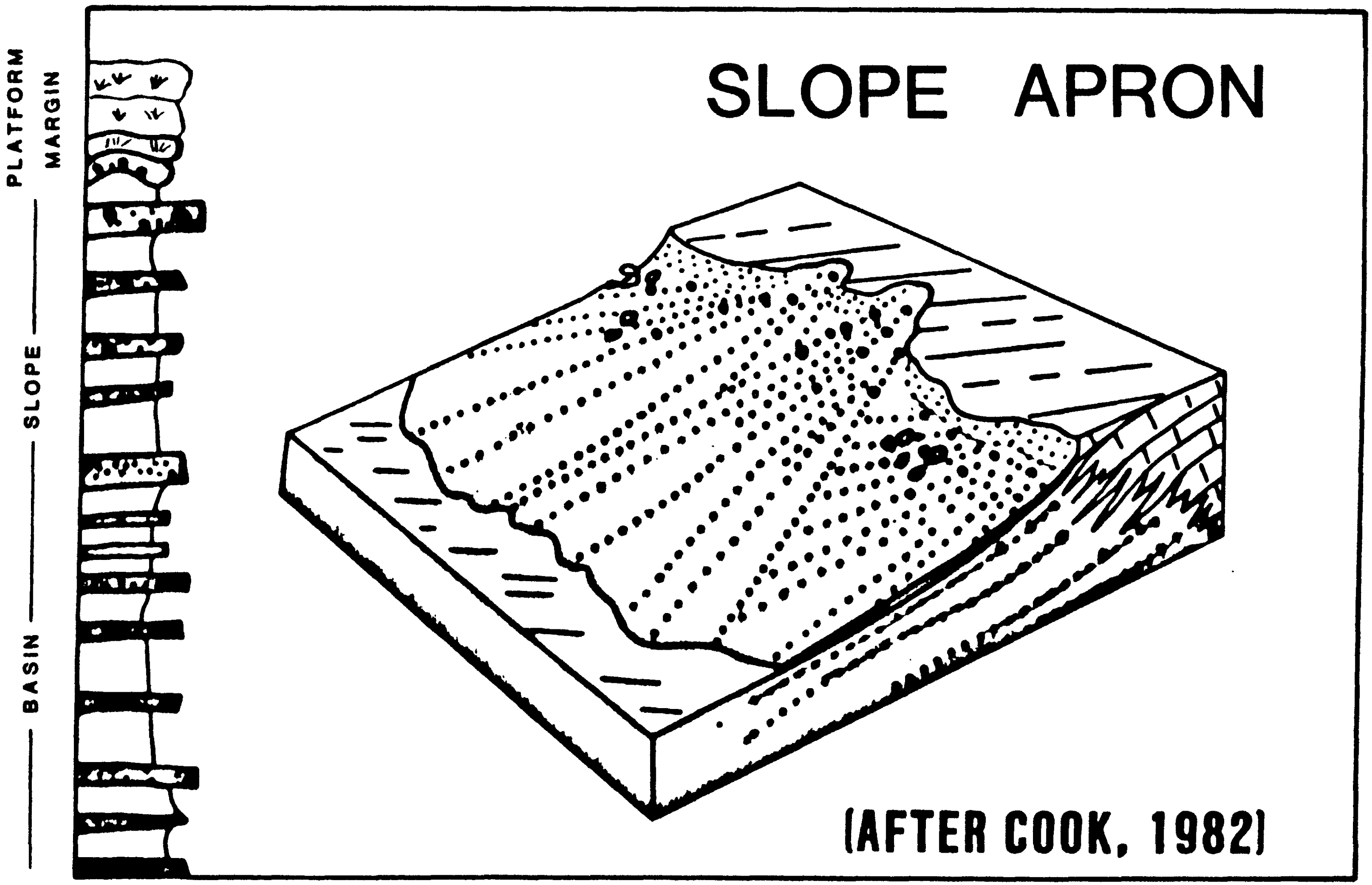
Block diagram of drowned platform.

Figure 1-55. (from Read, 1982)



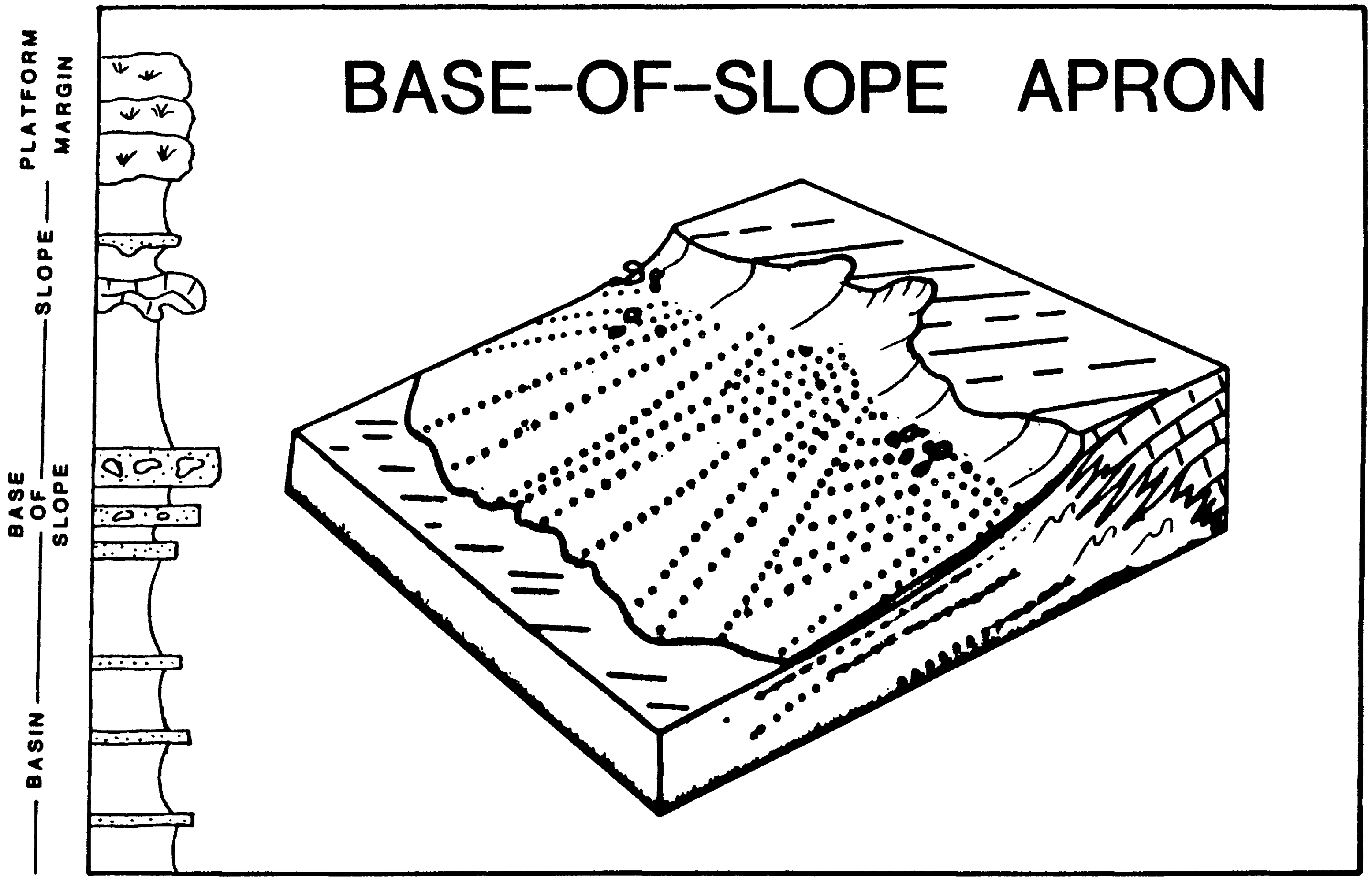
Carbonate debris sheet model. Generalized representation of allochthonous debris deposits showing textures, shapes and relation to bank and basin facies.

Figure 1-56. (from cook et.al., 1972)



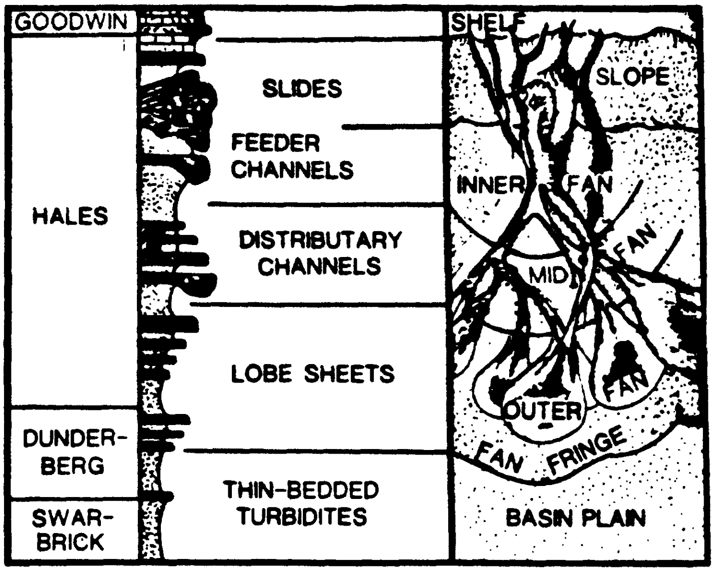
Carbonate slope apron model showing shoal water derived debris originating along a line source. Debris extends virtually up to the platform margin along low angle slope. Debris is transported as broad sheet flows.

Figure 1-57. (from Cook, 1982 and Cook and Taylor, 1983)



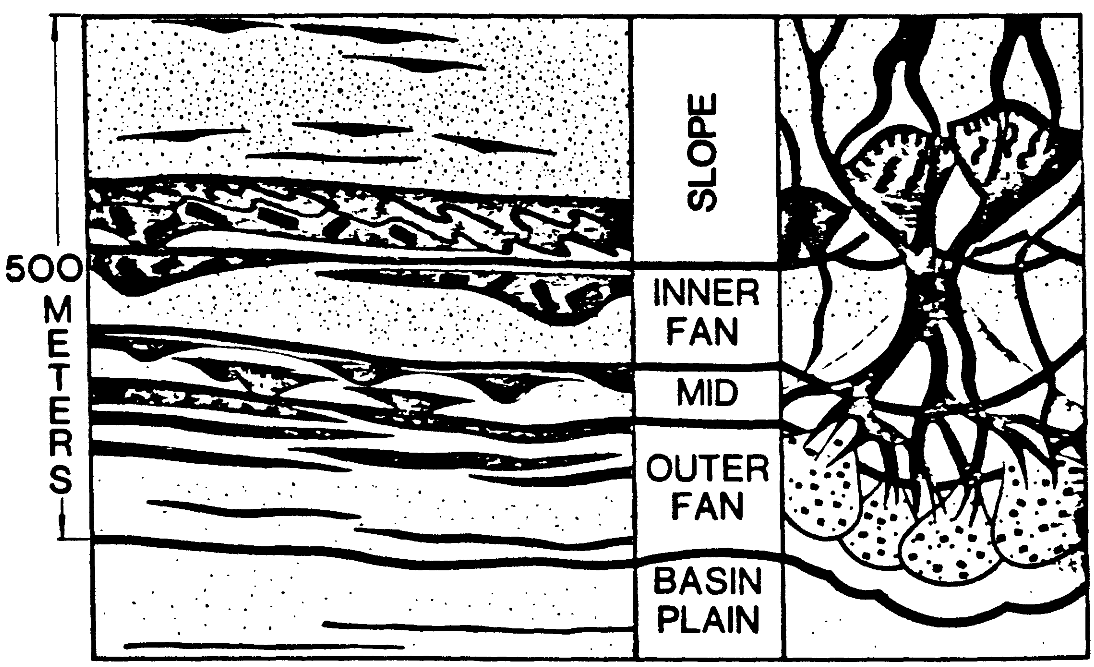
Carbonate base-of-slope apron model showing debris originating along a line source. Mass-flow deposits originating at platform margin largely by-pass the slope with the bulk of the debris deposited at the base-of-slope. Debris is transported as broad sheet flows.

Figure 1-58. (modified from Cook, 1982)



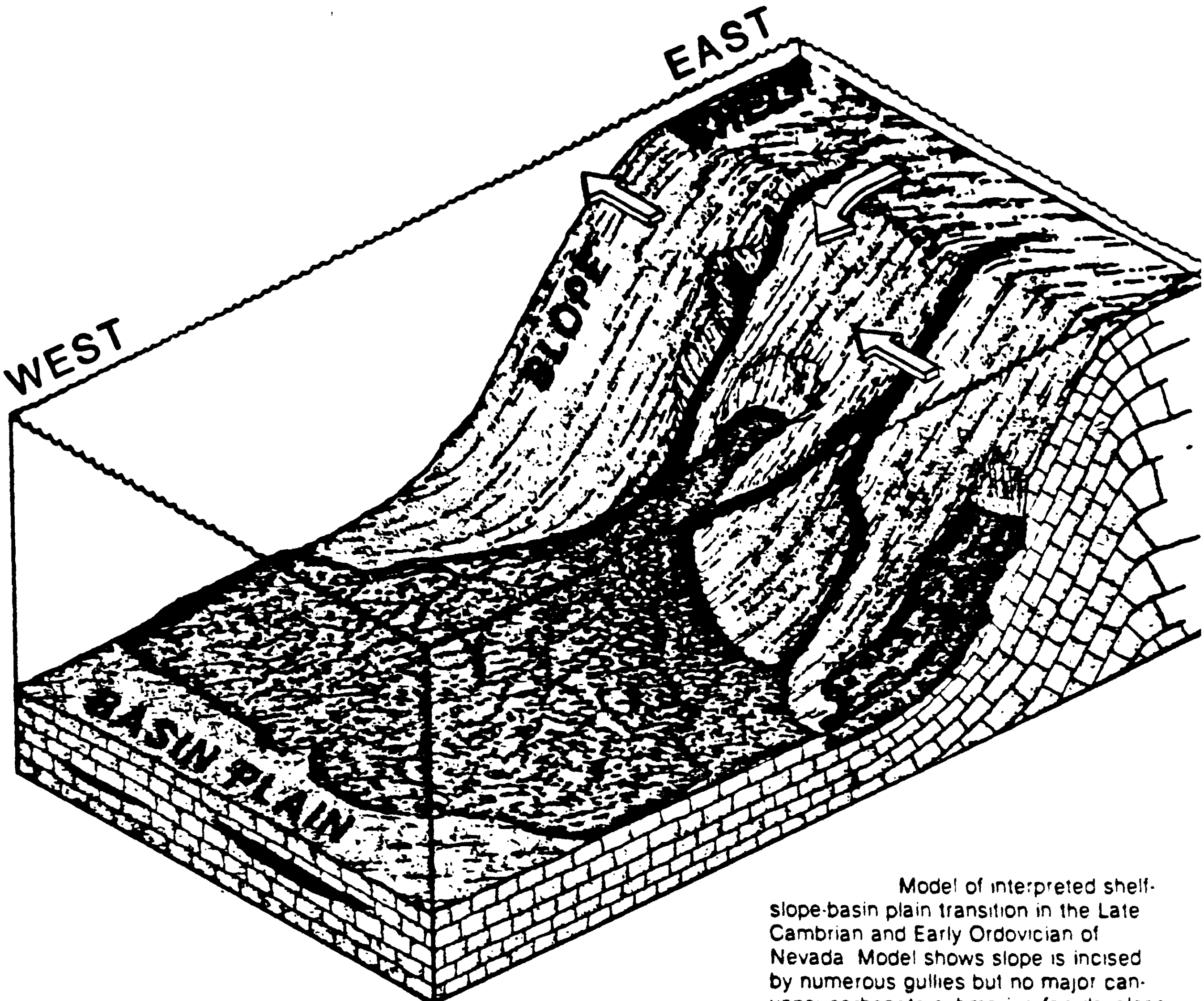
Preliminary local carbonate submarine-fan model showing that fan sediment is derived from both shoal-water shelf areas and by the remolding of deeper water slides and slumps into mass-flows, large slides and channelized conglomerates that occur in outer fan sites, calcarenites in non-channelized sheets in mid-fan sites, and thin-bedded silt to fine sand-sized carbonate turbidites in fan fringe and basin plain. Slope and fan facies about 500 m thick, basin plain facies about 1000 m thick. Model based on studies in Cambrian and Ordovician strata in Nevada

Figure 1-59. (from Cook and Egbert, 1981b,c and Cook and Mullins, 1983)



Preliminary local carbonate submarine fan model. Schematically shows vertical and lateral facies sequences that occur in prograding continental margin section. Model based on studies in Cambrian and Ordovician strata in Nevada

Figure 1-60. (from Cook and Egbert, 1981a and Cook and Mullins, 1983)



Model of interpreted shelf-slope-basin plain transition in the Late Cambrian and Early Ordovician of Nevada. Model shows slope is incised by numerous gullies but no major canyons; carbonate submarine fan develops at base of slope and basin plain, fan sediment is a mixture of shoal-water shelf carbonates and deeper water slide generated debris, contour currents flow northerly along upper slope.

Figure 1-61. (from Cook and Egbert, 1981a and Cook and Mullins, 1983)

PART 2. ANCIENT CARBONATE PLATFORM MARGINS, SLOPES AND BASINS

INTRODUCTION

As was pointed out in Part 1, the need to locate new energy resources coupled with discoveries of petroleum in carbonate slope and base-of-slope settings (albeit usually by accident rather than by design) has intensified research and exploration efforts in these frontier deep water carbonate environments.

Ancient carbonate platform margins have historically been a major petroleum exploration target and accordingly there is a wealth of literature that pertains to ancient reef and bank margins. It is well beyond the intent or scope of this chapter to discuss the myriad of facies types at platform margins but several recent publications that are recommended reading include Laporte (1974), Wilson (1975), Enos (1977a), Toomey (1981), Halley et al (1983), and James (1983). Three well-written papers that present thoughtful overviews of platform margins are Kendall and Schlager (1981), Read (1982), and James and Mountjoy (1983).

What has not been extensively studied, however, are carbonate slope and base-of-slope settings, how deeper water facies interrelate to their temporal equivalents on the platform margin, the various facies associations that comprise basin margin sequences, and the potential value of deeper water carbonate facies in petroleum and minerals exploration (Cook et al, 1972; Cook and Enos, 1977a; McIlreath and James, 1978; Cook, 1982; Cook and Mullins, 1983; Mullins and Cook, in prep.).

This chapter focuses on slope and basin settings but it also stresses that the type of shoal water platform margin can play a key role in determining the facies sequences which develope in the adjacent deep water environments. One cannot fully understand the vagaries of submarine slides and slimps, carbonate debris sheets, carbonate aprons, or carbonate submarine fans without some knowledge of their time-stratigraphic shoal-water counterparts. This point is well documented for modern carbonate platform margin/slope couplets. Conversely, as will be discussed in this chapter redeposited shoal-water derived carbonates that now reside in deep basin environments can provide important clues as to the nature, origin, and proximity of platform margins.

Chapter 5 is divided into three main parts - Sedimentary Facies, and Processes, Facies Patterns and Depositional Models, and Implications for Petroleum and Minerals Exploration.

SEDIMENTARY FACIES AND PROCESSES

This section includes a general descriptive overview and summary of the major facies that occur in platform margin, slope, and basin environments and some aspects of the processes that form these facies.

Platform Margins

The platform margin-to-slope break in ancient carbonate complexes, whether the margin of a small isolated platform (ex: Cook et al, 1972), or the margin of a 500 Km wide continental shelf (ex: Cook and Taylor, 1977; Cook and Taylor, 1983), was a crucial part of their anatomy. As James and Mountjoy (1983) state, "the zone was crucial because, unlike shelves of terrigenous clastic sediments, the facies developed at the carbonate shelf-slope break controls the way in which the platform evolves. It was here that the most diverse community of organisms grew, the most rapid accretion took place, the most intensive diagenesis probably occurred and the most rewarding hydrocarbon and mineral deposits may have accumulated". They go on to say that "this facies is elusive because it is relatively narrow and so chances of it outcropping or being intersected by drilling are low. Also because of the marked lithological differences between shelf carbonates and basin shales, it tends to be strongly deformed during orogenesis. As a result, the nature of the shelf-slope break is commonly interpreted rather than observed, and synthesized on the basis of information from surrounding facies".

Platform margins can be either rimmed or non-rimmed. Modern platforms are rimmed by a complex array of reefs and/or carbonate sand shoals. These facies normally developed under fairly high energy conditions. The same is true for rimmed ancient carbonate platform margins on which either organic facies or inorganic carbonate sand shoal facies dominated. The specific character of the organic margin facies will be strongly influenced by the major skeletal elements that were dominant at a particular time in geologic history (Fig. 2-1). In contrast certain inorganic facies that occur at ancient platform margins look much the same whether they are of Cambrian or Holocene age (ex: oolite grainstones).

Non-rimmed carbonate margins (i.e. homoclinal ramps of Read, 1982) contain no clear shelf-slope break unless the deeper water part of the ramp is distally steepened. The outer margin of a homoclinal or distally steepened ramp is an environment of low energy and is usually characterized by mud-supported facies rather than by high energy grain-supported textures.

The present day location of ancient carbonate platform margins is quite diverse owing to the migration of crustal plates through geologic time as well as whether the platform margins were on continental shelves or within continents (Fig. 2-2). James and Mountjoy (1983), using the three types of platform margin models of Wilson (1975) (Fig. 2-3), generalize the temporal variation in platform margin facies types from the Precambrian through the Cenozic (Table 2-1). However, Wilson (1975) did not include the homoclinal ramp or distally steepened ramp in his three platform margin models. Thus as James and Mountjoy (1983) point out, even though Table 2-1 may account for many cases in the geologic record it does not accomodate non-rimmed (ramp) platform margin sequences (ex: Cambrian-Ordovician of the western United States, Cook and Taylor, 1977, and Jurassic of the U.S. Gulf Coast, Ahr, 1973).

As can be seen in figure 2-1 there were periods of time when carbonate platform margins had the potential to be dominated by reefs while at other times the platform margin facies was dominated by skeletal sands and/or skeletal mud mounds ("reef" mounds). An important point to also bring out is that even though a platform margin may have the potential to develop a massive true boundstone reefal facies, the initial facies on a platform margin substrate may consist simply of thinly bedded skeletal debris. There is commonly a vertical facies sequence that starts with small, rooted pelmatozoans that may simply trap mud and form packstones and grainstones. Within a reef core it is possible to develop four separate facies which represent different stages of development of the reef (Fig. 5-4) (James, 1983; James and Mountjoy, 1983). Thus, not only through geologic time were there periods in which platform margin rims were dominated by reef facies versus carbonate sand shoals (Fig. 5-1) but even a reef margin can exhibit a vertical zonation from an early stabilization stage of skeletal debris (packstones and grainstones) to a domination stage of a laminate encrusting skeletal metazoa (boundstones to framestones).

Pelagic, Hemipelagic, and Peri-Platform Sediments

Pelagic is used in a descriptive to mean open-marine deposits in deep seas on oceanic crust and shallow epicontinental seas (Scholle, et al, 1983b). The term pelagic is also assigned to organisms (planktic-nektic and benthic) that live in open-marine environments. Pelagic sediments contain a minimum of terrigenous sediment as well as shoal-water carbonate platform sediment. Hemipelagic is commonly used for those sediments that contain a mixture of pelagic constituents and terrigenous fine-grained clastics. Peri-platform sediments (Schlager and James, 1978) is a relatively new term especially coined for carbonate slope and basin margin sediments. Peri-platform oozes are a mixture of pelagic skeletal remains and fine-grained lime muds derived from shoal water platform margins.

Thus there are three main sources for the fine-grained, laminated, lime mudstones and wackestones that are so characteristic of ancient carbonate slope and basin sequences:

1. Shallow water lime muds
2. Pelagic constituents from open-marine environments
3. Terrigenous clastics

The first and third sources can clearly supply material to deeper water settings throughout geologic time. However, carbonate slope and basin settings adjacent to continental margins or within the interior of continents normally have more terrigenous clastics that slope and basin sequences adjacent to open ocean isolated carbonate platforms.

There is a wide diversity of major biogenic components of modern and ancient pelagic limestones (ex: see Scholle et al, 1983, Table 1). During the Paleozoic some of the organic pelagic components of slope and basin carbonates include sponge spicules, tentaculitids, benthic forams, graptolites, radiolarians, conodonts, belemnites, nautiloids and ammonites. Although the list of components is extensive the bulk volume of these components to the pelagic realm was relatively low. Thus, Paleozoic slope and basin sequences are often referred to as "starved-basin facies". Widespread radiolarian chert and graptolitic limestones is a consequence of the lack of major sources of pelagic carbonates during the Paleozoic. A typical Paleozoic in situ slope or basin margin limestone is not a pelagic limestone but is normally a peri-platform carbonate. It consists dominately of shoal-water, platform derived lime muds with minor amounts of pelagic microfossils and terrigenous clastics.

It was not until about 100 to 150 m.y. ago that carbonate pelagic organisms began to flourish at such a scale that they became a dominant component in pelagic environments. Since the Jurassic there has been virtually a continuous rain of calcareous planktic forams and coccolithophoroids into deep water such that collectively these two microfossil groups are the major components in pelagic carbonates (Cook and Egbert, 1983). Thus, whereas Paleozoic pelagic carbonates and cherts accumulated at rates normally less than 10 m/my some Cretaceous chalks have sedimentation rates of about 60 m/my (Cook and Egbert, 1983; Scholle et al, 1983b).

The characteristics of ancient deep-water carbonates are discussed in detail by Wilson (1969) and Cook and Enos (1977b) and Scholle and others (1983). Throughout the geologic column, undisturbed slope and basin sediment has numerous common features. Typical rock types are dark gray to black lime mudstones, calcisiltites, and wackestones. Variable amounts of insoluble residue are usually present as organic carbon, pyrite, silt size quartz grains and clay minerals. Beds exhibit contacts that range from planar and nearly parallel and continuous for tens of meters to more wavy and discontinuous (Fig. 5-5). Slope sediment is further characterized by its thin bedding to millimeter-thick laminae. Preservation of laminae under quiet water conditions will depend mainly on whether the sediments formed in aerobic or anaerobic waters and the influence these conditions exerted on burrowing organisms (Fig. 5-6; Byers, 1977). In silled basins only the upper part of the water column is well oxygenated whereas at water depths below a few hundred meters the water is anoxic. In open ocean conditions there is commonly a three-layer water system with the surface and deep waters being well oxygenated and water at intermediate depths on the slope having very low oxygen contents (oxygen minimum zone). Thus that part of the slope which is intersected by the oxygen minimum zone will have fewer burrowers and better preserved laminations than slope sediment which formed in well-oxygenated waters.

Submarine Mass Transport

Mass transport is used here for the en masse downslope movement of material containing various amounts of water, for which gravity is the driving force (Dott, 1963; Cook et al., 1972). A selected list of papers that treat various aspects of mass transport includes: Bagnold (1954, 1956, 1966), Bouma (1962), Dott (1963), Dill (1966), Morgenstern (1967), Stauffer (1967), Middleton (1970), Fisher (1971), Cook et al.

(1972), Hampton (1972, 1975), Mountjoy et al. (1972), Middleton and Hampton (1973, 1976), Walker and Mutti (1973), Carter (1975), Walker (1975), Wilson (1975), Lowe (1976a, b), Cook and Enos (1977a, b), Enos (1977c), Shanmugam and Benedict (1978), Stanley et al. (1978), Varnes (1978), Cook (1979a, b, c), Krause and Oldershaw (1979), Lowe (1979a, b), Mullins and Van Buren (1979), Nardin and others (1979), Bosellini et al (1981), Cook and Mullins (1983), Enos and Moore (1983), Ruiz-Ortiz (1983), and Mullins and Cook (in prep.). Table 2-2 and Figures 2-7 and 2-8 summarize the characteristics of the main types of mass transport and the classification schemes that are currently most widely accepted.

Mass transport can be divided into three types--rockfalls, slides, and sediment gravity flows (Table 2-1). Slides and sediment gravity flows can be further subdivided on the basis of their internal mechanical behavior and dominant sediment support mechanism (Table 2-2, Fig. 5-8).

Rockfalls, also referred to as talus accumulations, are only abundant in the marine environment at the base of steep slopes, canyon walls, or fault scarps. Deposits of this type accumulate by the rolling or freefall of individual clasts.

Slides can be divided into translational (glide) and rotational (slump) types (Varnes, 1978). The shear plane of a translational slide is predominantly along planar or gently undulatory surfaces parallel to the underlying beds. Slumps (rotational slides) exhibit concave-upward shear planes and usually a backward rotation of the slumped body. Slides can exhibit variable amounts of internal deformation. Some slides show purely elastic behavior, the original bedding is virtually undisturbed except at the basal shear plane. Other slides behave in both an elastic and plastic manner, and semiconsolidated sediment is deformed into overfolds. Some slides become so internally deformed that they have been remolded into debris flows (Cook and Taylor, 1977; Cook, 1979a, b, c).

Much of the literature on the mass transport of ancient submarine sediment does not distinguish between deformed strata that have moved along discrete shear planes (slides) and deformed strata with no obvious basal shear plane. Also, literature on submarine slides often does not differentiate between translational slides (glides) and rotational slides (slumps) (Table 2-2). Some authors commonly use the term "slump" for any type of feature that exhibits soft-sediment deformation but no clear basal features. Thus, some "slumps" in the literature may be translational slides rather than rotational slides (slumps) or some "slumps" may simply be deformed strata with no sharp upper and lower boundaries.

Sediment gravity flows are defined by Middleton and Hampton (1976, p. 197) as being "flows consisting of sediment moving downslope under the action of gravity . . . synonymous with mass flows . . . ." They distinguish four main types of such flows based on the forces that support the grains above the sediment-water interface during downslope transport due to gravity (Fig. 2-8): "(1) turbidity currents, in which the sediment is supported mainly by the upward component of fluid turbulence, (2) grain flows, in which the sediment is supported by direct grain-to-grain interactions (collisions or close approaches), (3) fluidized sediment flows, in which the sediment is supported by the upward flow of fluid escaping from between the grains as the grains are settled out by gravity, and (4) debris flows, in which the larger grains are supported by a "matrix," that is, by a mixture of interstitial fluid and fine sediment, which has a finite yield strength" (Middleton and Hampton, 1976, p. 198).

Lowe (1976a) correctly draws the distinction between fluidized sediment flow and liquefied sediment flow. In fluidized flows there is an upward movement of fluid between the grains which themselves are not moving downward. For example, the mobility of ignimbrites or ash-flow tuffs is best explained by fluidization of the constituent particles in which gases emitted by the particles develop a pressure equal to, or greater than, the hydrostatic pressure due to the weight of the particles themselves, and the mass starts to expand, and behaves like a fluid (Cook, 1968). In liquefied flows the upward movement of water between grains is caused by the downward movement of grains which displaces the water upward. As Lowe (1976a) points out, except in volcanic vents and ignimbrites, where escaping gases fluidize the vitroclastic particles, fluidization as a sedimentary process under subaqueous environments probably does not occur. Biogenic gas from decaying organic matter or even gaseous hydrocarbons are unlikely to fluidize significant volumes of sediments, although they can significantly reduce shear strength and precipitate mass movements. Fluid escape structures in sediment gravity-flow deposits are probably the result of liquefication and not fluidization. Table 1 separates sediment gravity-flows into five types drawing on the above distinctions as recognizied by Lowe (1976b) and Nardin et al (1979).

In a grain flow, sediment is supported above the sediment-water interface by grain-to-grain interaction (that is, dispersive pressures; Bagnold, 1956; Cook et al, 1972); Middleton and Hampton, 1976). Because of these dispersive pressures, larger grains are pushed to a zone of least shear stress near the top of the flow (Bagnold, 1954, 1956). Consequently when the grains are deposited, inverse grading theoretically develops, which is presently the main criterion for recognizing grain-flow deposits.

Middleton (1970) proposed that inverse grading is the result of a kinetic sieve mechanism whereby small grains fall downward between large grains durng flow displacing the large grains upward. A kinetic sieve process may operate in sediments that have a low matrix (i.e. like a box of popcorn) or even a low-density matrix. However, it is unlikely this process can account for inversely graded carbonate conglomerates that had a high density muddy matrix. Other criteria for grain flow include massive tops, grain orientation parallel to the flow direction, larger floating clasts near the top of the deposit, and injection structures at its base (Middleton and Hampton, 1976; Mullins and Van Buren, 1979). With the exception of inverse grading this author questions the validity of the above criteria as being solely indicative of grain flows.

Massive tops of beds, parallel clast orientation, and large clasts floating near the top of beds are common fatures in highly viscous, thick debris flow deposits (Cook, 1979; Cook and Mullins, 1983).

Lowe (1976b, p. 188) defines a "true" grain flow as the "gravity flow of cohesionless solids maintained in a dispersed state against the force of gravity by an intergranular dispersive pressure arising from grain interactions within the shearing sediments." Another very geologically significant part of his definition is the limitation that the "fluid interstitual to the dispersed grains is the same as the ambient fluid through which the flow is moving." Under these conditions, true grain flows require a steep slope of 18° to 30+° to sustain movement (Bagnold, 1954; Lowe, 1976b; Middleton and Hampton, 1976). Lowe (1976b) further concludes that true grain flows of cohesionless sand-sized grains would produce deposits less than 5 cm thick.

Bagnold (1954) used spherical droplets composed of a lead stearate and paraffin mixture in his grain-flow experiments. To discuss the degree to which experimental data can be used to interpret field examples of possible grain-flow deposits is beyond the scope of this paper. The reader is referred to Middleton (1970), Middleton and Hampton (1976), and Lowe (1976b) for aspects of this problem.

As pointed out by Middleton (1970) and Lowe (1976b p. 193-194) "several processes may aid grain dispersive pressure in maintaining a dispersion against the force of gravity: (1) the fluid interstitial to the grains may be denser than the ambient fluid; (2) shear may be transmitted downward to the flow from currents moving over its surface; (3) the interstitial fluid may become turbulent, and (4) escaping pore fluids may partially liquefy or fluidize the dispersed particles." A grain flow aided by any of the above processes is termed a "modified grain flow" by Lowe (1976b). Thus, a grain flow containing clay-sized material mixed with the interstitial fluid would be termed a modified grain flow. This type of density-modified grain flow could be mobile over slopes on the order of 9°-14° (Lowe, 1976b), considerably less than for true grain flows that require gradients of 18° to 30+°.

The dominant internal mechanical behavior is plastic in the case of debris flows (the mixture of sediment and water has a finite strength). Liquefied flows, fluidizied flows, and turbidity flows are considered to behave mainly as a fluid (the sediment-water mixture has not internal strength). Grain flows may behave either as a plastic or highly viscous fluid. The reader is referred to Dott (1963), Cook et al. (1972), Hampton (1972, 1975), Walker (1975), Middleton and Hampton (1976), Lowe (1976a, b), Enos (1977c), and Nardin et al. (1979) for a more detailed discussion of sediment gravity-flow processes.

The classification shown in Table 2-2 and Figures 2-7 and 2-8 represents end-member concepts. Several processes can operate simultaneously during transport (Cook et al., 1972; Middleton and Hampton, 1976; Lowe, 1979b) and some of the photographs in this chapter clearly show that a single depositional unit can exhibit fabrics and sedimentary structures characteristic of more than one process. During mass transport of sediment, one process may dominate at anyone point in time or space, even though several processes may operate before the sediment is deposited.

It should be kept in mind that the rock record is a picture of the final transportational, depositional, and compactional event(s). Compaction may modify clast fabric and increase the clast to matrix ratio and possibly influence one's interpretation of the transportational and depositional mechanism(s).

The terminology described above has been developed mainly from studies of ancient sediment and experimental studies. There are some differences between mass transport as observed in rocks and those observed on modern slopes where ephemeral or intermediate types of movement are recorded acoustically.

The subject of mass transport processes and classification schemes is an area of active research and is rapidly changing. As a result, some concepts discussed in this paper and included in Table 2-2 and Figures 2-7 and 2-8 will undoubtedly be modified as more data are collected and interpreted and should be applied prudently.

Rock Falls.--One example of rock fall material is illustrated in Figure 2-9 (also see McIlreath, 1977, and McIlreath and James, 1978). In the absence of good stratigraphic relationships to an obvious steep scarp, suggested characteristics to distinguish rock fall deposits from other types of sedimentary conglomerates and breccias are discussed by Cook et al (1972, p. 465) and Enos and Moore (1983).

Slides, Slumps, and Intraformational Truncation Surfaces.--Features described as slides and slumps range in thickness from a few centimeters to tens of meters or more (Fig. 5-10). Maximum three-dimensional geometries of ancient submarine slides are usually not accurately known due to limited exposures.

The degree of internal deformation in slides ranges from only slight to moderate to the complete disruption of bedding. Complete disruption of bedding occurs when the shear strength of the sediment is exceeded and the mass begins to deform plastically and move as a highly viscous debris flow (Cook and Taylor, 1977; Cook, 1979a, b, c). Not only are all gradations of intensity of internal deformation probably present in ancient slides but a single slide can exhibit various degrees of deformation. Well-exposed examples of the sequencial stages of slides remolding into debris flows are found in Upper Cambrian and Lower Ordovician continental slope carbonates in the western United States (Cook 1979a, b, c; Cook and Mullins, 1983).

Some modern slides may have more internal deformation than is reported. Their "undeformed nature" may in some cases represent the problem of the limited resolution of conventional seismic-reflection systems (Cook and Taylor, 1977; Cook, 1979a, b).

Features that show intraformational truncation surfaces in carbonate slope sediment are illustrated in Figures 5-11 - 5-13. All three cases could represent slide scars or alternatively they could have originated by some type of abrasion process. Yurewicz (197ˀ, p. 215) prefers an abrasional origin for the surface in Figure 5-11. Figure 5-12, from the Permian in the Guadelupe Mountains of west Texas, exhibits a slight but distinct deformation of beds immediately at and above the truncation surface. This suggests that the beds immediately above the truncation surface have undergone soft-sediment deformation and these beds are part of the basal shear zone of a slide. Wilson (1969) recognized similar "cut and fill" or slump structures in lime mudstones in Europe, Montana, and the Guadelupe Mountains of west Texas. Davies (1977, p. 242-244) presents a lucid argument for the truncation surfaces in Figure 5-13 having formed by a gravity-slide mechanism rather than by some type of current scouring or other erosional process.

Sediment Gravity Flow Deposits.--Extensive piston coring of carbonate slopes in the northern Bahamas has documented the existence of sediments deposited by mass flows. However, turbidity currents and debris flows appear to be the dominate transport mechanisms for the downslope movement of coarse detritus on modern carbonate slopes.

In the ancient record carbonate mass-flow deposits in slope and basinal settings are common throughout the geologic column on a world-wide basis (for example, Pray and Stehli, 1962; Thomson and Thomasson, 1969; Wilson, 1969, 1975; Cook et al., 1972; Mountjoy et al, 1972; Conaghan et al., 1976; Cook and Enos, 1977b; Keith and Friedman, 1977; Cook, 1979a; Krause and Oldershaw, 1979; Pfeil and Read, 1980; Cook and Egbert, 1981a; Crawford, 1981; McGovney, 1981). Indeed, to find carbonate base-of-slope sequences with no hint of allochthonous sediment is most unusual. Of the five end-member types of sediment gravity-flow deposits, debris flows and turbidity-current flows are the best documented and appear to be the dominant processes for transporting large volumes of sediment-fluid mixtures downslope.

Debris-flow Deposits.--Coarse-textured debris-flow deposits occurring in both sheet and channel forms afford a striking contrast to the laminated dark lime mudstones of the enclosing pelagic and hemipelagic slope and basin facies (Fig. 2-14). This contrast is all the more evident because the debris-flow deposits have a resistant character and are usually lighter colored than the enclosing host facies. What constitutes field evidence for debris flow (Table 2-2) is generally well accepted (Cook et al., 1972, p. 478-479; Hampton, 1975; Walker, 1975; Middleton and Hampton, 1976; Enos and Moore, 1983). Figure 2-15 summarizes the main characteristics of Devonian debris-flow deposits in Canada that are composed of both shallow-water and deeper water clasts (Cook et al., 1972). Many of these features are common to carbonate debris flows throughout the geologic column that originated at platform margins. Debris flows that originated in deeper water by the remolding of submarine slides can consist totally of dark colored lime mudstone clasts (Cook, 1979a, c, b).

Debris flows can originate in areas of both low depositional relief ("depositional margins") as well as high depositional relief ("by-pass margins"). Field data at the well-exposed Devonian carbonate buildups of Alberta, Canada demonstrate that impressive debris flows with clasts up to 25 x 50 m can be initiated in areas of low depositional relief and that, once initiated, the flows can transport very coarse-textured material 10 or more kilometers across slope angles of a degree or less (Cook et al., 1972). Figure 2-16 illustrates these Devonian debris-flow sheet deposits initiated from "depositional margins."

Grain-Flow Deposits.--In this author's experience, carbonate deposits that can be reasonably inferred to be the result of true grain flows are rare in the ancient record. Perhaps this is to be expected due to the very high slopes required to sustain true grain flow and the conclusion that true grain flows probably cannot form thick sedimentation units (Lowe, 1976a, p. 198). Steep slopes will be areally restricted to special geological circumstances and this, combined with locating beds a few centimeters thick, limits the occurrence and geological importance of true grain flows.

A probable grain-flow deposit modified by the presence of a lime mud matrix is shown in Figure 2-17. This example is from the Upper Devonian Ancient Wall carbonate complex (Cook et al., 1972). Slopes on the bank margin were no more than 5 to 10° over a horizontal distance of 650 m (Mountjoy, 1967, p. 398). These gradients decrease rapidly basinward to 1 or 2°. Figure 2-17 is a 1-m-thick deposit with reverse grading of clasts ranging up to 5 cm in maximum diameter. This bed occurs about 4 km from the margin of the Ancient Wall carbonate buildup (Cook et al., 1972). It may have been initiated on slopes of 5 to 10° but, after a transport distance of less than 1 km, it moved across very low gradients, probably less than 2°. Its maximum transport distance is not known.

Turbidity-current Deposits.--Carbonate turbidites are very common on slope, base of slope, and more distal basinal settings. As in terrigenous clastic turbidites, carbonate turbidites are quite diverse in their sedimentary structures, textures, grain types, bed geometry, and origin.

Cobble-bearing carbonate turbidites are usually restricted to slope and near slope settings where depositional gradients are the highest (Fig. 2-18). There are exceptions to this as seen in Figure 2-19 where a 15 cm thick, cobble-bearing turbidite containing shoal-water clasts was transported at least 75 km from a platform margin (also see Crevello and Schlager, 1980). Sand to pebble-sized carbonate turbidites can be found on slopes as well as in basinal settings (Fig. 2-20).

Some sand-sized turbidites appear to be genetically related to debris-flow deposits and to represent the uppermost more dilute turbulent part of the debris flow (Cook et al., 1972, p. 479-480; Krause and Oldershaw, 1979). This two-mechanism origin of debris flow-turbidity current flow couplets is supported by experimental data on clastic debris flows (Hampton, 1972).

Generation of Carbonate Sediment Gravity Flows

Carbonate sediment gravity flow deposits can be generated at shoal-water platform margins in which case the redeposited debris consists mainly of light colored grain-supported clasts (ex. Cook et al, 1972). Alternatively, submarine slides generated within deep water semilithified carbonate slope deposits can remold into sediment gravity flows (Cook, 1979). In these cases the redeposited debris is largely dark gray to black mud-supported clasts.

Because most carbonate sediment gravity flows suggest an origin near a platform margin setting this section of Part 2 will focus on their origin. Cook et al (1972) have discussed the problems of prime importance in the genesis of platform margin derived sediment gravity flows. These problems include: (1) detachment of reef or bank margin material; (2) initiation of mass movements; (3) submarine transport mechanism(s); and (4) depositional mechanism(s). Only the first two problems of detachment and initiation will be addressed in this chapter. The subjects of transport and deposition have already been touched on earlier in this chapter and are discussed in detail in Cook et al (1972) and numerous papers by other workers since 1972. In the following discussion the genetic features of detachment and initiation are treated separately in their geologic and logical order of occurence. These topics are difficult to discuss separately, as often aspects of one have a significant bearing on another, so that some overlap is unavoidable.

Detachment of Platform-Margin Material.--Irregular-shaped and variable-sized clasts, derived predominantly from platform margins, are commonly spar-cemented lime grainstones and boundstones indicating that pervasive cementation occurred prior to breakage and movement. Breaking of a 20- to 25-m (or greater) stratigraphic thickness of cemented rock must have occurred at some reef and bank margins (ex: Cook et al, 1972; Mountjoy et al, 1972; Johns et al, 1981; Cook and Mullins, 1983; Enos and Moore, 1983). Several fracture mechanisms can be suggested: (1) earthquake shocks; (2) the action of stormwaves or tsunamis on a buildup margin; (3) gravity acting on an unstable, overloaded or oversteepened buildup margin which could be fractured in place; (4) during movement of a slide or slump mass; or (5) subaerial erosion during a long-term relative sea level lowering creating a karsted and structurally weakened buildup margin.

Initiation of Mass Movements.--Regardless of the general type of transportation mechanism(s) or the exact nature of the internal flow motion of the clasts and their matrix, some mechanism(s) is first necessary to initiate mass flows or movement. Any factors which reduce either the shear resistance between particles, or between blocks and the substrate, or the concentration of solids will help initiate movement (Cook et al, 1972, Fig.10). Several mechanisms that probably would initiate mass flows or movement appear to be: 1) faulting along fault scarps, 2) platform margin gravitational instabilities caused by depositional or diagenetic factors, 3) storm-wave activity, 4) earthquake shocks, 5) tsunamis, and 6) increased pore pressure during rapid sedimentation and/or during an earthquake.

Platform margin instability may occur when a reef and/or carbonate sand shoal progrades seaward over slope sediments. Earthquake shocks or tsunamis may detach a large part of a margin. Storm and large waves would be capable of dislodging small boulders or the occasional large block but might not be capable of initiating a mass flow. Earthquakes are currently accepted as an important agent for the initiation of submarine mass movements (Morgenstern, 1967). They could also initiate slumps from the margins of some reefs as has been observed and interpreted for some Pacific reefs. Tsunamis would impart tremendous amounts of kinetic energy to buildups, particularly during the back surge stage. Surges caused by tsunamis could trigger debris flows, slumps or rock falls if cliffs were present.

Carbonate Contourites

Well-documented examples of carbonate contourite deposits are sparse. In the absence of good paleocurrent data, clear facies associations, and regional trends in the slope, suspected contourites can often be ascribed to other origins.

Figure 5-53 is believed to represent thin-bedded carbonate contourites (Cook and Taylor, 1977; Cook and Egbert, 1981b). These calcarenites occur on the upper part of a north-trending Paleozoic continental slope interbedded with pelagic and hemipelagic lime mudstone beds. The grains comprising these calcarenites are shoal-water-derived algae particles.

Paleocurrent data from these current rippled calcarenites indicate a northerly current direction parallel to the paleoslope (that is, approximately perpendicular to the paleocurrent data on the carbonate mass-transport deposits). As pointed out by Cook and Taylor (1977) and Cook and Egbert (1981b), the rippled calcarenites do not appear to be the product of muddy turbidity currents. A different origin is indicated by: (a) the near perfect hydraulic sorting, (b) common lack of a mud matrix, (c) sharp lower and upper contacts, (d) laterally continuous evenly spaced current ripples, and (e) transport direction parallel to the slope. These sediments most likely are the result of winnowing of previously resedimented material by strong bottom-hugging contour currents (i.e. 15-30 cm/sec). Similar limestone beds deposited on a Cretaceous continental slope have been ascribed a contourite origin (Bein and Weiler, 1976).

Deep-Water Coral "Reefs"

In contrast to the modern, which has numerous examples of deep-water ahermatypic coral buildups, analogous deposits in the rock record are rare. In fact, only a handful of examples have appeared in the literature (for example, Squires, 1964; Coates and Kauffman, 1973; Stanley, 1979; Pfeil and Read, 1980). Whether this disparity represents an actual paucity of ancient bioherm or simply their misinterpretation remains to be seen. However, considering the commonality of modern examples, it is likely that more ancient examples of deep-water bioherms will soon be discovered (Mullins et al., 1981).

In those examples known from the rock record (ranging in age from Triassic to Pliocene), the deep-water bioherms appear as lenticular thickets with a framework usually constructed by a single species of coral (Squires, 1964; Coates and Kauffman, 1973). Large volumes of coral debris are also typical of such buildups, which appear to have developed in current swept environments. The Miocene/Pliocene coral thickets of New Zealand are up to 3.4 m thick, 36.6 m long, and about 75 m in diameter (Squires, 1964). In addition to the corals themselves, a host of other calcareous invertebrates are commonly associated with these deposits (Stanley, 1979). Figure 5-21 is an example of an ancient biological buildup on a Paleozoic carbonate slope (also see Coates and Kauffman, 1973).

Diagnesis

The degree of early marine cementation of slope material can range from the patchy development of pseudoclasts (Hopkins, 1977), to a dense network of nodules (Snavely, 1981), to a more uniform cementation as suggested by the remolding of submarine slides into clasts (Cook, 1979a, b, c).

Nodular limestones that formed on an Eocene carbonate slope in Egypt have been recently reported by Snavely (1981). These early diagenetic nodules (Figs. 2-22 and 2-23) bear a striking resemblance in size and shape to nodules forming on modern slopes (Mullins et al., 1980b). Nodular limestone and pseudobreccias on slopes are probably more common than is currently recognized (Hopkins, 1977). Clearly early marine cementation is probably a fairly pervasive event on some slopes as indicated by the common occurrence of semiconsolidated pelagic and hemipelagic lime mudstones that are involved in submarine sliding (Fig. 2-10; Cook and Mullins, 1983). These slides moved the uppermost 1 to 10 m of sediment, and thus their semiconsolidated nature is unlikely simply the result of compaction.

The role that early marine cementation may play in the development of clasts and the initiation of conglomeratic mass-flows in the Devonian of Canada was discussed by Cook et al. (1972, p. 470) and Hopkins (1977). More recently Snavely (1981) has shown that nodular limestones and hardgrounds, that formed on Eocene carbonate slopes were, in places, displaced downslope as debris flows.

Allochthonous carbonate debris in sediment gravity flow deposits can be composed of aragonite, magnesium calcite, and calcite, or any mixture of the three. Thus, significant potential exists for post depositional diagenesis. For example, much of the porosity in the Permian deep water carbonate reservoirs of west Texas as well as the giant petroleum fields in the Cretaceous of Mexico is of a moldic origin (Cook, 1983; Hobson et al, in press). Deep down-dip circulation of fresh water from the exposed Cretaceous Golden Lane platform margin has been proposed as the leaching agent for the deep water allochthonous carbonate reservoirs in Mexico (Enos and Moore, 1983).

FACIES PATTERNS AND DEPOSITIONAL MODELS

Ancient carbonate facies patterns in platform margin, slope, and basin sequences can be quite varied. As Mullins points out in Chapter 4 of this volume the multitude of facies patterns are controlled by several interacting processes. In the ancient, the added dimension of time adds to this complexity.

The approach in this section of Part 2 is to discuss and illustrate the nature of the platform margin-to-slope break and its relation to facies patterns developed on different types of slopes and adjacent basins. Selected ancient examples will be discussed in the framework of the platform margin and deep water carbonate models presented in Part 1. For some examples the platform margin-slope-basin triplet can be directly observed, or inferred using Walthers' Law of Correlation of Facies, such that the nature of the stratigraphic sequence is reasonably clear (i.e. figs. 1-35 - 1-40). In other cases only part of the triplet is preserved and the complete stratigraphic profile must be pieced together on the basis of data and interpretations from surrounding facies.

Non Rimmed - Homoclinal Ramp Model

As discussed by Read (1982) shelves with profiles of the ramp model (Table 2-3, Fig. 1-52) have gently sloping (1 to a few meters/km) substrates that progress into offshore, deeper-water environments without a marked break in slope(Fig. 2-24). On ramps, wavebase impinges close to the strandline, resulting in the localization of high-energy, potential reservoir facies that trend parallel and proximal to the strandline. These high-energy facies may consist of peloid/ooid grainstones or bioclastic grainstones. Shoreward of these shoals lagoonal lime muds, wackestones, and tidal-flat sediments occur. Seaward of the shoals deeper ramp argillaceous lime wackestone/mudstone occur that contain normal open marine biotas. These facies pass gradually into deeper-water pelagic muds and/or periplatform muds. Only minor evidence of mass-transport processes occur in the deeper-water facies. With perhaps the exception of inner shelf high-energy shoals, broad gradational and irregular facies belts seem to characterize ramps.

The Persian Gulf is an example of a modern ramp (Wilson and Jordan, 1983, Fig. 32), whereas the Jurassic Smackover of the U.S. Gulf Coast is considered to be an excellent example of an ancient continental margin ramp (Ahr, 1973; Read, 1982) (Figs. 2-25 and 2-26). In the Basin and Range Province the Ordovician Hansen Creek Formation may represent homoclinal ramp facies (Dunham, 1977) (Figs. 2-27 and 2-28).

Non Rimmed - Distally Steepened Ramp and Submarine Fan Models

These ramps have many of the same facies of homoclinal ramps. The main difference, however, is that at some location on the seaward part of the ramp a major break in slope occurs (Fig. 2-29). This break in slope, however, is in relatively deep water and thus shoal water carbonates do not form at the shelf edge. The shelf/slope break is characterized by submarine slides and slumps, and a wide variety of sediment gravity flow deposits that are organized into apron and fan facies.

Examples of distally steepened ramp-slope-carbonate submarine fans facies occur in the upper Cambrian-lower Ordovician sequences in the Basin and Range Province (Cook and Taylor, 1977; Taylor and Cook, 1976; Cook, 1979; Mullins and Cook, 1983; Cook and Taylor, 1983; Cook, in prep. b). The Yucatan area may be a modern example (Read, 1982).

The upper Cambrian-lower Ordovician example is a shoaling upward sequence from basin-plain to carbonate submarine fan to slope to deep water platform margin sediments (Cook and Egbert, 1981a, b; Cook and Mullins, 1983). This sequence represents a seaward progradation (offlap) of the continental margin and is interpreted to have formed in shelf edge, slope, base-of-slope and basin plain settings (Figs. 2-30 - 2-35). The depositional facies consist of a basin-plain sequence of laminated hemipelagic lime mudstones, argillaceous limestones, thin-bedded cherts and turbidites (Figs. 2-36 - 2-38) (Swarbrick Formation and Dunderberg Shale). This is gradationally overlain by a wide variety of carbonate turbidite and debris-flow deposits whose facies collectively form a submarine fan (uppermost Dunderberg Shale and lower Hales Limestone (Figs. 2-39 - 2-48) (Cook and Egbert, 1981a, b). The submarine fan facies, in turn, grade upward into submarine slide, slump, and contourite deposits that formed on the continental slope (Figs. 2-49 - 2-53) (upper Hales Limestone). High on the slope is an intraslope (perched) basin that contains about 50 meters of carbonate turbidites and debris flow deposits (Figs. 2-54 and 2-55). This relatively small intraslope basin is in turn overlain by more fine-grained slope deposits and small upper slope erosional gullies that funneled platform margin debris down the slope (Fig. 2-56). The uppermost part of the sequence (uppermost Hales Limestone and lowermost Goodwin Limestone) appears to have been deposited on or near the outer shelf margin (Fig. 2-57).

Rimmed Depositional Margin and Slope Apron Models

Rimmed shelves (Table 2-3; Figs. 2-58; 1-47 - 1-51; 1-53) are shelves whose outer margin is in shallow agitated water depths and is characterized by a relatively steep (few degrees to 60° or more) increase in declevity marking the boundary between the outer shelf and slope. Rimmed shelves often have well-developed high-energy linear facies belts, trending parallel to the shelf edge.

Silurian-Devonian, Basin and Range Province, Nevada.--The first example to illustrate a rimmed depositional margin shelf with slope apron facies is in the Upper Silurian-Lower Devonian Roberts Mountains Formation and overlying Lone Mountain Dolomite, Nevada (Figs. 2-32; 2-59 - 2-63). The overall vertical cycle is a shoaling upward sequence from basinal and slope facies (Roberts Mountains Formation) to shelf edge bank ("reef") and tidal flat facies (Roberts Mountains Formation and Lone Mountain Dolomite).

Winterer and Murphy (1960) originally interpreted the dark gray Roberts Mountains Formation to be a basinal facies and the overlying light gray Lone Mountain Dolomite to be a true ecologic reef. Matti et al (1975) and Matti and McKee (1977) modified the earlier interpretation of Winterer and Murphy (1960) by abandoning the reef hypothesis and proposing that the uppermost Roberts Mountains Formation was a skeletal bank margin facies that interfingered with the Lone Mountain Dolomite. Nicols and Silberling (1977) refute several interpretive elements of Winterer and Murphy (1960), Matti et al (1975), and Matti and McKee (1977). Nicols and Silberling (1977) agree with earlier interpretations in that the shelf-edge carbonates represent skeletal sands (bank) rather than skeletal boundstone facies (reef). However, Nicols and Silberling (1977) propose that an unconformity exists between the dark-colored Roberts Mountains Formation and the light-colored Lone Mountain Dolomite. They state (p. 224) "the abrupt change from outer-platform or off-platform crinoidal grainstone of the upper Roberts Mountains Formation to inner-platform desiccated primary dolomite of the Willow Creek (Lone Mountain Dolomite), and the pronounced seaward overstepping of the latter over the former suggests that deposition of the two was interrupted by an episode of exposure and erosional beveling of the Roberts Mountain carbonate ramp or platform.

An alternative interpretation that is similar to that of Matti et al (1975) and Matti and McKee (1977) in the broad sense but differs in detail is offered here. First, it is important to bear in mind that the mappable boundary between the two formations is a change from dark gray limestone to light gray dolomite. However, this color change does not always parallel bedding planes or depositional facies. Cook (1966) earlier pointed out that the color boundary between these two formations is of a diagenetic origin and not a primary depositional feature. In the Hot Creek Range of central Nevada the color boundary between the Roberts Mountains Formation and Lone Mountain Dolomite is wavy and crosses bedding planes (Cook, 1966). Thus, where the beds are dark gray they are assigned to the "Roberts Mountains Formation" and where the beds are light gray they are referred to as the "Lone Mountain Dolomite". There is no compelling evidence that supports the "missing facies" theory of Nicols and Silberling (1977). The mappable contact between the Roberts Mountains Formation is interpreted to be a diagenetic feature and the two formations are in depositional contact. When one ignores the color differences between the formations and looks at the depositional facies themselves there appears to be a gradual transition in facies from coral-rich shelf edge bank sediments upward into bedded and cross-bedded lime grainstones and conglomerates to tidal channel facies, to fenestral fabrics and oolite shoals. The dolomitizing fluids did not uniformly follow any one facies boundary but crossed facies boundaries. The resulting contact is considered to be a complex collage of interfingering limestones and dolomites (Fig. 2-61).

The above discussion refers to the area where the Lone Mountain Dolomite was prograding seaward over the Roberts Mountains Formation (i.e. the left-hand side of Fig. 2-62). In the same canyon but stratigraphically lower this Silurian-Devonian bank margin was upbuilding (Fig. 2-62). In the upbuilding area the beds in the Roberts Mountains Formation interfinger along strike into Lone Mountain sediments (Fig. 2-62) with no apparent "missing facies" evidence for an unconformity as proposed by Nicols and Silberling (1977).

The upbuilding phases of the Roberts Mountains-Lone Mountain during the latest Silurian corresponds approximately with a rise in sea level (Vail et al, 1977). Vail et al's (1977) sea level curve shows a pronounced relative sea level drop near the Silurian-Devonian boundary. It is interesting to note that at about this time the Lone Mountain bank margin changed from an upbuilding phase to a rapid westerly seaward progradation out over the Roberts Mountains Formation. If the age of the rocks at this stop do correspond to a relative drop in sea level it documents an important principle that seaward progradation of shelf edge facies can occur whether the relative change in sea level is rising or falling. Much depends on relative rate of sea level change and sedimentation rates at the shelf edge.

<u>Chief features observable in this platform margin - slope apron sequence</u>

Roberts Mountains Formation:

1. Laminated in situ lime mudstones and wackestones (slope/basin) (Fig. 2-64).
2. Carbonate turbidites (slope) (Fig. 2-65).
3. Cross-bedded crinoid-ooid packstones and grainstones (subtidal marine tidal bars and/or tidal deltas on gentle slopes just seaward of the bank margin (Figs. 2-66 and 2-67).
4. Skeletal-rich bank margin limestones (subtidal, moderately high energy shelf edge) (Figs. 2-69 and 2-69).
5. Cross-bedded limestone conglomerates and grainstones (shallow, subtidal high energy to supratidal) (Figs. 2-70).
6. Nature of contact between Roberts Mountains and Lone Mountain.

Lone Mountain Dolomite:

1. Dolomite breccia facies (tidal flat channels) (Fig. 2-71.
2. Dolomitized coral facies (possible storm deposits washed onto tidal flats from bank margin).
3. Oolite grainstones (oolite tidal bars and/or belts in tidal flat and shallow subtidal settings) (Figs. 2-72 and 2-73).

<u>Devonian, Yukon Territory, Canada</u>.--A second example is from the Mackenzie Platform Richardson Trough area within a large area centered around Margaret Lake (134°30'W Long. 65°20'N Lat.) (Figs. 2-74 and 2-75). The western side of the Mackenzie Platform, during the Lower and Middle Devonian was a rimed shelf depositional margin. A dominant biotic element on the platform margin was hemispherical stromatoporoids set within a grain-supported bioclastic matrix of pelmatozoans and other components (Fig. 2-76). The platform margin to slope facies transition takes place over a wide (about 15 km) low gradient interval. This

platform margin-slope-basin transition is characterized by crinoidal turbidites (Fig. 2-77), lime wackestones, and deeper water slope bioherms (Fig. 2-78). The presence of bioherms seaward of the stromatoporid platform margin resembles Wilson's (1975) TYPE I Downslope Mud Accumulation Model (Fig. 1-46). Gradually this low gradient transition facies gives way to a well developed carbonate slope apron (Fig. 2-79). The redeposited carbonates in this slope apron include pebble and cobble-sized debris flow deposits (Fig. 2-80), normally graded turbidites with cobble-sized clasts (Fig. 2-81), and calcarenite turbidites that exhibit a variety of bouma divisions (Fig. 2-82).

At a distance of about 50 km from the platform margin are a series of about 25 light colored knobs (Fig. 2-93) that range from 15 m thick and 50 m long to 75 m thick and 150 m long. These knobs occur within the deep water graptolitic-rich Prongs Creek Formation. The knobs are restricted to a 100-200 m thick stratigraphic interval within this slope-to-basin sequence. Lenz (1972, p. 328) interpreted these knobs as "small reef developements" that grew on the flanks of the Bonnet Plume High (Lenz, ibid). Macqueen (1974, p. 325) also studied these knobs and stated that "evidence is minimal that they are either ecologic or stratigraphic reefs.....". Macqueen (ibid) goes on to say, "The masses appear to be banks or biostromes - in situe accumulations of pelletoid and other non-skeletal grains and loose calcareous skeletal material - which originally may have been continuous". Macqueen states (p. 326) that the problem of their origin is unresolved as it is difficult to envision erosion sculpturing the upper surfaces to achieve the present day outcrop pattern (Fig. 2-83).

I disagree with both of the above interpretations. During the summer of 1968 I studied these anomalous giant knobs. First, they are anomalous because they are completely enclosed in deep water graptolitic argillaceous lime muds, carbonate turbidites and debris flows. Most of the knobs exhibit intense weathering such that internal textural features are difficult to resolve. However, one large knob in particular (Fig. 2-84A) exhibits an unusually well-exposed basal contact with the underlying graptolitic shales (Figs. 2-84B and 2-84-C). This knob has a concave-up base and an almost flat top - not the normal shape for a bioherm or reef. Where the basal part of the knob exhibits a knife-edge contact with the graptolitic shales, the contact is erosional and compacted (Fig. 2-84B). At this same contact the knob is clearly seen to be comprised of light-colored and dark-colored cobble-sized clasts set within a pervasive lime mudstone matrix (Fig. 2-84C). The light-colored clasts are pelloid grainstones and other shoal-water types of clasts including stromatoporoid and coral-bearing rocks. The dark-colored clasts are lime mudstones. This author interprets these knobs as representing debris flow deposits that are filling large gullies or channels encised in the slope and/or basinal facies. Gullies or channels of this type are common on carbonate slopes in the Bahamas (Cook and Mullins, 1983). These also resemble some of the so-called "patch reefs" in the Permian Basin of west Texas which are allochthonous platform-margin derived carbonates that fill large submarine gullies (Pray and Stehli, 1962). A similar allochtonous origin for these Yukon Territory "knobs" is consistent with their being enclosed within a normal quiet water, dark lime slope and basin facies, the concave-up base and flat top of some of the knobs, a basal erosional contact with the underlying graptolitic shales, and the fact that at least one knob is clearly comprised of a variety of shoal water and basin clasts in juxtaposition.

These deeper water slope and basin facies also contain rather spectacular megabreccia debris sheets that are areally widespread, have travelled several 10's of kms and contain platform-margin limestone blocks up to 7 m x 7 m across (Fig. 2-85).

Upper Devonian, Alberta, Canada.--Devonian carbonate buildups of two ages (Swan Hills and Leduc-Fairholme) are distributed in several distinct trends in the subsurface and within the Rocky Mountain outcrops of western Alberta (Figs. 2-86 and 2-87). Allochthonous carbonate megabreccias, conglomerates, and calcarenites occur at the margins of all three of the outcropping carbonate complexes, Ancient Wall, Miette and Southesk-Cairn (Fig. 2-86), whose margins are well exposed (Cook et al, 1972). The most spectacular megabreccias are two debris sheets forming mappable units up to 20 m thick on the southeast margin of the Ancient Wall complex. The megabreccias and thinner beds of finer debris are both interbedded with dark, basin-facies lime mudstones. The three carbonate complexes of the outcrop area have many similarities in form, facies, and stratigraphy to the subsurface Leduc complexes of equivalent age, and to the somewhat older Middle and Upper Devonian Swan Hills complexes (Fig. 2-86), although the stratigraphic nomenclature is different in these regions (Fig. 2-88).

Both the surface and subsurface carbonate buildups are mostly stratified carbonate banks from a few km to as much as 96 km long, and between 150 and 500 m thick . The outcropping complexes are laterally isolated from one another by up to 80 km of basin-facies mudrocks. On the buildups carbonate deposition apparently was able to keep pace with a gradual and/or intermittently rising sea-level.

Ancient Wall carbonate complex is a rimmed isolated platform with a slope apron that virtually extends all the way to the platform margin facies (Figs. 2-89 and 2-90). The platform margin facies forms a narrow zone usually 200-500 meters wide at the outer margin of the Ancient Wall and Miette complexes. Well defined parallel (horizontal) bedding characterizes most of it. This platform margin or skeletal margin facies contains abundant large massive and bulbous stromatoporoids and corals set within a predominant matrix of light-colored wackestones and boundstones. Most of the stromatoporoids functioned primarily in the role of a massive baffle, and loose skeletal armor on the sea floor (Cook et al, 1972).

The allochthonous carbonate debris at Ancient Wall (Figs. 2-89 and 2-90) is best characterized by the debris slope apron and debris sheet models (Figs. 2-63 and 2-91). Figures 2-92 and 2-93 are different views of the same debris sheet labeled "Megabreccia Sheet 1" in figure 2-89. These megabreccia sherts have clasts up to 25 x 50 m which are large enough to protrude above the debris bed and can be easily confused with bioherms. The "matrix" for these boulder-sized clasts consists of pebble- to cobble-sized clasts and lime mud (Fig. 2-94). Figures 2-95 is a view of the debris sheets shown on the left-hand side of figure 2-89. Debris flow sheets at Ancient Wall were transported by debris flows a minimum distance of 10 to 15 km into the basin. Although debris flows are the most likely process capable of transporting boulder-sized material across low angle slopes for great distances (Cook et al, 1972) some of the debris was probably transported by grain flows (i.e. Cook and Mullins, 1983, Fig. 68).

Sheets of platform margin derived carbonate sand containing small carbonate pebble-size fragments form distinct thin beds 0.3 to 3 m thick interbedded with muddier basin strata. In figure 2-92 all of the light-colored thin-bedded sheets are allochthonous carbonate turbidites that collectively make up the slope apron facies. Although the megabreccia debris sheets are clearly the most prominant and spectacular deposits the slope apron facies are the most abundant allochthonous rock type at all of the buildup margins studied by Cook et al (1972).

Rimmed Bypass Margin and Base-of-Slope Apron Models

Carbonate sediment gravity flows that originate adjacent to low gradient depositional margins form slope aprons as at the Ancient Wall buildup in Alberta, Canada. However, if the gradient at the platform margin is high shelf-edge generated mass flows are likely to flow down the slope and deposit much of their debris at or near the base of the slope (Fig. 2-96).

Base-of-slope aprons occur in several Devonian platform margin sequences in the Basin and Range Province of Nevada. The first example of a base-of-slope apron occurs within a Middle Devonian to Upper Devonian shoaling upward sequence in central Nevada (Fig. 2-97). This shoaling upward section reflects a seawrd progradation of the platform margin Devils Gate Limestone over the slope and basinal Denay Limestone. (Fig. 2-32). The base of Denay Limestone is characterized by organic rich, dark petroliferous lime mudstones and thin-bedded turbidites. At or near what is interpreted to be the base-of-slope is a thickening-upward sequence of carbonate turbidites and debris flow deposits (Figs. 2-98 and 2-99) that are rich in crinoid grains and occasional massive coral heads and hemispherical stromatoporoids derived from the platform margin (Cook and Taylor, 1983). Stratigraphically above the base-of-slope apron are thin-bedded, laminated lime mudstone that comprise the slope facies. These slope carbonates exhibit soft-sediment slumping and a few channelized, laterally restricted turbidites (Figs. 2-100 and 2-101). The overlying platform margin consists of light-colored limestones and dolomites with stromatoporoids, tabulate and colonial corals, and calcarenite sands (Figs. 2-102 and 2-103).

Stratigraphically above the Denay-Devils Gate seaward prograding platform margin, but in northern Nevada, is a well-exposed retrograding platform margin sequence of Upper Devonian age (Poole et al, 1979) (Figs. 2-104 and 2-105). At this locality the basal most exposed beds of the Devils Gate Limestone (Fig. 2-32 contains abundant massive-hemispherical and bulbous stromatoporoids and the dendroid stromatoporoids Stachyodes and Amphipora--these facies represent the platform margin facies (Fig. 2-106). Overlying the platform margin facies are slope, base-of-slope, and basinal sediments (Cook and Taylor, 1983; Figs. 2-104, 2-105, 2-107). The base-of-slope apron facies is similar to that described above in the Middle Devonian Denay Limestone in that the bulk of the debris forms several thickening-upward cycles. These thickening-upward cycles contain pebble-to-cobble-sized clasts of stromatoporoid and coral fragments as well as deeper water lime mudstone material.

In a few, very remote localities of the Yukon Territory, Canada, are some beautifully exposed platform margin-slope-basin triplet exposures. In the vicinity of 135° W. Longitude and 65° N. Latitude (Figs. 2-74 and 2-75) in a southern finger of the Richardson Trough is a completely exposed back reef, reef, slope, and basinal sequence in East Royal Creek that exhibits upbuilding, erosional, onlapping, and prograding modes (Figs. 2-108 - 2-110). The Royal Creek area was studied by this author and W. J. Meyer in 1968 as part of a larger Marathon Oil Co. field party.

Figure 2-108 is a stratigraphic cross-section of figure 2-109. This platform margin is divided into five units (i.e. U1-U5) that began as a crinoid bank margin (Unit 1) and evolved into a stromatoporoid-coral-red algae broundstone reef (Units 3 and 5; Fig. 2-111). During the early colonization stage of the Royal Creek platform margin (Units 1 and 2) the allochthonous debris formed a slope apron (Fig. 2-108, 2-109). After Unit 3 but before Unit 4 the platform was eroded (Fig. 2-108, 5-112) resulting in a seaward sloping gradient of about 30° or more. Basinal lime mudstones of Unit 4 onlapped the eroded reefal boundstones of Unit 3. Soon after the platform margin prograded seaward forming Unit 2. It was during the deposition of Unit 4 that base-of-slope debris apron facies were deposited (Figs. 2-113 and 2-114). Figure 2-115 is seaward of figures 2-109 and 2-110 a few 10's of kms where the Lower Devonian basinal section is dominated by light-colored, resistant carbonate debris flow and turbidity-current deposits. Within this more basinward part of the carbonate apron there appears to be two thickening-upward cycles (Fig. 2-115). Stratigraphic control is not good enough to know whether this particular locality represents a base-of-slope apron, slope apron, or even part of an outer fan lobe.

This last example is from the subsurface of west Texas in the Permian Basin. Being in the subsurface it forces one to be imaginative and draw on all available depositional models and one's perspective in order to interpret the available data. In 1970 this author studied a number of Permian reservoirs in the Delaware and Midland Basins of west Texas and New Mexico and it became readily apparent that some of these Permian fields were developed in "allochthous debris transported basinward from the Central Basin Platform, Eastern Shelf, and Northwestern Shelf" (Cook et al, 1972, p. 467).

During the Wolfcampian, sediment gravity flows were common events at some shelf margins in the Permian basin. These mass flows transported large volumes of shoal-water bank and reef carbonates downslope into the Midland and Delaware basins (Fig. 2-116), forming a wide variety of redeposited lithofaces. For example, along a segment of the Eastern shelf margin at least 40 km (25 mi) long, redeposited carbonates extend into the Midland basin 25 km (16 mi) or more such as in the Hutto, Triple-M, and Credo fields (Fig. 2-117).

Redeposited Wolfcampian carbonates are subdivided into three major lithofacies. (1) Limestone and dolomite conglomerate debris flows and turbidites with dark interstitial micrite. Individual beds are as much as 8 m (26 ft) thick, normal to massively graded, and some beds are arranged by thinning-upward sequences (Figs. 2-118 - 2-120; 2-125 and 2-126). These carbonates form one of the reservoir facies with intercrystalline, solution interparticle, fracture, and vuggy porosity (Figs. 2-122 and 2-123). (2) Wackestone to packstone calcarenite turbidites consisting largely of biotic grains. This lithofacies forms the most abundant type of redeposited sediment. The calcarenites occur in beds a few cm to 2.5 m (8 ft) thick that exhibit a variety of Bouma turbidite divisions and in some localities are arranged in thickening-upward units (Figs. 2-121, 2-129, 2-130). Calcarenite turbidite locally form petroleum reservoirs with solution interparticle, intrabiotic, biomoldic, and fracture porosity (Figs. 2-124 and 2-127). (3) Wackestone to packstone calcisiltite and calcarenite turbidites that occur in less than about 5 cm (2 in.) thick beds. This facies dows not exhibit vertical cycles of bed thickness nor good reservoir qualities (Figs. 2-128 and 2-131).

Analyses of cores from 12 wells both within and outside the petroleum fields suggest that these redeposited carbonates may represent a combination of debris sheet and submarine fan depositional processes. The conglomerates in the Upper Hutto could be genetically unrelated to the Lower Hutto calcarenites and represent episodic debris sheet pulses; or alternatively, these Upper Hutto conglomerates may be channelized deposits in inner fan to mid-fan positions near the basin margin and the Lower Hutto thickening upward sequences be part of a seaward prograding carbonate submarine fan. Alternatively, these thickening upward beds in the Lower Hutto as well as those in the Credo (Fig. 2-129) could be base-of-slope apron facies similar to the thickening upward base-of-slope apron facies in the Devonian of the Basin and Range Provinces, Nevada (Figs. 2-98 and 2-105).

Some of the thick-bedded calcarenites possibly represent mid-fan channelized deposits whereas the more basinward thickening-upward calcarenites resemble unchannelized outer-fan calcarenite lobes. Thin-bedded calcisiltite turbidites appear to occupy basin plain, outer-fan fringe, and interchannel settings.

If these reservoirs are developed within one or more fan facies or base-of-slope apron facies the size and apatial arrangement of the individual fans or aprons still remain to be determined.

Many of the debris flow conglomerates and calcarenite turbidites in these deep water Permian reservoirs resemble similar allochthonous deep water carbonate reservoir facies in the giant Cretaceous Poza Rica oil field in Mexico (Figs. 2-132 - 2-134).

IMPLICATIONS FOR PETROLEUM AND MINERALS EXPLORATION

One of the prime objectives of these course notes is to stress the point that slope, base-of-slope, and basinal sequences can contain a large quantity and diversity of allochthonous carbonate sediment-gravity flow deposits. The overall geometry and internal textural variations of these redeposited facies are strongly controlled by the nature of the platform margin and its morphologic relationship to the seaward adjacent slope. This point has been stressed throughout this volume.

Cook et al (1972) pointed out that the recognition and correct interpretation of basin-margin allochthonous deposits can be important for several reasons: (1) to signal the presence of banks or reefs in an area, (2) as proximity indicators for locating buildup or reef margins, (3) to better determine the nature and morphology of the platform margin buildups, (4) to provide stratigraphic markers useful for correlation in the subsurface between carbonate buildups and the enclosing slope and basin faces, (5) to provide important clues about the time and development of diagenesis of carbonate complexes and adjacent basin strata, and of course (5) as potential petroleum and mineral reservoirs.

Throughout these course notes we have tried to demonstrate that basin-margin debris can occur in several ways: as (1) megabreccia debris sheets, (2) slope aprons, (3) base-of-slope aprons, and (4) as submarine fans. In designing exploration strategies for these types of frontier deep-water reservoirs one must develop appropriate depositional models. Some questions come to mind. Do these deposits represent episodic, widespread, single-pulse debris sheets, or debris aprons dominated by numerous rather random pulses of areally extensive sheet-flow calcarenites, or more systematically developed submarine fan facies having both channelized deposits in inner and mid-fan settings as well as sheet-flow calcarenites deposited as outer-fan lobes? Exploration as well as production strategies will vary depending on which model or combination of models are used.

Figure 2-135 is a compilation of selected stratigraphic horizons that produce petroleum, and in a few cases minerals, from carbonate shelf, platform margin, and basin-margin facies. The depositional environment of the reservoir facies is plotted by horizontal bars.

There are potentially more reservoir facies in rimmed shelf models than in ramp models. Going from deep water to shallow water environments potential reservoir facies include 1) carbonate submarine fans, aprons, and debris sheets (Cook et al, 1972; Enos, 1977a; Cook, 1983; Cook and Mullins, 1983; Enos and Moore, 1983; Mullins and Cook, in prep.); 2) shelf-edge reefs and tidal bars (Wilson and Jordan, 1983); 3) middle shelf grainstone facies (Powers, 1962; Wilson, 1975; Wilson and Jordan, 1983); 4) inner shelf offshore bar and beach facies, and tidal flat facies (Enos, 1983); Inden and Moore, 1983; Shinn, 1983).

A few well studied petroleum-rich examples of rimmed shelf reservoirs cited by Wilson and Jordan (1983) include the Permian Hueco Limestone of New Mexico and West Texas, the Cretaceous Edwards Formation of Texas, and the Jurassic D zone in the Persian Gulf area. The Devonian carbonate province of Alberta, Canada has abundant examples of giant oil fields, especially in isolated rimmed shelves (ex: Klovan, 1964; Cook et al, 1972; Harris, 1983). Notable billion barrel oil fields occur in deep-water carbonate aprons in the Cretaceous of Mexico (Enos, 1977a; Enos and Moore, 1983). Lesser known fields in the Permian of west Texas occur in carbonate submarine fan, apron and possibly debris sheet facies (Cook et al, 1972; Cook, 1983; Cook and Mullins, 1983; Cook, in prep. a).

Debris Sheet Model

Debris sheets are the relatively rare, episodic major events that take place at platform margins. As discussed in several chapters of these notes debris sheets can be areally very widespread and a single debris sheet can contain huge volumes of debris. Some of the conglomeratic debris flow reservoir in the Permian Basin and the Cretaceous of Mexico could represent episodic debris sheets (Enos, 1977a; Cook et al, 1972; Cook, 1983; Hobson et al, in press).

Debris sheets can occur at rimmed depositional platform margins as well as at rimmed bypass platform margins. Thus in the former case the sheets are not laterally separated from the shelf edge, however, in bypass margin sequences the debris sheets will occur seaward of the shelf edge, at a distance that is proportional to the gradient of the slope.

Porosity trends in debris sheets are not well understood but the porosity may be quite erratic and difficult to predict. If the redeposited debis contains abundant aragonite and magnesian calcite clasts and lime mud the potential for post depositional solution is great. Interconnected porosity may be better developed in debris sheets that have a low mud matrix such that the clasts and biotic constituents that are susceptible to leaching are in contact with one another.

Slope Apron and Base-of-Slope Apron Models

Carbonate aprons develop via line source sedimentation which results in mass-transport facies that parallel the adjacent shelf edge and thin in a seaward direction, producing an overall wedge-shaped geometry (Mullins and Cook, in prep.). Unlike submarine fans, carbonate aprons are likely to produce linear to arcuate facies belts that parallel the adjacent shelf edge. The length of the belt will mainly be a function of the nature and length of the platform margin itself. Large isolated platforms such as in the Bahamas (Cook and Mullins, 1983) or the Cretaceous of Mexico (Enos, 1977a) appear to have very long aprons. Small isolated banks, such as the Devonian Ancient Wall and Miette of Alberta, Canada, have carbonate aprons that form relatively small concentric bands around the bank margins (Cook et al, 1972). Large intracontinental shelf margins such as developed around the perimeter of the Permian Basin in west Texas may form continuous aprons 10's to 100's of km n length (Cook, 1983; Mazzullo, pers. comm., 1983, Mazzullo, in press).

As illustrated in this chapter slope apron and base-of-slope apron models appear to account for most of the redeposited facies in deeper water carbonate environments. Slope aprons are most abundant along platform margin slopes that have low gradients as exemplified by the Upper Devonian Ancient Wall carbonate bank in Alberta, Canada (Cook et al, 1972). At low gradient margins the slope and basin sequences will have abundant carbonate turbidites that commonly do not exhibit any systematic vertical cycles. Where the slope gradient at the platform margin is relatively steep, the shoal-water derived sediment gravity flow deposits will be more likely to traverse down the slope and accumulate most of their debris at or near the base-of-slope. The Devonian base-of-slope aprons in the Basin and Range Province are separated from the platform margin and exhibit thickening-upward cycles. Likewise, some of the thickening-upward cycles in the Permian reservoir facies of west Texas described above may, in part, represent base-of-slope aprons.

Both slope and base-of-slope apron facies could form attractive exploration targets. However, base-of-slope aprons may be better exploration targets for several reasons. First, because they occur at or near the base-of-slope their updip extension is sealed by fine-grained lime muds and shales of the normal in situ pelagic and hemipelagic facies. This contrasts with facies in the apron model that can extend virtually all the way updip to the shelf edge. An attractive feature of the slope apron facies, however, may be that because slope apron facies do extend to shelf edges the apron facies could form porous conduits for transmitting petroleum to shoal water bank and reef margin reservoirs. Second, base-of-slope apron facies may form relatively thick systematic cycles if the examples in the Basin and Range Province are representative of other bypass margins. Third, as Enos (1977a) points out there may be a relationship between shel-edge slope, relief, and volume of debris deposited in base-of-slope environments. Figure 5-136 plots a few examples of shelf edge slope and relief. As can be seen in this figure the Cretaceous platform margin studied by Enos (1977a) has high slope gradients (30°) and high relief (1,000 m). Likewise redeposited carbonate debris flow and turbidites in the adjacent basin facies are several hundreds of meters thick (Enos, 1977a).

Carbonate Submarine Fan Model

As discussed in Part 1 carbonate submarine fan facies appear to be rare in contrast to siliciclastic fan facies (Cook, 1982, 1983). This may be largely a result of carbonate sediment gravity flow deposits originating along a line source and not having major point source canyons as in siliciclastic settings (Mullins and Cook, in prep.). Other factors are propably also important in determining whether well developed channelized carbonate fan facies develop (Cook, in prep. b).

The carbonate fan model as presented in this chapter must be considered a local depositional model. It's applicability to other areas remains to be seen. However, based on this fan model it is clear that depositional patterns of the mass-flow facies are different than for those in the debris sheet, slope apron, and base-of-slope models. Inner-fan feeder channels can be expected to be laterally discontinuous along a platform margin, whereas the mid-fan distributary channels and the outer fan lobe sheets will be laterally more continuous. If a direct relationship exists between reservoir quality and specific parts of a carbonate fan then the stratigraphic predictability of reservoir facies may be better in carbonate fans than in debris sheets or aprons due to the development of more orderly facies patterns in fans.

Summary

Carbonate basin margins offer new objectives for petroleum exploration (Cook et al, 1972, p. 467; Enos, 1977a). Enos (1977a) in his study of the billion barrell deep water Poza Rica field of Mexico suggests that the following considerations converge to optimize petroleum potential in deep water carbonate environments: (1) Depositional facies--relief and gradient of the platform margin slope are primary controls on the volume of redeposited debris; (2) Predictability--relief and steepness of the slope entrance definition of the platform margins (3) Favorable diagenesis--high relief in a humid environment may favor downdip migration of fresh water for leaching the debris (Enos and Moore, 1983); (4) Source rocks--fine-grained slope and basinal sediment encase the potential debris reservoirs and also form potential source beds and stratigraphic seals.

As exploration goes into more deep water frontier areas it is likely that more Poza Ricas will be found. It will accordingly become important to understand the geologic conditions that favor the development of carbonate fans versus aprons versus debris sheets, and to determine when and where these conditions prevailed in the geologic past (Cook, 1982).

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EXAMPLES OF FOSSIL CARBONATE SHELF-SLOPE BREAKS

Time	Setting	Reef-Building Organisms	Shelf-Slope Break
Mesozoic-Cenozoic	Open ocean	Complete spectrum	III II
Late Paleozoic	Intracratonic	Small-delicate	I
Middle Paleozoic	Intracratonic	Complete spectrum	II
Early Paleozoic	Open ocean	Small-delicate	I
Precambrian	Open ocean	Stromatolites	II I

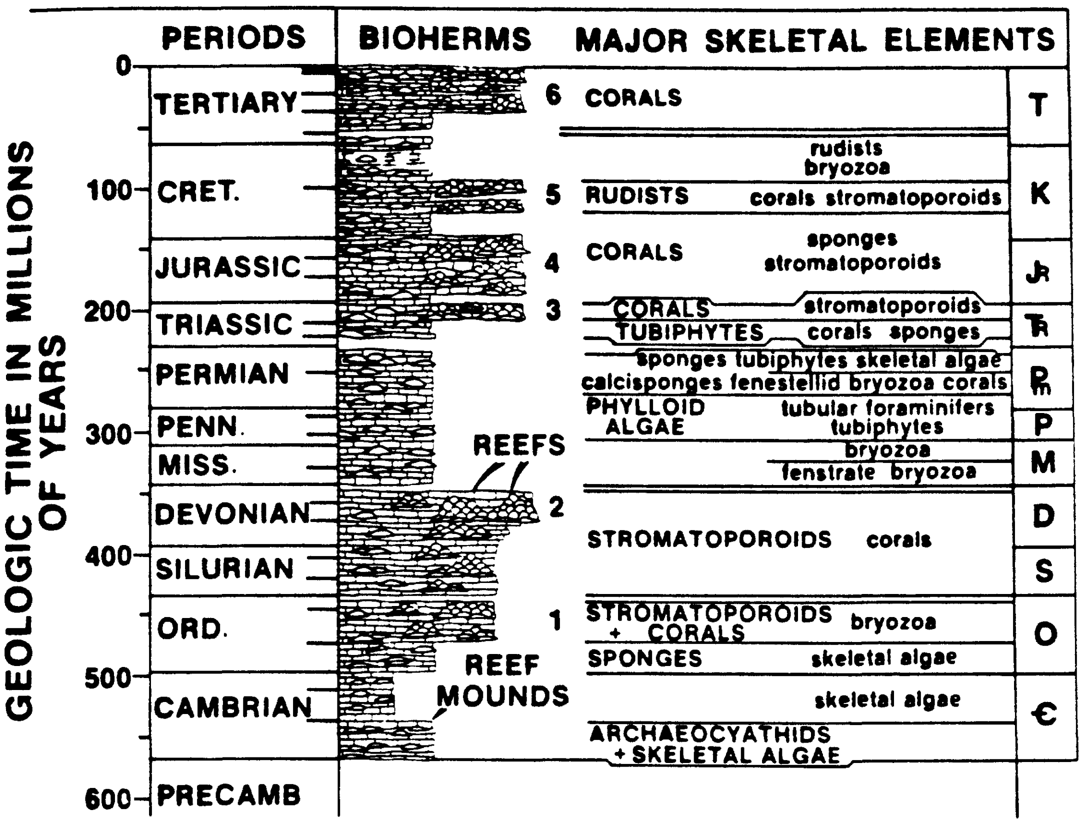
TABLE 2-1. (from James and Mountjoy, 1983)

TYPES OF MASS TRANSPORT		INTERNAL MECHANICAL BEHAVIOR	TRANSPORT MECHANISM AND DOMINANT SEDIMENT SUPPORT	ACOUSTIC RECORD CHARACTERISTICS	SEDIMENTARY STRUCTURES AND BED GEOMETRY
ROCKFALL		ELASTIC	FREEFALL AND ROLLING SINGLE BLOCKS ALONG STEEP SLOPES.	STRONG HUMMOCKY BOTTOM RETURN, HYPERBOALE AND SIDE ECHOES COMMON. WEAK, CHAOTIC INTERNAL RETURN; STRUCTURELESS.	GRAIN SUPPORTED FRAMEWORK, VARIABLE MATRIX, DISORGANIZED. MAY BE ELONGATE PARALLEL TO SLOPE AND NARROW PERPENDICULAR TO SLOPE.
SLIDE	TRANSLATIONAL (GLIDE)	ELASTIC	SHEAR FAILURE ALONG DISCRETE SHEAR PLANES SUBPARALLEL TO UNDERLYING BEDS. SLIDE MAY BEHAVE ELASTICALLY AT TOP; PLASTICALLY AT BASE AND THIN LATERAL MARGINS.	INTERNAL REFLECTORS CONTINUOUS AND OFTEN UNDEFORMED; ABRUPT TERMINATIONS. STRATA OF GLIDE BLOCKS MAY BE UNCONFORMABLE OR SUBPARALLEL TO UNDERLYING SEDIMENT.	BEDDING MAY BE UNDEFORMED AND PARALLEL TO UNDERLYING BEDS OR DEFORMED ESPECIALLY AT BASE AND MARGINS WHERE DEBRIS FLOW CONGLOMERATE CAN BE GENERATED. HUMMOCKY, SLIGHTLY CONVEX-UP TOP, BASE SUBPARALLEL TO UNDERLYING BEDS; 10's TO 1000's OF METERS WIDE AND LONG.
SLIDE	ROTATIONAL (SLUMP)	ELASTIC / PLASTIC	SHEAR FAILURE ALONG DISCRETE CONCAVE-UP SHEAR PLANES ACCOMPANIED BY ROTATION OF SLIDE. MAY MOVE ELASTICALLY OR ELASTICALLY AND PLASTICALLY.	INTERNAL REFLECTORS CONTINUOUS AND UNDEFORMED FOR SHORT DISTANCES WITH DEFORMATION AT TOE AND ALONG BASE. CONCAVE-UP FAILURE PLANE AT HEAD AND SUBPARALLEL TO ADJACENT BEDDING AT TOE. SURFACE USUALLY HUMMOCKY.	BEDDING MAY BE UNDEFORMED. UPPER AND LOWER CONTACTS OFTEN DEFORMED. INTERNAL BEDDING AT ANGULAR DISCORDANCE TO ENCLOSING STRATA. SIZE VARIABLE.
SEDIMENT GRAVITY FLOW	DEBRIS FLOW OR MUD FLOW	PLASTIC	SHEAR DISTRIBUTED THROUGHOUT THE SEDIMENT MASS. CLASTS SUPPORTED ABOVE BASE OF BED BY COHESIVE STRENGTH OF MUD MATRIX AND CLAST BUOYANCY. CAN BE INITIATED AND MOVE LONG DISTANCES ALONG VERY LOW ANGLE SLOPES.	SEA FLOOR REFLECTORS MAY BE HYPERBOLIC, IRREGULAR, OR SMOOTH. COMMONLY ACOUSTICALLY TRANSPARENT WITH FEW OR NO INTERNAL REFLECTORS. MOUNDED OR LENS SHAPED WITH BLUNT TERMINATION AT HEAD. MAY BE CHAOTIC INTERNALLY.	CLASTS MATRIX SUPPORTED; CLASTS MAY EXHIBIT RANDOM FABRIC THROUGHOUT THE BED OR ORIENTED SUBPARALLEL, ESPECIALLY AT BASE AND TOP OF FLOW UNITS; INVERSE GRADING POSSIBLE. CLAST SIZE AND MATRIX CONTENT VARIABLE. OCCUR AS SHEET TO CHANNEL-SHAPED BODIES CM'S TO SEVERAL 10's OF METERS THICK AND 100's TO 1000's (?) OF METERS LONG; WIDTHS VARIABLE.
SEDIMENT GRAVITY FLOW	GRAIN FLOW	PLASTIC / FLUID	COHESIONLESS SEDIMENT SUPPORTED BY DISPERSIVE PRESSURE. USUALLY REQUIRES STEEP SLOPES FOR INITIATION AND SUSTAINED DOWNSLOPE MOVEMENT.	INDIVIDUAL FLOW DEPOSITS VERY THIN; MAY NOT BE RESOLVABLE WITH PRESENT SEISMIC-REFLECTION TECHNIQUES. REPEATED FLOWS MAY PRODUCE A SEQUENCE OF THIN, EVEN, REFLECTORS.	MASSIVE; CLAST A-AXIS PARALLEL TO FLOW AND IMBRICATE UPSTREAM, INVERSE GRADING MAY OCCUR NEAR BASE.
SEDIMENT GRAVITY FLOW	LIQUEFIED FLOW	FLUID	COHESIONLESS SEDIMENT SUPPORTED BY UPWARD DISPLACEMENT OF FLUID (DILATANCE) AS LOOSELY PACKED STRUCTURE COLLAPSES; SETTLES INTO A TIGHTLY PACKED TEXTURE. REQUIRES SLOPES>3°		DEWATERING STRUCTURES, SANDSTONE DIKES, FLAME AND LOAD STRUCTURES, CONVOLUTE BEDDING, HOMOGENIZED SEDIMENT.
SEDIMENT GRAVITY FLOW	FLUIDIZED FLOW	FLUID	COHESIONLESS SEDIMENT SUPPORTED BY UPWARD MOTION OF ESCAPING PORE FLUID. THIN (<10 CM) AND SHORT-LIVED.		
SEDIMENT GRAVITY FLOW	TURBIDITY CURRENT FLOW	FLUID	CLASTS SUPPORTED BY FLUID TURBULENCE. CAN MOVE LONG DISTANCES ALONG LOW ANGLE SLOPES.	THIN, EVEN, CONTINUOUS, ACOUSTICALLY HIGHLY REFLECTIVE UNITS; ONLAPS SLOPE OR RAISED TOPOGRAPHY. DISCONTINUOUS, MIGRATING AND CLIMBING IN CHANNEL SEQUENCES.	BOUMA SEQUENCES. MM'S TO SEVERAL 10's OF CM THICK. 10's TO 1000's OF METERS IN LENGTH; WIDTHS VARIABLE.

TABLE 2-2. MAJOR TYPES OF SUBMARINE MASS TRANSPORT ON SLOPES AND SUGGESTED CRITERIA FOR THEIR RECOGNITION. (modified from Cook and Mullins, 1983 and Nardin et al, 1979)

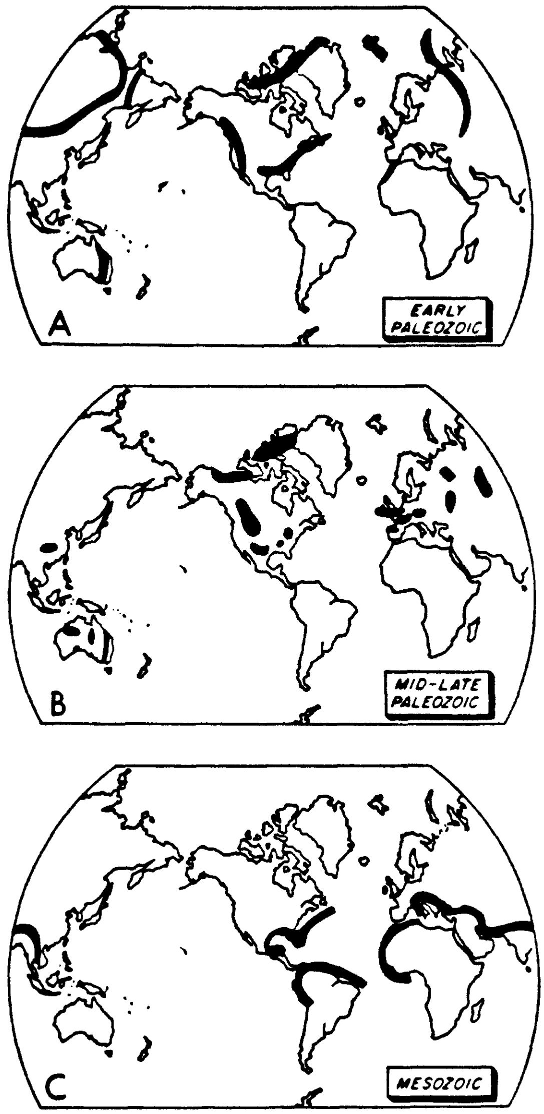
TABLE 2-3. COMPARISON OF PLATFORM MARGIN MODELS AND TERMINOLOGY

	WILSON (1975)	MCILREATH & JAMES (1978)	READ (1982)	JAMES & MOUNTJOY (1983)
NON-RIMMED SHELVES	- NONE -	- NONE -	RAMP - HOMOCLINAL	RAMP
	- NONE -	- NONE -	RAMP - DISTALLY STEEPENED	- NONE -
RIMMED SHELVES	TYPE I DOWNSLOPE MUD ACCUMULATION	- NONE -	- NONE -	- NONE -
	TYPE II KNOLL REEF RAMP	DEPOSITIONAL MARGIN (reef dominated)	RIMMED SHELF ACCRETIONARY (reef and/or sand shoal)	DEPOSITIONAL MARGIN (reef and/or sand shoal)
	- NONE -	DEPOSITIONAL MARGIN (sand shoal dominated)		
	TYPE III FRAMEWORK REEF RIMS	BYPASS MARGIN (reef dominated)	BYPASS MARGIN ESCARPMENT TYPE (reef and/or sand shoal)	BYPASS MARGIN (reef and/or sand shoal shallow basin)
	- NONE -	BYPASS MARGIN (sand shoal dominated)		
	- NONE -	- NONE -	BYPASS MARGIN GULLIED SLOPE (reef and/or sand shoal)	BYPASS MARGIN (reef and/or sand shoal deep basin)
	- NONE -	- NONE -	EROSIONAL MARGIN (reef and/or sand shoal)	- NONE -



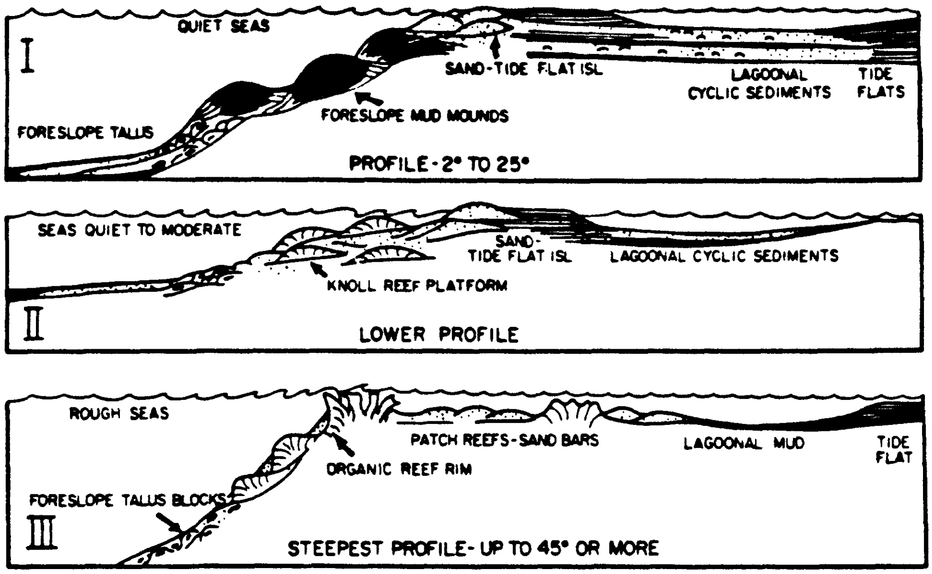
Idealized stratigraphic column representing the Phanerozoic and illustrating times when there appear to be no reefs or bioherms (gaps), times when there were only reef mounds, and times when there were both reefs and reef mounds and the organisms that built them.

Figure 2-1. (from James, 1983)



Generalized sketch maps illustrating the position of major carbonate platform margins during (A) Early Paleozoic (Cambro-Ordovician), (B) Mid-Late Paleozoic (Silurian-Permian) and (C) Mesozoic time.

Figure 2-2. (after James and Mountjoy, 1983)



Three types of carbonate shelf margins: I, downslope lime-mud accumulation; II, knoll reef ramp or platform; III, organic reef rim.

Figure 2-3. (from Wilson, 1975)

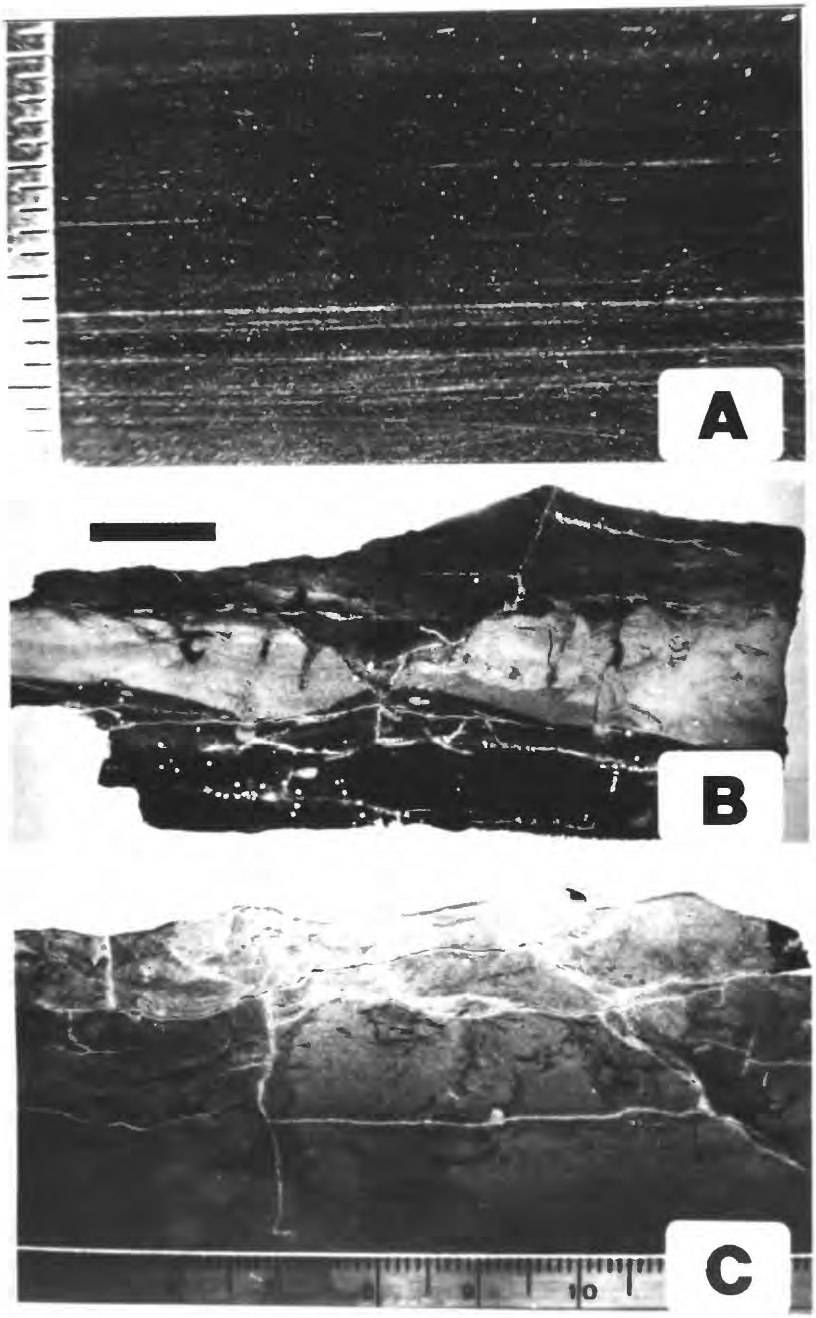
STAGE	TYPE OF LIMESTONE	SPECIES DIVERSITY	SHAPE OF REEF BUILDERS
DOMINATION	bindstone to framestone	low to moderate	Laminate encrusting
DIVERSIFICATION	framestone (bindstone) mudstone to wackestone matrix	high	domal massive lamellar branching encrusting
COLONIZATION	bafflestone to floatstone (bindstone) with a mud stone to wackestone matrix	low	branching lamellar encrusting
STABILIZATION	grainstone to rudstone (packstone to wackestone)	low	skeletal debris

A sketch illustrating the growth form of reef-building metazoans and the types of environments in which they most commonly occur.

Figure 2-4. (after James, 1983)

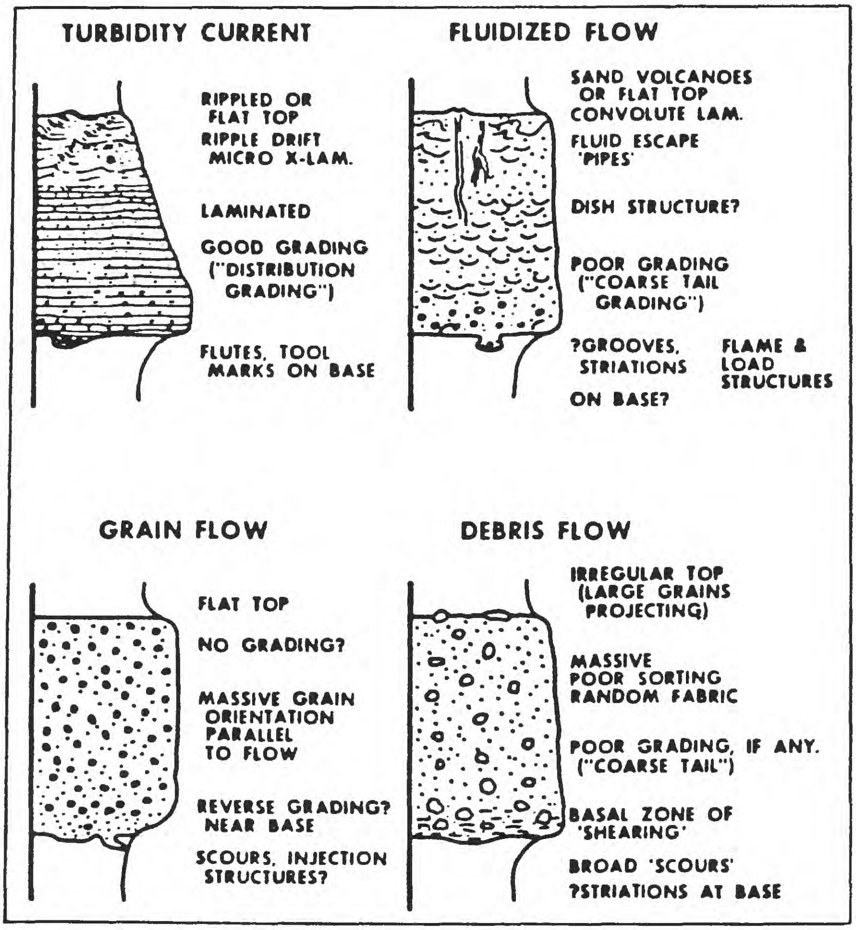
Peri-platform ooze; evenly-bedded, grey lime mudstone with thin interbeds of argillaceous lime mudstone, Cooks Brook Formation, Middle Cambrian, Humber Arm, Western Newfoundland.

Figure 2-5. (from McIlreath and James, 1978)



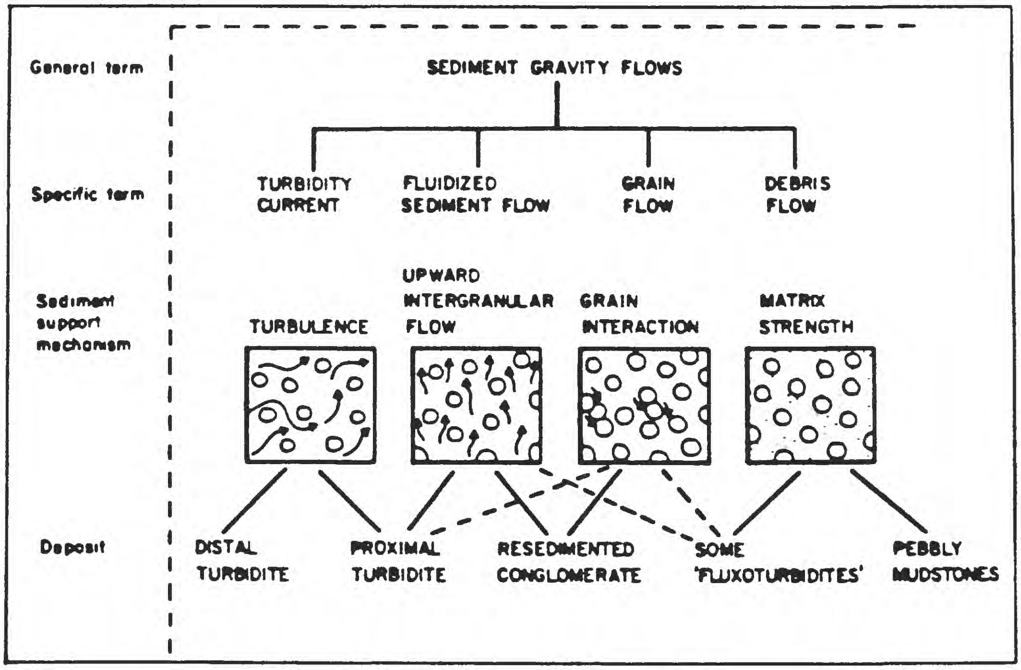
Lithologies in the Upper Devonian Middlesex Shale and Sawmill Creek Shale, New York. (A) Laminated Middlesex Shale from westernmost outcrop at Lake Erie. Clay-silt laminae couplets are undisturbed by bioturbation. Scale divisions are millimeters. (B) Bioturbate Sawmill Creek Shale from area east of Ithaca. Dark mudstone has been completely reworked; lighter silt layer is broken and mottled by burrowers. Bar scale equals 1 cm. (C) Totally bioturbated Sawmill Creek Shale from easternmost area of outcrop, near Sidney. Both silt and clay layers have been obliterated by reworking; almost no depositional structure remains. Outcrops in this facies are sparsely fossiliferous. Centimeter scale.

Figure 2-6. (from Byers, 1977)



Idealized sequences of sedimentary textures and structures in hypothetical single-mechanism deposits of deep-water coarse clastic sediments.

Figure 2-7. (modified from Middleton and Hampton, 1976)

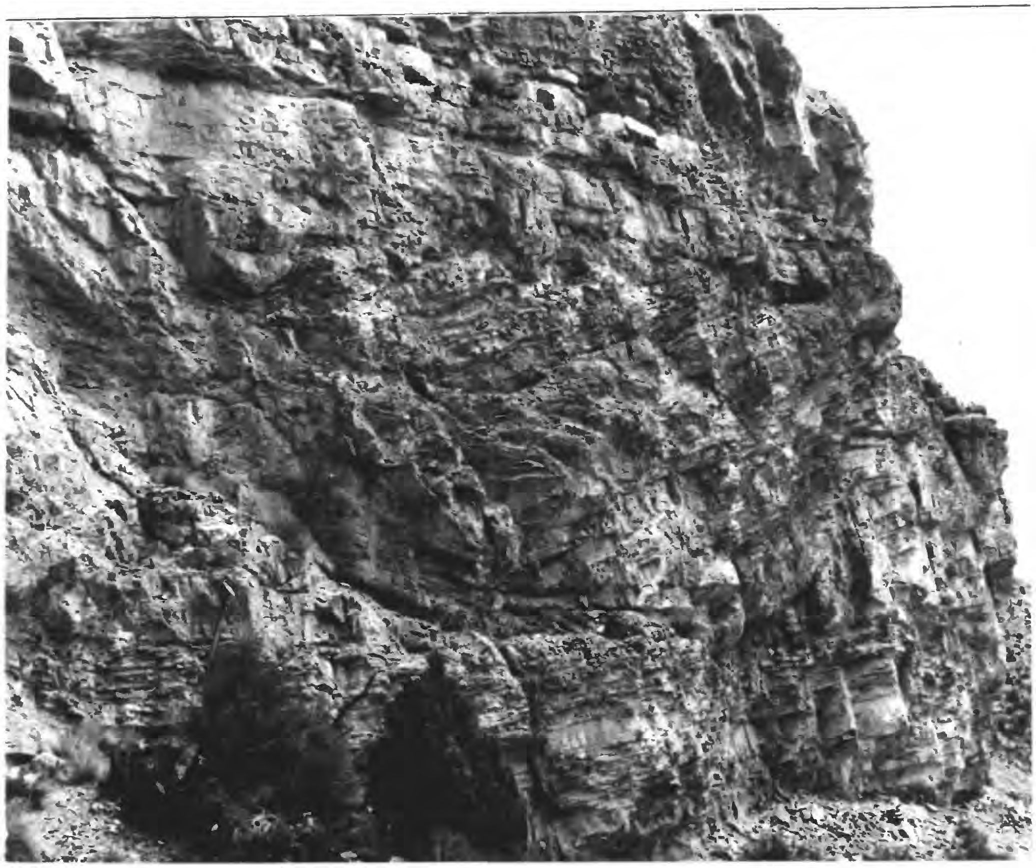


Classification of subaqueous sediment-gravity flows.

Figure 2-8. (from Middleton and Hampton, 1976)

Epiphython-Renalcis clasts in fore-reef slope, Devonian, Canning Basin, western Australia.

Figure 2 -9. (from Cook and Mullins, 1983)



Rotational slide (slump) in lower slope facies, 10 m thick which in turn is truncated by an overlying translational slide. Upper part of Hales Limestone, Lower Ordovician, Nevada.

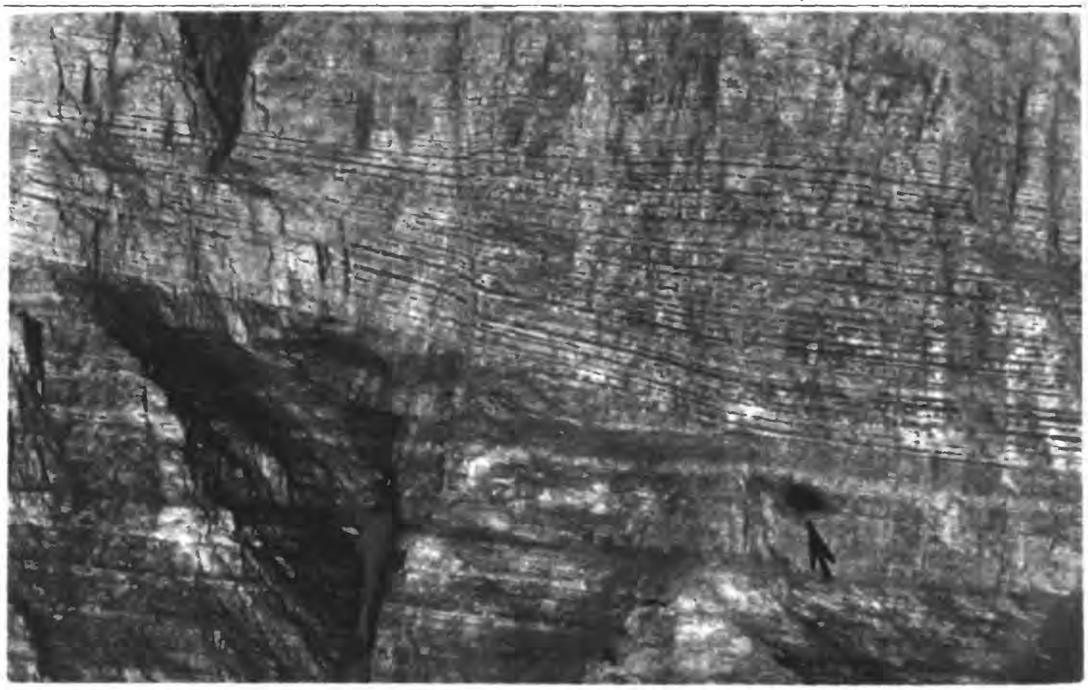
Figure 2-10. (from Cook, 1979a)

Intraformational truncation surface, Rancheria Formation, Mississippian, Sacramento Mountains, New Mexico. Width of outcrop about 15 m.

Figure 2-11. (from Yurewicz, 1977)

Intraformational truncation surface, Bone Spring Formation, Permian, Guadelupe Mountains, west Texas. Width of outcrop abut 5 m.

Figure 2-12. (from Cook and Mullins, 1983)



Large intraformational truncation surface in argillaceous and cherty limestones, Hare Fiord Formation, Permo-Pennsylvanian, Ellesmere Island, Arctic Archipelago. Note smooth curved concave-up (listric) geometry of the truncation surface and lack of obvious deformation of beds below or above truncation surface, downdip thickening of sedimentary fill, with highest beds parallel with beds below truncation surface. Shadow at lower center (arrow) just below truncation surface is of a helicopter. Width of view about 150 m.

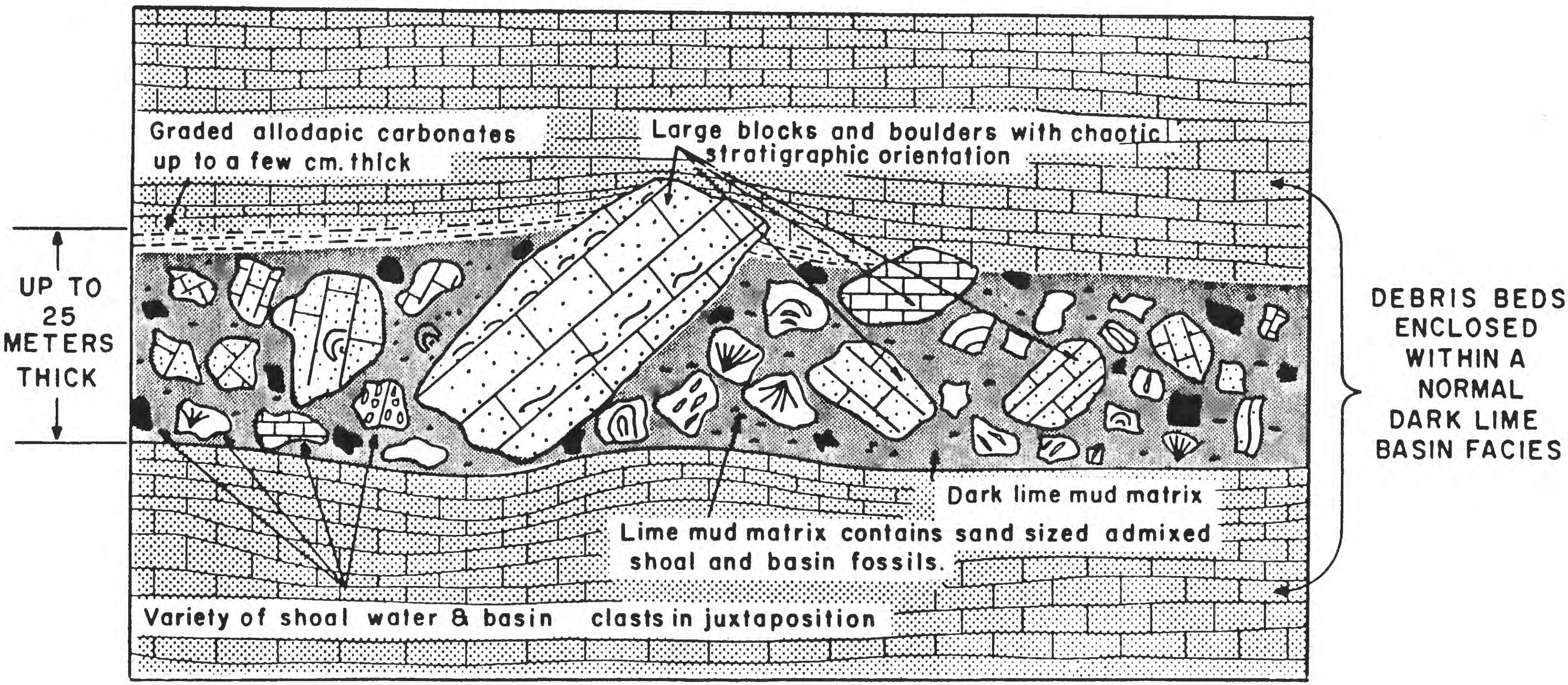
Figure 2-13, (from Davies, 1977)

Thin lateral margin of debris flow channel deposit. Tabular clasts in lateral margins of channel are normally oriented subparallel to bedding but clast size distribution is still random. Thickness of bed shown is 60 cm.

Figure 2-14. (from Cook, 1979a)

Thin lateral margin of debris flow channel deposit. Tabular clasts in lateral margins of channel are normally oriented subparallel to bedding but clast size distribution is still random. Thickness of bed shown is 60 cm

Figure 2-14. (from Cook, 1979a)

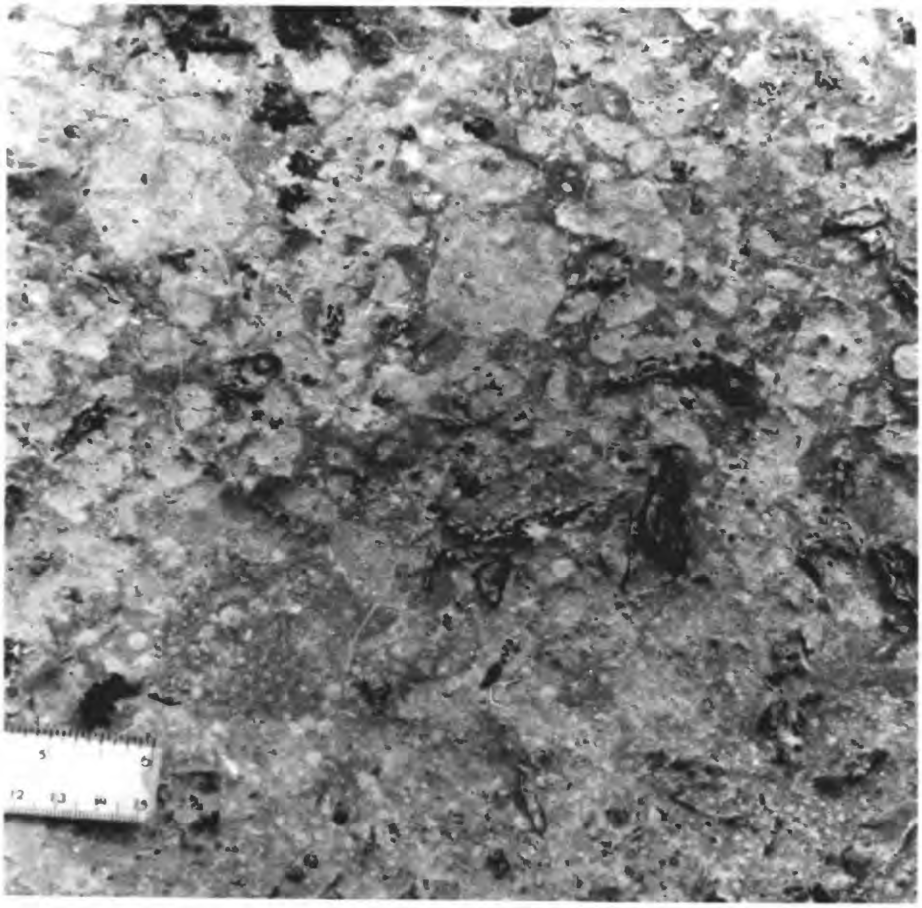


Generalized sketch of the major characteristics of Upper Devonian carbonate debris-flow deposits, Rocky Mountains, Alberta, Canada.

Figure 2-15. (from Cook et al, 1972)

Looking southeast (basinward) at the same portion of debris sheet in Figure 2-93. Large knob is the same 10 x 30 m clast seen in Figures 2-92 and 2-93. Note fairly planar base.

Figure 2-16. (modified from Cook et al, 1972)

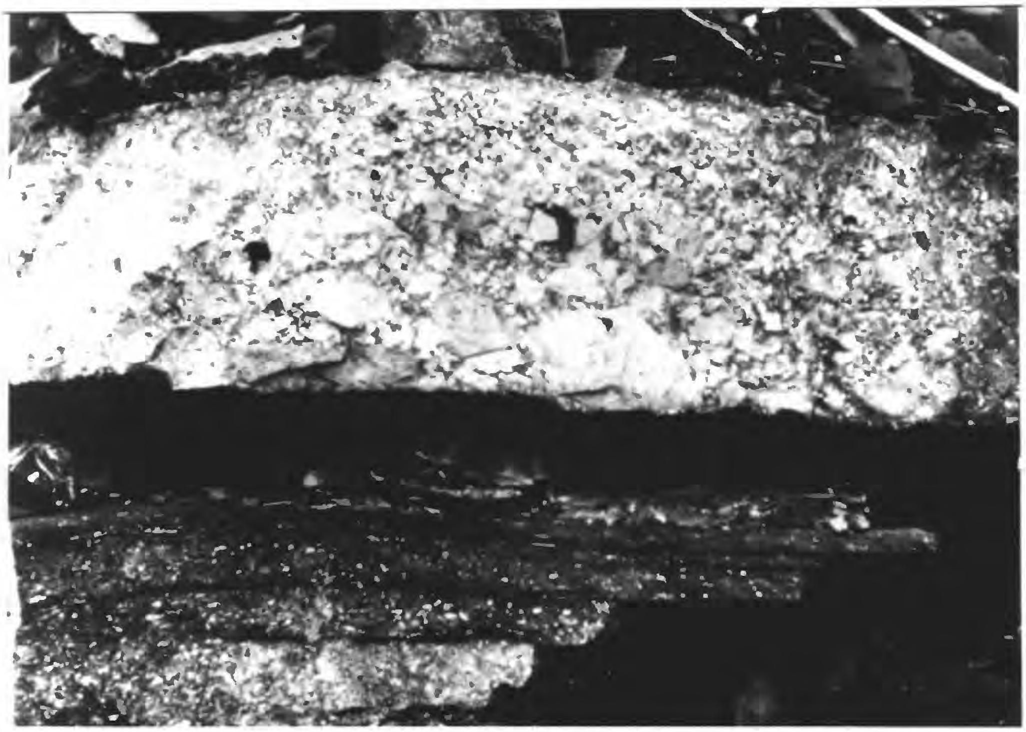


One of the redeposited sheets shown in Figure 5-95, about 4 km from the southeast margin of Ancient Wall buildup. Probable modified grain-flow deposit 1 m thick. Reverse grading involves clasts ranging up to 5 cm in maximum diameter. The dark-colored resistant clasts are partially silicified fossil fragments. The ruler is in inches (top) and centimeters (bottom); the upper and lower contact is not seen in this photo.

Figure 2-17. (from Cook et al, 1972)

Possible modified grain-flow deposit (lower slope) with reverse grading (right side of photo) of clasts up to about the 10 inch mark on tape. From the 10 in mark to the top of tape the clasts may be slightly normally graded(?). Upper part of Hales Limestone, Lower Ordovician, Nevada.

Figure 2-18. (from Cook and Mullins, 1983)



10-cm-thick normally graded conglomeratic turbidite. Note flat base and mounded surface. Bed occurs in graptolitic basinal lime mudstones 65 km from bank margin. Prongs Creek Formation, Middle Devonian, northern Mackenzie Mountains, Yukon Territory, Canada.

Figure 2-19. (Cook and Mullins, 1983)

Normally graded grainstone turbidites interbedded with limey shale. Note erosional surface and flame structures at tops of shale layers, and boudin structures in lower grainstone layer.

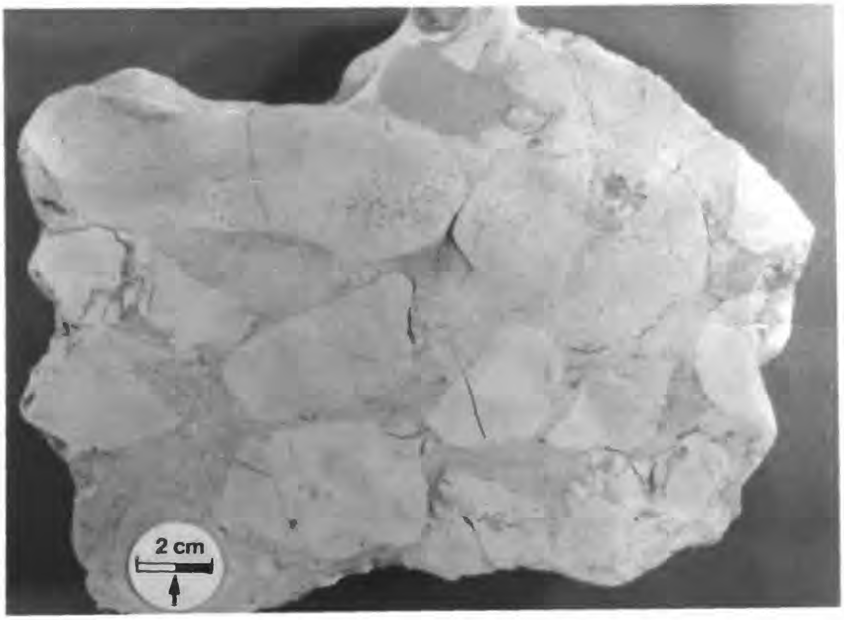
Figure 2-20. (from Pfeil and Read, 1980)

Epiphyton-Renalcis bioherm (10 m high) in slope facies. Man at top of photo for scale. Shady Dolomite, Cambrian, Appalachians.

Figure 2-21. (from Pfeil and Read, 1980)

Early cementation and exposure of hardground at the sediment-water interface is evidenced by boring of nodules and common encrustation by oysters.

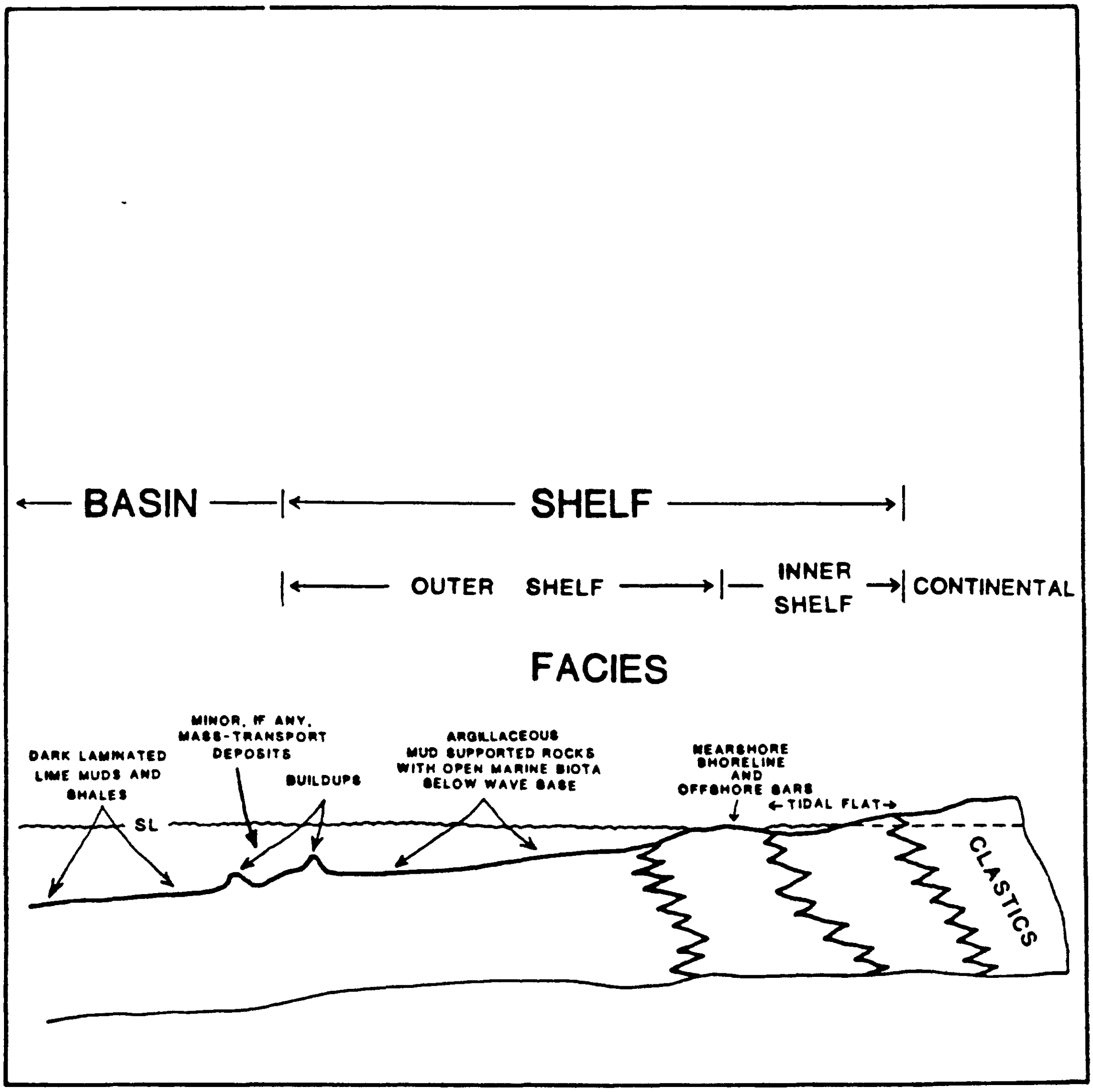
Figure 2 -22. (from Cook and Mullins, 1983)



Conglomeratic debris flow deposit, slope facies. Nodules composed of early cemented fine-grained carbonate, matrix composed of mud-supported fine-grained skeletal sand. Thebes Formation, Eocene, Egypt.

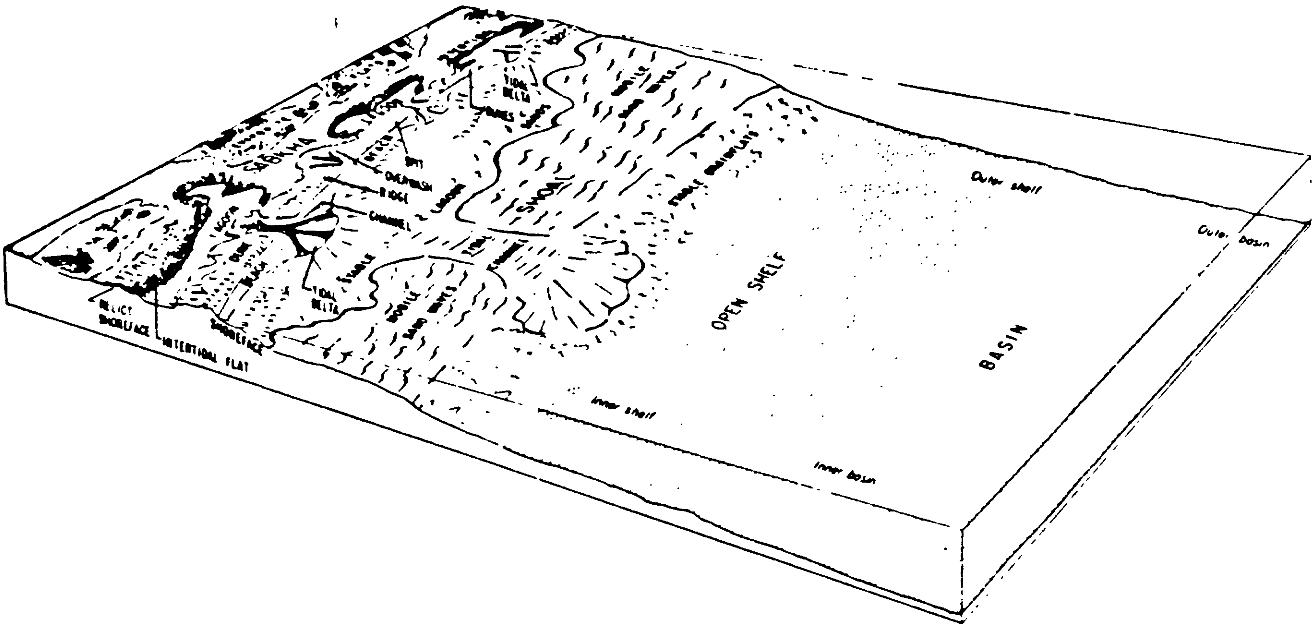
Figure 2-23. (from Cook and Mullins, 1983)

HOMOCLINAL RAMP MODEL



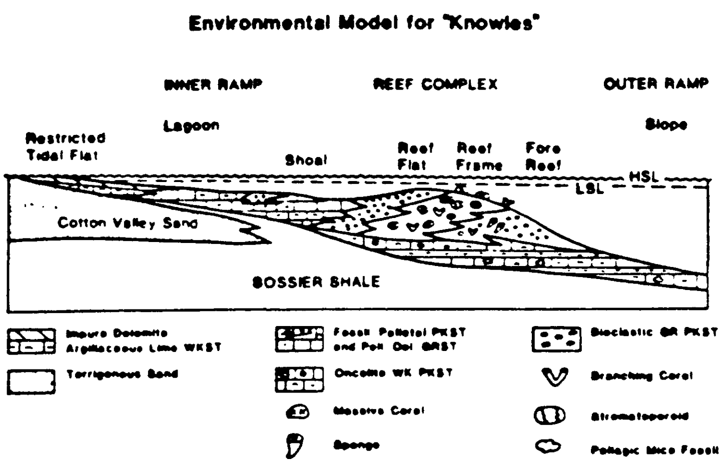
Profile of homoclinal ramp model (depositional profile format modified from Wilson and Jordon, 1983, Fig. 1a)

Figure 2-24.



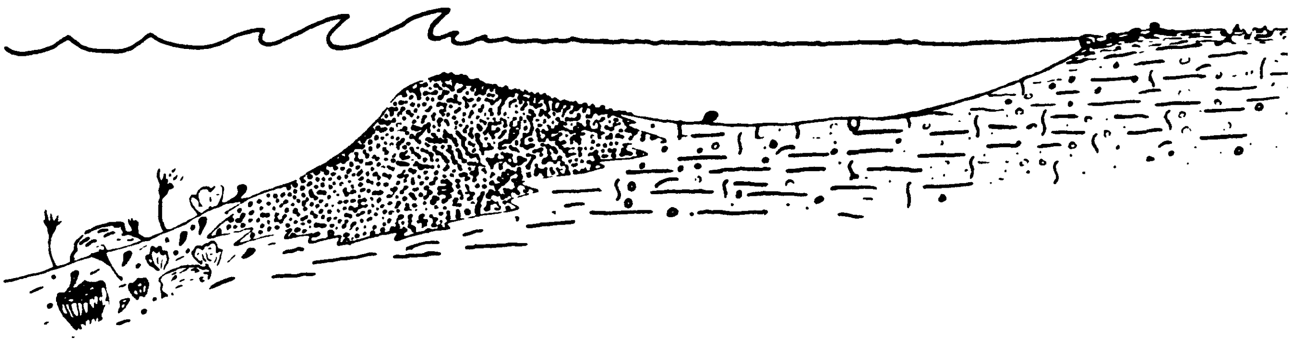
Depositional model, Smackover and lower Buckner basinal, shelf, shoal and sabkha systems, South Texas

Figure 2 -25. (from Budd and Loucks, 1981)



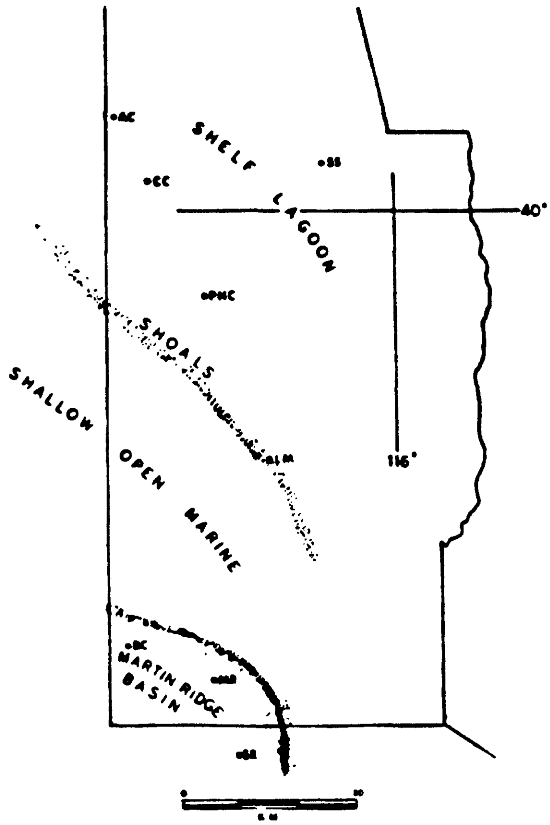
Environmental model of "Knowles Limestone" illustrating distribution of facies. Figure not to scale.

Figure 2-26. (from Finnerman et al, 1982)



Lateral distribution of temporally equivalent Hanson Creek depositional environments and rock textures. Vertical scale is in meters to tens of meters, horizontal scale is in kilometers.

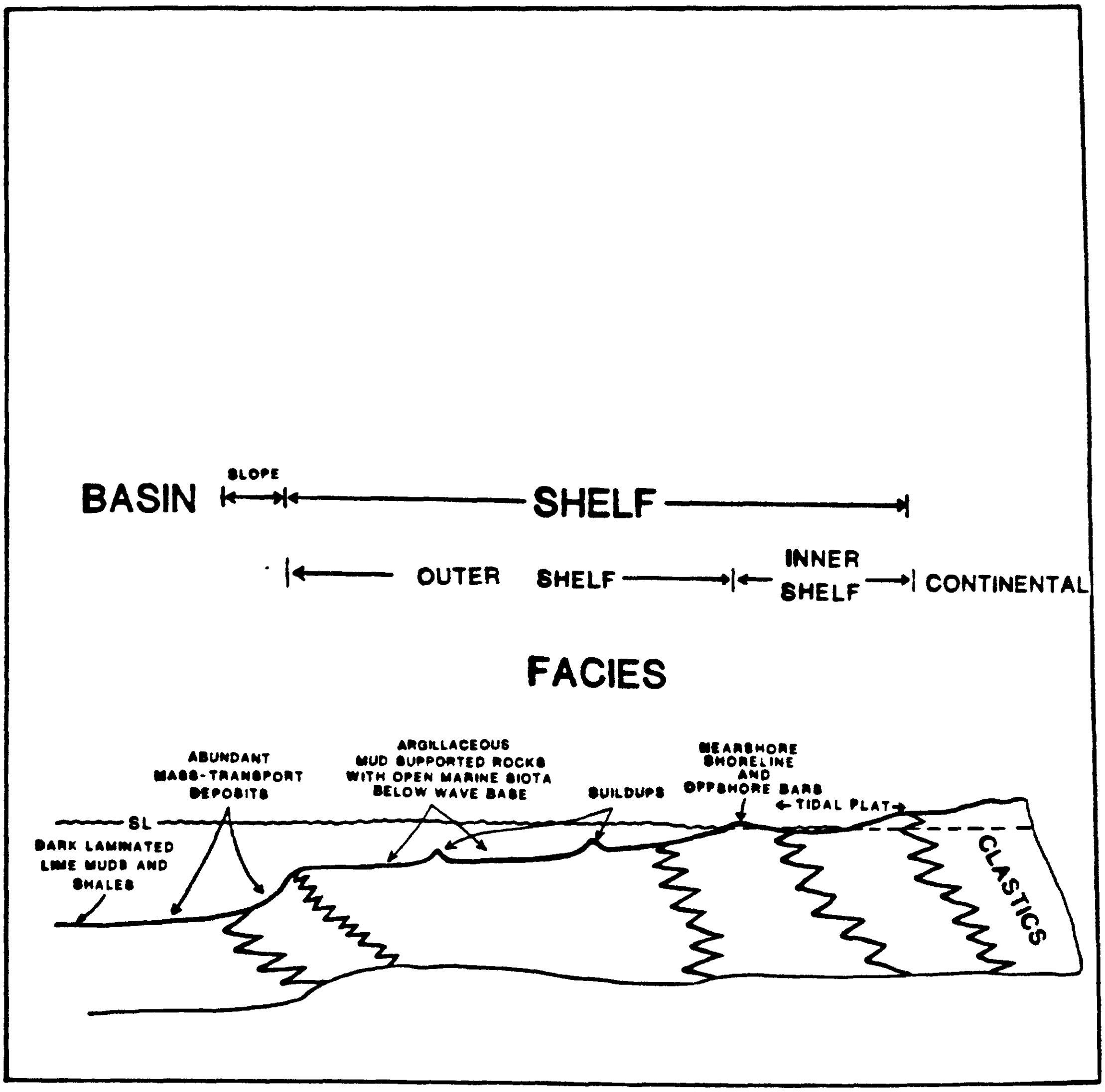
Figure 2-27. (from Dunham, 1977)



Generalized Ashgillian paleogeography of Eureka County.

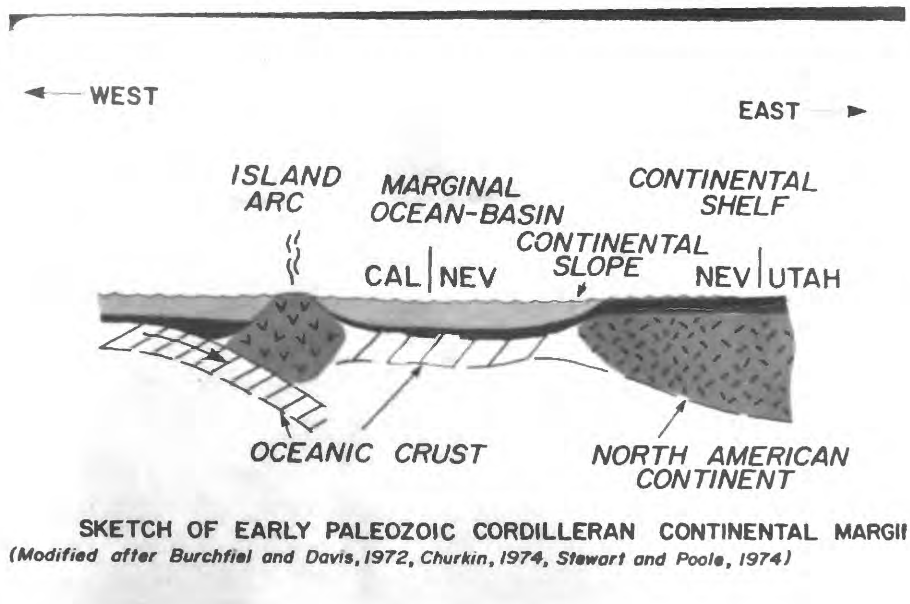
Figure 2-28. (from Dunham, 1977)

DISTALLY STEEPENED RAMP MODEL



Profile of distally steepened ramp model (depositional profile format modified from Wilson and Jordan, 1983).

Figure 2-29.

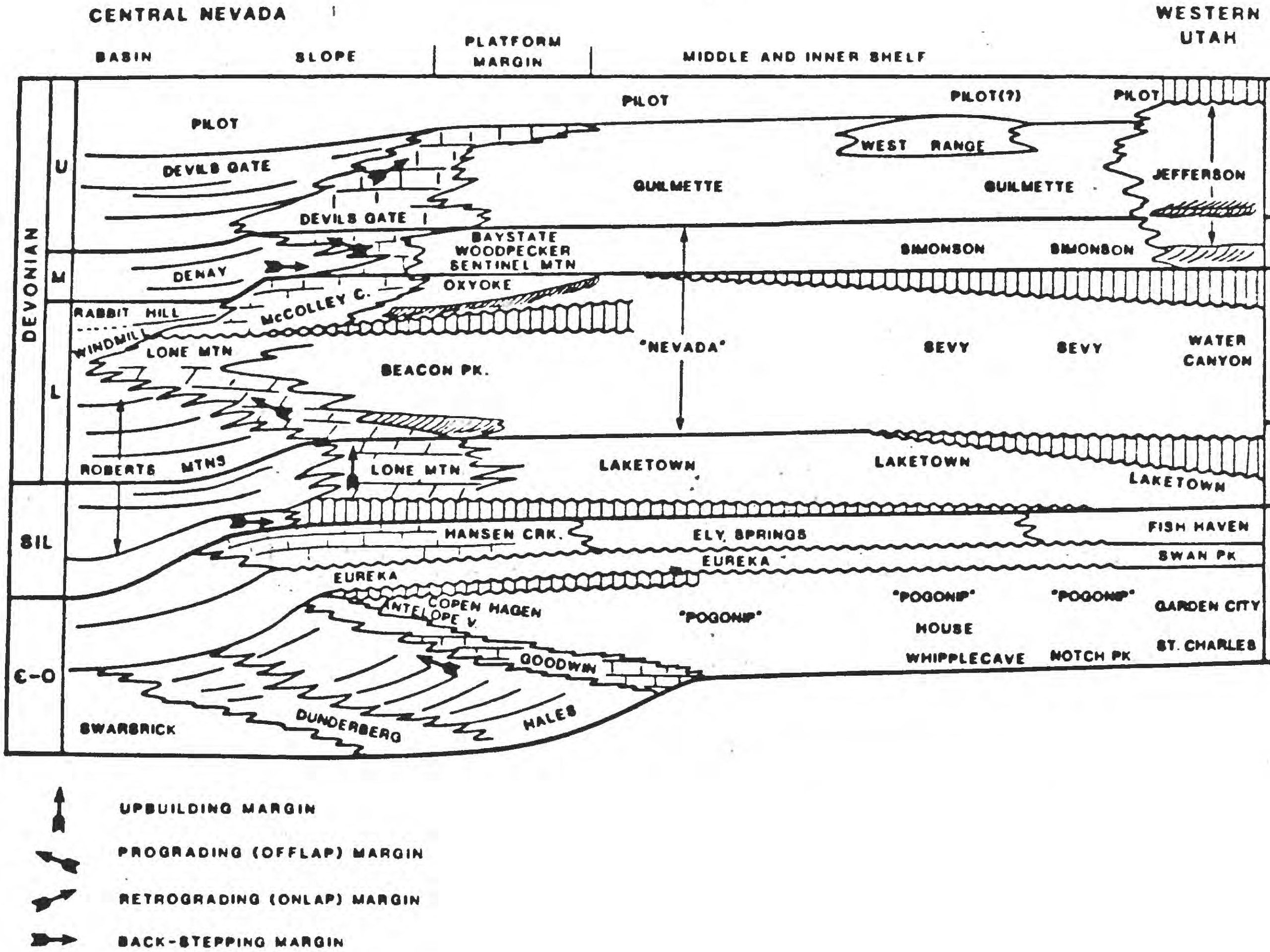


Sketch of early Paleozoic Cordilleran continental margin.

Figure 2-30.

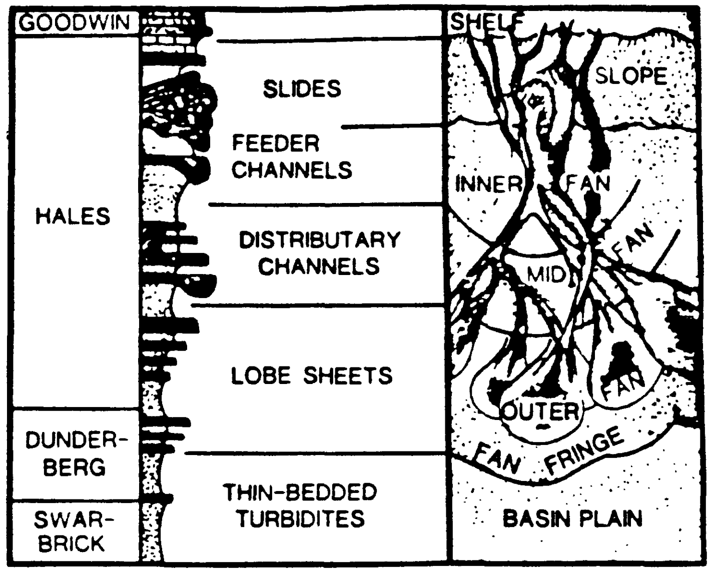
1500 m thick seaward prograding continental margin sequence. Width of photo about 2 km. Arrow points to base of 10 m thick, 400 m wide translational submarine slide shown in Figs. 2-49 and 2-51

Figure 2-31. (from Cook and Mullins, 1983)



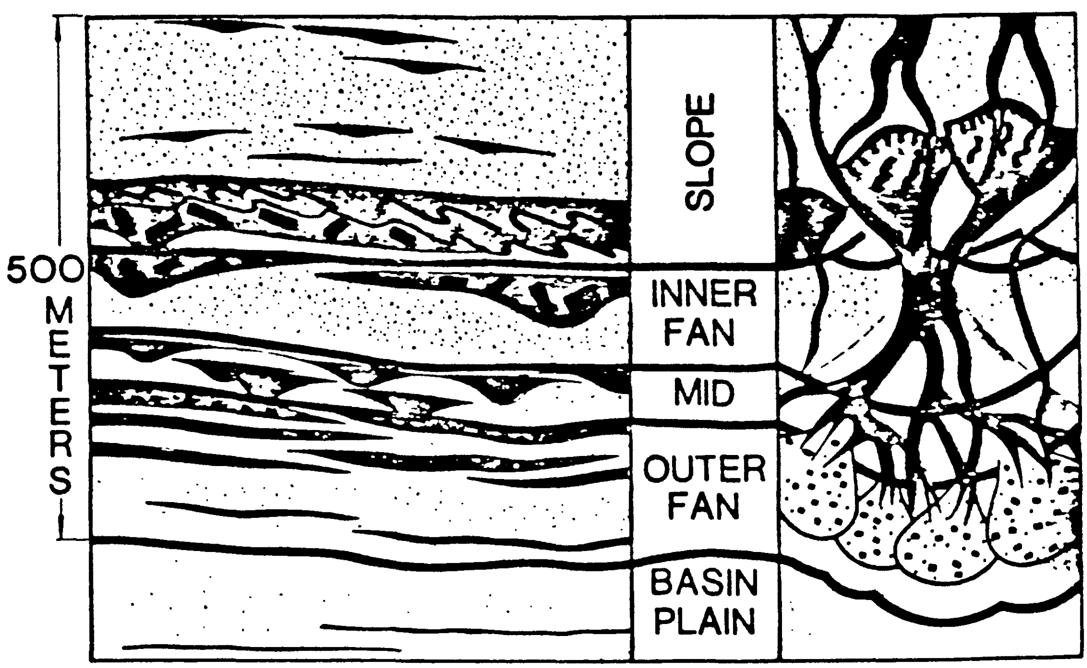
Pre-Antler orogeny depositional profile from western Utah to central Nevada showing formational terminology from Upper Cambrian through the Devonian. Unconformities are shown by vertical bars enclosing wavy horizontal windows of missing time. The total stratigraphic thickness shown at the platform margin is on the order of 10,000 to 15,000 feet, although the relative thickness of each System has been altered for diagramatic purposes. The distance across this continental margin from inner shelf settings to basin-margin settings is about 250 to 300 miles.

Figure 2-32. (modified from Cook and Taylor, 1983)



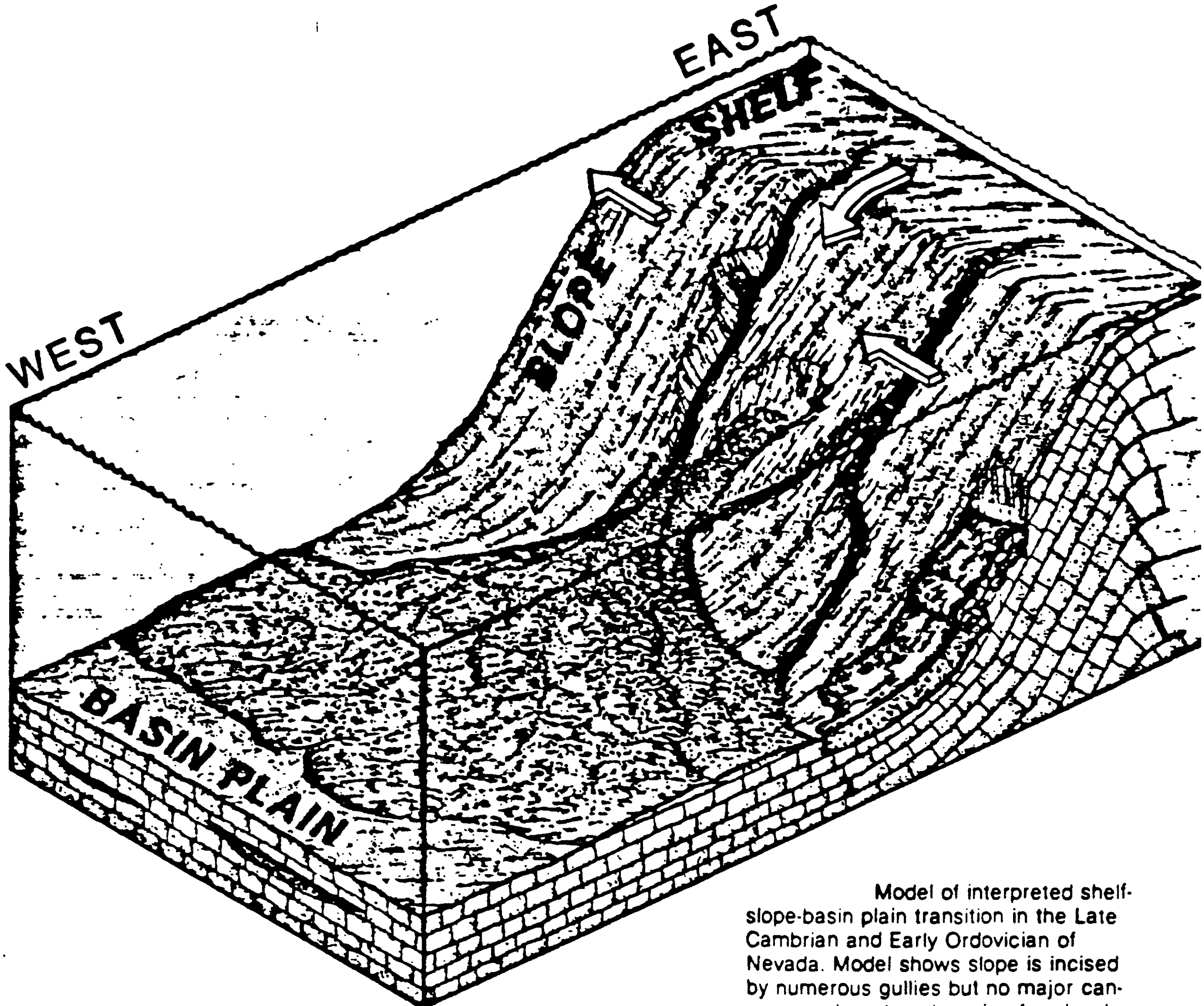
Preliminary local carbonate submarine-fan model showing that fan sediment is derived from both shoal-water shelf areas and by the remolding of deeper water slides and slumps into mass-flows, large slides and channelized conglomerates that occur in outer fan sites, calcarenites in non-channelized sheets in mid-fan sites, and thin-bedded silt to fine sand-sized carbonate turbidites in fan fringe and basin plain. Slope and fan facies about 500 m thick, basin plain facies about 1000 m thick. Model based on studies in Cambrian and Ordovician strata in Nevada

Figure 2-33. (from Cook and Egbert, 1981 b,c and Cook and Mullins, 1983)



Preliminary local carbonate submarine fan model. Schematically shows vertical and lateral facies sequences that occur in prograding continental margin section. Model based on studies in Cambrian and Ordovician strata in Nevada

Figure 2-34. (from Cook and Egbert, 1981a and Cook and Mullins, 1983

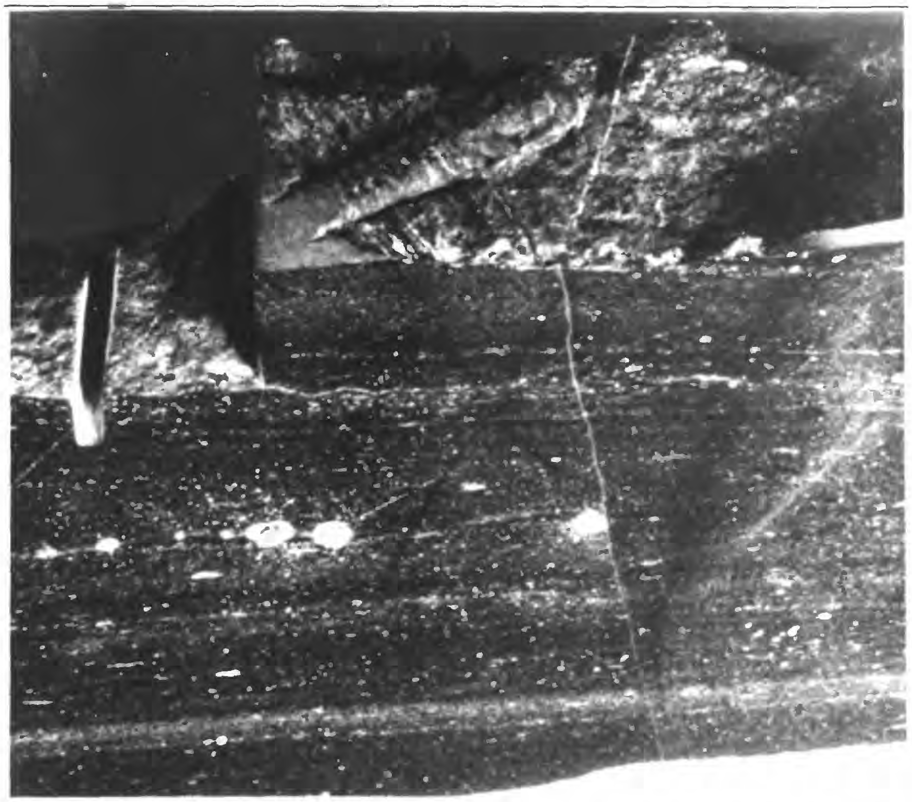


Model of interpreted shelf-slope-basin plain transition in the Late Cambrian and Early Ordovician of Nevada. Model shows slope is incised by numerous gullies but no major canyons; carbonate submarine fan develops at base of slope and basin plain; fan sediment is a mixture of shoal-water shelf carbonates and deeper water slide generated debris; contour currents flow northerly along upper slope

Figure 2-35. (from Cook and Egbert, 1981a and Cook and Mullins, 1983)

Fine-grained, laminated lime mudstone and wackestone interpreted as slope deposit from lower part of Hales Limestone, Upper Cambrian, Nevada.

Figure 2-36. (from Cook and Mullins, 1983)



Laminated lime mudstone and wackestone; pervasive sponge spicules (small light-colored blobs); larger light-colored spherules are authigenic pyrite. Bed is 4 cm thick. Lower part of Hales Limestone, Upper Cambrian, Nevada.

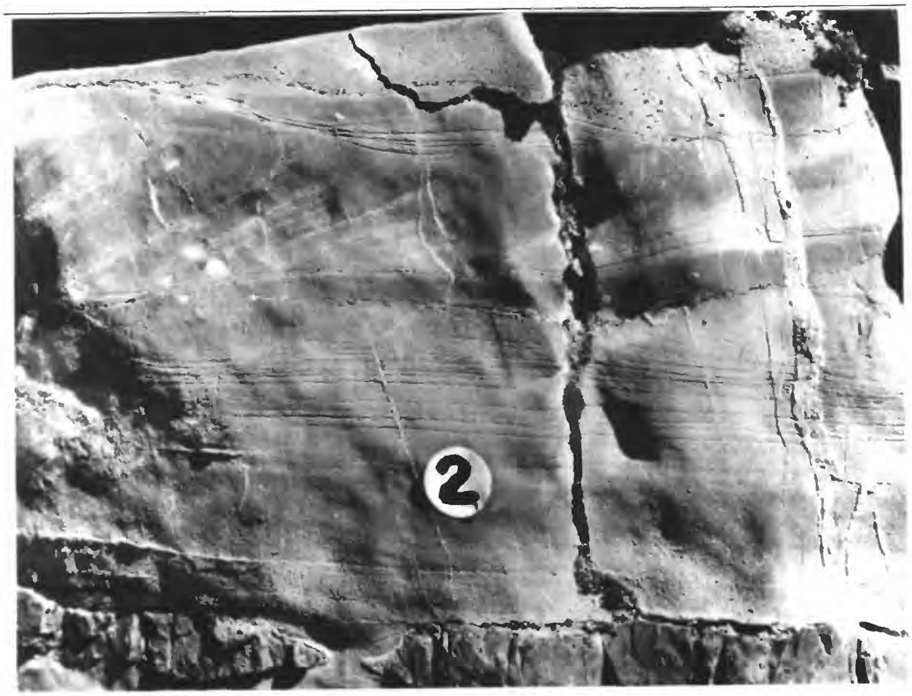
Figure 2-37. (from Cook and Taylor, 1977)

Thin-bedded turbidites interbedded with hemipelagic sediments in fan fringe and basin-plain facies. White circle is 2 cm wide. Dunderberg Shale, Upper Cambrian, Nevada.

Figure 2-38. (from Cook and Mullins, 1983)

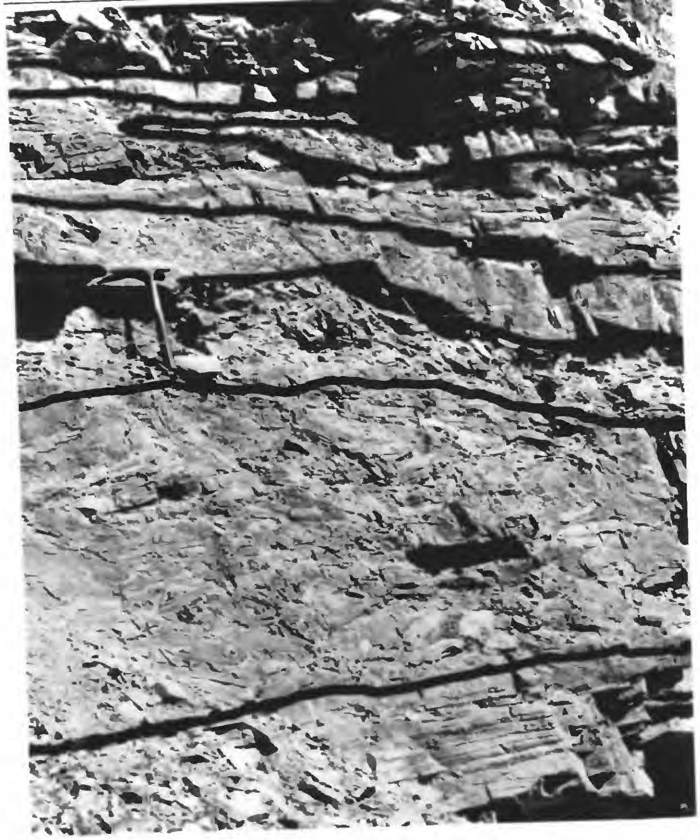
Thickening and coarsening upward nonchannelized turbidite sheets. Note flat bases and tops of turbidite beds. Inferred to represent outer fan lobe sheets. Lower Hales Limestone, Upper Cambrian, Nevada.

Figure 2 -39. (from Cook and Mullins, 1983)



Outer fan lobe turbidite. Shows two turbidite events. Lower 14 cm consist of a Bouma A-C sequence overlain by a Bouma A sequence within upper 2 cm of photo. White circle is 2 cm wide.

Figure 2-40. (from Cook and Mullins, 1983)

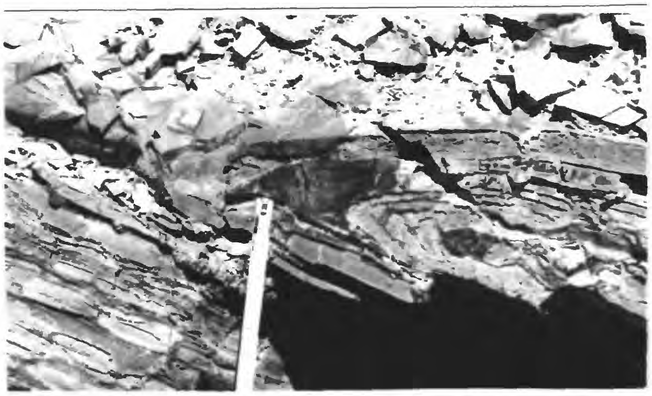


Thinning and fining upward sequences of mass-flow carbonates inferred to represent mid-fan distributary channels. Lower conglomeratic channel deposit is about 1.5 m thick. Lower Hales Limestone, Upper Cambrian, Nevada.

Figure 2-41. (from Cook and Mullins, 1983)

Wavy, discontinuous calcarenite turbidites with climbing ripples occur near margins of channels where grain size is small yet deposition is rapid. White circle is 2 cm wide. Lower Hales Limestone, Upper Cambrian, Nevada.

Figure 2-42. (from Cook and Mullins, 1983)



Small-scale slide 50 cm thick within interchannel facies. Tape is 15 cm long. Lower part of Hales Limestone, Upper Cambrian, Nevada.

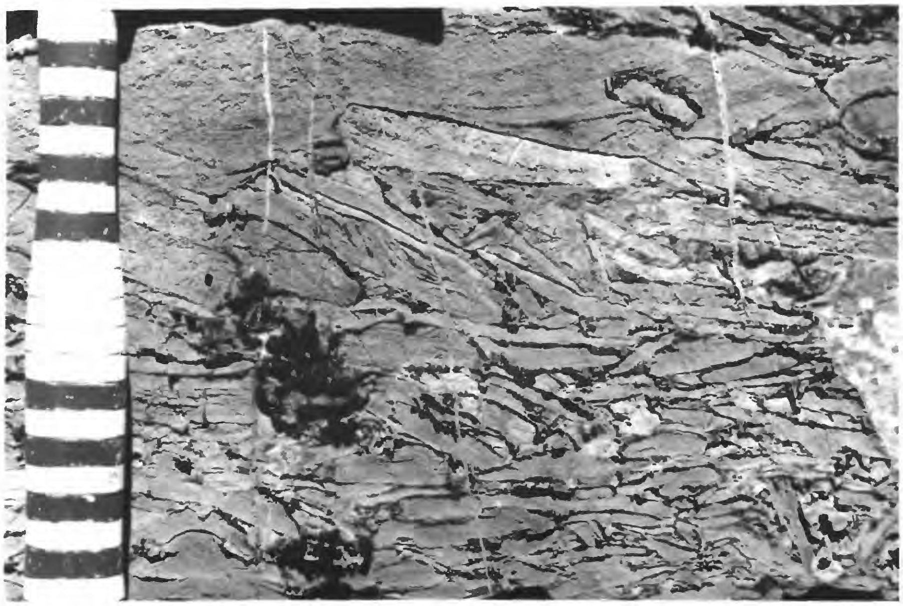
Figure 2 -43. (modified from Cook, 1979a)

Calcarenite and calcisiltite thin-bedded, laterally continuous turbidites within interchannel facies. Lower Hales Limestone, Upper Cambrian, Nevada.

Figure 2-44. (from Cook and Mullins, 1983)

Upper part of 1.5-m-thick channel deposit. Clasts are normally graded, imbricated in an upslope direction at the top of the channel and oriented subparallel below the top of the channel. Rippled calcarenites cap the bed. Located in mid-fan distributary channel system. Lower part of Hales Limestone, Upper Cambrian, Nevada.

Figure 2-45. (from Cook, 1979a)

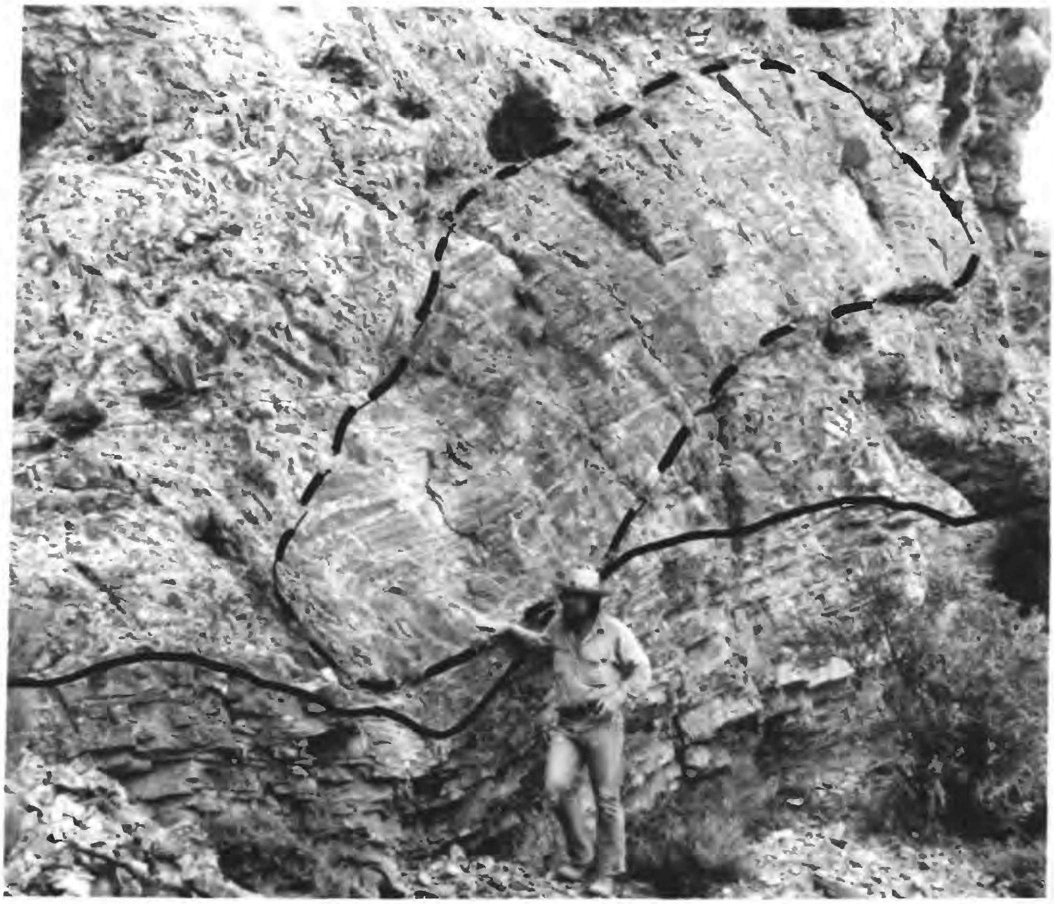


Possible modified grain-flow deposit. Bed exhibits reverse grading of tabular clasts, subparallel orientation of clasts, upslope imbrication of clasts in upper part of bed, and is capped by cross-bedded calcarenite sands. Bed is part of a mid-submarine fan distributary channel system. Lower part of Hales Limestone, Upper Cambrian, Nevada.

Figure 2-46. (from Cook and Mullins, 1983)

Normally graded limestone turbidite, 50 cm thick, contains both shelf- and slope-derived clasts. Tabular clasts with subparallel orientation. Located in inner fan facies near base of slope. Lower part of Hales Limestone, Upper Cambrian, Nevada.

Figure 2-47. (from Cook and Taylor, 1977)



Debris flow deposit. Inner submarine fan feeder channel about 10 to 15 m deep and 400 m wide that occurs at or near base of slope. Man's hand is on a single rectangular clast 3 x 15 m in cross section (dashed line) that lies subparallel to base of channel. Other clasts are randomly oriented and set within a lime mud matrix. Black solid line outlines base of channel. Top of channel not visible in photo. Upper part of Hales Limestone, Lower Ordovician, Nevada.

Figure 2 -48. (modified from Cook, 1979a)

Translational slide in lower slope facies, 10 m thick and 400 m wide. Slump shown in Figure 2-50 occurs just above the right-hand margin of this slide. Downslope transport direction was southeast, obliquely out of the photo to the left. Hales Limestone, Upper Cambrian-Lower Ordovician, Nevada.

Figure 2-49. (from Cook, 1979a)

Rotational slide (slump) in lower slope facies, 10 m thick which in turn is truncated by an overlying translational slide. Upper part of Hales Limestone, Lower Ordovician, Nevada.

Figure 2-50. (from Cook, 1979a)

Interior part of translational slide in Figure 49 showing large open overfolds developed in originally semiconsolidated hemipelagic limestone.

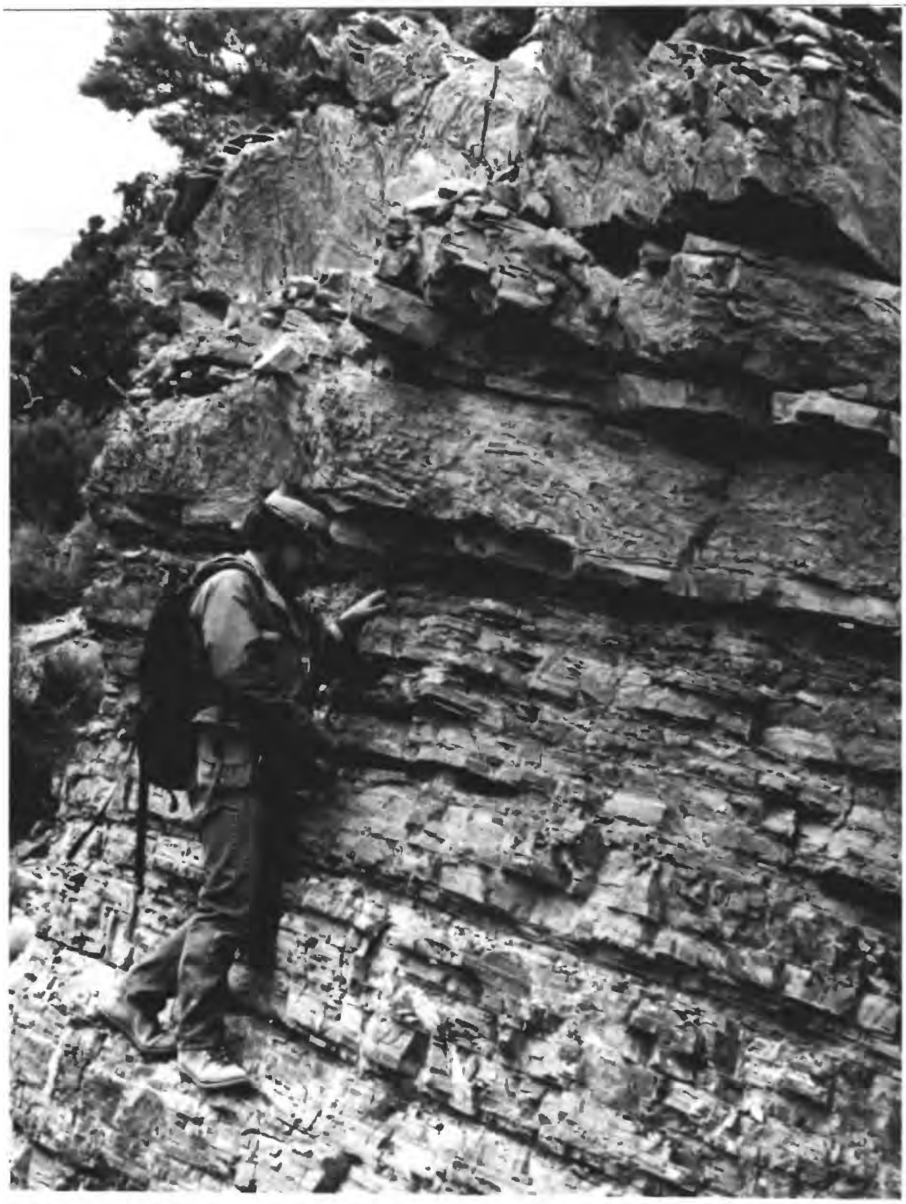
Figure 2-51. (from Cook, 1979a)

Base of a 3.5-m-thick translational slide in lower slope facies showing basal shear folds, developed in semiconsolida-ed sediment, breaking up into tabular clasts. Note that a range of clast sizes are in the process of forming. Tape is 45 cm long. Upper part of Hales Limestone, Lower Ordovician, Nevada.

Figure 2-52. (from Cook, 1979a)

Contourite grainstones occurring within upper slope facies. Composed of well-sorted silt to fine-grained shallow-water derived alga grains. Matrix is virtually mud free and filled with sparry calcite. Ripple forms have periods of about 9 cm and 0.5 to 1.0 cm amplitudes. Both base and top have sharp contacts with enclosing hemipelagic slope mudstone. Upper part of Hales Limestone, Lower Ordovician, Nevada. Scale in centimeters.

Figure 2 -53. (from Cook and Mullins, 1983)



Thickening-up sequence of carbonate sediment gravity flow deposits deposited within an intraslope (perched) basin.

Figure 2-54.

Close-up of a bed from Figure 2-54. Clasts are imbricated upslope.

Figure 2-55.

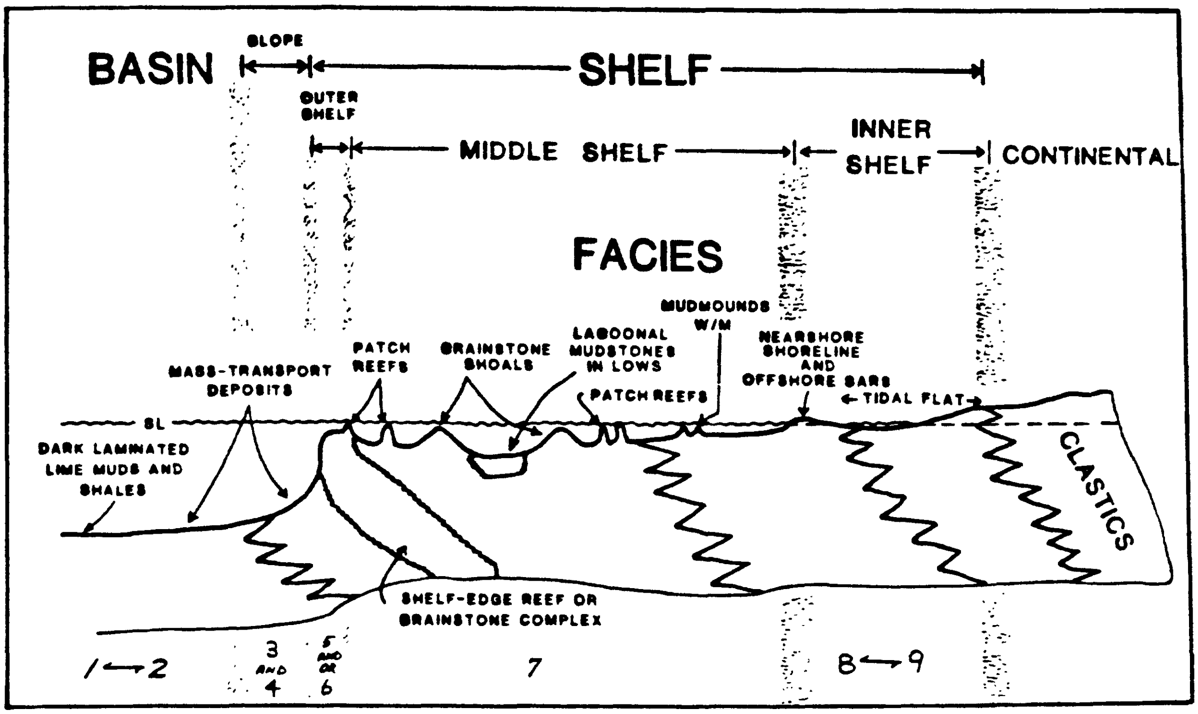
Carbonate turbidite filling a small erosional gully on the uppermost part of the slope near the platform margin.

Figure 2-56.

Thin-bedded, light-colored, platform margin wackestones.

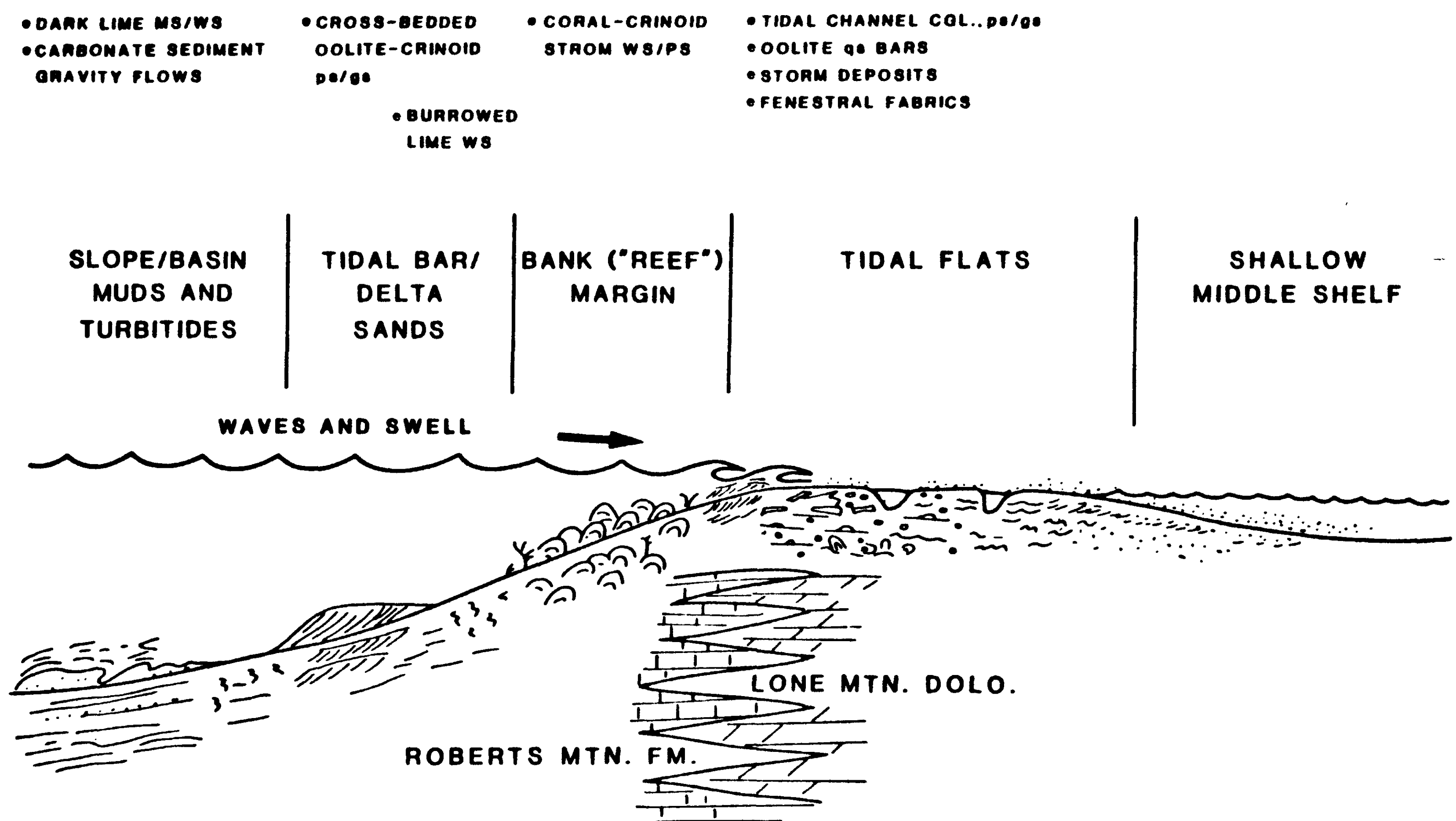
Figure 2-57.

RIMMED SHELF



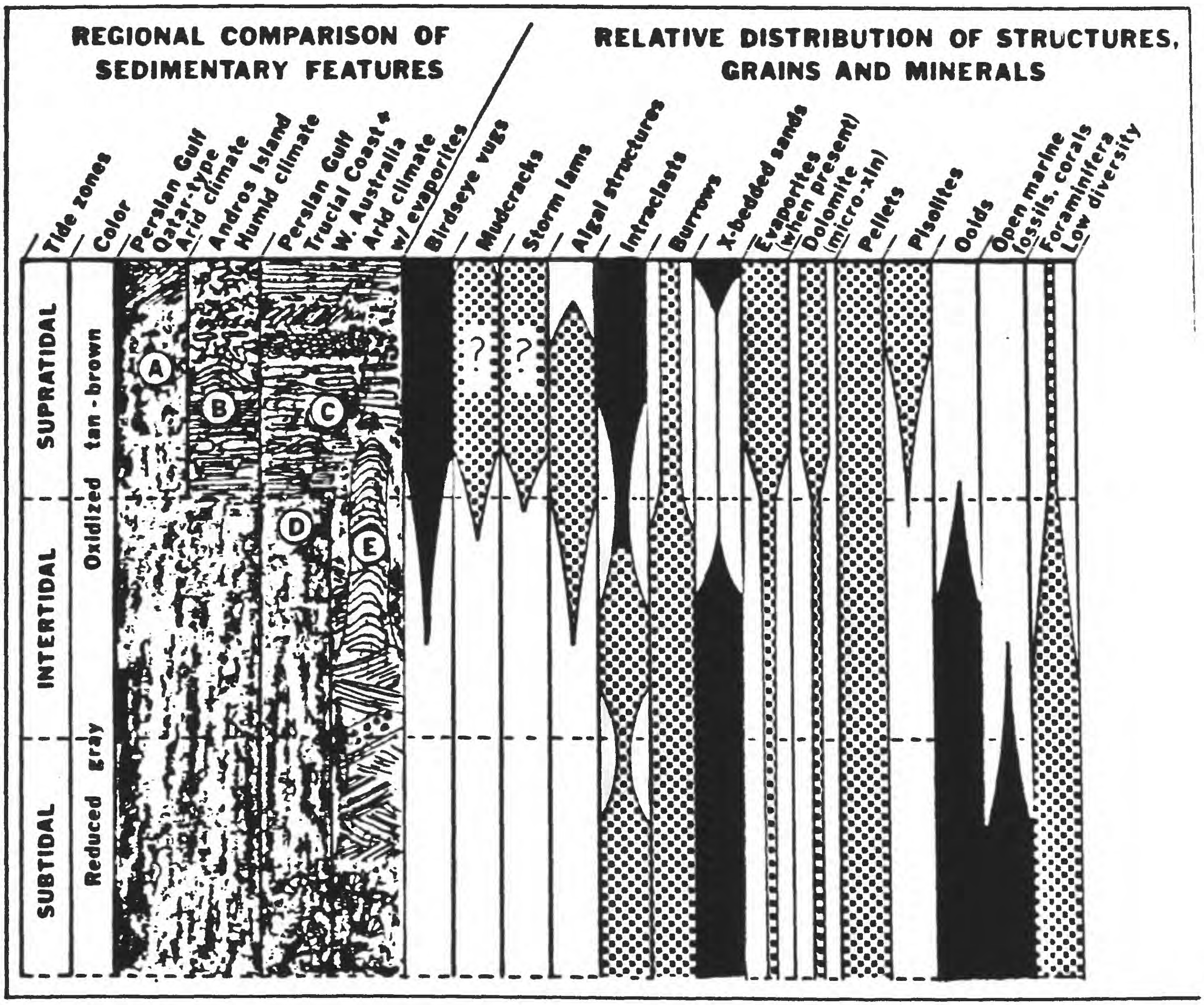
Profile of a rimmed carbonate shelf or drop-off model. Numbers at bottom of figure refer to Standard Facies Belts of Wilson (1975).

Figure 2 -58. (depositional profile format modified from Wilson and Jordan, 1983)



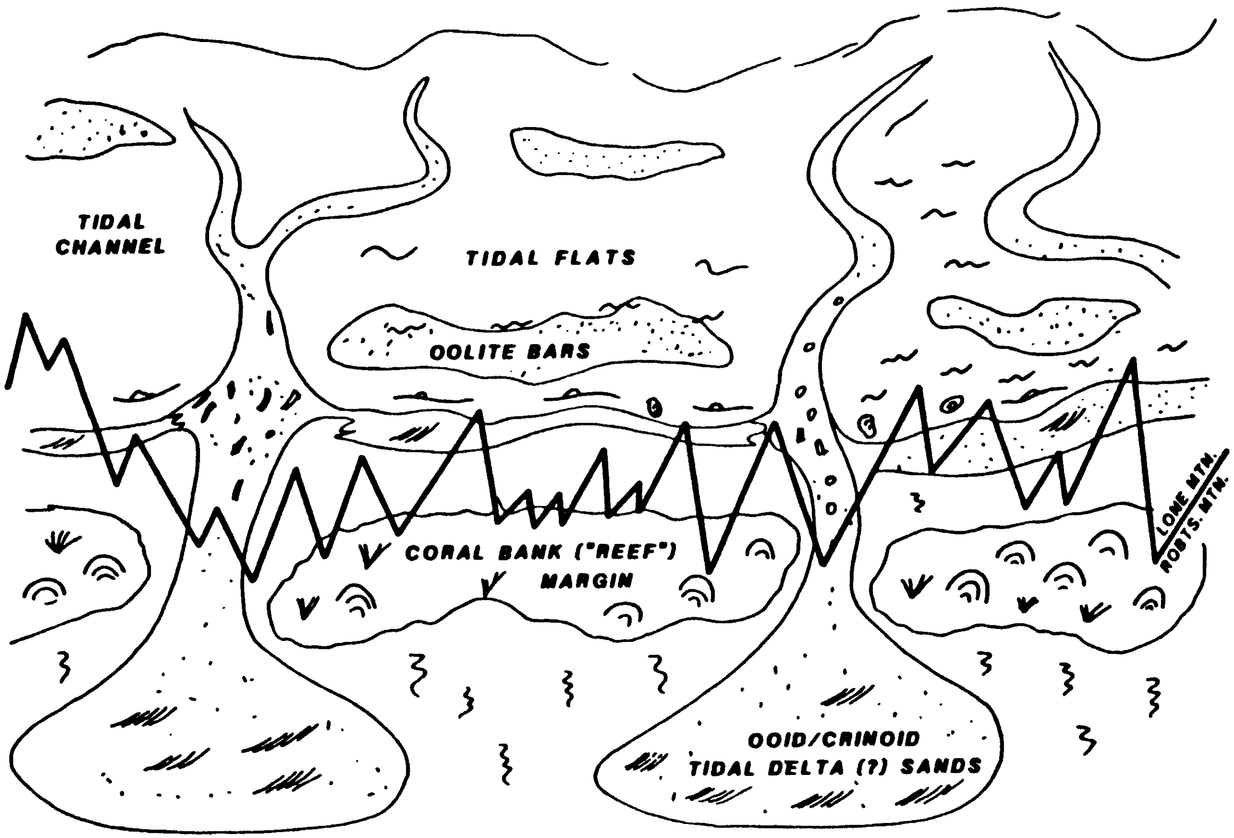
Interpretive depositional profile and environments for lower and upper Roberts Mountains Formation and lowermost Lone Mountain Dolomite

Figure 2-59. (from Cook and Taylor, 1983)



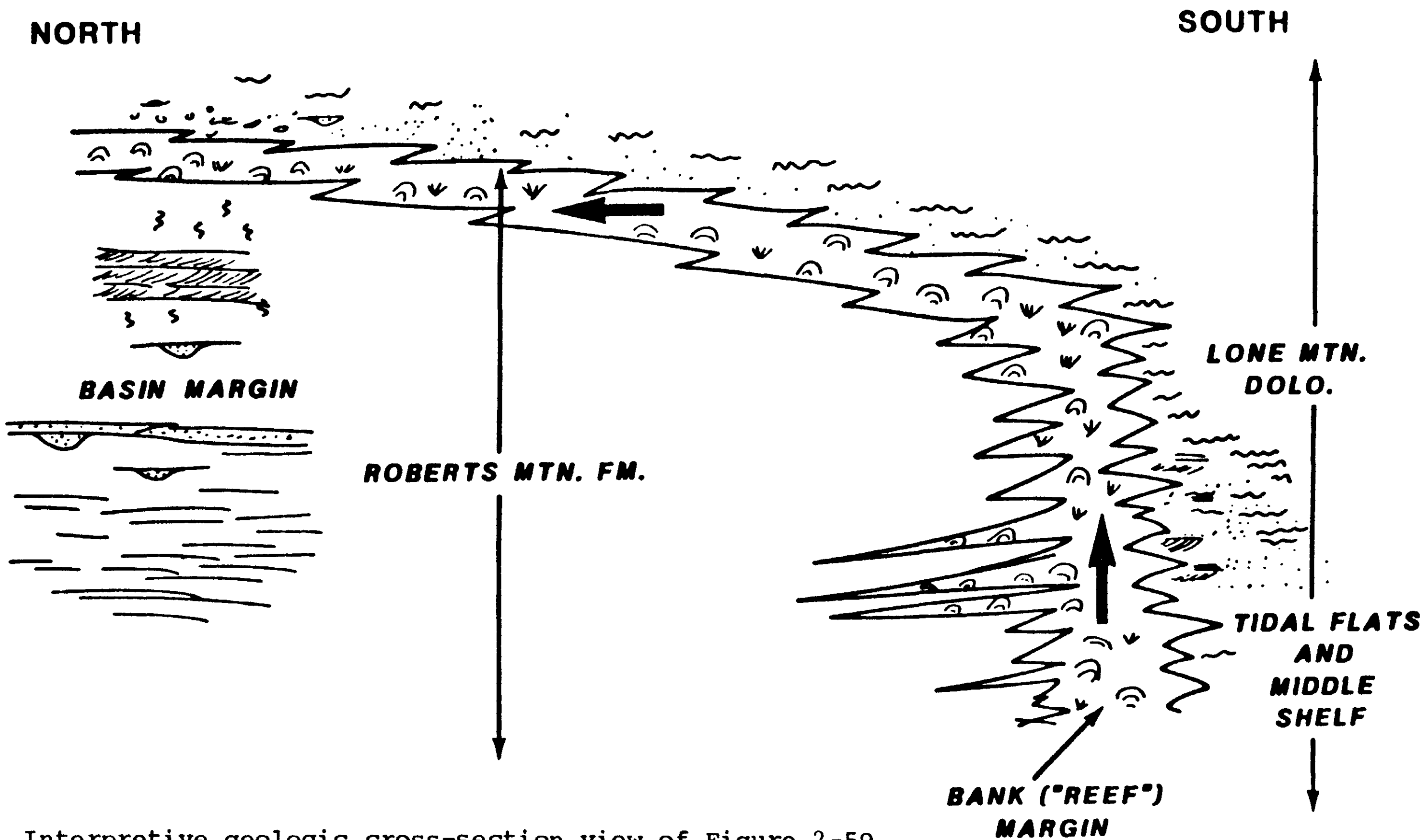
Solid black bars represent features present along the Roberts Mountains-Lone Mountain contact.

Figure 2-60. (from Cook and Taylor, 1983; diagram format modified from Shinn, 1983)



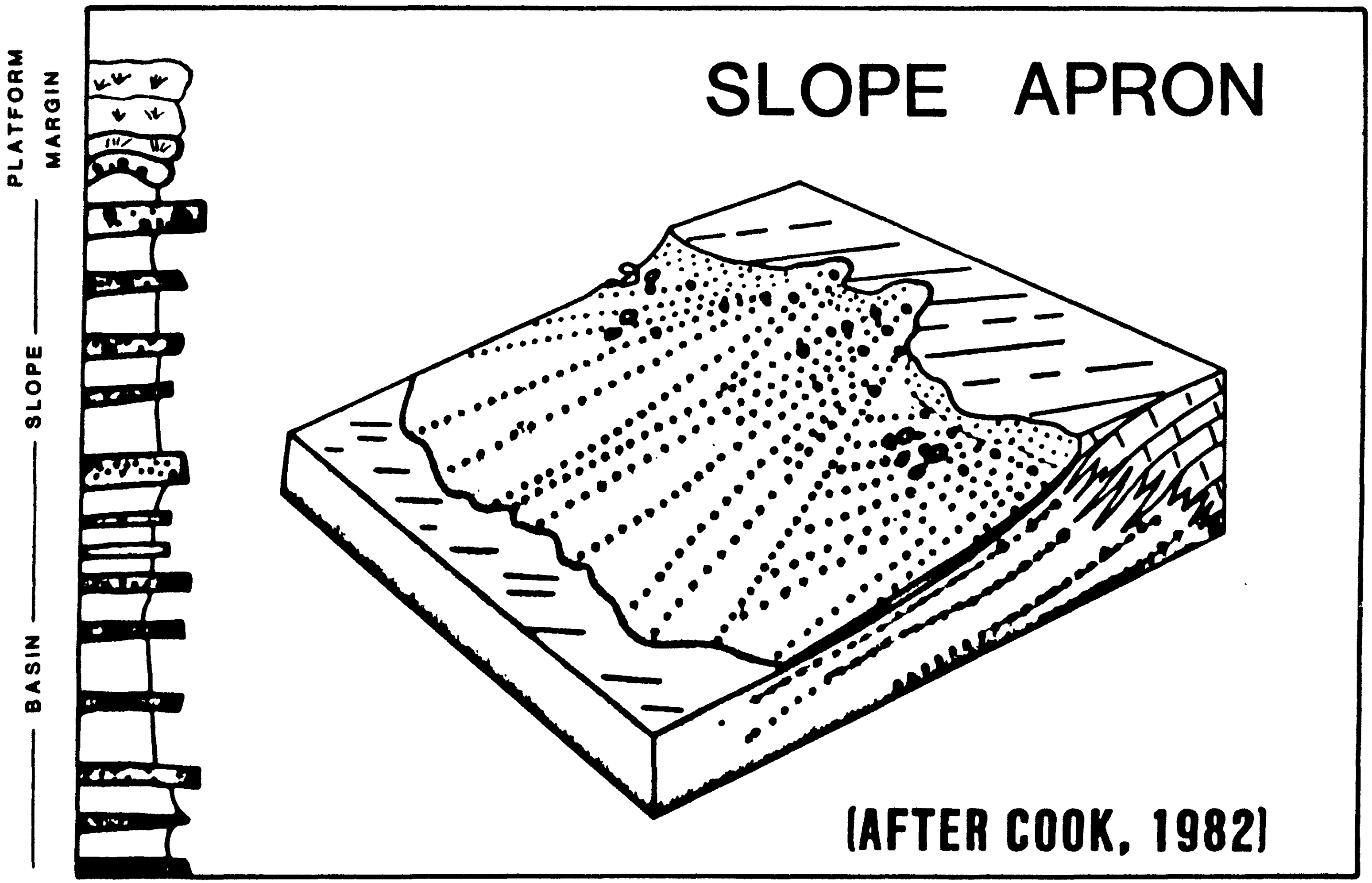
Map view of Figure 2-59 showing the interpreted diagenetic relationship between the Roberts Mountains (limestones) and the Lone Mountain (dolomites)

Figure 2-61. (from Cook and Taylor, 1983)



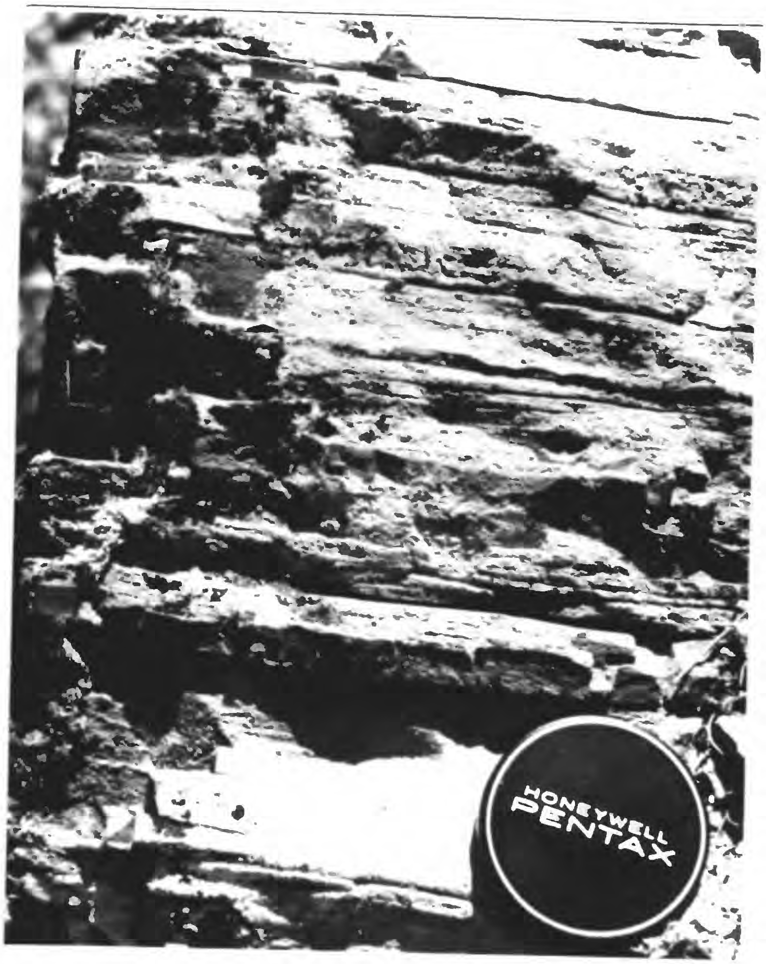
Interpretive geologic cross-section view of Figure 2-59 showing buildup phase in lower part of stratigraphic section and seaward prograding phase in upper part of section. Distance across figure is about 2500 feet. Upbuilding phase shown is about 500 feet thick.

Figure 2-62. (from Cook and Taylor, 1983)



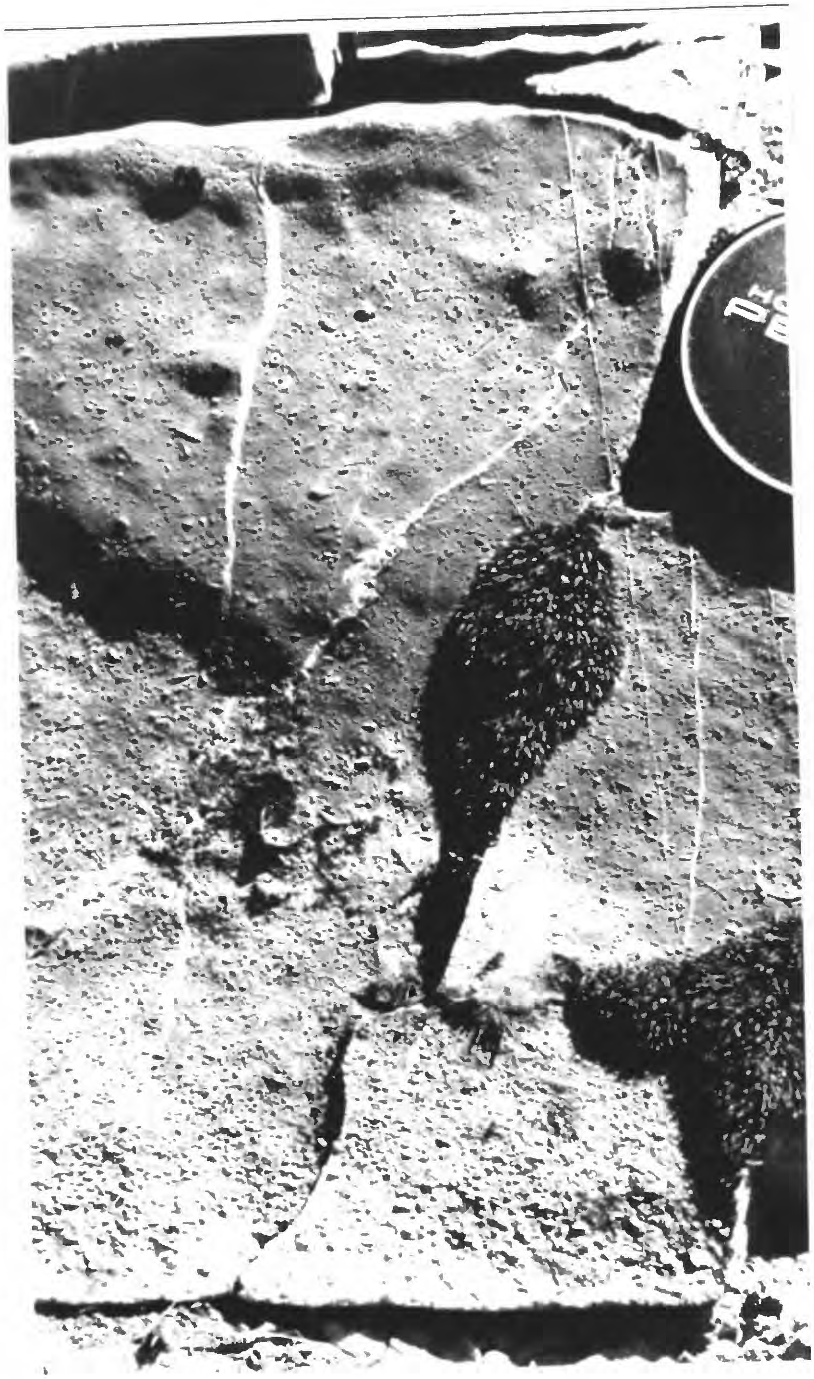
Carbonate slope apron model showing shoal water derived debris originating along a line source. Debris extends virtually up to the platform margin along low angle slope. Debris is transported as broad sheet flows.

Figure 2-63. (from Cook, 1982 and Cook and Taylor, 1983)



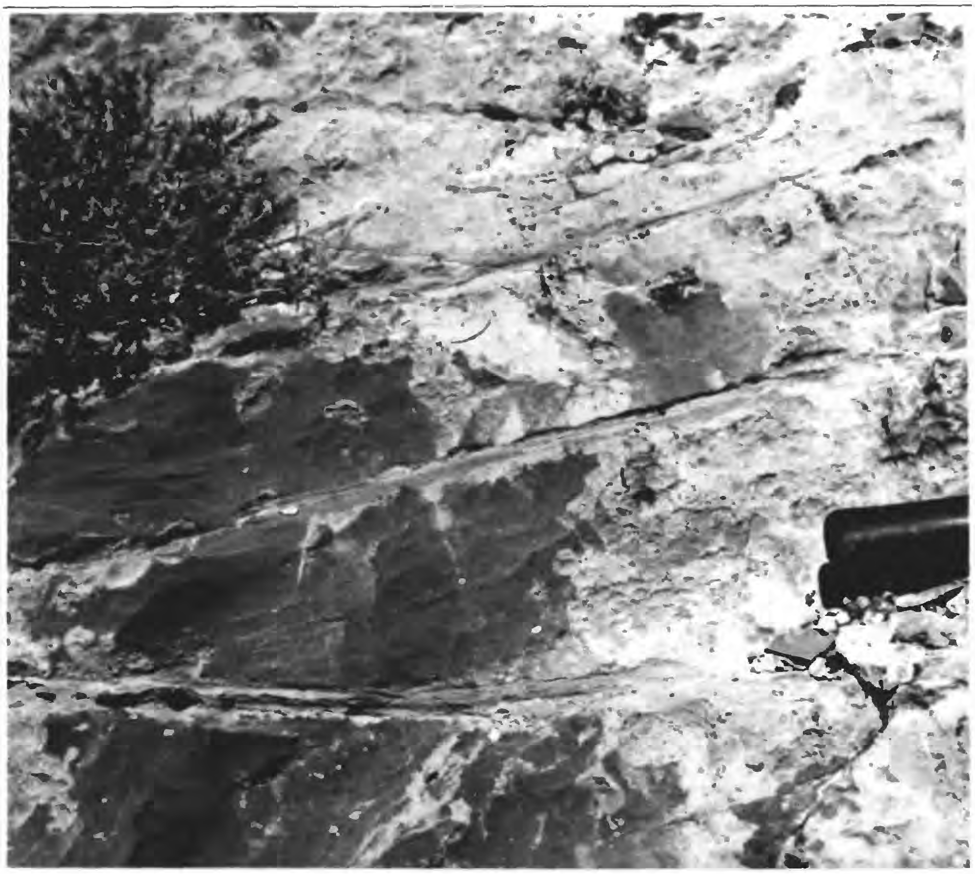
Thin-bedded, laminated basin facies of the Roberts Mountains Formation.

Figure 2-64.



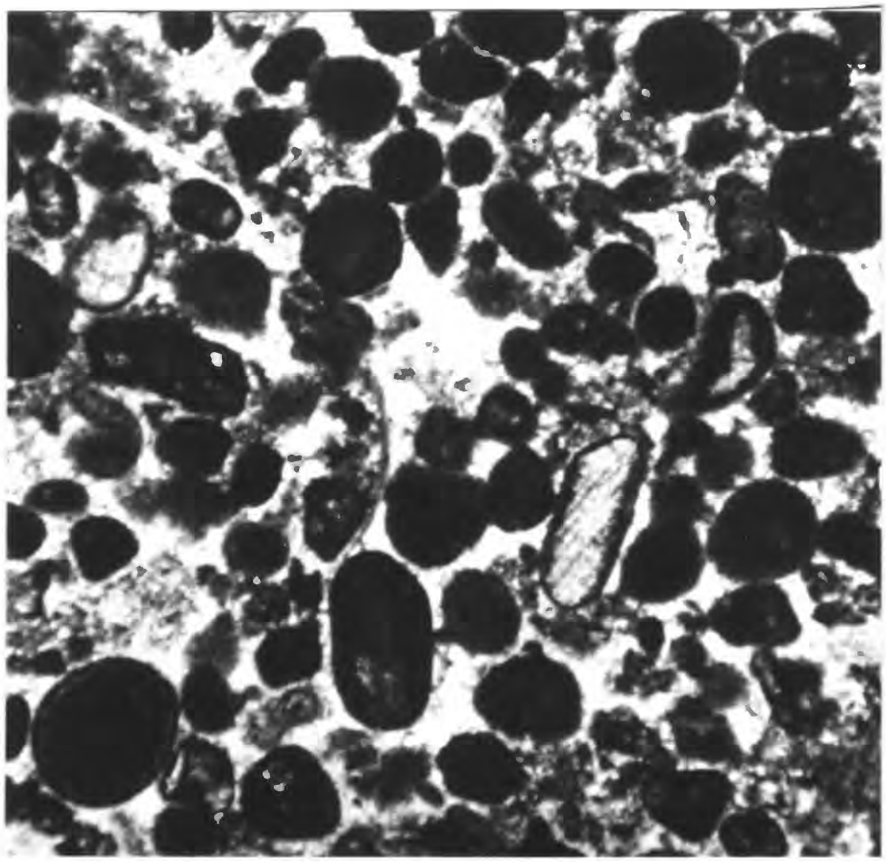
Crinoidal-rich turbidite in slope apron facies of the Roberts Mountains Formation.

Figure 2-65.



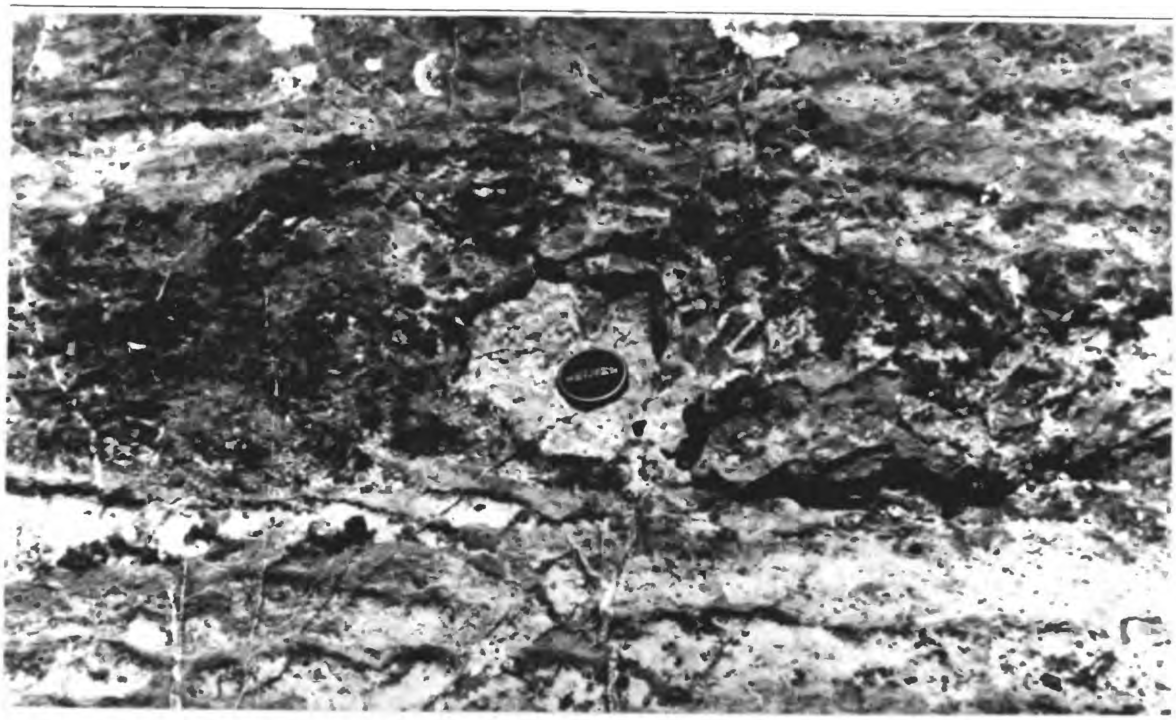
Cross-bedded crinoid-oolite packstones and grainstones forming part of a 20 to 50 m thick tidal delta(?) on the seaward side of the skeletal margin. Upper Roberts Mountains Formation.

Figure 2-66.



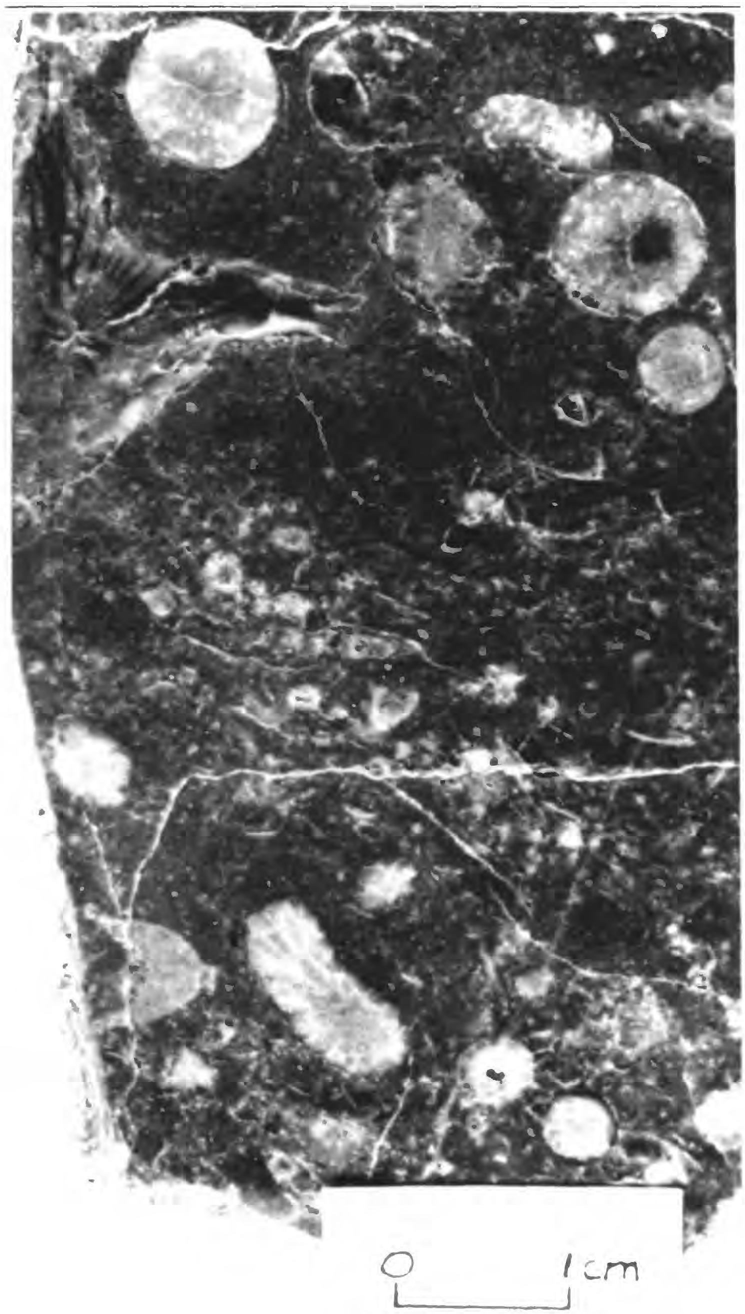
Thin-section of Figure 2-66. Width of field about 3 mm.

Figure 2-67.



Coral-rich bank margin facies in upper Roberts Mountains Formation.

Figure 2-68.



Close-up of Figure 2-68.

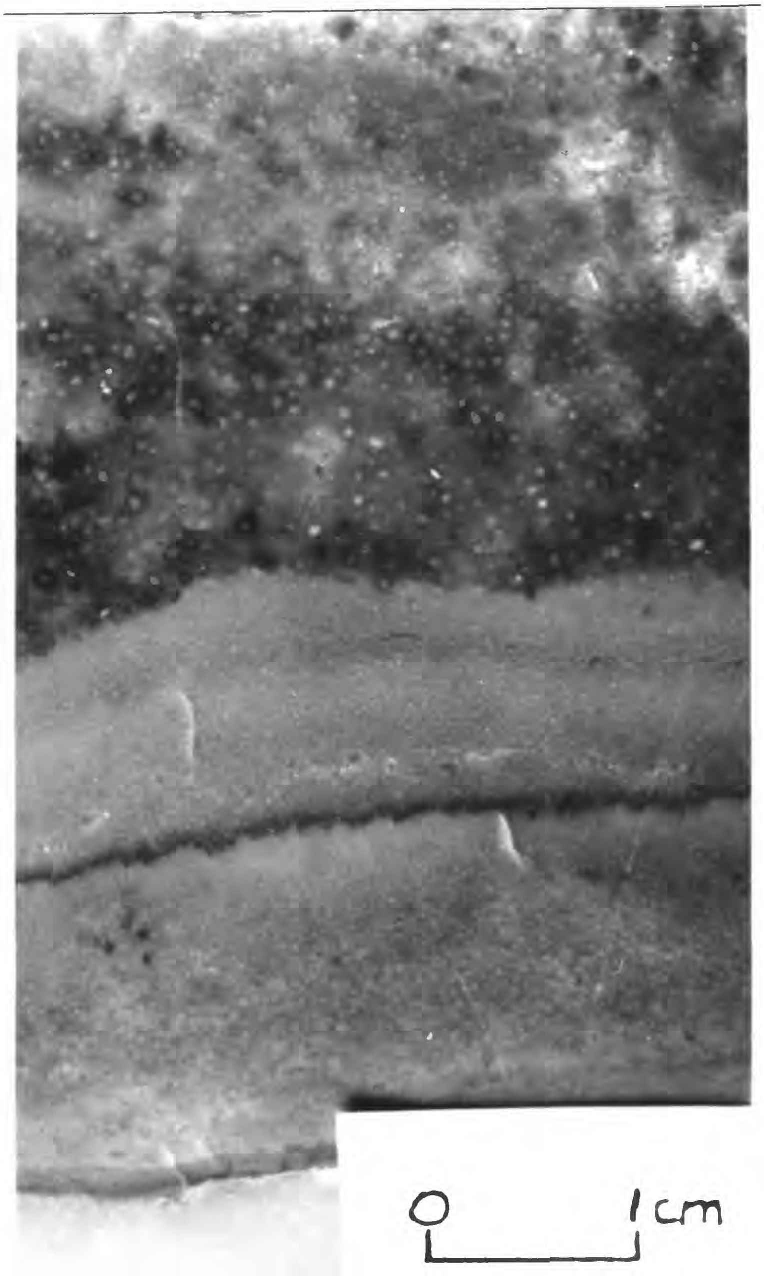
Figure 2-69.

Cross-bedded lithoclastic lime packstone and grainstone shoals, uppermost Roberts Mountains Formation.

Figure 2-70.

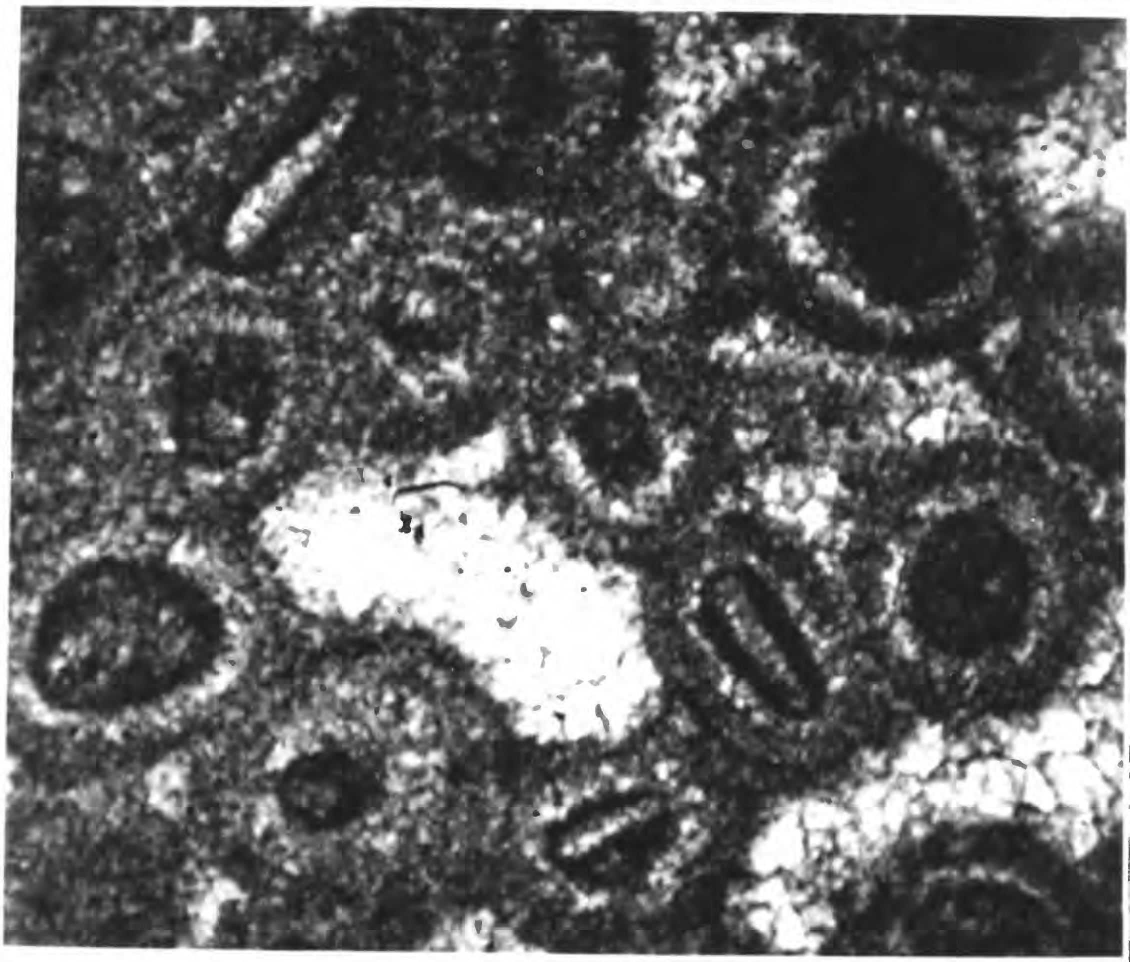
Dolomitized tidal channel conglomerates in lowermost Lone Mountain Dolomite.

Figure 2-71.



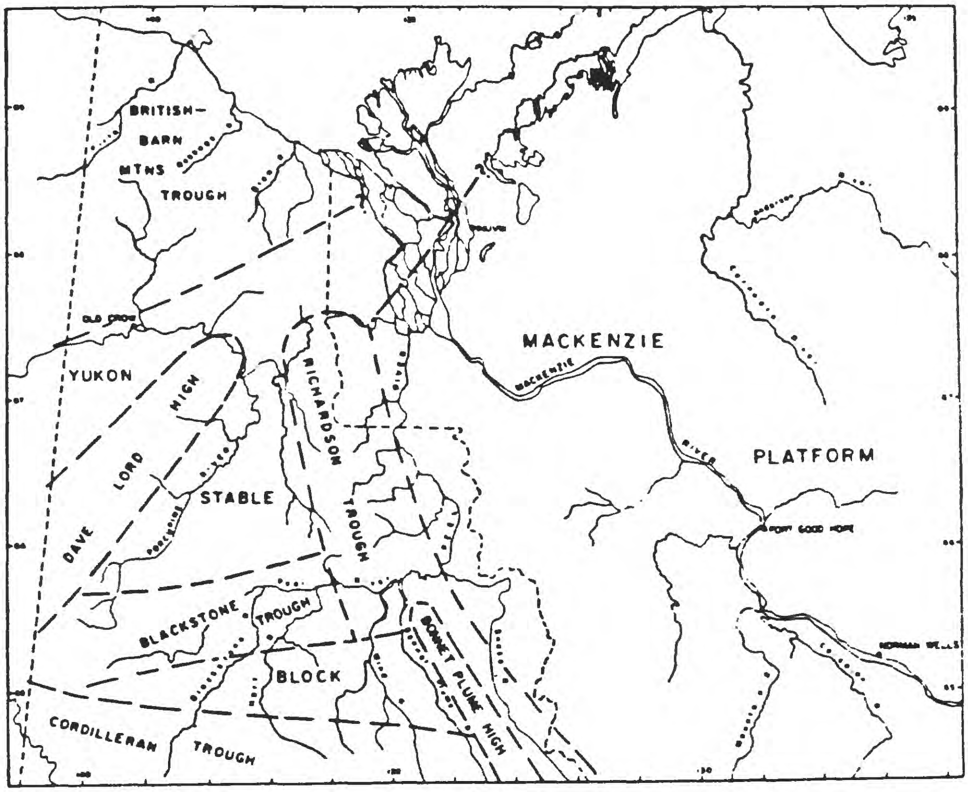
Dolomitized oolite grainstons in lower Lone Mountain Dolomite.

Figure 2-72.



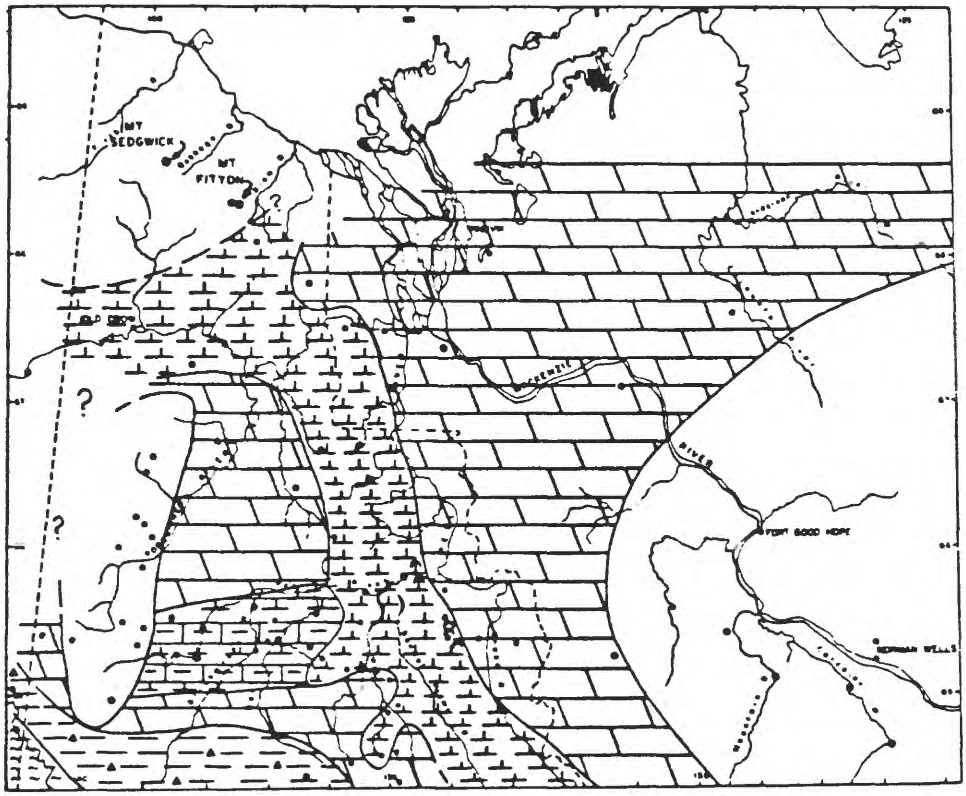
Thin-section of Figure 2-72. Width of view about 4 mm.

Figure 2-73.



Location and numbers of sections described in appendix and used in preparation of lithofacies maps.

Figure 2-74. (from Lenz, 1972)



Gedinnian to Lower Emsian (Lower Devonian exclusive of uppermost Lower Devonion) lithofacies.

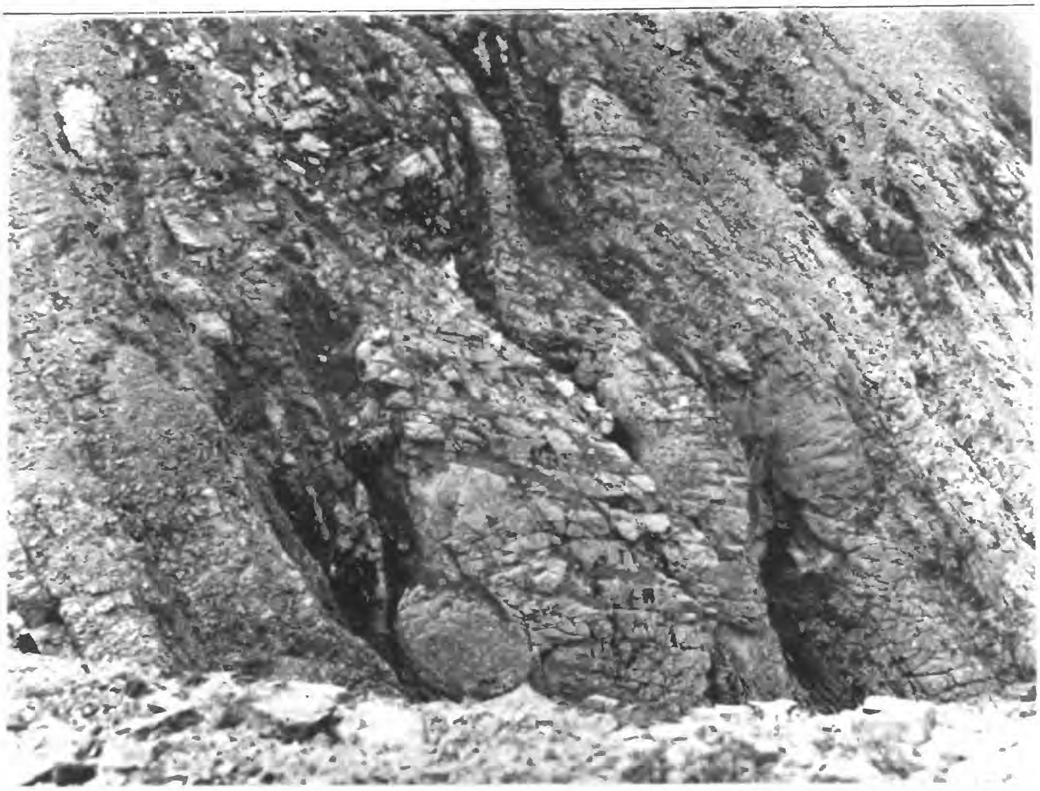
Figure 2-75. (from Lenz, 1972)

Hemispherical stromatoporoid-rich platform margin facies.

Figure 2-76.

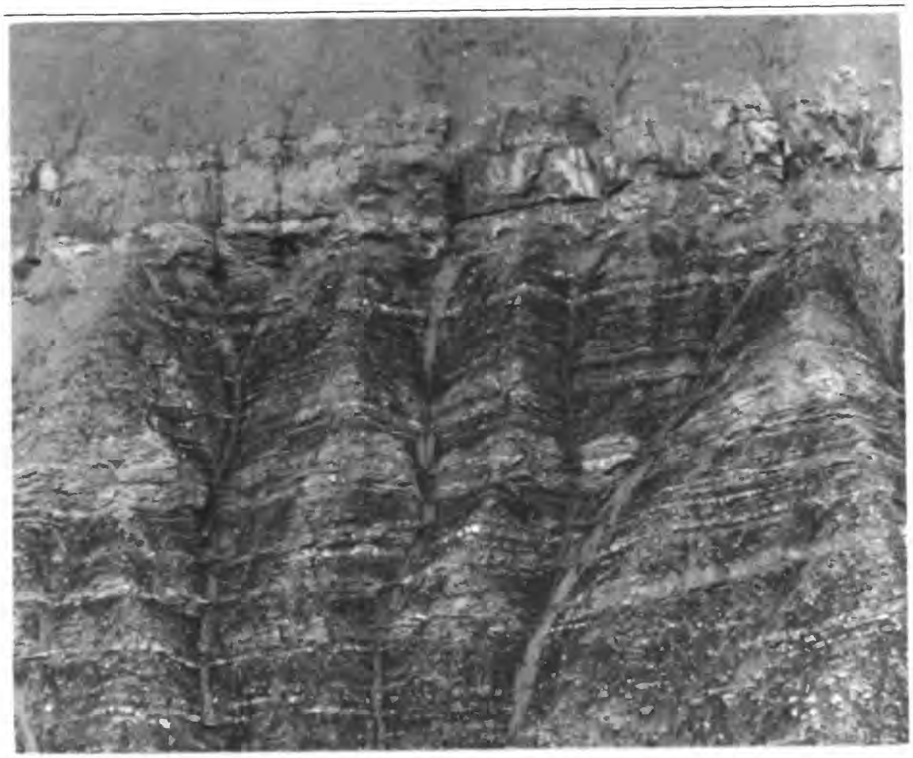
Normally graded turbidite with Bouma division b at top of bed. White circle is 2 cm wide. Same locality as Figure 2-79, in Yukon Territory, Canada.

Figure 2-77. (from Cook and Mullins, 1983)



Slope bioherms interbedded with crinoidal-rich turbidites and lime mudstones and wackestones. Stratigraphic top to right. Width of view about 20 m.

Figure 2-78.

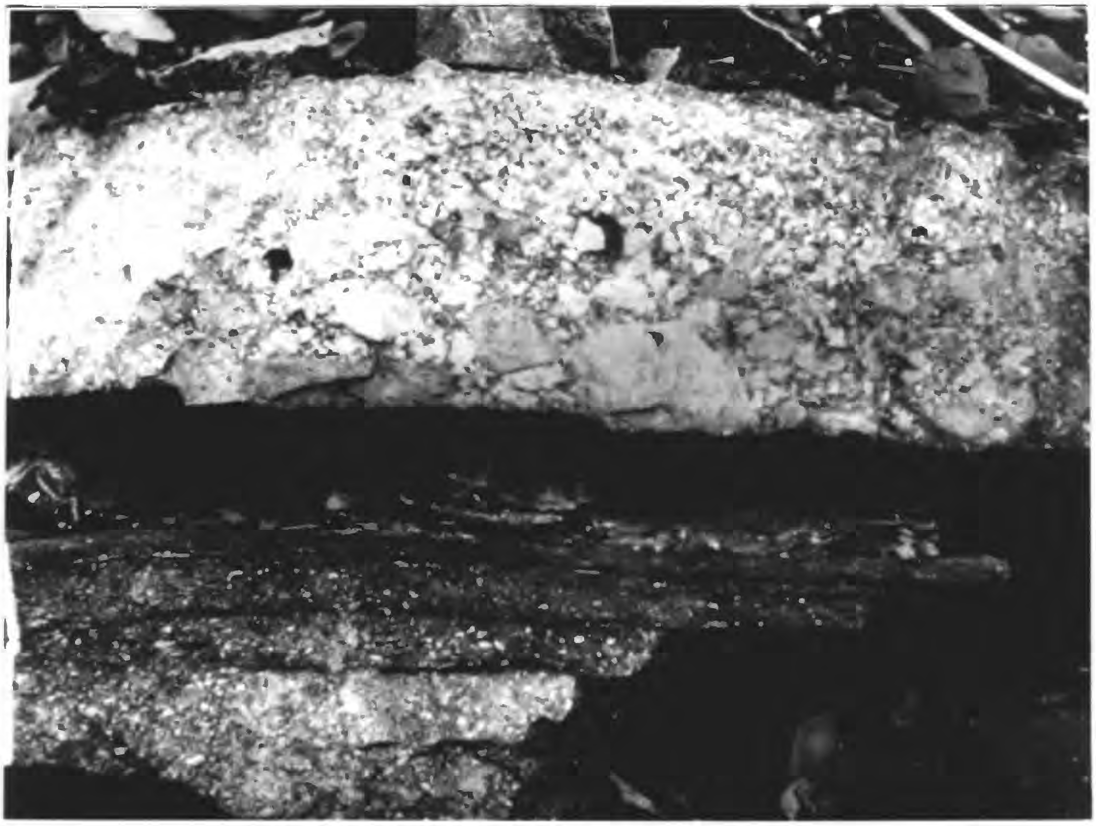


Sequence about 100 m thick of carbonate turbidites and debris flow sheets (white) within pelagic and hemipelagic lime mudstones (dark). Section is about 30 km from a low-relief bank margin. Prongs Creek Formation, Middle Devonian, northern Mackenzie Mountains, Yukon Territory, Canada.

Figure 2-79. (from Cook and Mullins, 1983)

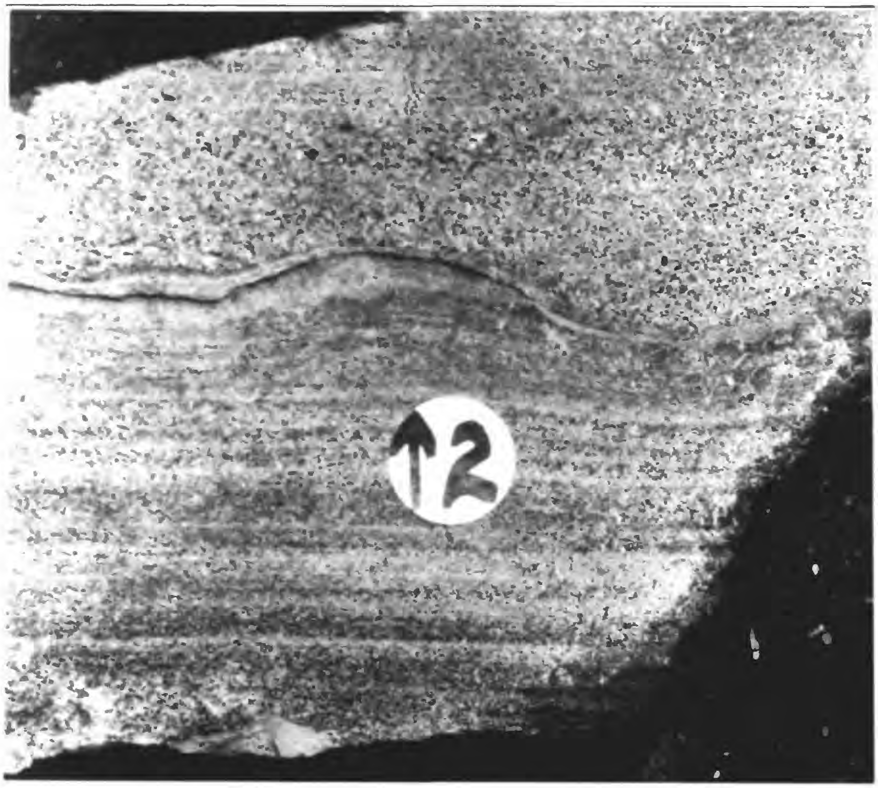
Debris slope apron debris flow deposit. Note 2 x 3 cm clast with fenestral fabric.

Figure 2-80.



10-cm-thick normally graded conglomeratic turbidite. Note flat base and mounded surface. Bed occurs in graptolitic basinal lime mudstones 65 km from bank margin. Prongs Creek Formation, Middle Devonian, northern Mackenzie Mountains, Yukon Territory, Canada.

Figure 2-81. (from Cook and Mullins, 1983)



Debris slope apron carbonate turbidite. Shows two turbidites, one with Tb division and one with Tab divisions. 2 cm scale.

Figure 2-82.

A

3

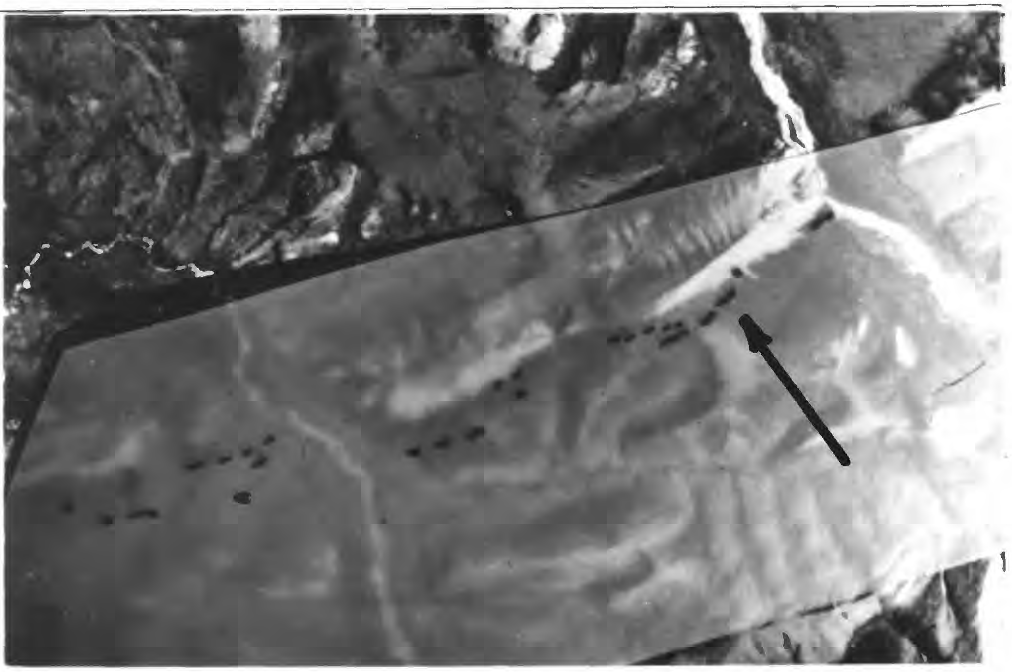
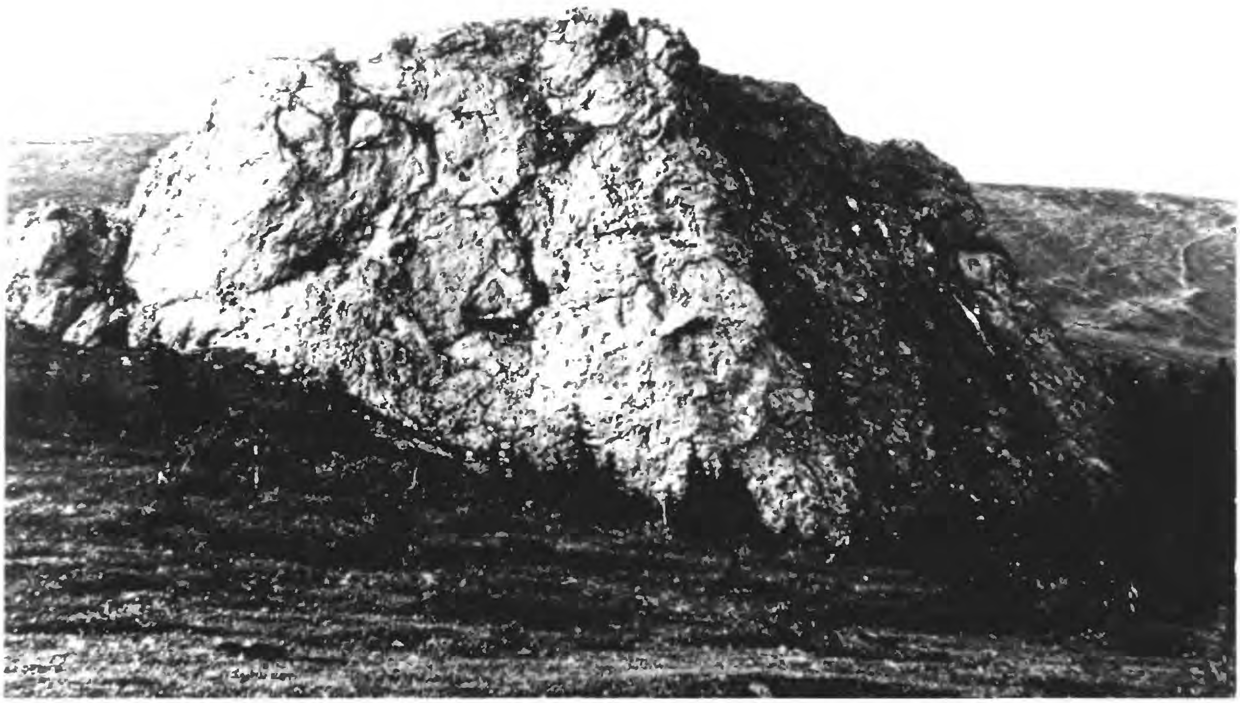


Figure 2-83. A. Areal photograph. Arrow points to large knob (debris flow channel) in Figure 2-84A. Width of photo about 5 miles. B. Same photograph as in A. Dark colored blebs on mylar overlay show the lateral and vertical distribution of the knobs.



Debris flow channel about 150 to 200 m deep and 300 to 400 m wide. Stratigraphic top at top of photo. Channel is cut in graptolitic lime mudstones which are dipping about 30° into the photo. Note pronounced concave up base. Channels have fairly flat tops. This large channel is one of at least 25 similar debris flow channel deposits that occur at the same stratigraphic horizon over a lateral distance of about 10 to 15 km. Channels occur about 50 to 60 km from bank margin. Prongs Creek Formation, Middle Devonian, northern Mackenzie Mountains, Yukon Territory, Canada.

Figure 2-84A. (from Cook and Mullins, 1983)

Erosional/compacted contact between debris flow channel deposits on left and deep-water graptolitic lime mudstones on right.

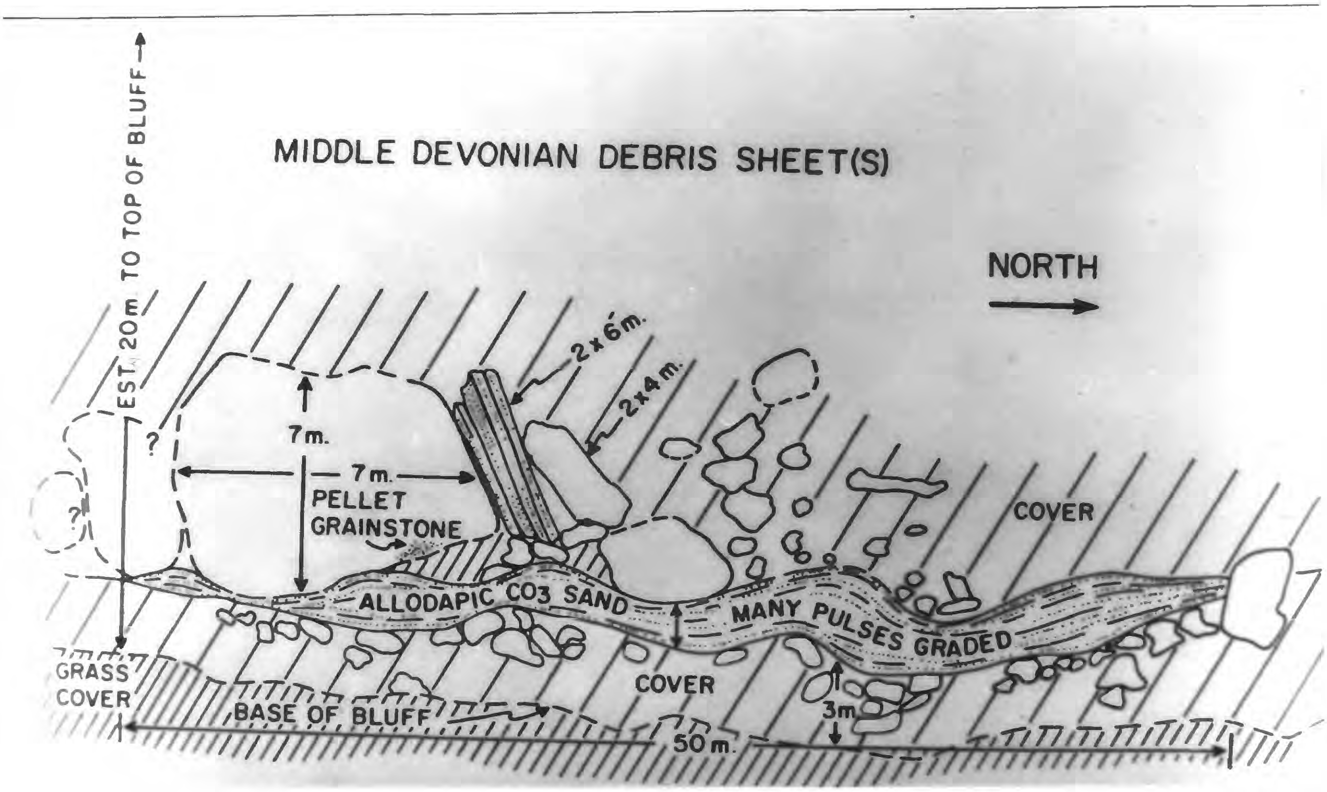
Figure 2-84B.

Debris flow channel deposits from channel shown in Figure 5-84A. Cobble-sized clasts are mainly pellet grainstones and stromatoporoids set within a pervasive lime mudstone matrix.

Figure 2-84C. (from Cook and Mullins, 1983)

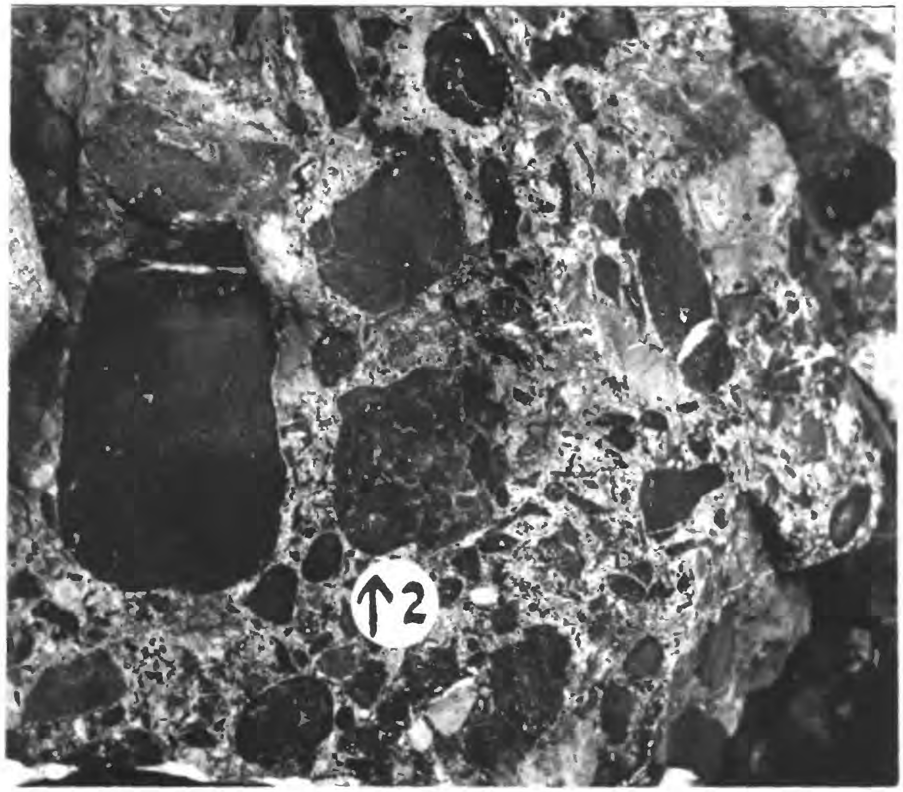
Looking northward at a ledge forming debris-flow sheet (arrows) which has a fairly uniform thickness of about 20 m over an area of at least 10 to 20 km^2. Shoal water clasts in debris-flow sheet (Figures 2-85B and 2-85C) were transported at least 50 to 75 km from a bank margin to the east. Prongs Creek Formation, Middle Devonian, northern Mackenzie Mountains, Yukon Territory, Canada.

Figure 2-85A. (from Cook and Mullins, 1983)



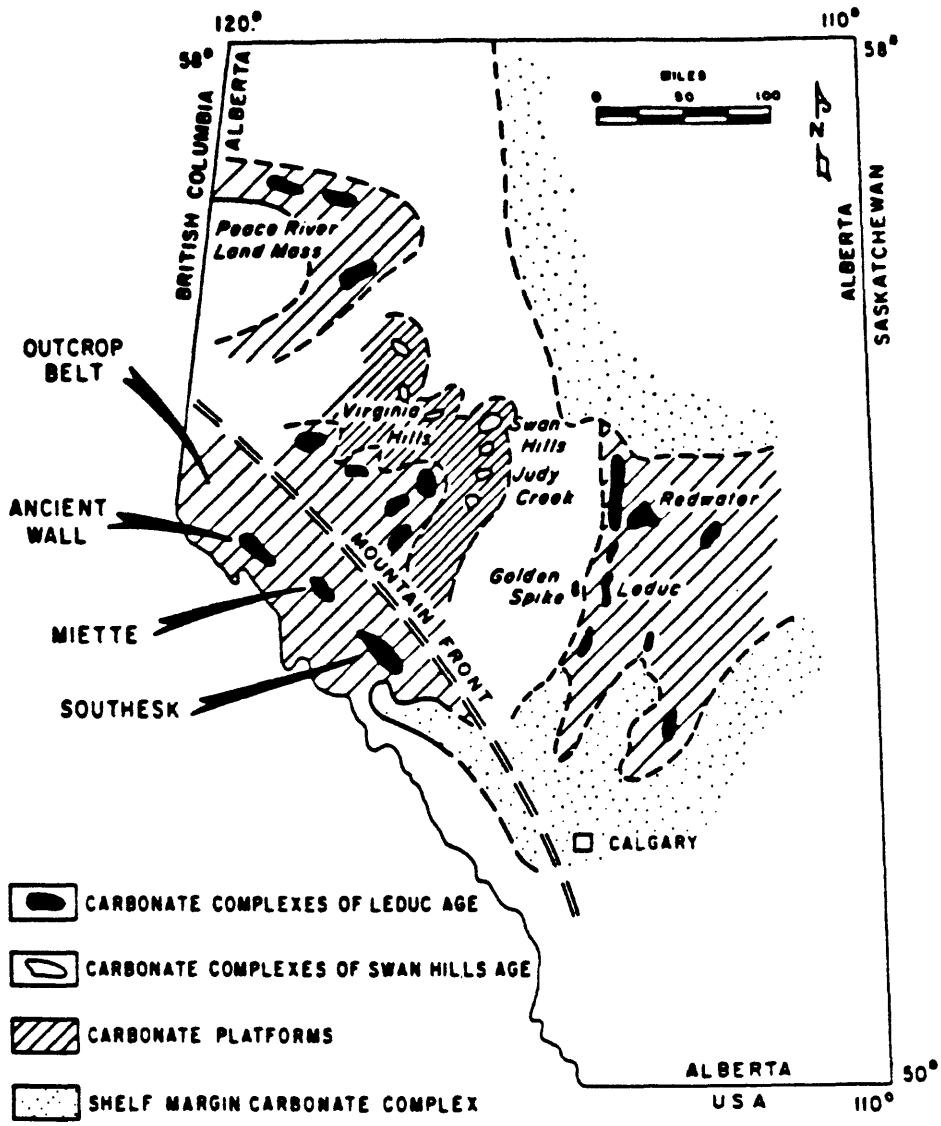
Sketch of ledge forming debris flow sheet(s) shown in Figure 2-85A. Debris flow deposits contain clasts of pellet grainstones up to 7 x 7 m in cross section. Sketch drawn by P. N. McDaniel.

Figure 2-85B. (from Cook and Mullins, 1983)



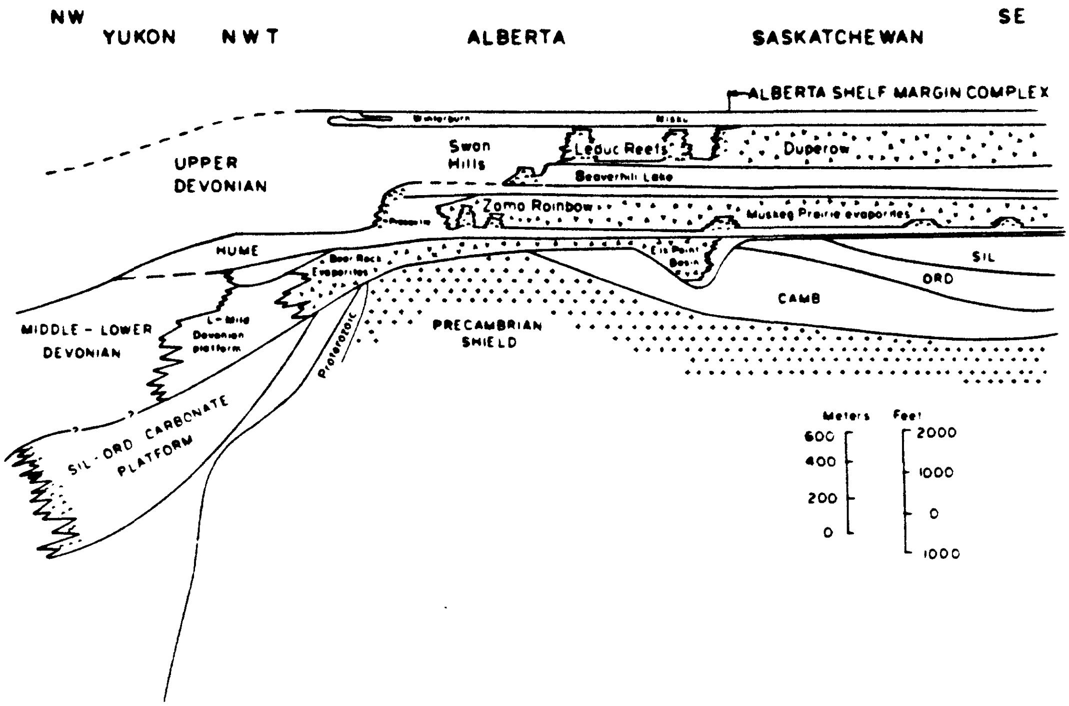
Texture of debris flow deposit shown in Figures 2-85A and 2-85B. Most of the darker clasts are pellet grainstones. Light weathering matrix is lime mud. White circle is 2 cm wide.

Figure 2-85C. (from Cook and Mullins, 1983)



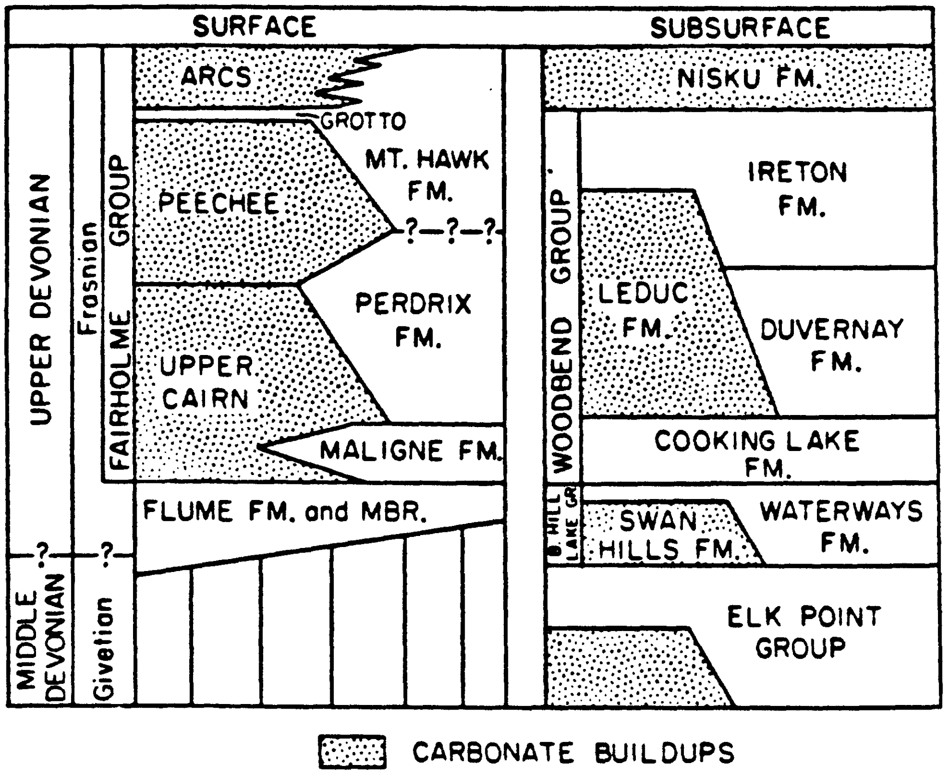
Generalized distribution of Upper Devonian carbonate buildups in Alberta, Canada.

Figure 2-86. (from Cook et al, 1972)



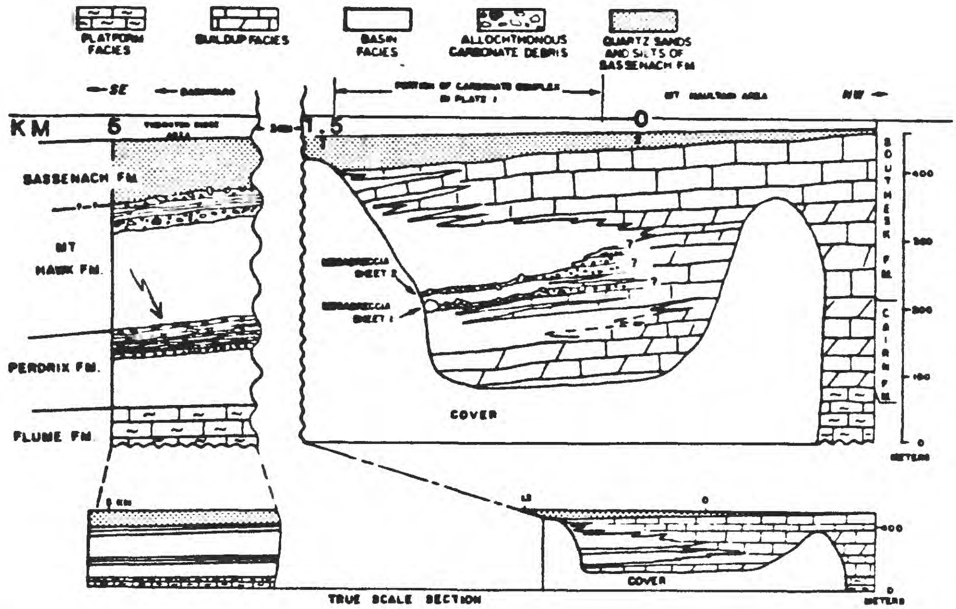
Subsurface diagrammatic cross-section from NW to SE through the western Canadian Sedimentary basin illustrating the stepped onlap mode during Late Devonian time.

Figure 2-87. (from James and Mountjoy, 1983)



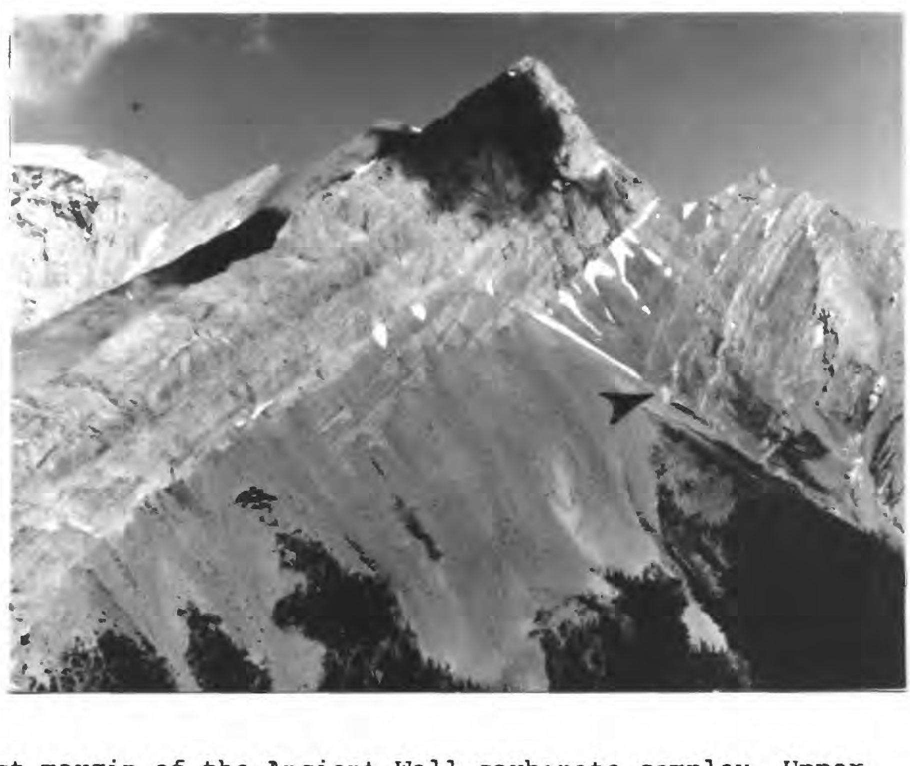
Correlation of formations exposed at Ancient Wall, Miette, and Southesk-Cairn with those of the subsurface in Alberta, Canada

Figure 2-88. (from Cook et al, 1972)



Stratigraphic cross-section at Ancient Wall carbonate complex.

Figure 2-89. (from Cook et al, 1972)



Southeast margin of the Ancient Wall carbonate complex, Upper Devonian, Alberta, Canada. Arrow points to debris flow bed shown in Figures 2-16, 2-92, and 2-93. Skyline is at the 0 km mark on Figure 2-89.

Figure 2-90. (modified from Cook et al, 1972)

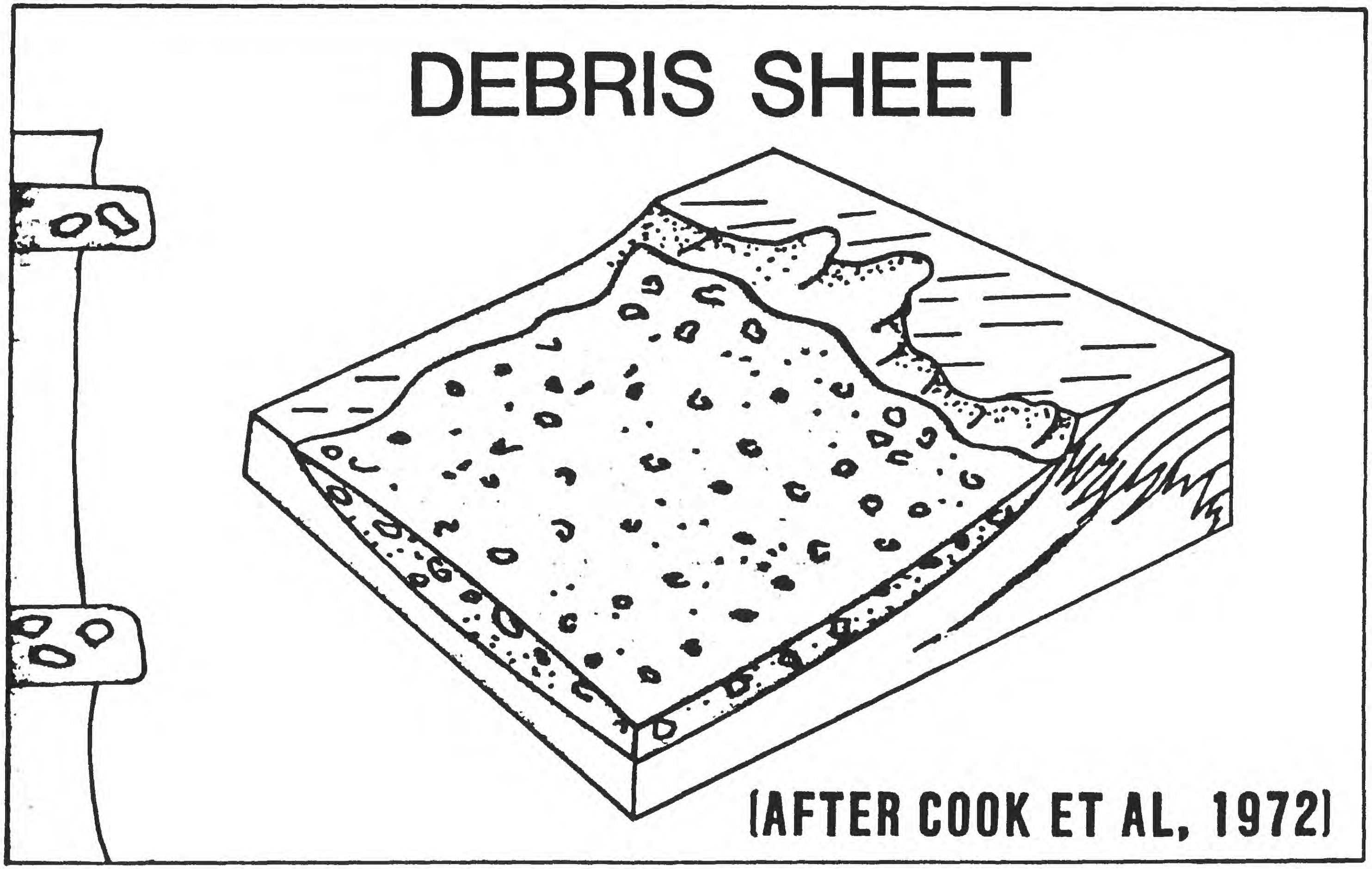
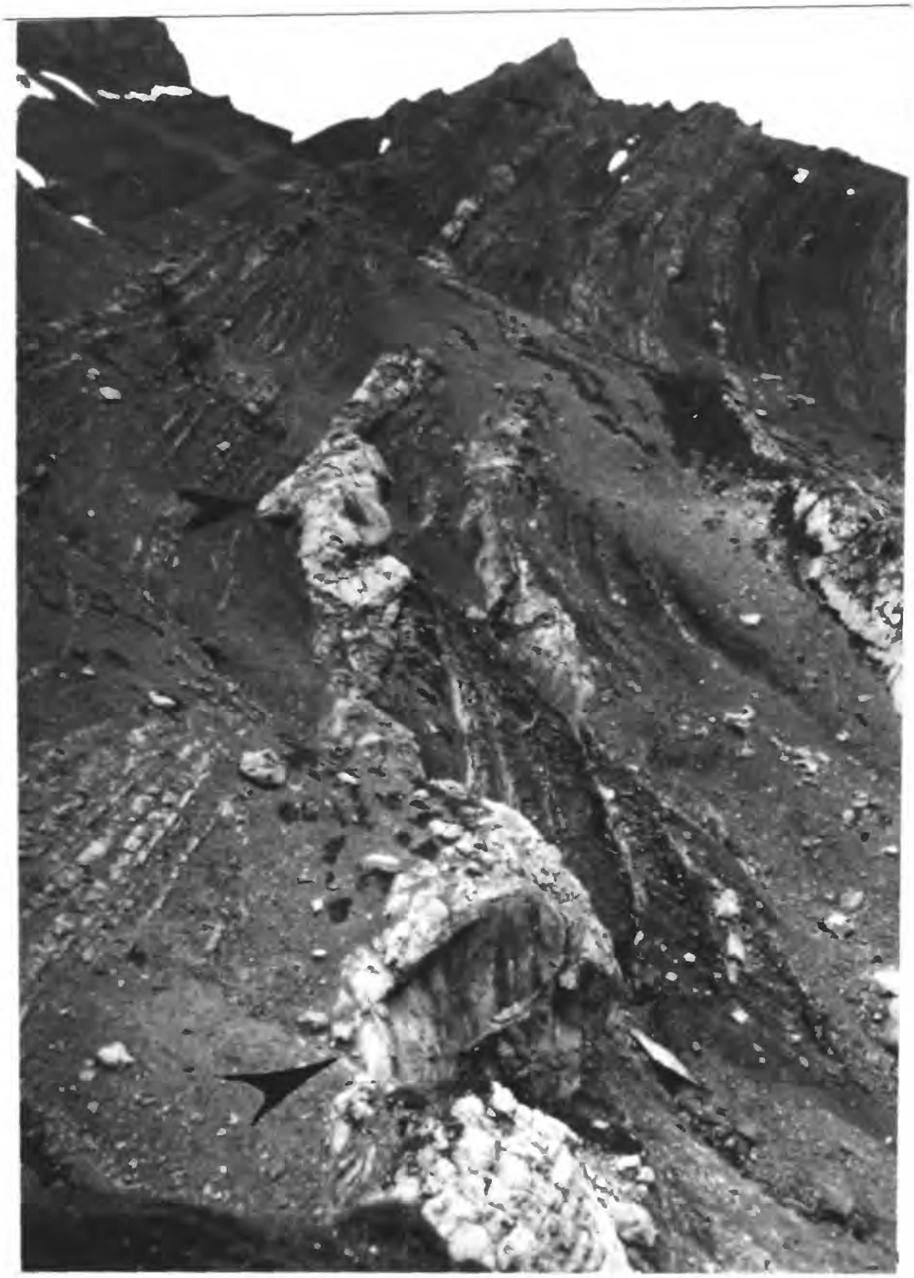


Figure 2-91. Carbonate debris sheet model showing debris originating along a line source. Debris is transported mainly as a broad sheet flow with a minimum of channeling.



Southeast margin of the Ancient Wall carbonate complex, Upper Devonian, Alberta, Canada. Looking northwest, within the Perdrix basin facies, toward the buildup margin which begins at the skyline. Stratigraphic top to left. View shows the light-colored resistant nature of the debris sheet which is enclosed in dark, less resistant basin facies. The top arrow in photo points to a large knob at the stratigraphic top of the debris sheet which is a single clast about 10 x 30 m in cross-section. The bottom arrow in photo points to a large knob which is a single clast 25 x 50 m in cross-section.

Figure 2-92. (modified from Cook et al, 1972)

Looking southeast (basinward) at the same portion of the debris sheet as in Figure 2-92. Stratigraphic top at top of photo. Arrow on right side of photo points to same 10 x 30 m clast in Figure 2-92; arrow on left side of photo points to same 25 x 50 m clast in Figure 2-92.

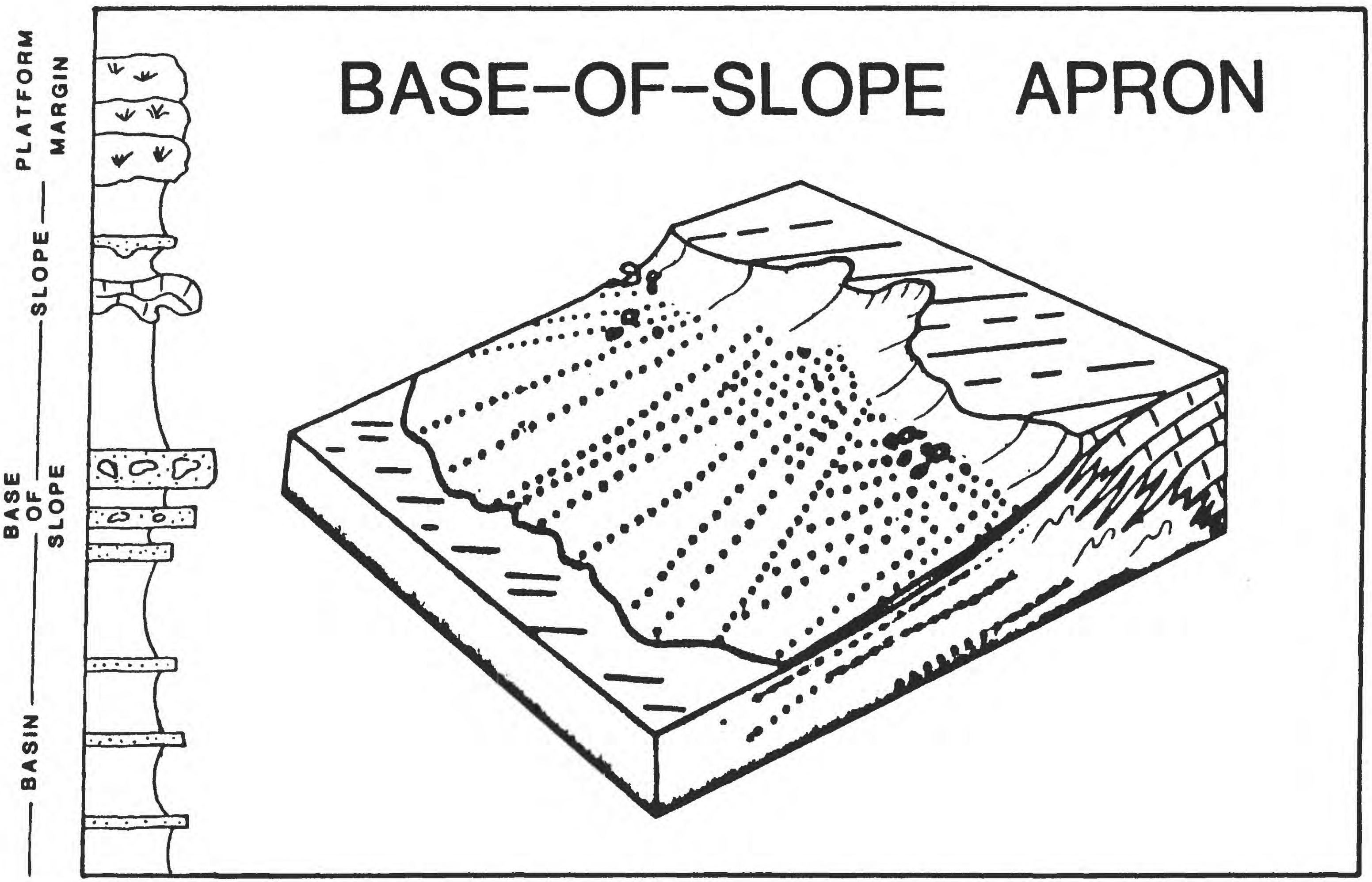
Figure 2-93. (modified from Cook et al, 1972)

Textures in debris sheets shown in Figures 2-16, 2-92, and 2-93. Note poorly sorted nature and variety of clast types. Large rectangular clast is a stromatoporoid. White circle is 2 cm wide.

Figure 2-94. (from Cook and Mullins, 1983)

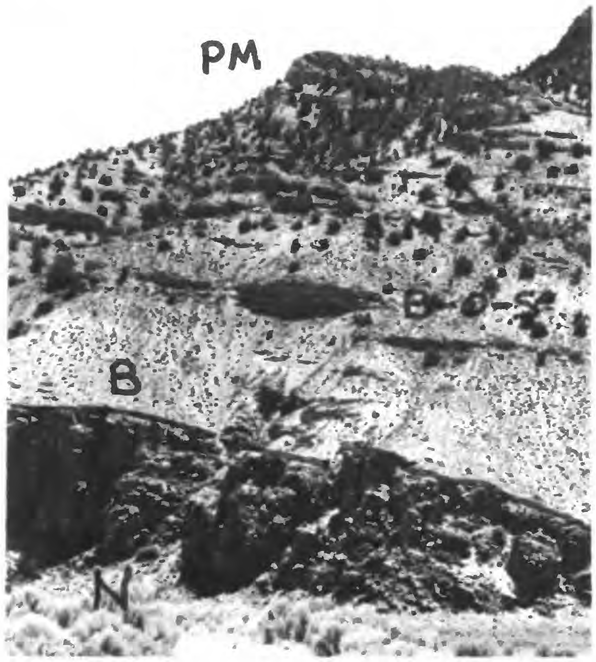
Arrow at left side of Figure 2-89 shows location of this photo. Series of stacked debris flow sheets, modified grain flow deposits and turbidity-current deposits, Thornton Ridge southeast margin Ancient Wall carbonate complex. Looking southeast (basinward) at a series of light-colored resistant debris sheets that occur at the top of the Perdrix basin facies. Stratigraphic top to right. Many of the sheets are separated by a few centimeters to meters of dark-colored basin facies. This stack of debris sheets totals about 50 m in thickness.

Figure 2-95. (from Cook et al, 1972)



Carbonate base-of-slope apron model showing debris originating along a line source. Mass-flow deposits originating at platform margin largely by-pass the slope with the bulk of the debris deposited at the base-of-slope. Debris is transported as broad sheet flows.

Figure 2-96. (modified from Cook, 1982)



Basin (B), base-of-slope apron facies (B-O-S), slope (S), and platform margin (PM). This shoaling upward sequence lies on the drowned Nevada Formation (N). Section shown about 600 to 700 m thick.

Figure 2-97.

Thickening-upward base-of-slope debris flow and turbidites shown in Figure 2-97 at "B-O-S".

Figure 2-98.

Platform margin derived coral head in base-of-slope apron facies.

Figure 2-99.

Soft-sediment overfolds developed in semiconsolidated slope facies in Figure 2-97.

Figure 2-100.

Small slope gulley filled with a calcarenite turbidite. 6 in. pen for scale.

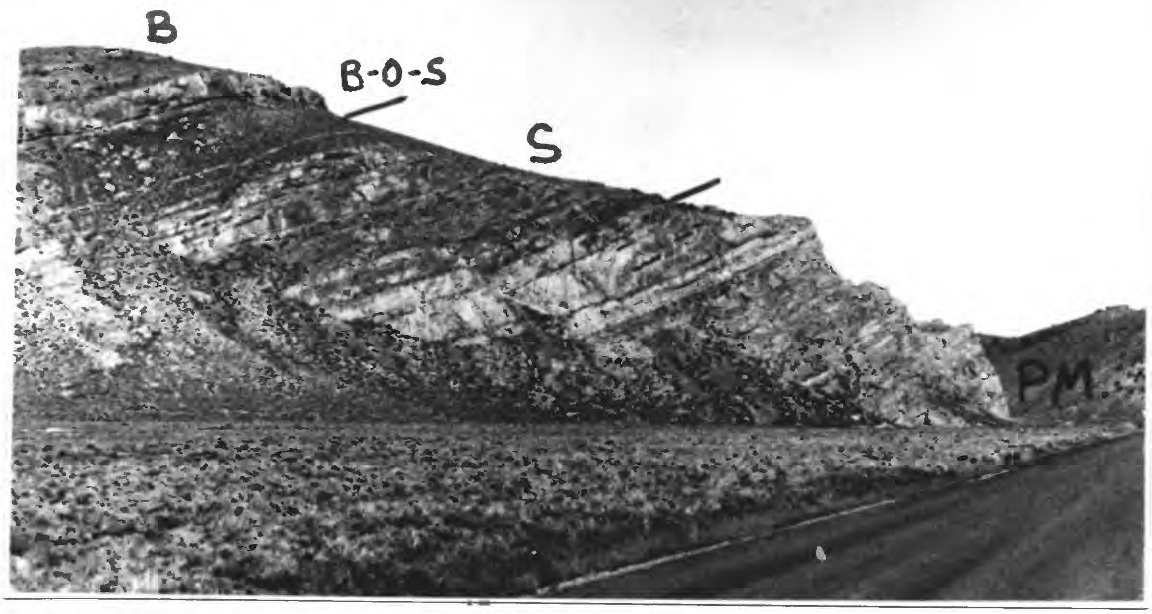
Figure 2-101.

Light-colored platform margin facies of Figure 2-97.

Figure 2 -102.

Dolomitized coral facies at platform margin of Figure 2-97.

Figure 2-103.



Retrogradational platform margin (PM), slope (S), base-of-slope (B-O-S), and basin (B) sequence. Section about 350 to 400 m thick.

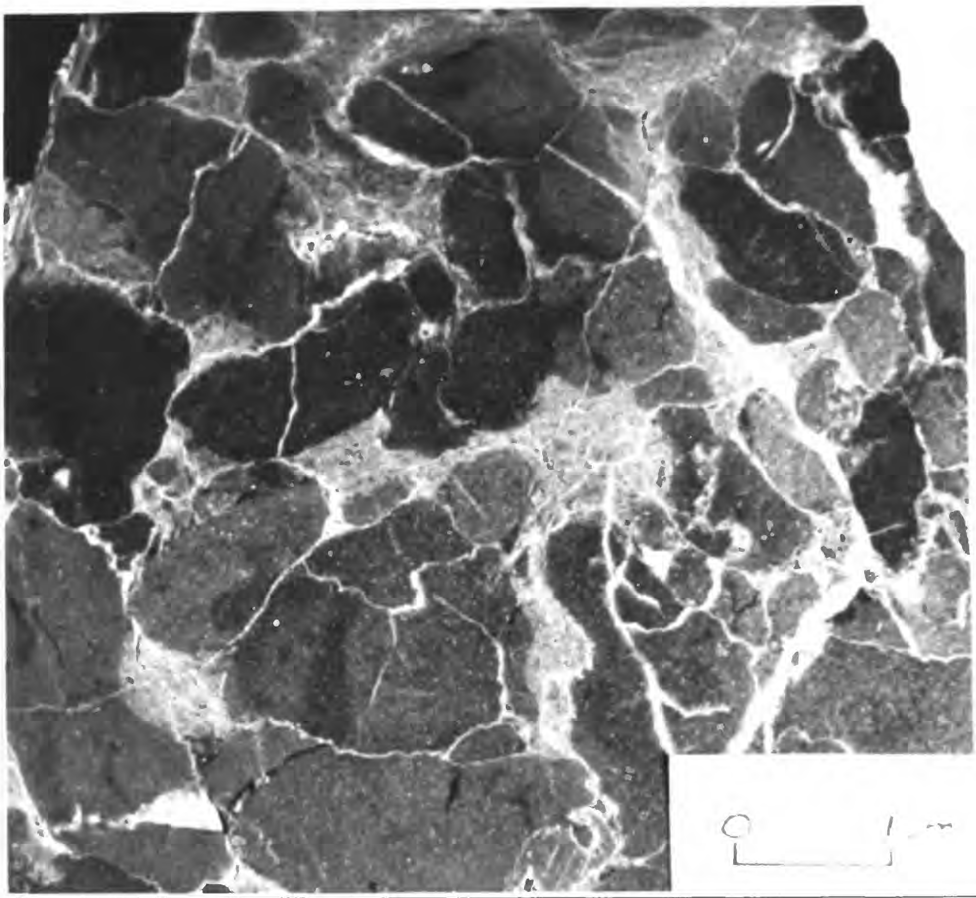
Figure 2-104.

Different view of same retrograding sequence as in Figure 2-104. Base-of-slope apron interval about 50 m thick. Letters explained in Figure 2-104.

Figure 2-105.

Platform margin stromatoporoid facies. Lens cover for scale.

Figure 2-106.

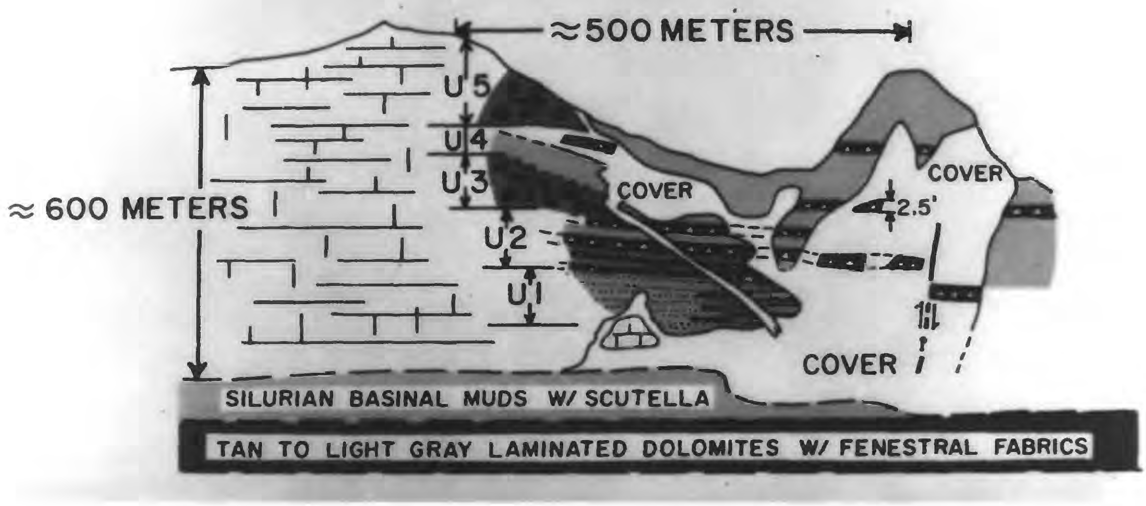


Debris flow facies from base-of-slope apron interval shown in Figure 2-105.

Figure 2-107.

EAST ROYAL CREEK SKELETAL MARGIN AND BASINAL FACIES

SILURO-DEVONIAN



U 5: SIMILAR TO U 3

U 4: LIME MUDS AND DEBRIS ONLAPPING (?) U 3

U 3: STROMS. AND CORALS BOUND (?) WITH ALGAE; EROSIONAL SURFACE

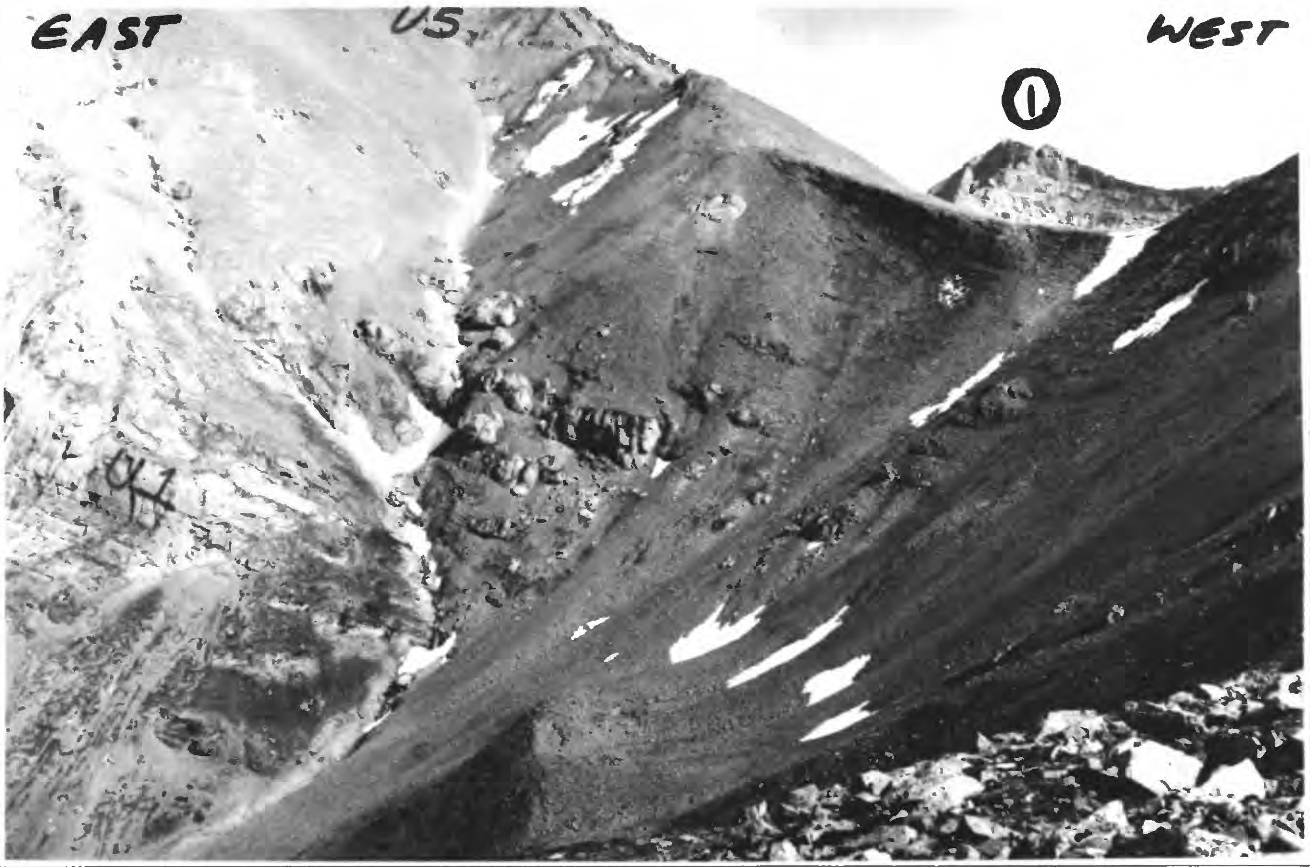
U 2: INTERBEDDED DEBRIS SHEETS, LIME MUDS, CRINOID GRAINSTONES

U 1: INTERFINGERING CRINOID GRAINSTONES AND LIME MUDS

H. E. COOK

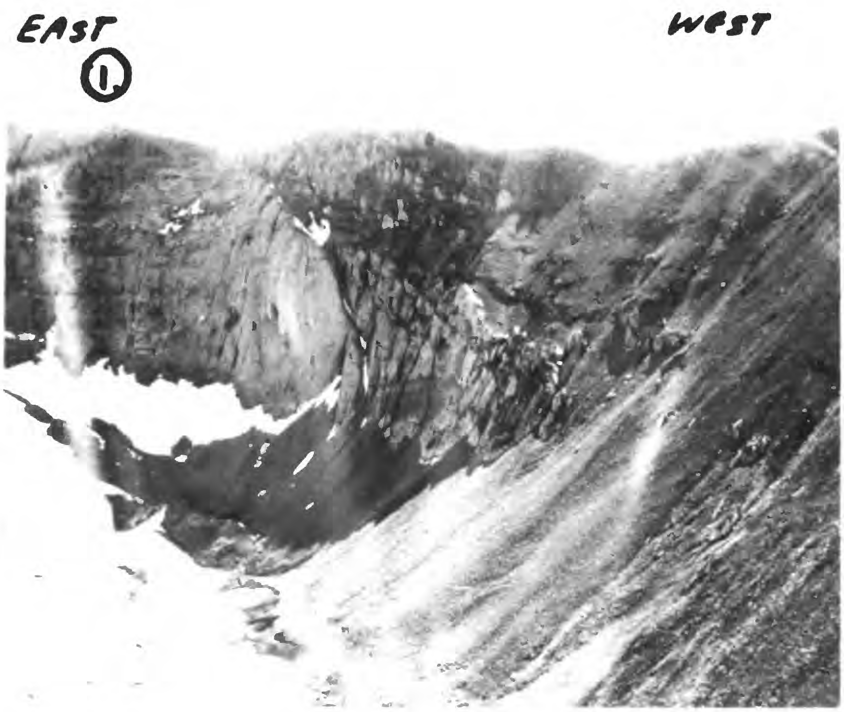
Stratigraphic cross-section of platform margin-to-slope transition. Based on field work in 1968 by H. E. Cook and W. J. Meyer. U1-U5 refers to Unit 1 through Unit 5 discussed in text. Unit 1 represents a crinoid sand shoal depositional margin phase. Units 3 and 5 are coral-algal boundstone phases.

Figure 2-108.



View looking south at East Royal Creek platform margin (on left) and slope (on right) facies illustrated in Figure 5-108. "Circled" 1 on top of distant peak is same circled 1 peak in Figure 5-110.

Figure 2-109.



View looking south at a different part of the East Royal Creek platform margin-to-slope transition. South of Figure -109 about 1.5 miles. Note well-bedded back reef facies, narrow coral-algal massive reef margin and darker colored slope and basinal facies with apron debris flows and turbidites.

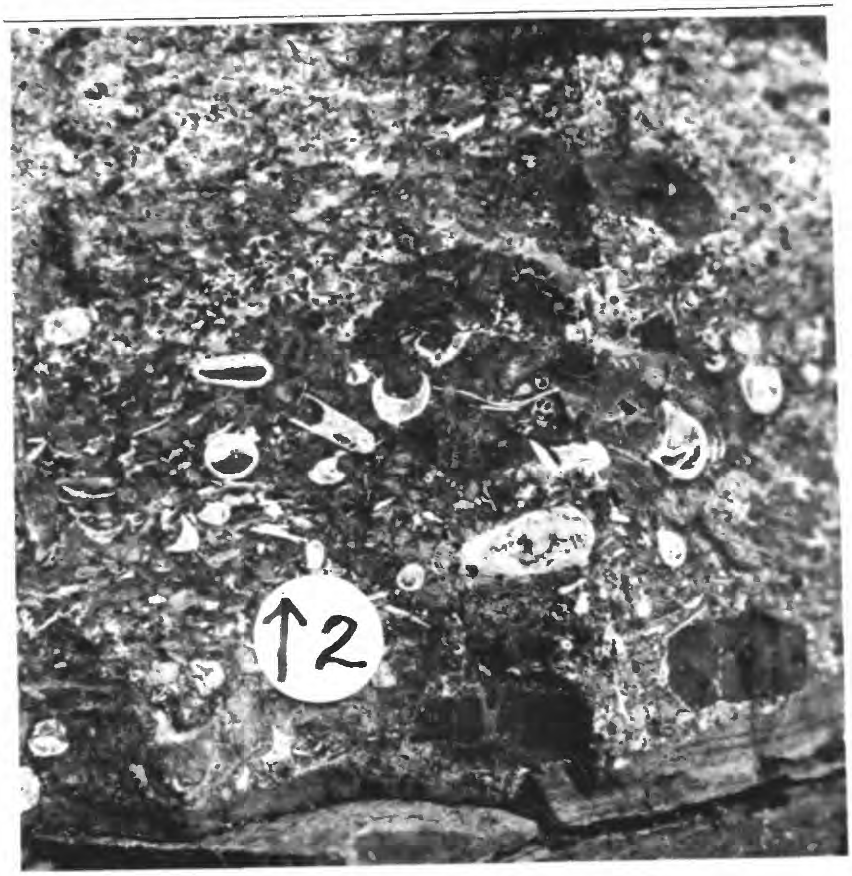
Figure 2-110.

Coral-algal boundstone facies in Unit 3 of Figures 2-108 and 2-109.

Figure 2-111.

Erosional contact between Unit 3 and 4. Dark slope lime mudstone of Unit 4 is filling erosional cavities in the uppermost part of Unit 3 coral-algal boundstones. Arrow points to stratigraphic top of surface.

Figure 2-112.

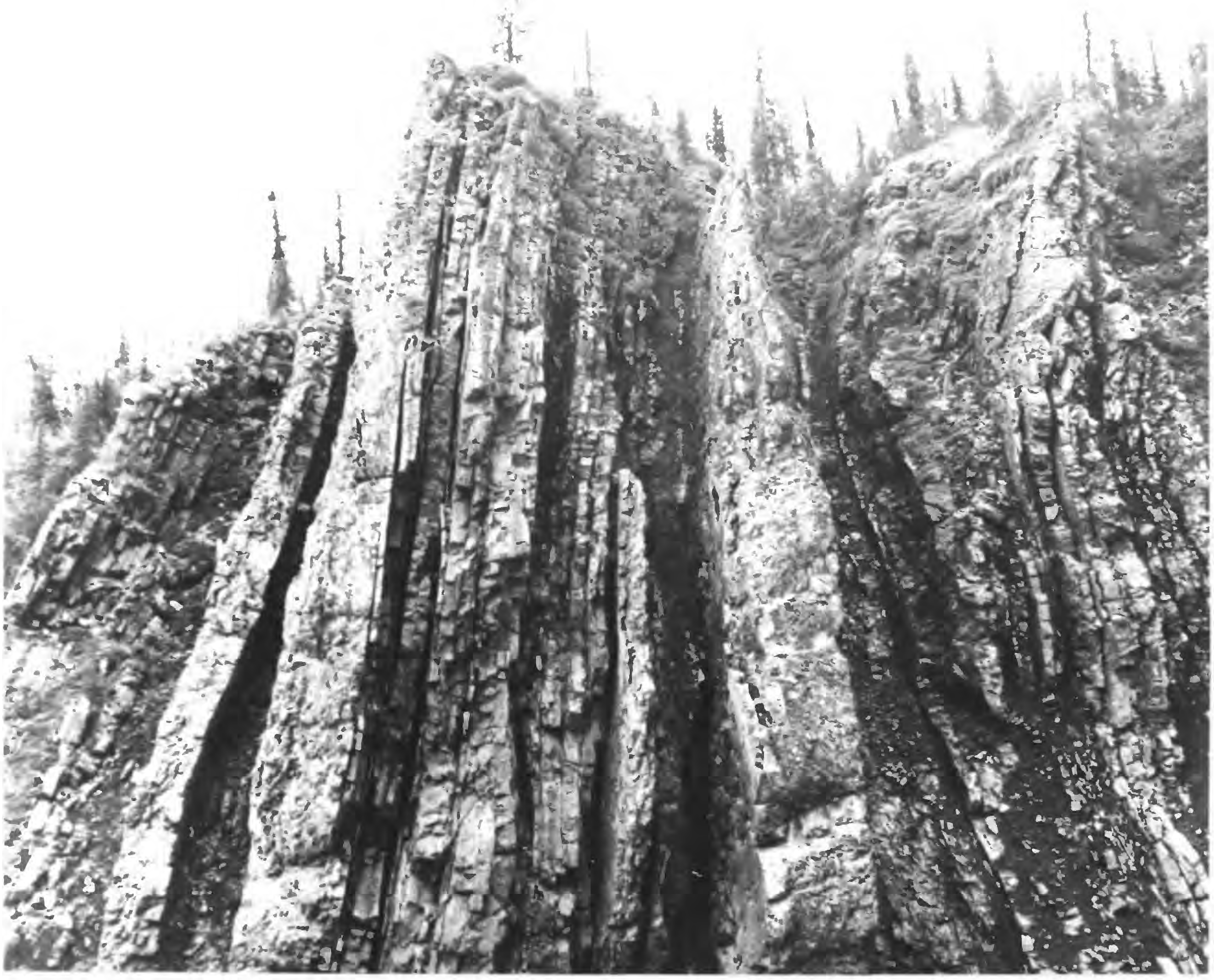


15-cm-thick conglomeratic turbidite. Clasts are normally graded. Note geopetal fabrics in gastropod shells indicating that shells were filled with lime mud after deposition of the turbidite. Turbidite occurs on slope 100 m from bank margin. White circle is 2 cm wide. Road River Formation, Siluro-Devonian, Wernecke Mountains, Yukon Territory, Canada.

Figure 2-113. (from Cook and Mullins, 1983)

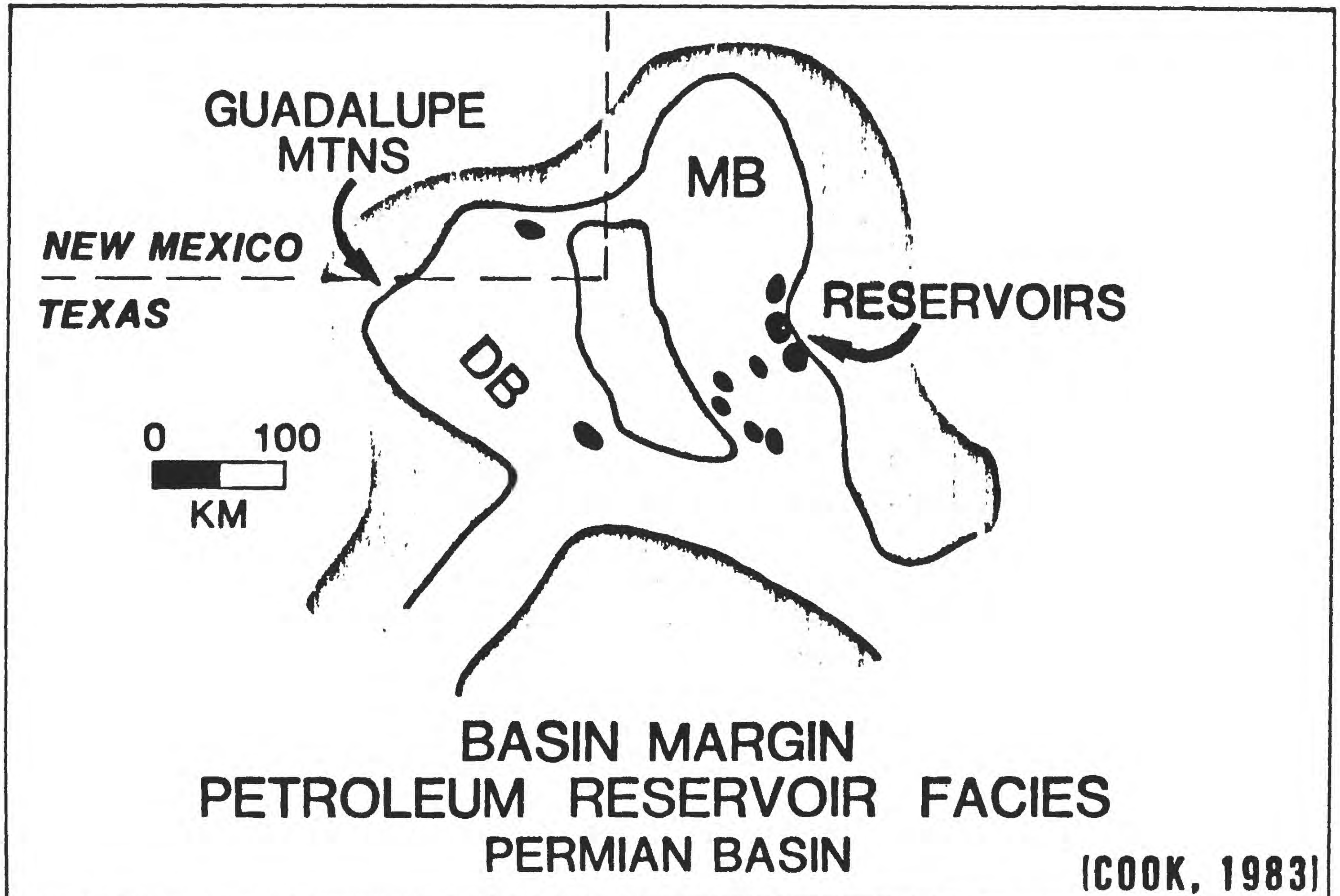
Close-up polished slab of bed in Figure 2-113.

Figure 2-114.



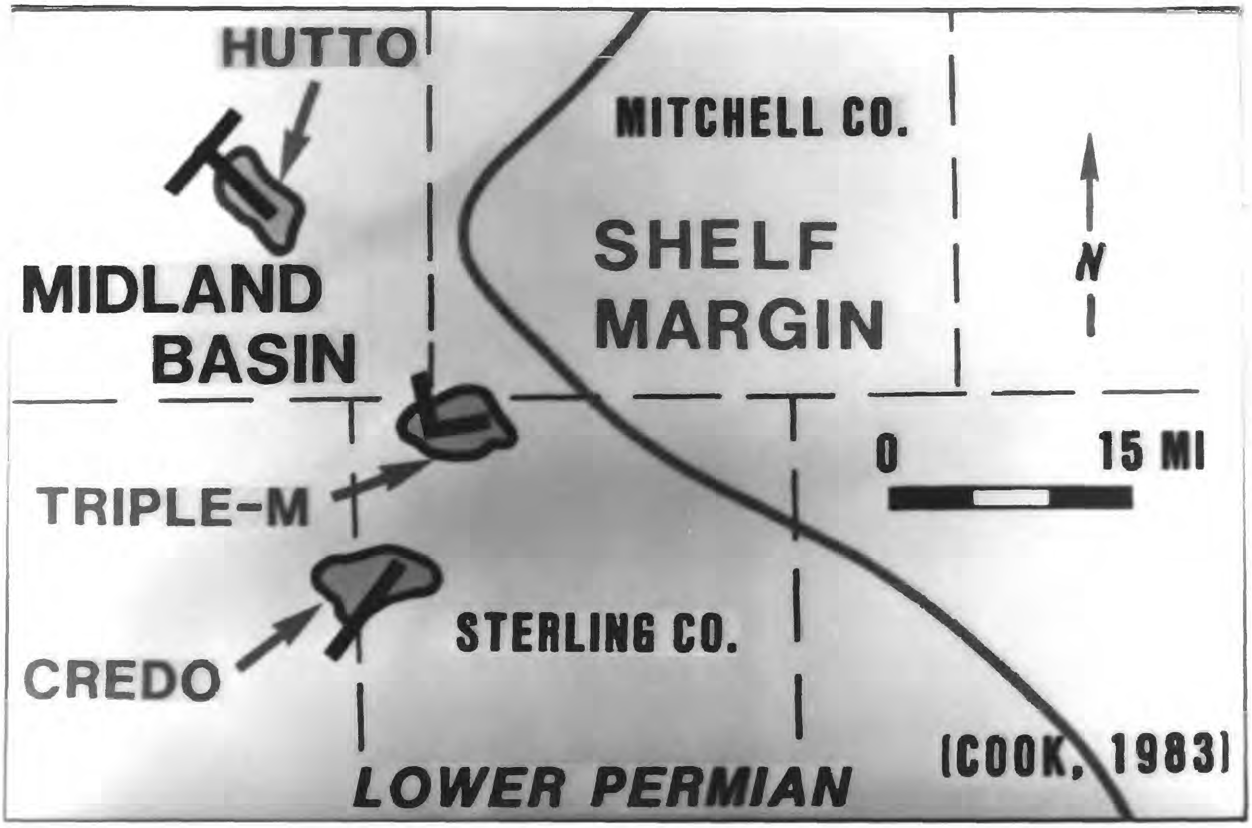
Platform margin derived carbonate debris flow and turbidite sheets. Stratigraphic top to left. Thickest mass-flow beds are about 2 m thick.

Figure 2-115.



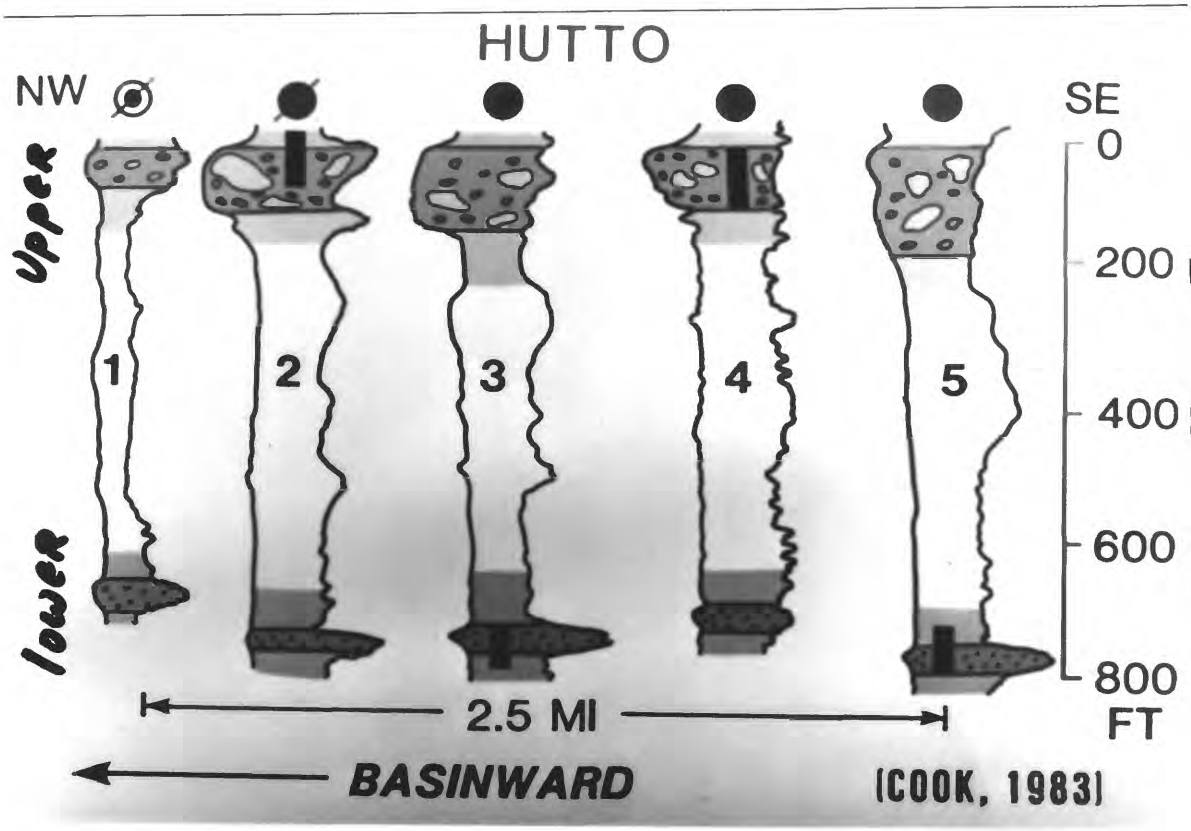
Index map of the Permian Basin, west Texas. DB (Delaware Basin) and MB (Midland Basin). Solid black circles are allochthonous deep-water carbonate petroleum fields.

Figure 2-116.



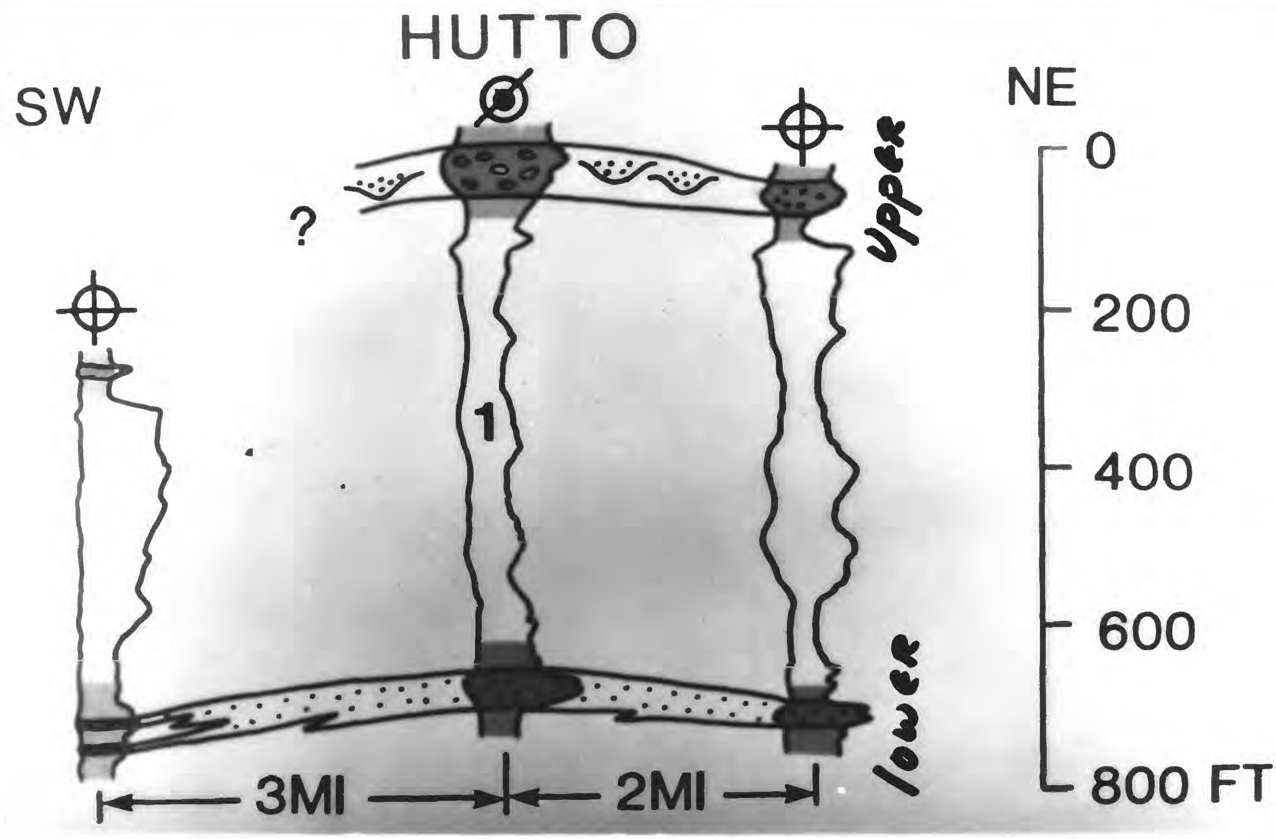
Index map showing location of the allochthonous carbonate petroleum fields discussed in text (Hutto, Triple-M, and Credo).

Figure 2-117.



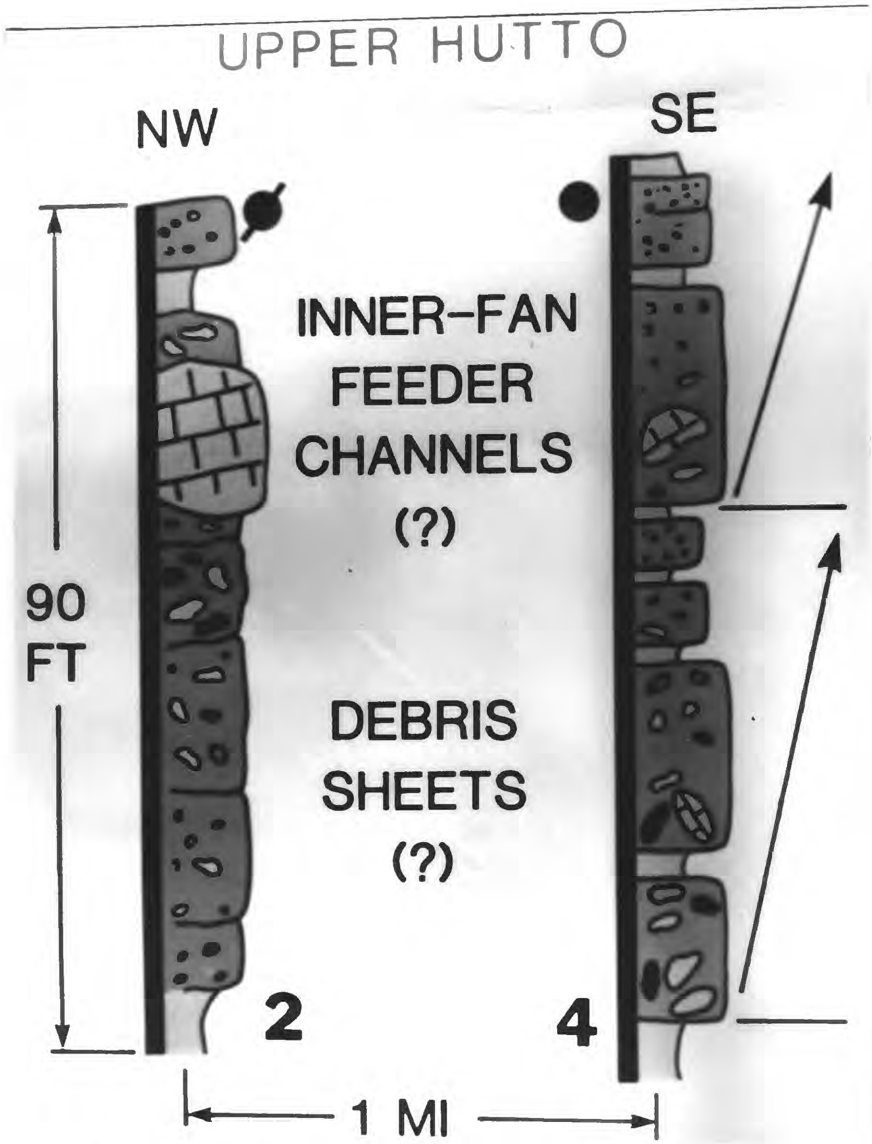
Cross-section through the Hutto field. Solid vertical bars are cored intervals studied. Wells numbered 1 through 5 are same numbered wells in Figures 2-119 through 2-121. Note the Upper Hutto debris thins basinward.

Figure 2-118.



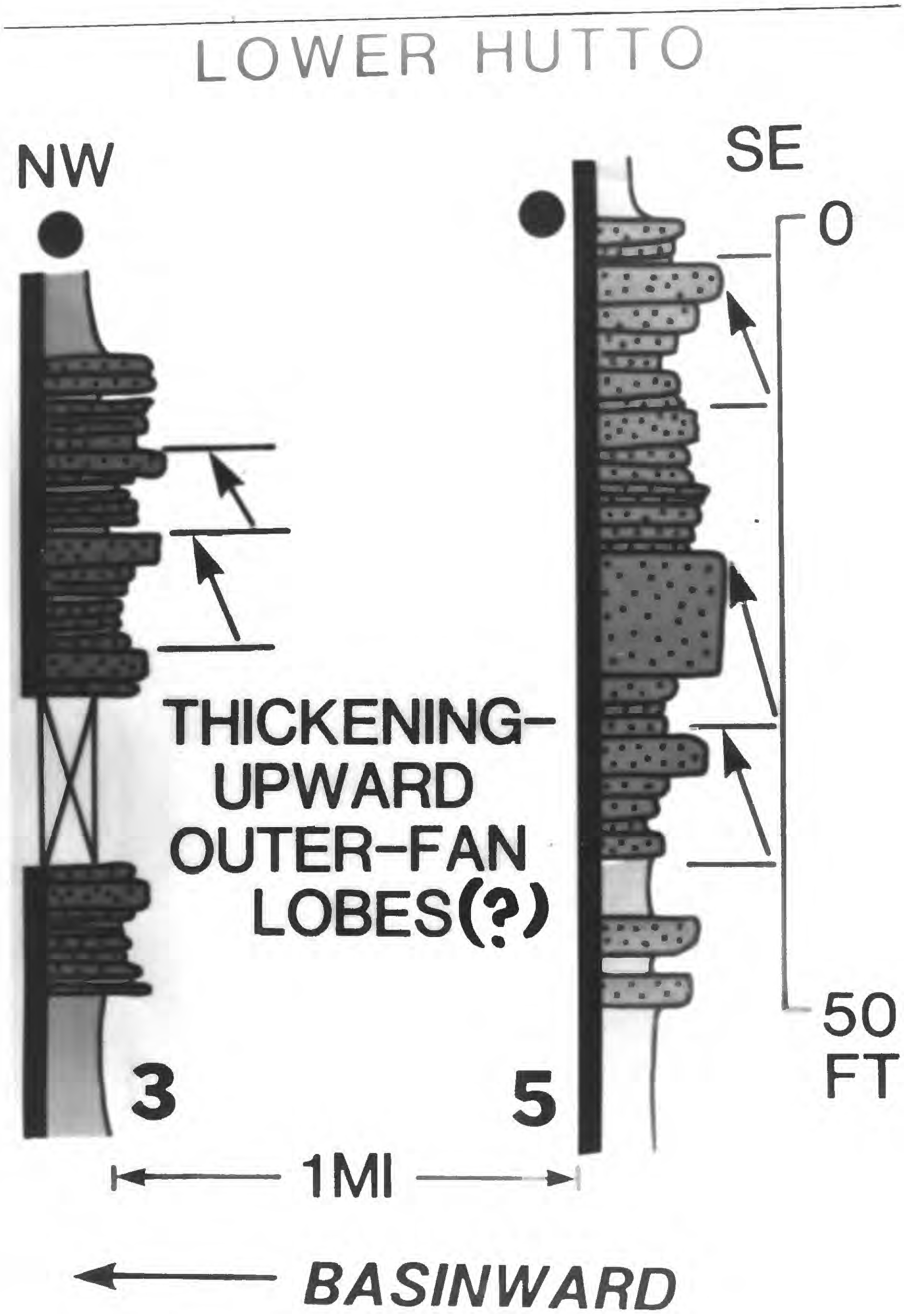
Cross-section through the Hutto field. Note the Upper Hutto debris thins to the SW and NE.

Figure 2 -119.



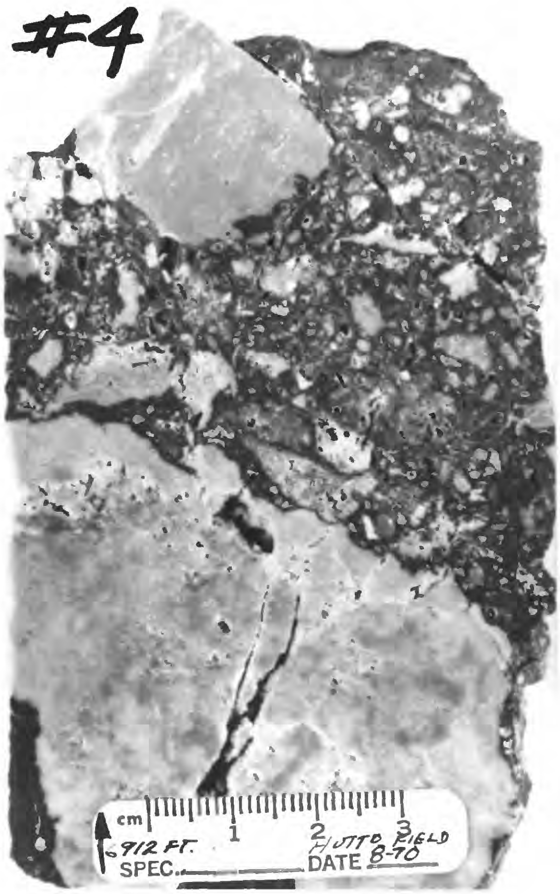
Upper Hutto cored interval in wells 2 and 4 of Figure 2 -118. Well 4 has possible thinning-upward cycles.

Figure 2 -120.



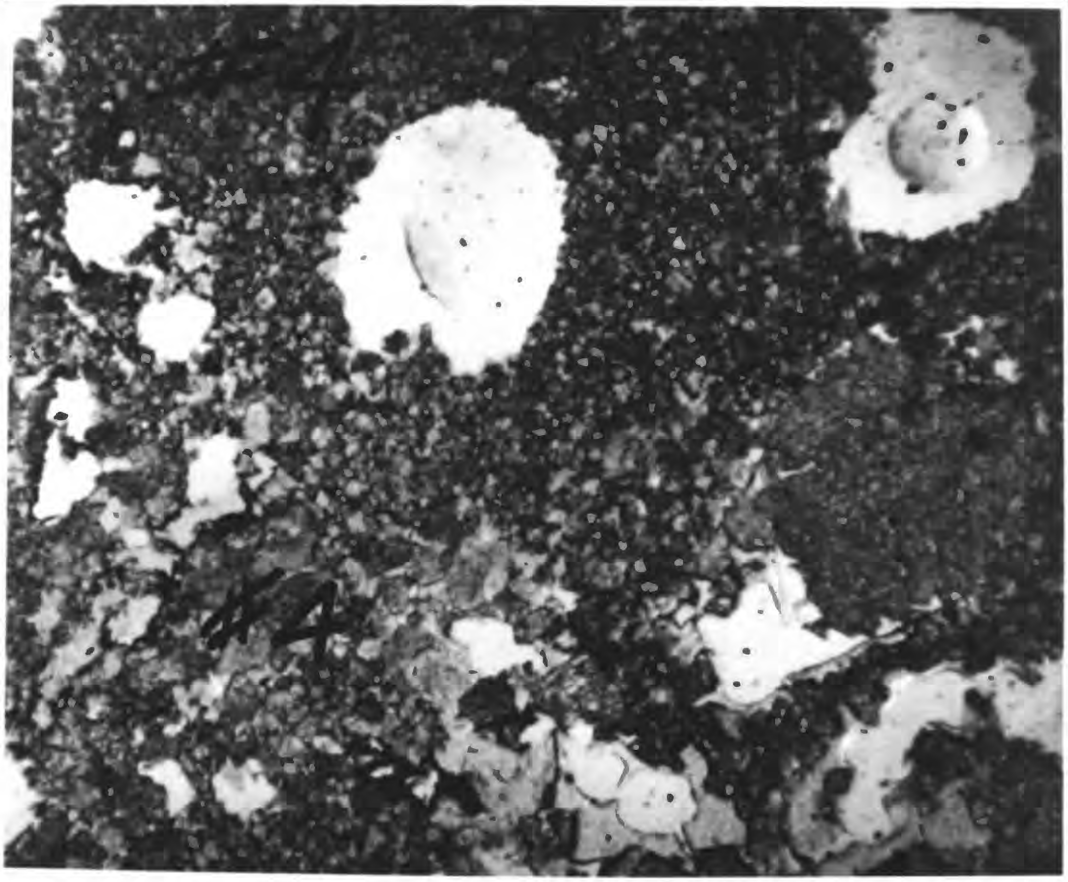
Lower Hutto cored intervals in wells 3 and 5 of Figure 2-118. Both wells have probable thickening-upward cycles. Beds in well 3 are thinner than in well 5.

Figure 2-121.



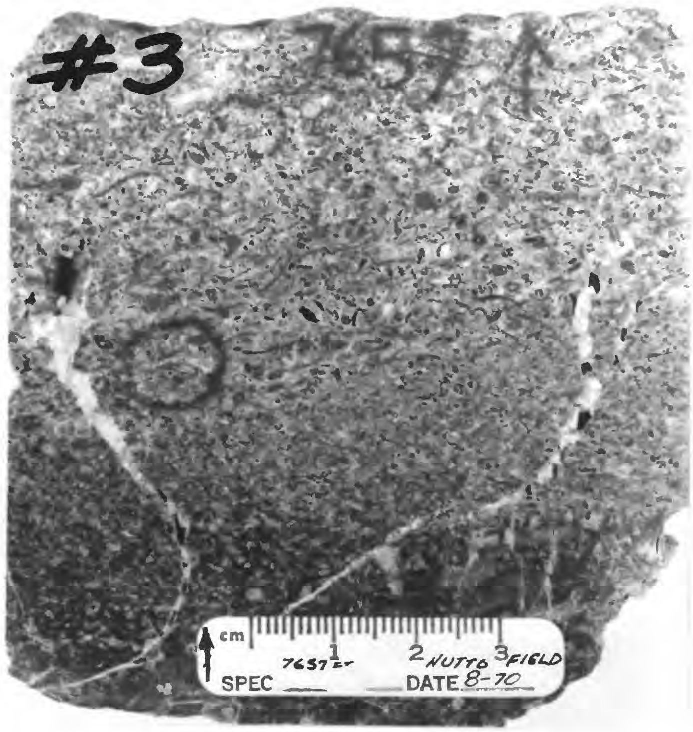
Dolomitized debris flow conglomerate from Upper Hutto in well 4. Porosity is mainly moldic, fracture, and intercrystalline types.

Figure 2-122.



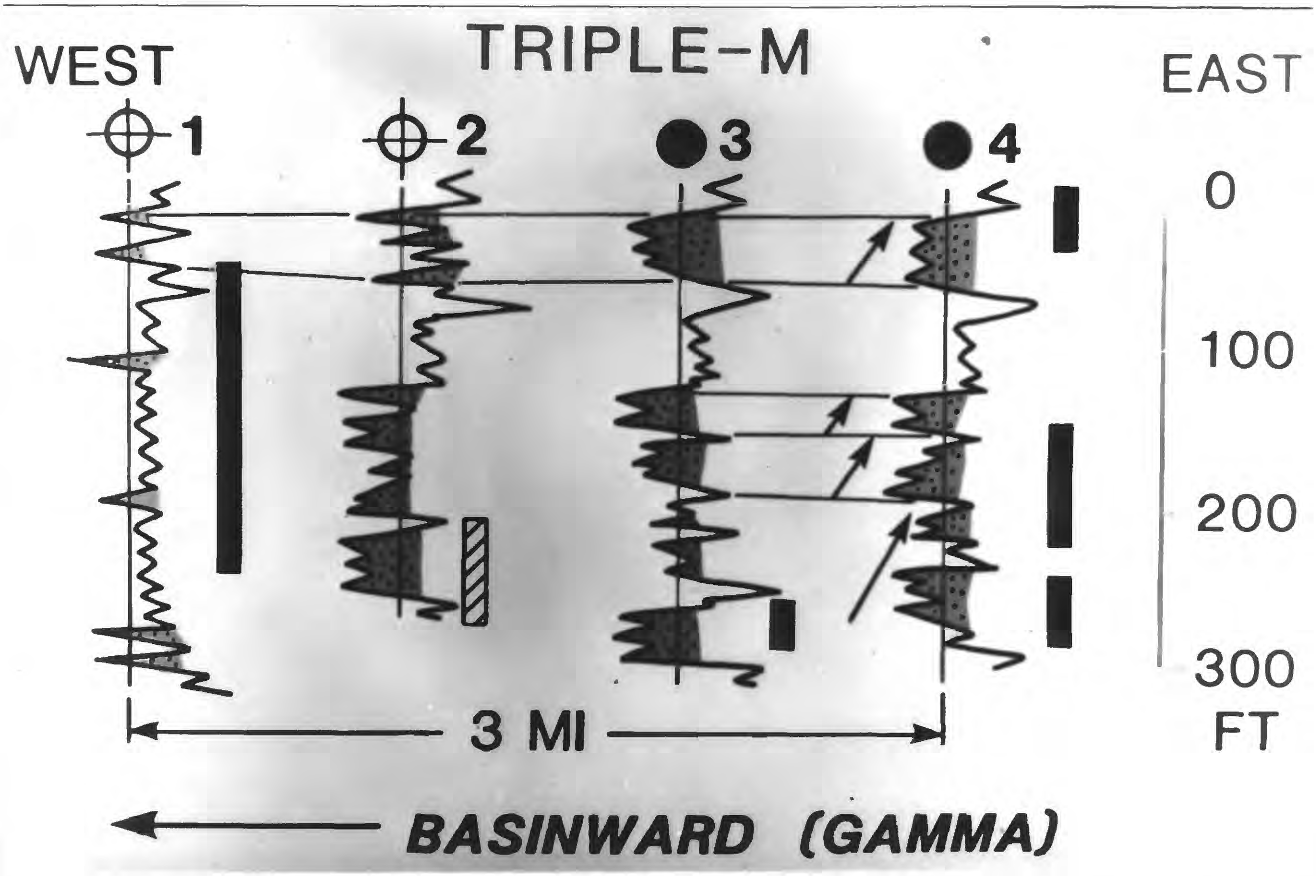
Thin-section of dolomitized debris flow deposit, Upper Hutto, well 4.

Figure 2-123.



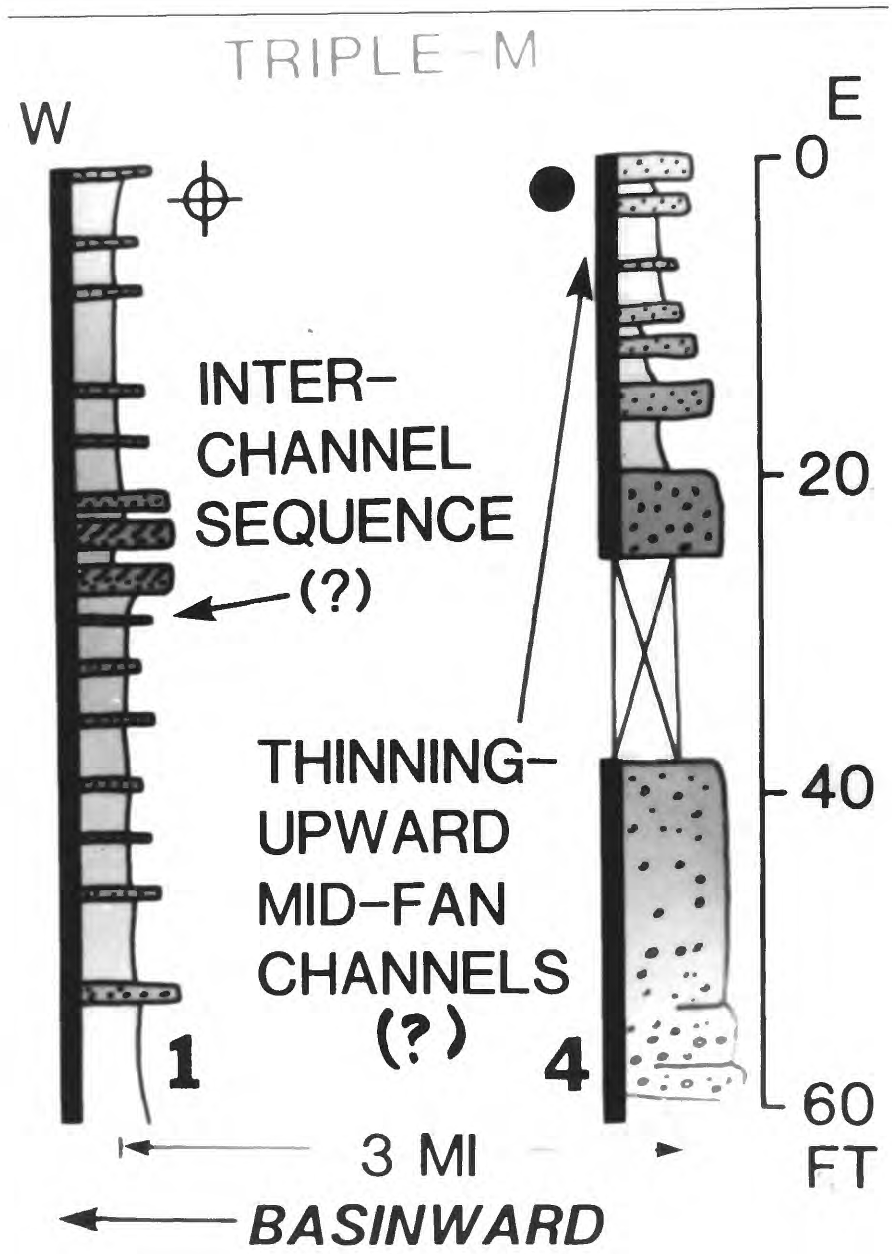
Bioclastic turbidite from Lower Hutto, well 3. Biomoldic, interparticle, and fracture porosity.

Figure 2-124.



Cross-section through Triple-M fie]d. Solid black vertical bars are cored intervals studied. Well 4 exhibits probable thinning-upward cycles. Note that uppermost cycle in well 4 thins basinward.

Figure 2 -125.

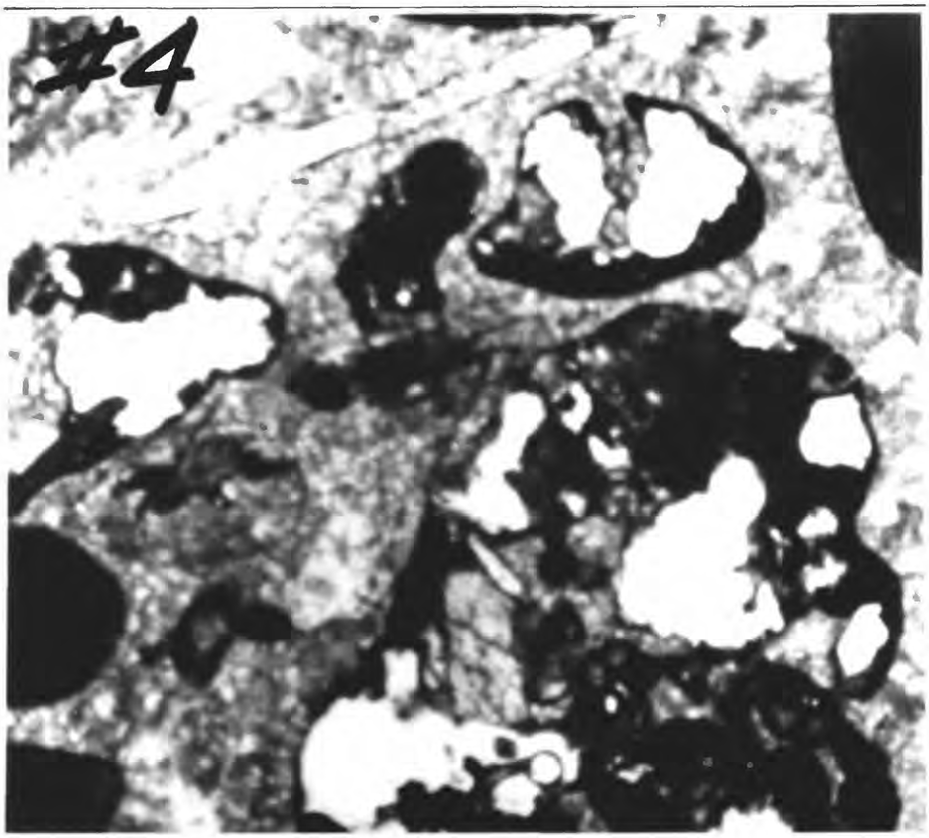


Cored intervals in Triple-M field in wells 4 and 1. Based on cores and log character, wells 3 and 4 may represent mid-fan channels and well 1 an interchannel or basinal facies. Well 2 may represent a transitional setting.

Figure 2-126.

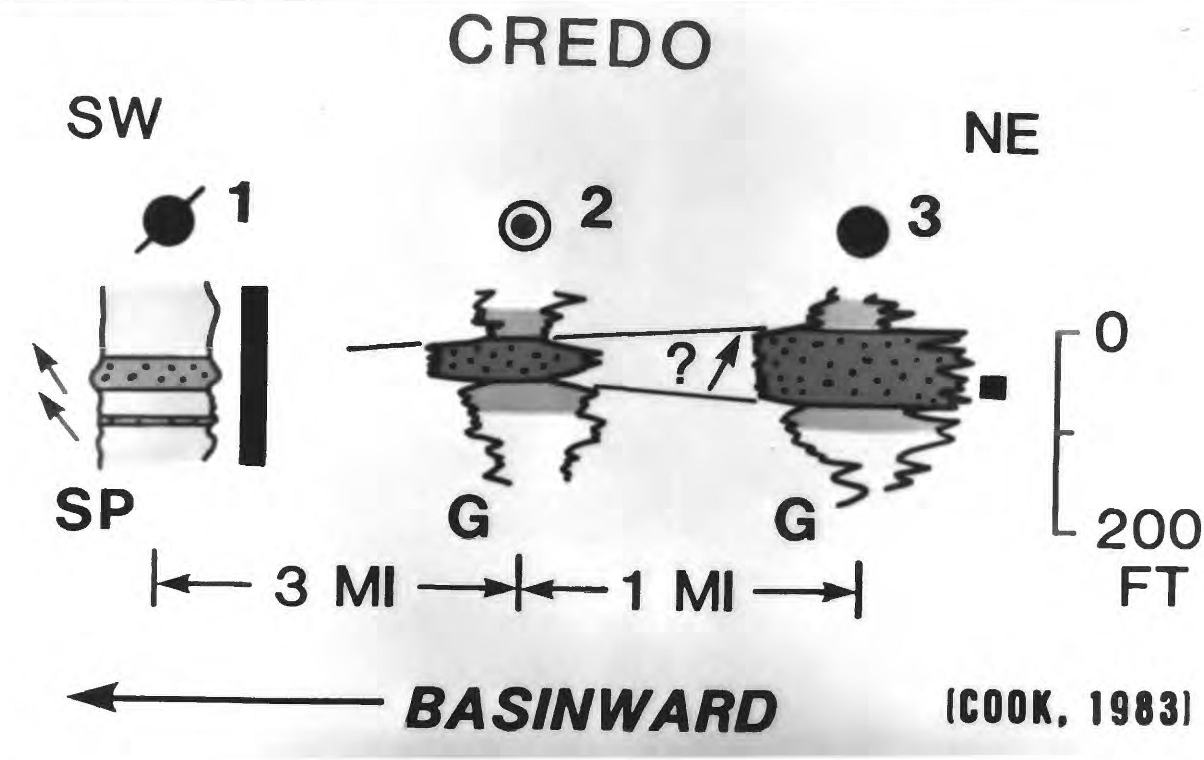
Normally graded calcarenite turbidite from well 1, Triple-M field. No porosity.

Figure 2-128.



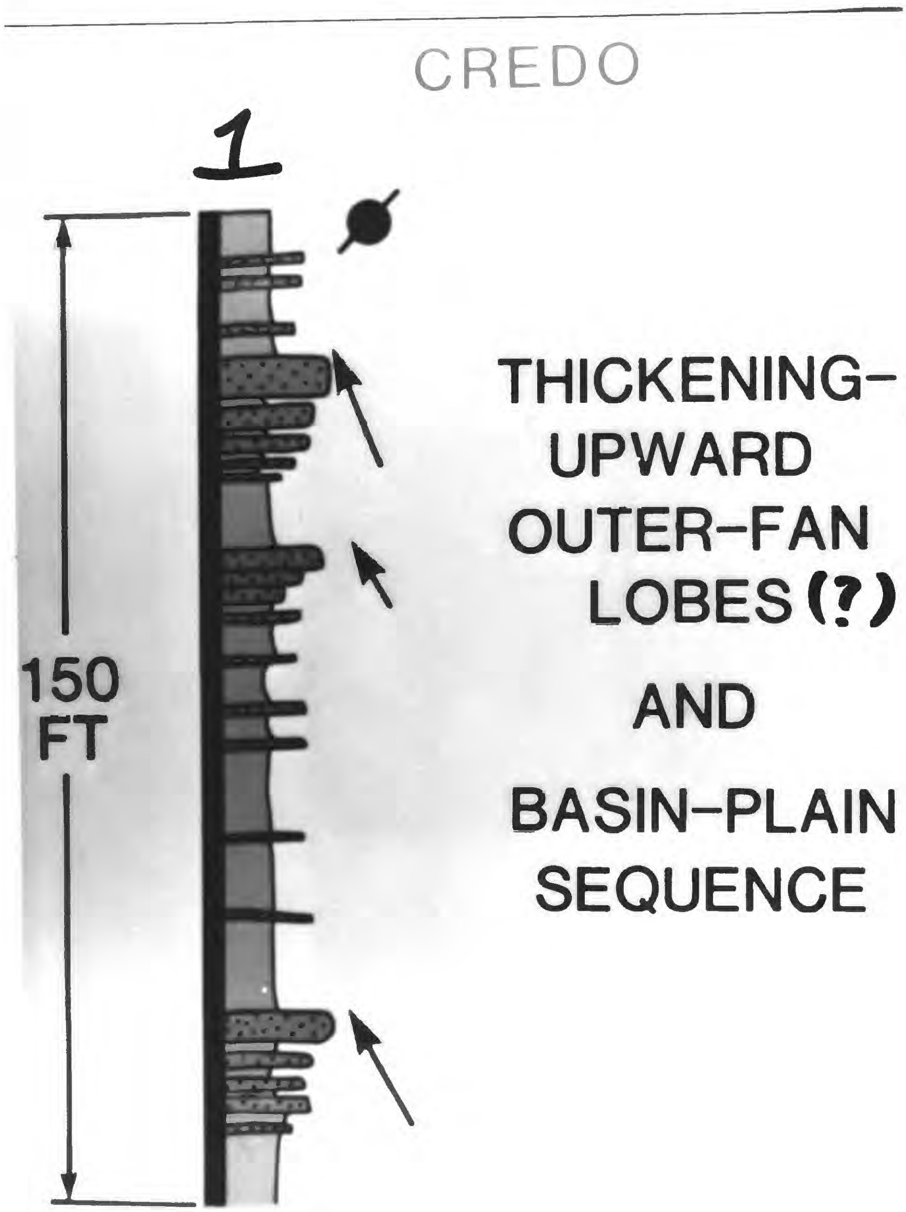
Thin-section of calcarenite turbidite in well 4, Triple-M field. Biomoldic and intergranular moldic porosity.

Figure 2-127.



Cross-section through Credo field. Solid black vertical bars are cored intervals studied. Note that stratigraphic correlation indicates a basinward thinning of debris flow and turbidite horizon.

Figure 2-129.



Well 1 in Credo field with several probable thickening-upward cycles. This stratigraphic interval is interpreted to correlate with the thicker debris interval 4 miles up dip in well 3.

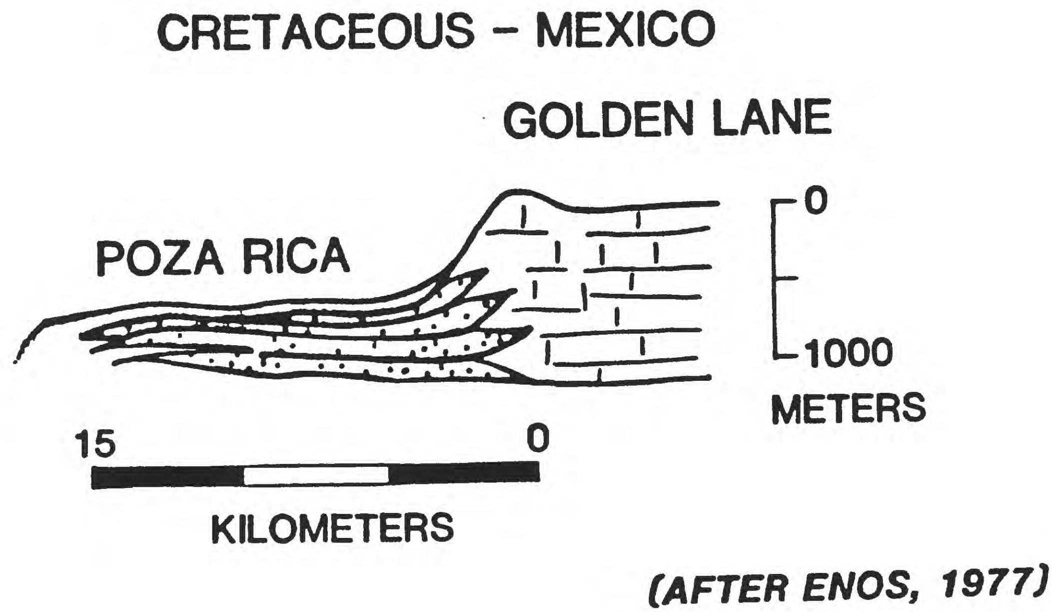
Figure 2 -130.

Thin-bedded bioclastic turbidites in Upper Hutto, well 4 interval. No porosity.

Figure 2-131.

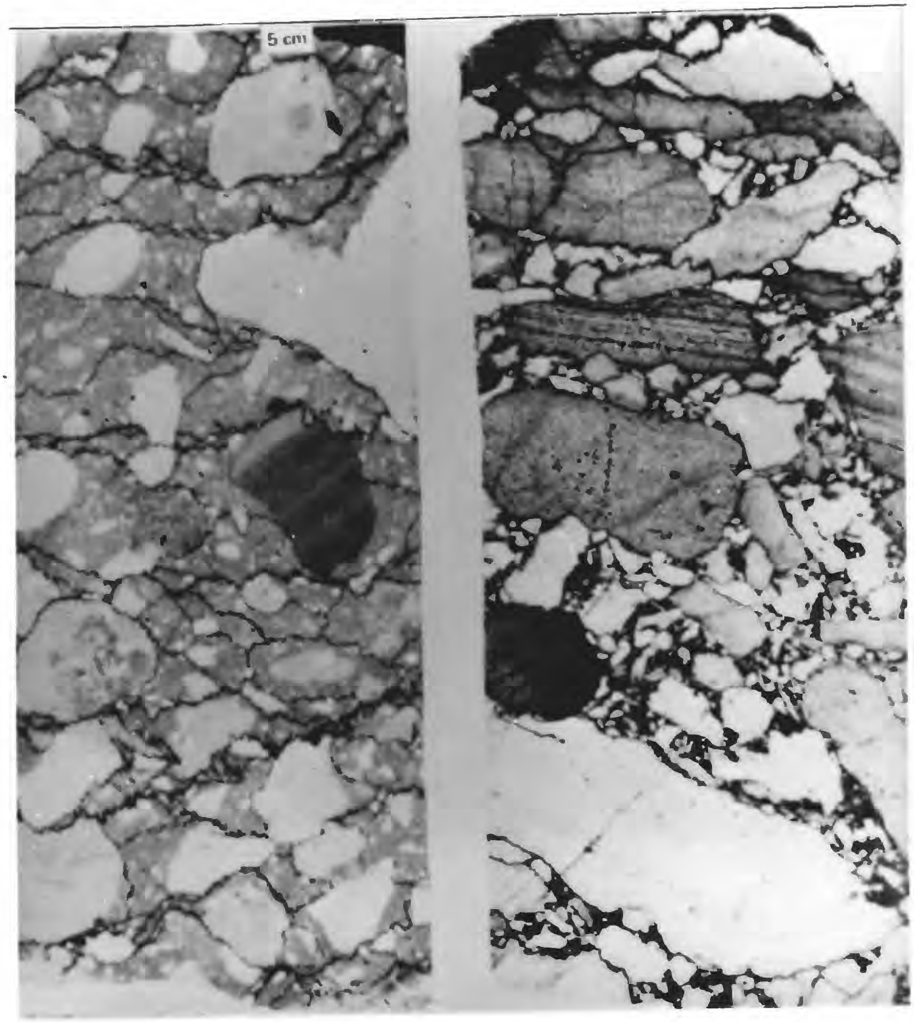
Location of the Cretaceous Poza Rica trend (solid black) and the adjacent Golden Lane fields, Veracruz, Mexico.

Figure 2-132. (modified from Enos, 1977)



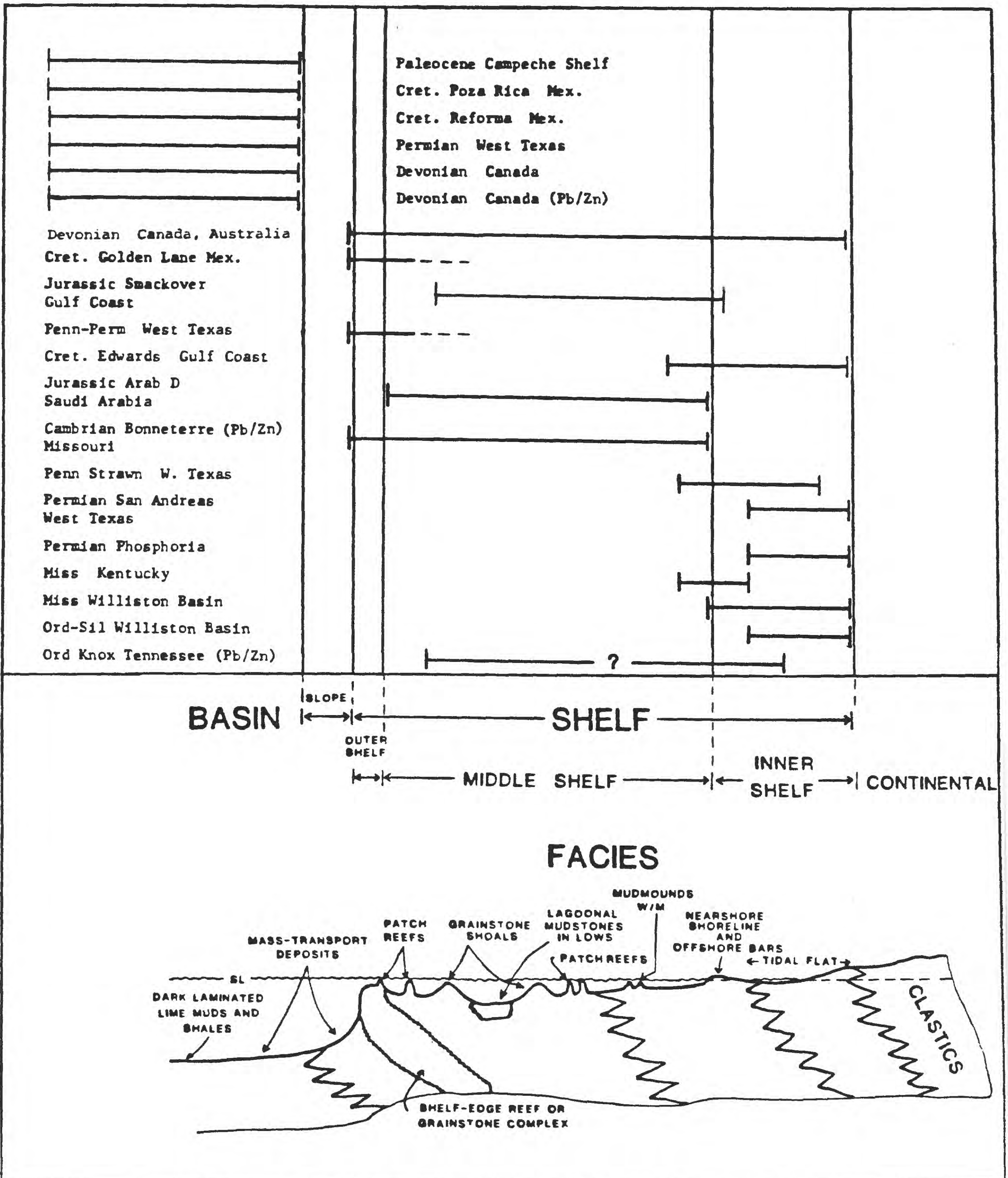
Interpretive cross section from Cretaceous Poza Rica field to Golden Lane, Veracruz, Mexico.

Figure 2-133. (modified from Enos, 1977)



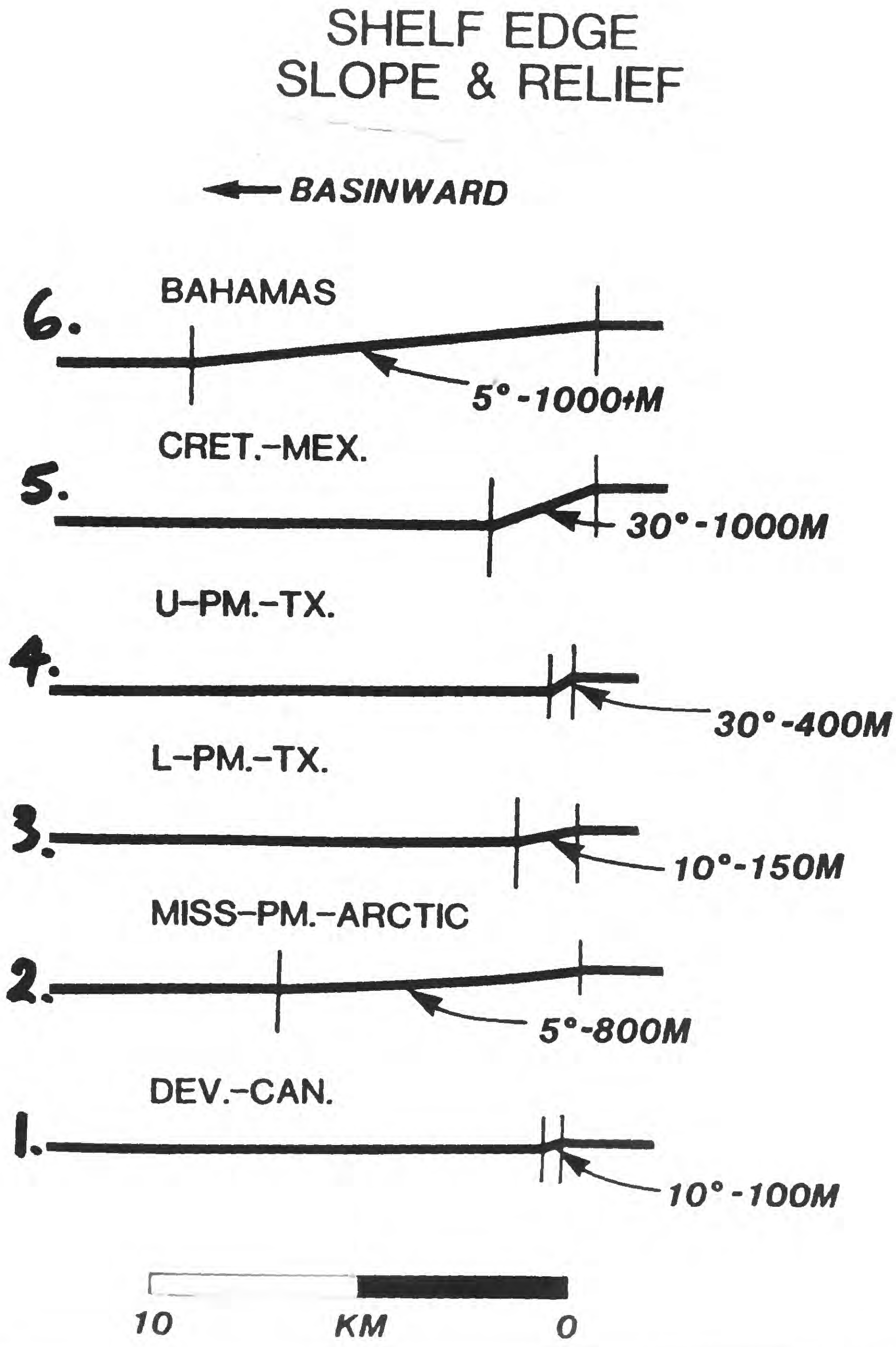
Breccia in Cretaceous Tamabra Limestone, Poza Rica oil field, Mexico.

Figure 2-134. (from Enos, 1977a)



Carbonate shelf profile showing examples of petroleum and mineral reservoirs in shelf and deeper water off-shelf environments.

Figure 2-135. (data from Mazzullo, 1982 and Scholle et al, 1983a; profile modified from Wilson and Jordan, 1983)



Shelf edge slope and relief at several platform margins. From base to top: (1) Devonian Ancient Wall, Alberta, Canada; (2) Mississippian to Permian Sverdrup Basin, Arctic, Canada; (3) Lower Permian, west Texas; (4) Upper Permian Guadalupes, west Texas; (5) Cretaceous Golden Lane - Poza Rica area, Mexico; (6) Northern Little Bahama Bank.

Figure 2 -136.