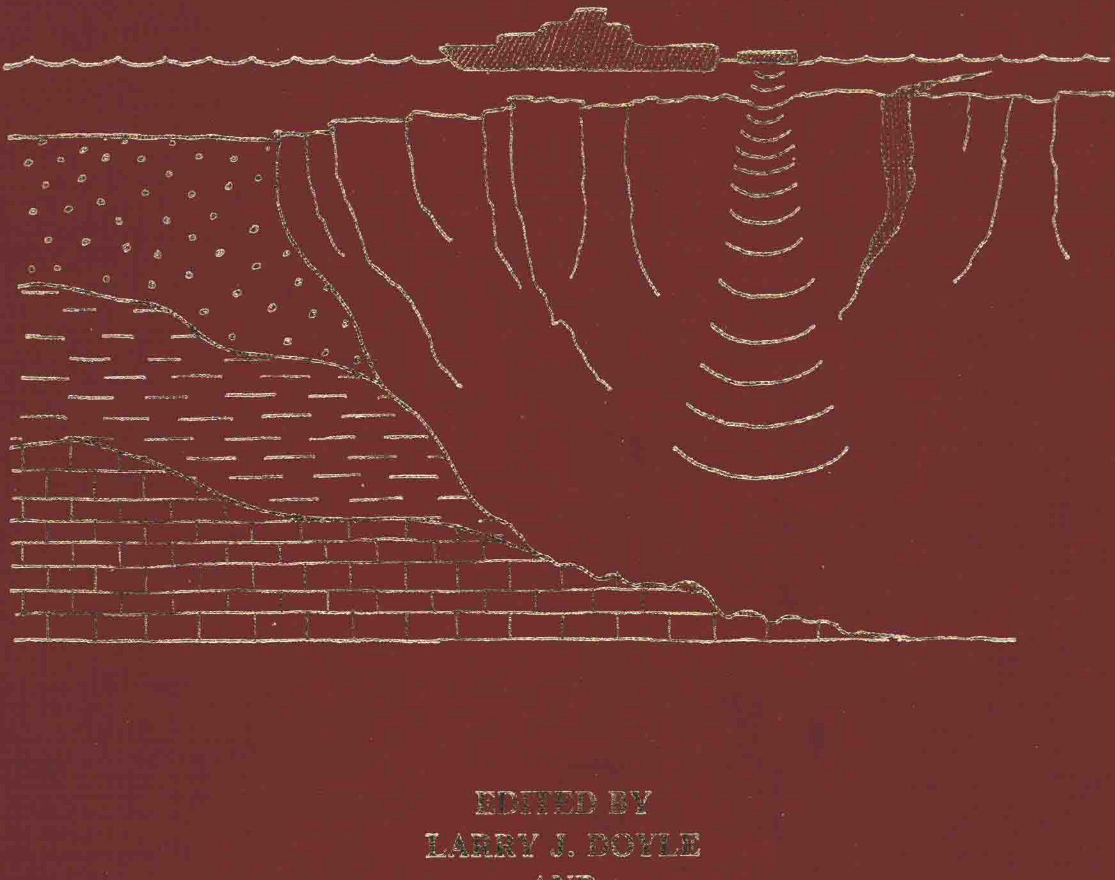
GEOLOGY OF CONTINENTAL SLOPES



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AND
ORRIN H. PILKEY

Society of Economic Paleontologists and Mineralogists

Special Publication No. 27

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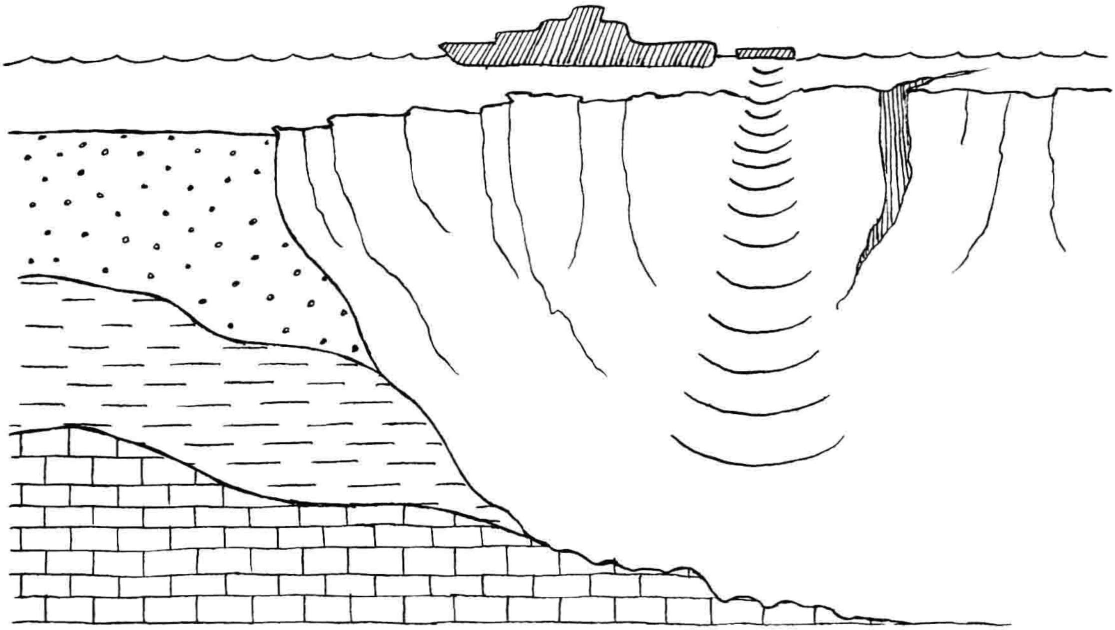

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SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

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PREFACE

Continental slopes are the edges of continental blocks, the zones of change from continental crust to oceanic crust. Here, prograded shelf sedimentary prisms end. Slopes and their associated water columns are also zones of flux through which pass all sediments destined to reach the continental rise and deep ocean basins. They are critical links in the chain of sedimentary processes that eventually carry sediment to the true ocean basin floor. In spite of their importance, until recently continental slopes have been largely ignored when compared with research focused on other provinces of the continental margins and deep sea.

Now, spurred by the recognition that a key portion of the margin has been overlooked and by the extension of hydrocarbon exploration into ever deeper waters, interest in continental slopes has burgeoned. In response to this, we convened a special symposium sponsored jointly by the Society of Economic Paleontologists and Mineralogists and the American Association of Petroleum Geologists at the 1978 meeting in Oklahoma City. This volume, a result of that meeting, is comprised of papers presented at that time with the addition of several papers in order to round out certain subjects.

The book is organized into three major parts. In the first, CONTINENTAL SLOPES: OVERVIEWS, general concepts of slope geology, resource potential, and related engineering problems are dealt with. Since environmental impacts on organisms are so important, a chapter on slope biology is included in this section. Two chapters treat the important subject of down-slope bottom transport mechanisms and their classification, a subject which has caused much confusion in the past. These two chapters cover some common ground but differ significantly in that Lowe presents a fresh quantitative approach to the theory of rheologic behavior regimes while Nardin et al focus on mechanisms of slides, rockfalls, and sedimentologic and stratigraphic character of resultant sediment bodies.

Part 2, MODERN CONTINENTAL SLOPES, is composed of a series of chapters presenting the results of individual current geologic investigations of Atlantic, Gulf, Pacific, and Antarctic continental slopes. Here new insights are provided into slope structure, sediments and their engineering properties, and sedimentary processes which affect interpretation of whole margin systems.

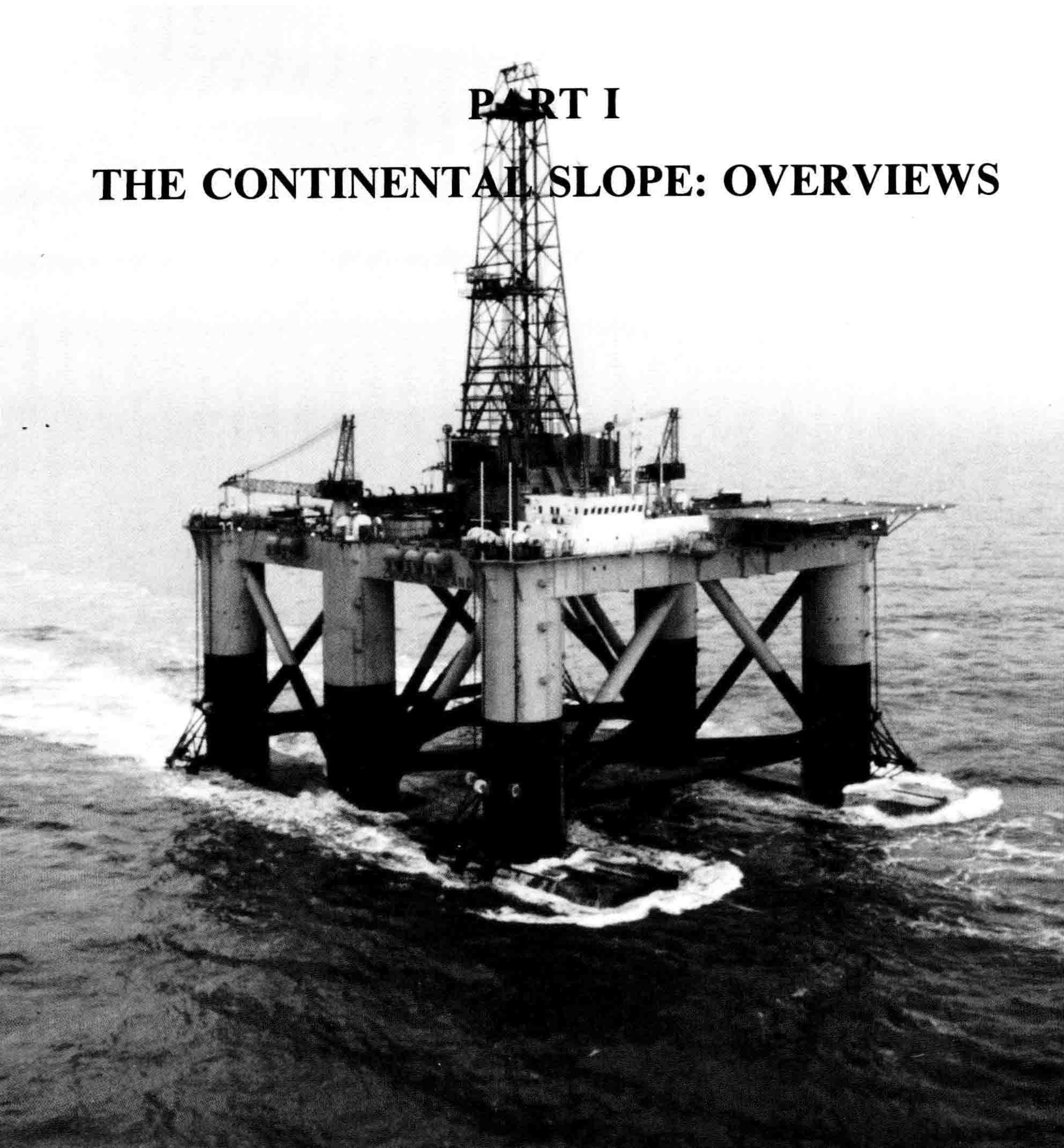
Part 3, ANCIENT CONTINENTAL SLOPES, presents in a series of chapters, current investigations of ancient slope deposits and the interpretation of the processes which were their antecedents. Cook's chapter bridges the gap between recent and ancient, pointing out that study of the past in many cases may be the key to understanding the present.

Finally, we would like to acknowledge Marina Doyle, whose artwork appears on the first cover and cover page, and Phyllis Frothingham and Sharlene Pilkey, who provided major contributions in technical editing.

LARRY J. DOYLE
AND
ORRIN H. PILKEY
Co-Editors

PART I

THE CONTINENTAL SLOPE: OVERVIEWS



GEOLOGY OF CONTINENTAL SLOPES

Edited by Larry J. Doyle and Orrin H. Pilkey, Jr.

CONTENTS

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CONTINENTAL SLOPES

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ABSTRACT

The continental slope is defined as the zone extending from the shelf break and terminating at the continental rise where the gradient becomes less than 1:40 or where the slope is bounded by a deep-sea trench or a marginal plateau. Although the slope is commonly the steepest physiographic province of the continental margin, a single simple definition cannot be given. Its width ranges from 20 to 100 kilometers; its upper limit at the shelf break normally starts in water depths between 100 and 200 meters; its lower boundary falls in the depth range 1400 to more than 3200 meters. The slope province can be smooth or terraced, may contain steep escarpments or intraslope basins, or can be very irregular as a result of slumping, fault scarps, or diapirs. Most slopes are cut transversely at many places in their upper part by submarine canyons that connect to deep-sea fans which form constructive sediment bodies on lower slopes, rise, trenches, and parts of the abyssal plain.

Because slopes are located in both active and inactive tectonic settings, the concepts of sea-floor spreading and plate tectonics are critical for interpreting the evolution of the slope. Construction by sediment up- and out-building, slumping and sliding, the influence of sea level fluctuations, reef formation or salt tectonics result in different slopes than are formed by the action of subduction and plate accretion alone. However, the accretionary basins in some active margin settings may have substantial sediment buildup as in passive margin settings.

As the transition zone between the continental shelf and the deep sea, the continental slopes form a major segment of sea-floor studies for scientific, economic and political reasons. Differing tectonic and depositional histories result in a variety of sediment suites and morphology, and in some areas these factors combine to produce conditions favorable for accumulation of economic quantities of oil and gas as well as selected hard minerals.

INTRODUCTION

The continental slope is the central part of the continental margin and is generally located above the transition between continental and oceanic crust. Morphologically, the slope starts at the shelf break. Its lower boundary, however, is less well defined, as it can lie in different physiographic provinces. Half of the world's continental slopes terminate in deep-sea trenches or shallower bordering depressions, the rest in continental rises or deep-sea fans (Curray, 1966). The continental slopes cover an area of approximately 28.7 million km^2, which is 5.6% of the earth's surface (Drake and Burk, 1974). Their lengths total more than 110,000 km (Stanley, 1969 b).

The term "continental slope" was proposed by Wagner (1900) for the entire area between the shelf break and the abyssal floor. Heezen, Tharp, and Ewing (1959, p. 18–19) restricted the term to "that relatively steep (3–6°) portion of the sea floor which lies at the seaward border of the continental shelf." Their definition is still in use and is sufficiently general to define the continental slopes despite their nonuniformity.

The physiographic components of continental margins have characteristics that depend on their tectonic and sedimentary histories. The sedimentary history is closely governed by sediment input and structural deformation. Yarborough (1977) distinguishes three fundamental styles of structural deformation related to evolution of margins and plate tectonics. The first is based on extensional tectonics caused by the break-up of the super continents. The second refers to the deformation of plate boundaries by shear-zone tectonics, while the third relates to subduction that occurs at the leading edge of moving plates.

An understanding of the structural style, geologic history, and types of sediment accumulation on slopes not only suits a scientific curiosity but is critical to the petroleum geologist who has to evaluate source rock and reservoir characteristics, influence of evaporites and related tectonism, maturation levels, effectiveness of seals, and other parameters.

Research by the academic and government oceanographic communities, as well as the petroleum industry, has provided a better, though still incomplete, understanding of the geologic processes of this physiographic province. More effort, especially from the industrial side, has been concentrated on the continental slope of the northern Gulf of Mexico than on any other slope in the world, and even knowledge gained by that effort is far from complete (see Bouma, Moore and Coleman, 1976, 1978).

MORPHOLOGIC CHARACTERISTICS

Nonuniformity of continental slopes makes it impossible to give a sharp definition of this physiographic province. The variation in shape, gradient, and location of the lower boundary makes it necessary to provide a lengthy description if all slopes are to be discussed. Shepard, in his "Submarine Geology" (1948, 1963, 1973), presents a tour du monde which is still the best available. In his third edition (1973), he combines the continental shelf and slope under the term continental terrace because of their close interrelations.

The upper boundary of the continental slope is at the shelf break, a physiographic feature usually easy to define. The break is found in water depths ranging from about 100 to 200 m and may be sharp or gradual, but the increase in slope can generally be found.

The lower boundary typically is gradual and located at depths ranging from 1400 to 3200 m of water, and locally at much greater depth. The most classical boundary is at the change into the continental rise where the gradient decreases to 1:40. This boundary is found in less than half of all continental slopes, however. Locally, the lower slope and the rise may be covered by a deep-sea fan, and where it is, no real lower boundary exists. In places the lower boundary is found in a depression, such as a deep-sea trench, where the continental slope may terminate at a depth of 10,000 m, or a shallower group of bordering depressions such as the southern California Borderland. Where such a borderland or a marginal plateau is present, the slope may be divided into two parts, one on the inner edge and one on the outer edge. The outer-edge slope is referred to as a marginal escarpment (Heezen, Tharp and Ewing, 1959).

The continental slope is a very narrow province, its width ranging from 20 to 100 km. As a consequence, it displays a relatively steep gradient, averaging 4.17° for the upper 1800 m (Shepard, 1973). Off major deltas, this angle may be 1.3°, off fault coasts with negligible shelves about 5.6°, off young mountain coasts 4.6°; the average slope over the upper 2000 m off stable coasts that have no major rivers averages about 3° (Shepard, 1963, p. 298). Within the realm of generalization, it can be stated that continental slopes in the Pacific are steeper than those in the Atlantic, and those in the Atlantic are steeper than those in the Indian Ocean. Steepness greater than 10° may occur in walls of submarine canyons and at places on margins of small basins such as those in the southern California Borderland (Emery, 1960). The steepest slopes observed are off coral islands, where the angle can be 45° down to considerable depth (Fairbridge, 1966).

The slope may be smooth, slightly convex, or irregular on a large or small scale. It may be terraced on the middle part as in the western Gulf of Alaska above the Aleutian Trench (von Huene and Shor, 1969; von Huene, 1972), or consist of an inner and an outer slope as in the southern California Borderland (Emery, 1960; Moore, 1969) or the Blake Plateau (Curray, 1966). The borderland consists of banks and islands with separating deep basins. In borderland regions, the continental slope is off the outer bank where the drop to the deep sea is located. The Blake Plateau is a marginal plateau of intermediate depth with a relatively smooth surface that separates the continental slope into an upper and a lower section. Smaller scale irregularities are produced by mass movement, folding and faulting, diapirism causing intraslope basins and highs, and slope erosion.

Slope trends are remarkably straight or gently curving and do not reflect the irregular nature of the shoreline. Such trends strongly favor structural control and/or smoothing by prograding sediments. Major deltas are an exception. Audley-Charles, Curray, and Evans (1977) recognize four principal types of modern deltas in terms of drainage patterns and tectonic setting: deltas on continental crust, at continental margins, at rifted continental margins, and at marginal ocean basins. Deltas that develop entirely on continental crust generally do not build over extensive marine evaporites that might underly a deltaic pile, nor are they likely to have a well-developed deep-water fan facies. In contrast, most major deltas developed at continental margins have a deep-water fan, commonly larger in volume than that of the shallow-water deltaic prism.

A dominant characteristic of the morphology of continental slopes is the many incisions cut more or less transversely. These submarine canyons may start near the top of the slope or even on the continental shelf. Where they head depends primarily on the width of the shelf and secondarily on the availability of sand and silt-sized material that can be transported by bottom flow from shallow to deep water, thereby causing erosion. These remarkable features are the feeders for sands and silts to deep-sea fans, continental rises and abyssal plains. Submarine canyons are influenced by different dynamic processes and contain in their axes sediments that are different from those normally found on the adjacent uncut parts of the continental slopes (Shepard and Dill, 1966; Whitaker, 1976; Shepard et al, 1977).

Origin and Internal Structure

Modern geophysical techniques and the Deep Sea Drilling Project have provided significant data needed to understand the internal structure and the origin of the continental slope and a base for replacing older theories by new ones. An attempt to review the great body of modern geologic literature falls beyond the scope of this paper. Most of those works can be found in Shepard (1973) and in the many bibliographies in edited publications such as those of Stanley (1969a), Bird and Isacks (1972), Kahle (1974), Burk and Drake (1974a), Bouma, Moore and Coleman (1976, 1978), and McFarlan, Drake and Pittman (1977).

One of the first contributions dealing specifically with the origin of the continental slope is a paper by Dietz (1964), who discussed a number of earlier views, and then proposed a new classification (Table I) (see also Emery, 1965; Fairbridge, 1966; Curray, 1969). Since the slope is part of the continental margin, it can belong to either an active or an inactive (passive) margin, depending on whether or not the margin is associated with young deformation, volcanism, or active seismicity. It should be kept in mind, however, that even passive margins are not undeformed (Burk and Drake, 1974b). Inactive margins are also known as Atlantic-type continental margins, though not entirely restricted to the Atlantic. They border the Arctic and Norwegian Seas, the north and south Atlantic except for some small areas (see below), the Indian Ocean except for the Sunda Sea, the Antarctic except for the Scotia Arc, the Bering Sea, the Sea of Okhotsk, the Sea of Japan, the South China Sea, and parts of the Mediterranean (Heezen, 1974). Tectonically active margins or Pacific-type continental margins (Fisher, 1974) are not all confined to the Pacific Ocean; they occur off the Antilles and South Antilles in the Atlantic and off the Indonesia-Sunda Trench in the Indian Ocean.

Thinning of the continental crust and transition to oceanic crust generally takes place underneath the continental slope. Specifically in active margins, however, this transition can become complex. On passive margins, the transition may lie underneath the shelf if progradation of the slope has taken place.

Emery (1977) distinguishes six distinct types of continental slope (Fig. 1) and mentions that some hard-to-define transitions exist. His first main type (Type A) consists of folded or faulted steps or ridges of rock more or less mantled by sediments. Steps may result from stretching, thinning, and isostatic sinking of continental crust during rifting or from deformation of post-rift sediments by rearrangement of crustal plates after rifting. Emery gives examples of type A slopes in the Atlantic (Fig. 1) in the following places: off southern Greenland, off northern Puerto Rico, in the Caribbean off Venezuela, Colombia and Panama, north slope off the Falkland Plateau, and off the northern and southern sides of the Bay of Biscay.

Slope type B is a progradational type, either as delta growth over the shelf edge or along continental margins with a large supply of detritial material from land. Layers of slope sediments very commonly continue seaward within the continental rise with no or few discontinuities. Good examples of Type B slopes, such as off Nova Scotia, inshore of the Blake Plateau, off Rio de Janeiro, off southwestern Africa, and off much of Europe (Fig. 1), are numerous.

Slope type C represents a continuation of shelves that are built upon pre-rift and initial rift rocks with surface irregularities that are small relative to the thickness of the covering sediments. The margin has been down-warped toward the ocean during the entire period of shelf sedimentation, causing shallow marine sediments to form a wedge with greatest thickness of from several to more than 10 km near the shelf break. The face of the continental slope is more or less continuously eroded by mass movement and bottom-density currents, causing a steepening, possi-

TABLE I—CLASSIFICATION OF CONTINENTAL SLOPES

		Example	Declivity
I.	*Primary* (Structural)		
	Flank of accretionary orogen (usually collapsed continental rise prism)	California (Mesozoic); West coast of South America	Steep Steep
II.	*Secondary* (Structural)		
	Continental Rift Scar	Atlantic coast of Africa (?); Gulf of California	
III.	*Secondary* (Modified by Sedimentation)		
Type	1. Face of prograded paralic beds	Atlantic coast of USA	Moderately steep
	2. Up-lapped Continental Rise	Parts of Antarctica	Gentle
	3. Continental Embankment (uplapped continental rise in turn converted by delta foreset beds)	Gulf Coast of USA, Texas and Louisiana	Very gentle
	4. Carbonate up-building (atoll-like)	Florida (west coast) Yucatan	Very steep

(After Dietz, 1964)

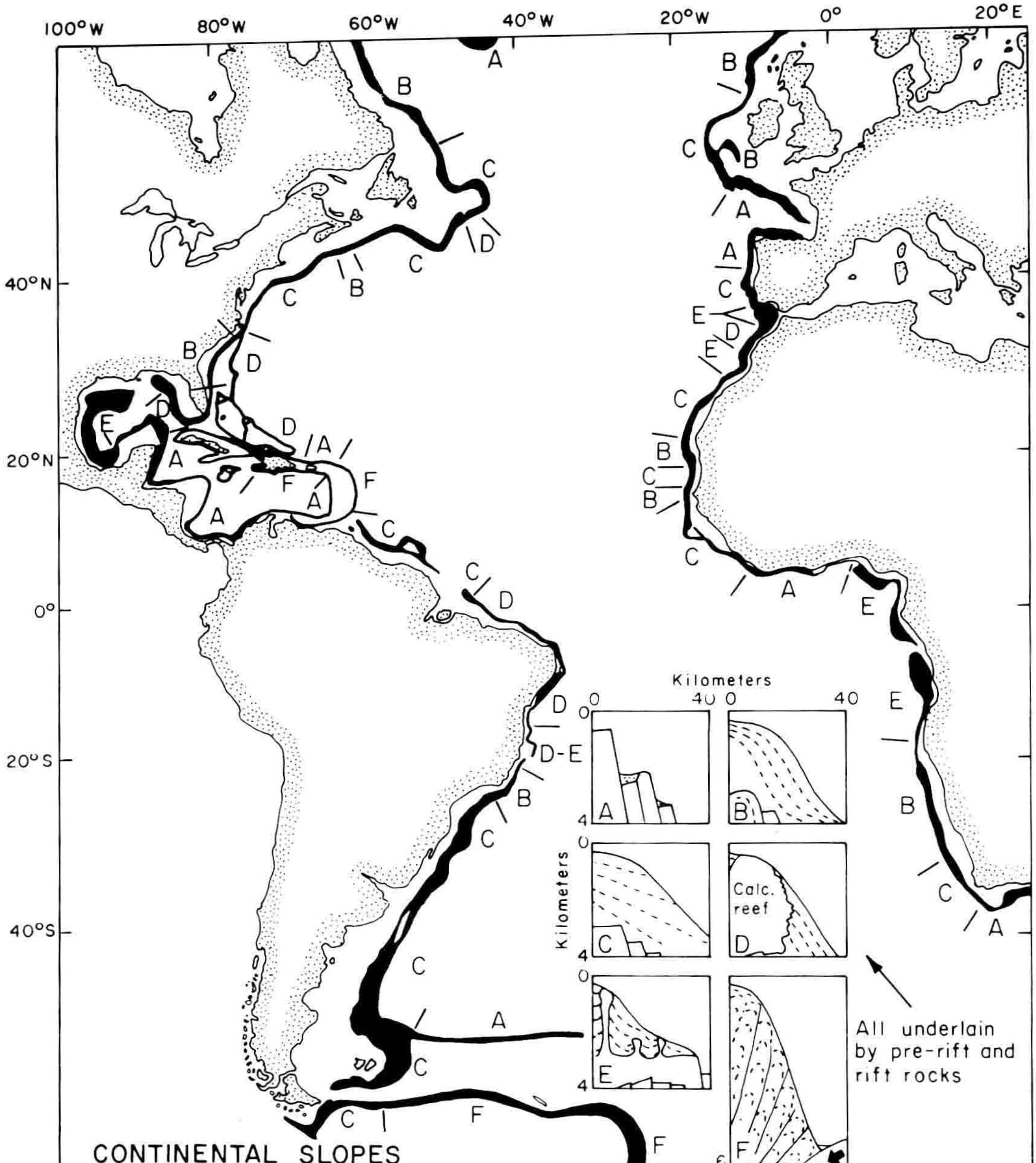

FIG. 1.—Types and distribution of continental slopes in the Atlantic Ocean. Redrawn with permission from K. O. Emery (1977, Fig. 5).

bly a response to a slight rotation during the down-warping. This type of continental slope is the most common in the Atlantic Ocean (Fig. 1).

Slope type D is related to type C in history but differs in that the continental slope is supported by the growth of massive calcareous reefs. The thickness of these reefs requires large subsidence of the underlying crust. The reef may be exposed as a steep outer escarpment or its flanks may be covered by predominantly calcareous sediments. This type slope is restricted to near-tropical waters of the present time, where the input of terrigenous material is low.

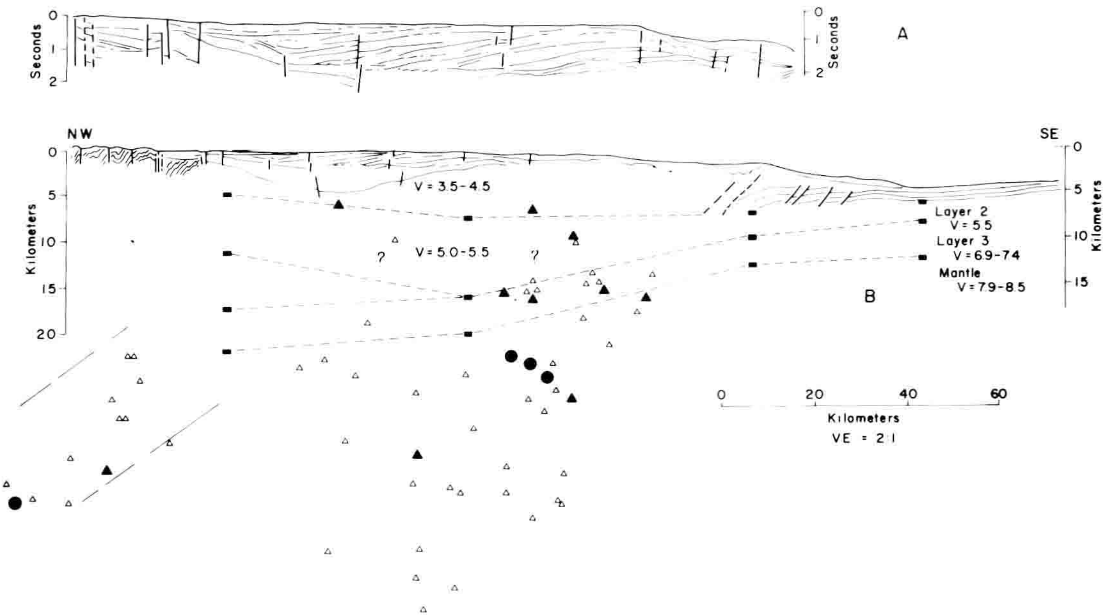

FIG. 2.—Cross section from Kodiak Island to Aleutian Trench, based on 24-fold multichannel record. A) a reflection section. B) depth section. Hypocenters: filled triangle located with more than 50 stations; open triangle located with 10-50 stations; filled circle located from more than 50 stations with depth from $_{p}$p phase. Velocity V in km/s. Dashed lines from Shor and von Huene (1972), geology of Kodiak Island from Moore (1969). Reproduced with permission from R. von Huene.

Slope type E is controlled by evaporite layers and their resulting diapirs, commonly an extension of a similar-type shelf. This group includes the mud and shale diapirs, chiefly a product of prodelta clays. The best known examples are in the Gulf of Mexico, in particular near the Sigsbee Escarpment (see contributions in Bouma, Moore, and Coleman, 1976, 1978), off Angola-Gabon, and off Nigeria (Fig. 1). Sediments become strongly deformed under diapiric action and very irregular bottoms with highs and lows result. Salt diapirism in northwestern Gulf of Mexico is known to prograde seaward, thereby bringing rise sediments to slope depths and slope deposits to shallower locations (Watkins, Worzel, and Ladd, 1976; Watkins et al, 1978).

Emery's last slope type (F) incorporates those structures that are related to convergence. The underthrusting process scrapes off sediments riding on top of the oceanic crust, mixes them with lower continental slope and trench sediments, and deforms the mix into stacked wedges with shearing in between or in any of a number of other arrangements (Fig. 2) (see also Seely and Dickinson, 1977). Although this type can be found in the Atlantic Ocean (south of Puerto Rico and Hispaniola; outer Antilles arc; south of Falkland Plateau), it is far more common in the Pacific.

Both active continental margins and flanks of active island arcs are associated with plate consumption that generates arc-trench systems. Subduction in trenches is reflected by deformation of sediments lying on oceanic crust and can involve part of the upper basement as well. As subduction continues, the deformed rocks form a mass of growing bulk known as the subduction complex (Seely and Dickinson, 1977). Apparently, this complex grows in width as successive increments are added by underthrusting at the trench, and at the same time it tends to grow upward and becomes a positive structural feature. Part of the continental slope in deep-sea trench areas is called the trench inner slope (i.e., from the trench-slope intersection to the first major change in inclination above this intersection) to differentiate it from the trench outer slope, the area between the trench and the seamount chain bordering the adjacent abyssal plain (Fig. 3) as can be observed in the Aleutian setting. This example is actually somewhat unique when considering the rest of the Pacific basin because the trench outer slope may not have a seamount chain and no abyssal plain. At least the lower part of the trench inner slope is generally underlain by the subduction complex, a thick section of deformed abyssal plain and trench deposits containing vari-

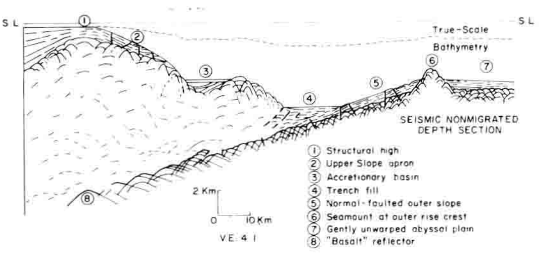

FIG. 3.—Composite diagram of common active margin characteristics. Redrawn with permission from D. R. Seely and W. R. Dickinson (1977, Fig. 6).

able proportions of oceanic crustal pieces (Seely, Vail, and Walton, 1974). This section of lower slope is covered in places by a rather thin veneer of lower slope sediments. It is characterized by a highly irregular surface with accretionary basins and structural bathymetric highs (Fig. 4). The upper part of the inner slope of many trenches is covered by a rather thick sediment apron that has prograded across the edge of the shelf or has been transported by contour currents. Such slopes are found in the eastern Aleutians, Mid-America, Peru-Chile, Tonga-Kermadec, and Japan.

Plate-surface deformation may decrease from the toe of the slope in an upslope direction and faults steepen landward because of the active belt of thrust and folds that influences the abyssal plain and trench sediments scraped off the underthrusting plate. Normally the thrusts dip landward in areas where inner-slope structure can be discerned, and associated folds have seaward vergence. This gives a prevailing landward dip at lower structural levels beneath the slope, causing progressive landward tilting of accretionary basins seen in the steeper landward dips of former slope-basin sedimentary units. Landward vergence is also observed in some cases (Seely, 1977).

The characteristics of the sediments overlying any part of the continental slope are thus constrained by their tectonic and sedimentary histories. Geotechnical properties of the slope's surfi-

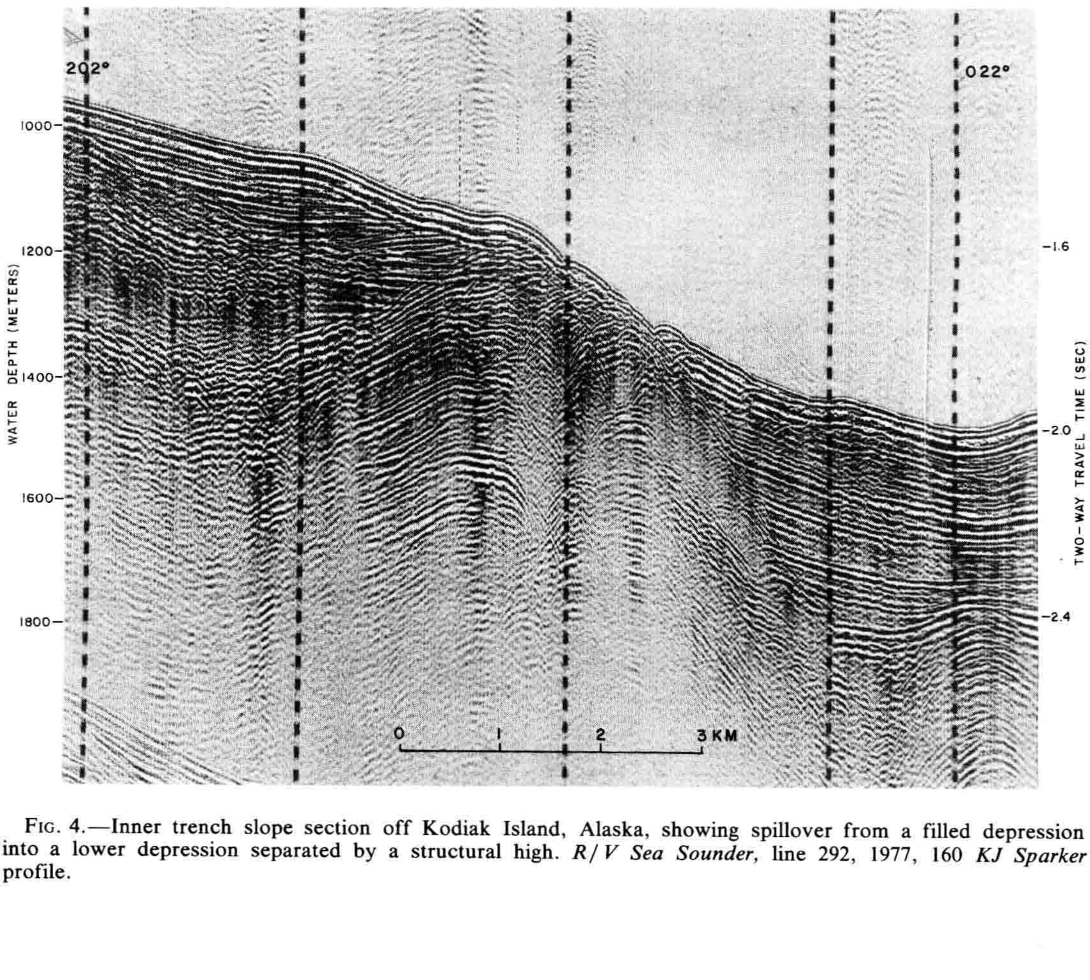

FIG. 4.—Inner trench slope section off Kodiak Island, Alaska, showing spillover from a filled depression into a lower depression separated by a structural high. *R/V Sea Sounder,* line 292, 1977, 160 *KJ Sparker* profile.

cial sediments are critical to an understanding of the history of a slope segment.

Sediments and Processes

Sediments.—Mud is the predominant sediment on the continental slope with lesser amounts of sandy and gravelly material. Rock outcrops are common on steep slopes off narrow shelves adjacent to mountainous coasts (Cotton, 1918; Shepard, 1948, 1963 1973; Stanley, 1969a, b; McCave, 1972; Stanley and Swift, 1974). Carbonate sediments are less represented but can be a major constituent in certain regions (Milliman, 1974). In general, the slope sediments are finer than those on the adjacent shelf and continental rise.

Utilization of high-resolution seismic techniques can provide insight into the structural and depositional characteristics of the sediments. Several workers are using the seismic facies models from Sangree and others (1976, 1978) or follow similar approaches. Additional coring and shallow drilling can provide the ground truth and stratigraphy needed to get full value from the seismic results (e.g., Amery, 1976, 1978; Mitchum, 1976, 1978; Sidner, Gartner, and Bryant, 1977, 1978). Damuth and Hayes (1977) demonstrated the value of 3.5 kHz high-frequency precision depth recordings for studying the depositional/erosional processes on the sea floor on the basis of the character of the echo. The echo also reflects the amount of coarse material present. A combination of seismic and coring/drilling is to be expected to provide data needed to understand the sedimentary processes responsible for the materials encountered at any part of sea bottom.

Sea-level Changes.—Several workers stress the significance of sea-level changes as well as tectonic processes as a control of amount and coarseness of sediment supply (Emery, 1968a; Curray, 1977; Vail, 1977; Sidner, Gartner, and Bryant, 1977, 1978). During sea-level lowering, an increase of river runoff takes place and coarse sediments are transported to an advancing coastline that may come close to the shelf break. Stanley, Fenner, and Kelling (1972) stated that transport across the shelf break during low stands of sea level certainly takes place where the shelf is wide. Consequently, an influx of granular material can be moved onto the continental slope under the influence of currents and waves, causing sheet flow or slumping.

During a rising sea level, less material arrives at the shoreline owing to a decrease in gradient of the lower reaches of a river system that results in deposition and reestablishment of a gradient of those lower reaches before sediment can arrive at the shore. Further, the transgressive shoreline will prevent much of the "grainy" material from

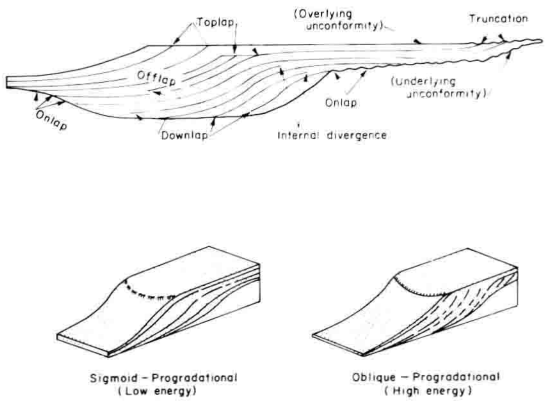

FIG. 5.—Seismic stratigraphic reflection terminations and shelf-margin seismic facies types. Redrawn with permission from P. R. Vail (1977, Figs. 1, 6).

being transported across the submerged shelf to the shelf break unless a vast growing delta progrades faster than the retreat of the land/sea boundary.

Vail (1977) and Vail et al (1977) recognize depositional sequence boundaries on seismic records by identifying reflections caused by lateral termination of strata, termed onlap, downlap, offlap, and truncation (Fig. 5). Age and areal distribution can be used to determine relative changes in sea level (Fig. 6). Sidner, Gartner, and Bryant (1977, 1978) combined seismic facies with textural and paleontological data and interrelated climatic zones with eustatic sea-level changes and with depositional characteristics for the northwest Gulf of Mexico outer shelf and upper slope (Fig. 7).

Input of Fine-grained Material.—About 8×10^9 tons per year of fine-grained suspended sediment will be deposited on the world's slope and the rise, the greater part going to the large deep-sea fans in front of major supply points of fine-grained materials such as the Ganges, Indus, and Mississippi Rivers (McCave, 1972). Although the transgressive period is lacking activity in a depositional sense, recent investigations clearly reveal that the area slope is far from quiescent.

Several processes take place under the influence of general meteorological and climatological conditions. Pierce, Nelson, and Colquhoun (1972) observed intrusion of colder slope water onto the shelf during winter and spring months, primarily a result of greater density of coastal waters at lower temperatures. Cascading of cold shelf water over the Carolinian Slope surface resulted from this temperature drop. During late summer and early fall, these workers observed intrusions of slope water onto the shelf caused by upwelling

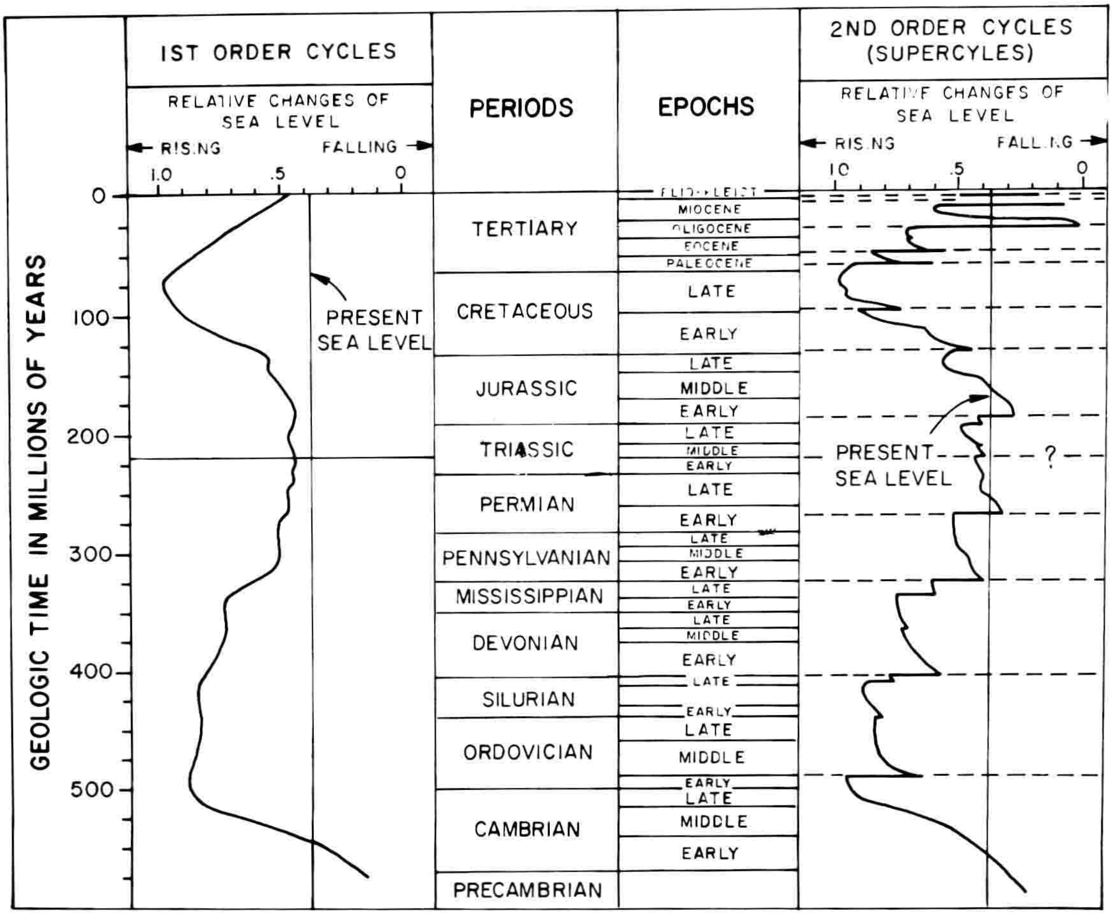

FIG. 6.—Relative changes of sea level based on seismic reflection stratigraphy. Redrawn with permission from P. R. Vail (Vail et al, 1977, Fig. 1).

and thermal stratification that prevented mixing. Such flows are strong enough to move fine bottom sediment or prevent deposition of fine-grained matter.

Bruce (1977) demonstrated the seasonal character of the Somali Current, which develops between May and September during the southwest monsoon in the Indian Ocean. The highest velocities, 350 cm/sec at the surface, were measured during July and August. Such a current is comparable to the Gulf Stream and the Kuroshio, but differs by being shallower (200–400 m) and basically wind driven. The current turns sharply in an offshore direction, and cold upwelling water is found in the turning area. Again, bottom effects were not investigated, but the impact may be considerable.

Internal Waves.—Cacchione and Wunsch (1974), in dealing with realistic periods and amplitudes, showed upslope amplification of near-bottom velocities beneath internal waves onto the continental margin. This will cause incipient movement of sediments of a wide range of sizes found on the outer shelf and upper slope, even prior to breaking of the waves (Cacchione and Southard, 1974). The experiments of Southard and Cacchione (1972) showed that near-bottom velocities in the zone of internal-wave breaking are much greater than the amplified velocities just downslope. It seems likely that breaking internal waves are capable of moving sediments, although direct observations are lacking. Southard and Cacchione (1972, p. 96) suggested that several dominant effects in their experiments might be observed when internal waves impinge onto the continental margin:

"1. Breaking of the waves, with advance of large decaying vortices upslope and return flow of mixed fluid downslope, creating a band of

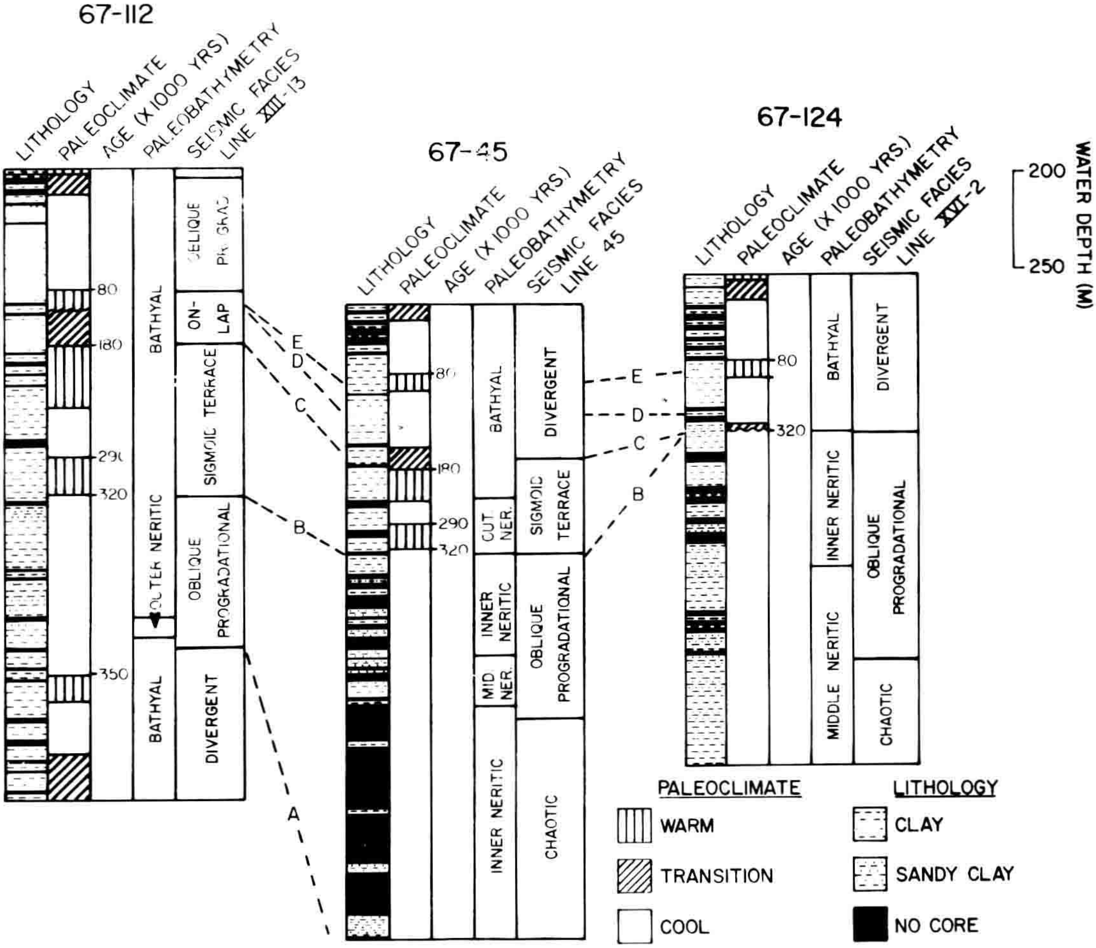

FIG. 7.—Lithologic, chronologic, paleoclimatic, paleobathymetric, and seismic facies summary from three drill sites in northwest Gulf of Mexico. Reproduced with permission from B. R. Sidner (Sidner, Gartner, and Bryant, 1978, Fig. 6).

sediment movement with width at least an order of magnitude greater than the wave amplitude;

2. Abrupt onset of sediment movement at the point of breaking and gradual decrease in intensity downslope;

3. Predominant downslope movement of sediment except near the breaking point, causing deposition in a narrow band just upslope of the point of breaking and erosion in a wide band farther upslope;

4. Generation of downslope-migrating bed forms in the wide band of net downslope sediment transport; and

5. Suspension of fine sediment by the advancing breakers and horizontal transport away from the slope in the mixed layer.

In regard to generation of bed forms, the downslope flow would produce trains of asymmetrical sediment ripples migrating downslope provided only that the current is strong enough to transport at least some sediment as bedload (and that sediment is not coarser than about one-half millimeter). If the maximum downslope velocity, attained not far upslope of the point of breaking, is great enough, dunes or sand waves migrating downslope might also be produced (Simons and Richardson, 1963; Southard, 1971). In regard to suspension of fine sediment, horizontal spreading of mixed fluid away from the slope at the appropriate density level might contribute to the development of turbidity maxima observed in oceanic thermoclines (Costin, 1970)."

Tidal Effects and Submarine Canyons.—Stanley, Fenner, and Kelling (1972) discussed the tidal influence of water masses in transporting coarse sediment from the outer shelf onto the upper slope. Their observations in submarine canyons and the many contributions from Shepard and his co-workers demonstrate that slow progradation of the outer continental shelf is continuing as modern spillover. These modern depositional processes continue to modify the shelf-break environment.

Dill and other investigators demonstrated in the late fifties and early sixties that inner shelf sediments transported along the coast by longshore currents can end up in the heads of submarine canyons. This trapping is particularly critical on narrow shelves when such canyons start close to shore (see Shepard and Dill, 1966).

Although it is generally accepted that turbidity currents originate from shallow-water sediment trapped in the upper reaches of submarine canyons, the less spectacular daily processes in submarine canyons and fan valleys commonly result in a net upward motion under the action of tidal forces that have a concentrated effect in these continental slope incisions. Shepard et al (1977) recently demonstrated the existence of a cycle consisting of a relatively strong upcanyon flow followed by a rapid build-up of a much stronger downcanyon current too weak to register. By their observations, these flows are slow turbidity currents activated by river, floods and favorable storm conditions. They distinguish two types of canyons. One type is present off large rivers with a clear relation to river mouths. The processes here are primarily marine; turbidity currents will be initiated at frequent intervals off such river mouths when large masses of relatively coarse material are introduced onto the sea floor which slopes steeply into deep water. The other type of canyon lies off large deltas that have built across the shelf; they are characterized by a large number of valleys cutting the advancing slopes.

Carbonates.—Although carbonate-containing continental slopes are less common than noncarbonate slopes, their presence warrants more than just their mention. Milliman (1974) has summarized much of the literature about carbonates; detailed discussions and references can be found in his book.

Marine carbonates are divided into shallow water (reef and upper shelf), sublittoral (shelf and upper slope: 20–300m), and deep sea (>200 m). Milliman (1974) states that the percentage of total carbonate in slope sediments averages 5.8% (see also Sverdrup, Johnson, and Fleming, 1942). The average carbonate deposition rate on the slope is 1.5 $g/cm^2/1000$ yrs. This value may be subject to revision when further data become available.

The sublittoral zone is the transition from shallow to deep sea. Decrease in temperature and amount of light penetration, accompanied by an increase in hydrostatic pressure characterizes this zone. Many present-day transitional carbonates consist of material that was deposited during the last rise in sea level (Milliman and Emery, 1968). Calcium carbonate solubility depends on the temperature of the water. Emery (1968b) suggested that biogenic carbonate deposition increases in lower latitude shelves and correspondingly is more important on the warmer western sides of the ocean than on the eastern sides. Complications arise where there is an influx of terrigenous sediment causing dilution and burial of many carbonate producing organisms. The carbonate content of the upper continental margin is, however, a first-order function of sediment supply and a second-order function of water temperature and corresponding carbonate productivity. One observes a decrease of benthonic foraminifera and a relative increase in planktonics from the outer continental shelf onto the upper slope. In addition one commonly finds echinoid spines in upper slope sediments.

Owing to a greater current activity and larger distances from rivers, many outer continental shelves and uppermost slopes contain deposits that are richer in carbonates than those on the adjacent inner shelf. Encrusting coralline algae, together with corals, bryozoans and barnacles form a prominent facies along the shelf edge. Barnacles tend to decrease toward tropical latitudes, a trend that is likely due to certain fish that graze seemingly continuously on the substrate, preventing settlement of larvae.

Many outer shelves and upper slopes in water depths of 40–100 m are characterized by small topographic highs rising normally not more than 1–5 m above the surrounding bottom allowing them to be covered with various carbonate producing organisms and sediments. Such algal ridge system or reef is discontinuous and tends to parallel the shelf break. The substrate normally is algal that started during low stands of sea level. It is suggested that increased biological productivity at the shelf break due to upwelling is the main reason for their location. Their inception during early-transgression is partly supported by the presence of oolites on many shelves and upper slopes. Modern oolites tend to form in warm, agitated water, generally in depths less than 2 m. The reddish-brown color and the 10–15 thousand-year age based on carbon-14 dating make those brown oolites relict. Their position outside the algal ridge system in depths greater than 163 m, however, is still hard to explain.

Instability.—Instability phenomena, predominantly slumps, are common features on the slope proper. Unstable conditions can result from "rapid" accumulation due to the nearness of a sediment source, sudden impinging forces such as large storm waves or earthquakes, tectonic upwarping resulting from diapiric activity or upheaval of the upper plate in a subduction zone as demonstrated by Hampton and Bouma (1977), and Hampton et al (1978) (Fig. 1). Quantitative information is still far from abundant although an increase in marine geotechnical studies can be noted. Such investigations, together with seismic surveying, side-scan sonar, direct bottom observations, coring, drilling and current and wave measurements, become a high priority task for understanding natural hazards as part of scientific and applied research (Hampton et al, 1978).

ANCIENT CONTINENTAL SLOPES

A study of the present continental margins commonly requires evaluation of their past history as well as an understanding of old margins now completely encased in continental crust (Burk and Drake, 1974a, b). Ancient continental margins in a general sense have been studied since the early days of geology, and during the past few decades the concepts of sea-floor spreading and plate tectonics have found their way into these studies. The body of available literature is overwhelming; some of the more recently edited works provide the more informative papers and bibliographies (see Burk, 1965; Kay, 1969; Bird and Isacks, 1972; Burk and Drake, 1974a; Dickinson, 1974; Dott and Shaver, 1974; Kahle, 1974; McFarlan, Drake, and Pittman, 1977).

Since the continental slope is part of the continental margin and tectonically not a unit by itself, no author has singled out this physiographic province for an in depth publication. The ancient slope is mentioned and sometimes described in sedimentological contributions as part of submarine canyon-deep sea fan studies where channelized facies cut into shaly slope deposits. Specifically worth mentioning are the Italian contributions (Mutti and Ricci Lucchi, 1972, 1975; Mutti, 1977) and subsequent investigations based on their work (e.g., Walker and Mutti, 1973; in Dott and Shaver, 1974; in Whitaker, 1976; Nilsen, 1977; Bouma and Nilsen, 1978).

ECONOMIC ASPECTS AND CONSIDERATIONS

Hedberg and Moody (1977, p. 62) claim that a review of the "probable geology of the continental slopes and rises over the world conclusively shows that the petroleum prospects of these oceanic realms are at least good enough to justify extensive exploration drilling, if, as, and when, there is demand for petroleum at prices adequate to cover the costs of production in these environments" (see also Hedberg, 1970). Weeks (1974) indicated that about 4.6×10^6 km^2 of continental slope may be prospective for hydrocarbons.

Although organic-rich sediments are commonly found in the oxygen minimum zone, which ranges from 200 m to 400 m off Peru (Hafferty et al, 1978), organic-rich deposits do occur at much greater depths on the continental slope (Suess, 1976). We know little in detail about the present slope as the recent studies of the northern Gulf of Mexico intraslope basins have shown (Bouma et al, 1975, 1976, 1978; Trabant and Presley, 1978; McKee et al, 1978) (Fig. 8). Moreover, Dow (1977) notes that continental slopes and rises are commonly the sites for high organic productivity because of nutrients supplied by upwelling and river runnoff. Slope sediments average 0.6–1.0% by weight organic carbon, which makes them the most organic-rich continental margin deposits. Appropriate time and temperature conditions are required to convert organic matter to petroleum, which means 2 to 4 km of burial is required for oil generation and 3 to 7 km for gas, depending on the geothermal gradient, rate of accumulation, and age of the source section. One of the major problems is to find reservoir rocks with adequate porosity and favorable structure. Except for carbonate areas we have to search for the submarine canyon-deep sea fan systems, as the slope sediments normally are too clayey to provide sufficient porosity and permeability (see also Yarborough, 1977).

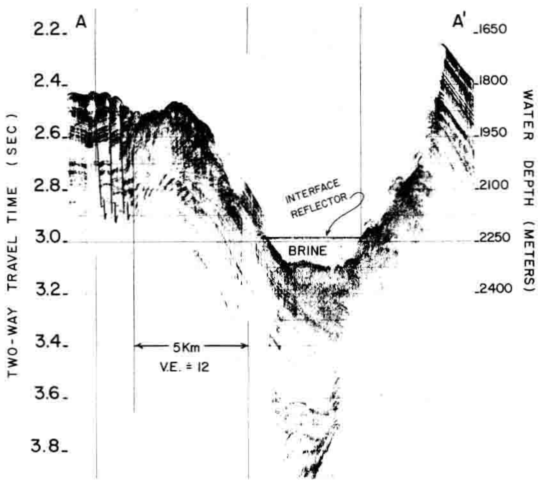

FIG. 8.—High-resolution, 3.5 kHz, seismic profile over the Orca Basin, north central Gulf of Mexico, showing a strong reflector between normal sea water and the brine. Reproduced with permission from P. K. Trabant (Trabant and Presley, 1978, Fig. 3).