

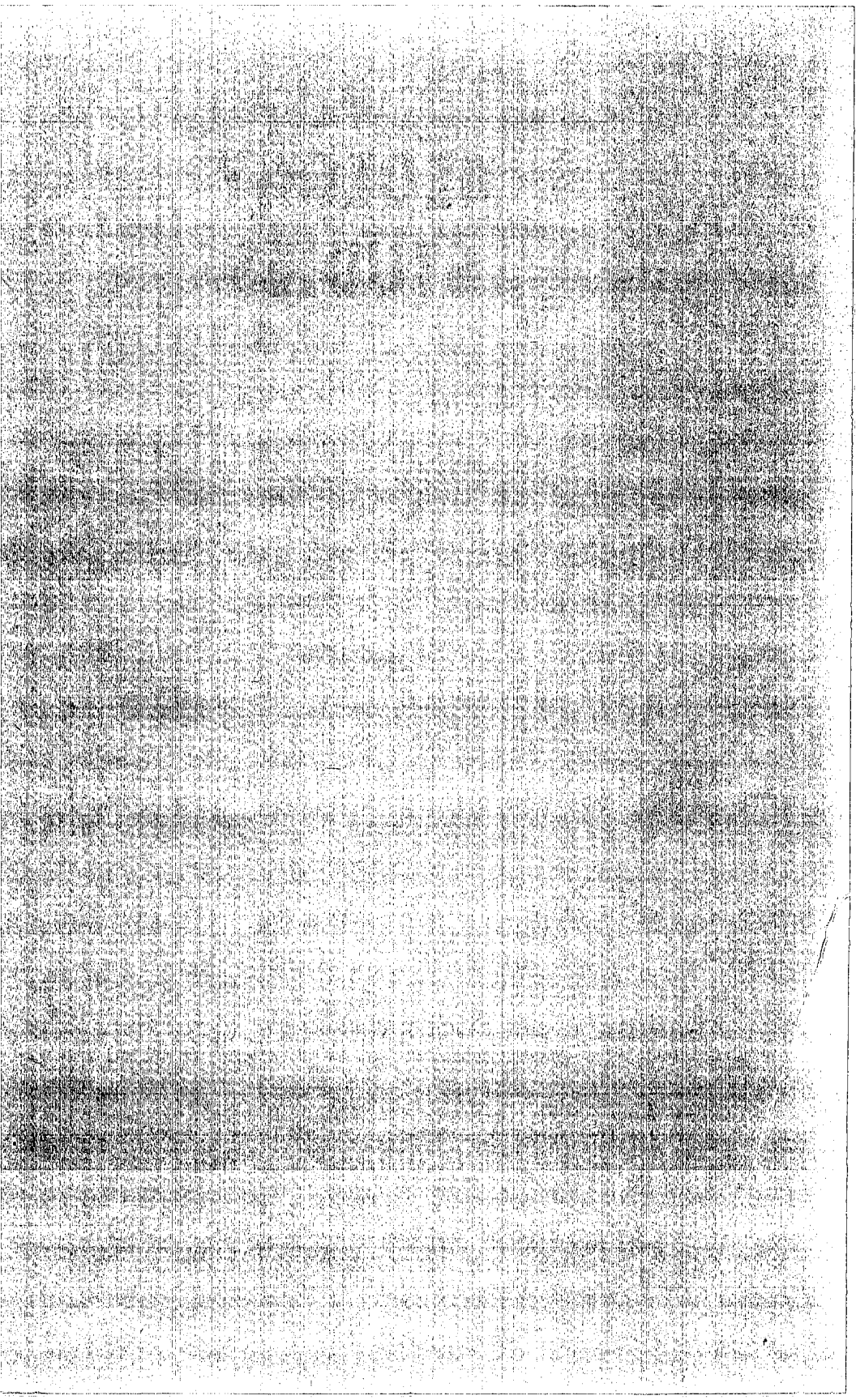
GEOLOGY STUDIES

Volume 14

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Paleoecology of Some Leonardian Patch Reefs in the Glass Mountains, Texas*

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ABSTRACT.—Excellent exposures of small patch reefs occur in Leonardian strata north-east of Split Tank on the Appel Ranch in the Glass Mountains of West Texas. A detailed examination of these reefs in an area 800 feet wide and 2200 feet long resulted in the recognition of several reef-associated faunal and lithologic facies.

They developed on a shallow, extensive shelf which was bordered on the north and northwest by a subsiding basin and the southeast by the eroding Marathon Folded Belt. Through time, subsidence caused a shelfward transgression of environments. With subsidence of the shelf, patch reefs migrated shoreward over a dolomitic limestone sequence into the study area in late Hess time. Reefs on the shelf margins produced a protected shelf environment. Patch reefs were constructed in 30 to 35 feet of water by *Acanthocladia*, calcareous sponges, fistuliporid bryozoans and calcareous algae, and rose to within 5 to 10 feet of sea level. Massive accumulations of bioclastic material surround reef structures and provided shoals inhabited by mollusks, bryozoans, echinoderms, fusulinids, brachiopods and rugose corals.

Subsidence increased depth of water at the close of Hess time, within the study area, submerging shelf-margin reefs and causing local destruction of the patch reef environment. Basal silt of the Cathedral Mountain Formation was deposited over a locally unconformable contact with the Hess limestone. As seas deepened, a varied siliceous sponge fauna migrated onto the shelf and inhabited this silt-bottomed environment.

With decreased subsidence, reef barriers formed on the shelf margin in the study area, producing a protected environment over the adjacent shelf. *Acanthocladia*, fenestrate and fistuliporid bryozoa, and calcareous algae constructed reefs in about 60 feet of water. Vast aprons of bioclastic sediment which circumscribe reef cores have been divided into bioclastic, molluscan, reefoid, and flank-back facies. Productid and richthofenid brachiopods, fenestrate bryozoa and rarely calcareous sponges formed shell banks and in some instances produced reefoid structures.

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*A dissertation submitted to the faculty of the Department of Geology, Brigham Young University in partial fulfillment of the requirements for the degree, Doctor of Philosophy, November 2, 1967.

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INTRODUCTION

Since 1858, the Permian strata and fossils of the Glass Mountains and Trans-Pecos Texas have attracted geologists, resulting in volumes of classical studies, including regional and historical geology, systematic paleontology, structural and tectonic geology and paleoecology. Combined, these studies have produced a geologic understanding of an area, for a particular period of geologic time, which is unrivaled elsewhere in North America. The present study was based on moderately detailed previous works and an abundance of compiled information. It has developed into a detailed investigation of an extremely small area within this well-studied and described larger framework.

The detailed paleoecology of the reef environment with respect to organic relationships within the reef, lithology of the rocks in which the reefs are found, and the sedimentary environment in which they formed, have been neglected in previous works. The present study is concerned with such detailed lithologic, ecologic and sedimentologic investigation of numerous small Leonardian patch reefs exposed in a limited belt in the Glass Mountains. Experience during this study proved that a detailed examination on a small scale could make possible interpretation of even the most subtle changes, and could give deeper insight into the most significant aspects of the reef environment. Many reef studies such as P. B. King (1931) in the Guadalupe Mountains, Newell *et al.* (1953) with the Permian reef complex, Lowenstam (1950) and Pitcher (1964) with the Silurian reefs of the Great Lakes region and Ordovician reefs of northeastern United States respectively, have preceded and greatly aided this investigation,

but nearly all these have concerned either large areas or extensive structures where it was impossible to note more than the gross relationships.

The Split Tank area on the Appel (Old Word) Ranch in the Glass Mountains provides an excellent opportunity for a detailed paleoenvironmental reef study. A strike valley in the Leonardian and lower Wordian strata exposes a complete section of the transition between the Hess and Cathedral Mountain Formations (see Cooper and Grant, 1966, for nomenclatural history) where numerous small patch reefs occur. Strata dip gently to the northwest and reef structures up to one hundred feet high and two hundred feet in diameter are well exposed in the rolling topography of the strike valley.

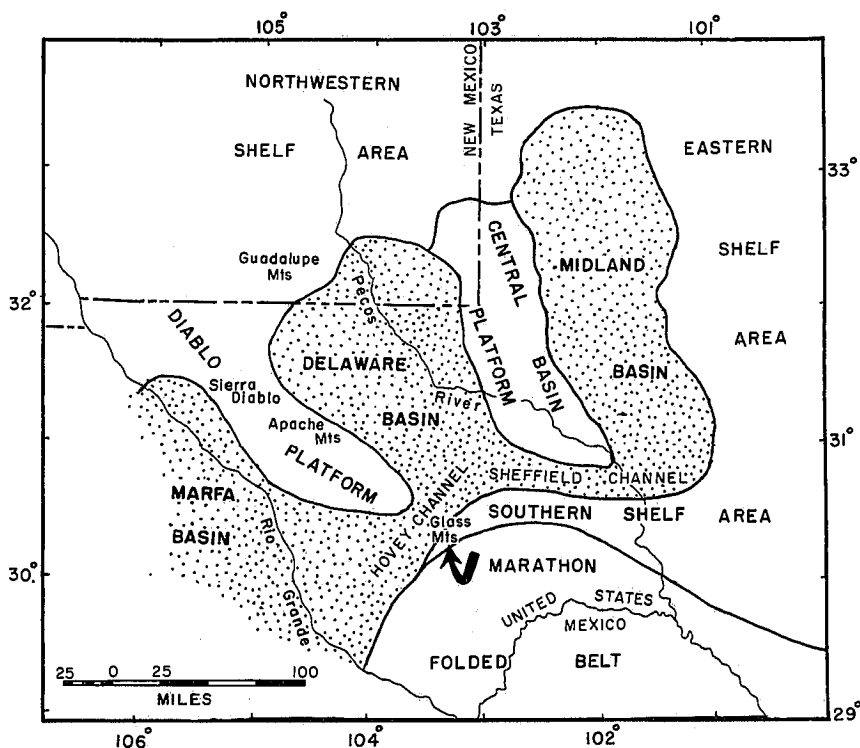
Small size, accessibility and excellent exposure of the small reefs made the area an ideal subject for the desired study. Abrupt lateral and vertical differentiation of various reef and inter-reef facies is easily distinguishable. The compact area of study enabled the author to examine and sample on an exceedingly small scale the lithology, paleontology and sedimentary features of the strata.

GEOLOGIC SETTING

Carboniferous.—Throughout the southwestern United States, Early Mississippian was a time of nondeposition, during which Lower Paleozoic sediments were eroded. Seas entered the region again during Late Mississippian time, depositing limestone and vast amounts of clastic sediments derived from the rising Ilanoria, to the southeast. Pennsylvanian sedimentation began with limestone which overlapped eroded Lower Paleozoic rocks. This limestone is overlain by terrigenous debris, derived locally from folds rising out of the depositional area. Deformation from the Marathon Orogeny advanced northwestward, during Late Pennsylvanian time, climaxing in tight folds and thrust faults affecting Carboniferous strata of West Texas (P. B. King, 1931, p. 51). Following culmination of the Marathon Orogeny, Late Pennsylvanian erosion reduced the uplifted area to moderately low relief.

Permian.—Early Permian seas transgressed over this somewhat subdued topography depositing Wolfcampian conglomerate and limestone. These shallow, but extensive seas entered from the Gulf of Mexico through Mexico (P. B. King, 1931, p. 89) and divided into two branches: one extending through Nebraska as far north as Wyoming, and the second into the southern Cordilleran region of Arizona, New Mexico and Utah. Maximum transgression of the eastern tongue occurred during Wolfcampian time, followed by withdrawal at the close of the epoch. Strata were then gently deformed by a late pulse of the Marathon Orogeny. These gently folded strata were eroded to varying depths before Early Leonardian seas invaded.

Shallow Leonardian seas transgressed into two subsiding basins, the Midland Basin and the Delaware Basin separated by a platform (Text-figure 1). The local rate of subsidence exceeded that of deposition, increasing the areal extent of basin deposits until Late Leonardian. At this time, the basins had reached their maximum areal extent, but they continued to subside reaching a maximum depth during Guadalupian time. Depth estimates for various areas have ranged from 500 feet (P. B. King, 1934, p. 788) to 2400 feet (Adams, 1936, p. 789). The most recent calculation of maximum relief between reef crest and basin floor along the western margin of the Delaware Basin is 1800 feet (Newell *et al.*,



TEXT-FIGURE 1.—Structural features of Permian age in western Texas and southeastern New Mexico. (After P. B. King, 1934, *Bull. Geol. Soc. America*, v. 45, p. 704.).

1953, p. 189). By Guadalupian time, the Delaware and Midland Basins covered large portions of West Texas and New Mexico. More than 10,000 feet of Permian sediments were deposited within this area, 7,000 feet during the Leonardian and Guadalupian alone. Marked lateral variation in lithology and thickness is characteristic of the Permian strata of western Texas and southeastern New Mexico. This variation is related to two controlling factors: 1) continued differing subsidence of the shallow sea floor, and 2) reef development marginal to subsiding basins.

Subsidence of previously shallow sea bottoms to form moderately deep stagnant basins resulted in marginal deposits being overlain locally by shelf and later by basin sediments during Leonardian time. Reefs developed in shallow marginal areas adding further lateral facies variation to the rocks. Patch reefs occur in Wolfcampian, Leonardian, and Early Guadalupian sediments of the Glass Mountains, Sierra Diablo, and Guadalupe Mountains (Text-figure 1). These patch reefs grew on and parallel to the shelf and migrated shelfward as the area continued to subside. Larger and more extensive barrier reef structures occur in Middle Guadalupian strata in the Glass, Apache, and Guadalupe Mountains. These reefs controlled sedimentation in two ways: 1) by acting as barriers to normal circulation which resulted in the formation of a hypersaline environ-

ment behind the structures, and 2) by supplying bioclastic material to the basin margin, enabling basinward growth of the reef over the basin facies (Newell, *et al.*, 1953, p. 12-14).

GLASS MOUNTAINS

The Glass Mountains are situated between the towns of Marathon and Fort Stockton in Brewster and Pecos counties in western Texas (Text-figure 2) and extend for almost fifty miles in a northeast-southwest trend, essentially parallel to U. S. Highway 385. The mountains are formed of dominantly Permian limestone and dolomite which dip gently to the northwest and expose a nearly complete Permian section. Limited areas of Permian sandstone and conglomerate, Cretaceous limestone, and Tertiary igneous rocks are also present.

Permian sedimentary rocks exposed in the Glass Mountains were deposited on the Southern Shelf between the Delaware Basin and the eroding Marathon Folded Belt (Text-figure 1). Late Permian warping gently tilted these shelf and marginal basin carbonate strata. Cretaceous (Comanchean) limestone was deposited unconformably over these Permian rocks (refer to works: Ross, 1963, Plate I; Stehli, 1954, p. 268, fig. 3). Patches of this Cretaceous limestone cap the higher summits. Post-Cretaceous movements warped the Marathon area into a broad dome. The Glass Mountains are a remaining northwestern flank of the eroded dome, standing 1000-2500 feet above surrounding plains of the Marathon Basin. Topographic relief within the area is the result of differential erosion of nonresistant units within the limestone of the Wolfcampian, Leonardian and Guadalupian strata and Tertiary and Quaternary faulting (Adams, 1965, p. 2148).

LEONARD SERIES

P. B. King (1931, p. 52-89) divided Leonardian strata of the Glass Mountains into two formations: Hess and Leonard. At that time he subdivided each formation into an eastern and western facies defined on lithology, stratification characteristics, thickness, and presence or absence of shale and marl interbedded with the dominant limestone. With more detailed study P. B. King (1932) concluded that the two formations were laterally equivalent. Massive limestone and shale of the Leonard Formation are shelf facies equivalent to the marginal Hess thick-bedded dolomitic limestone. Progressive transgression of the shelf environment resulted in deposition of Leonard facies over marginal Hess sediments. Ross (1963, p. 33) has discussed the nomenclatural history in great detail, and the reader is referred to this work for further information. Cooper and Grant (1966, p. E2-E6) redivided and reinterpreted these same strata. Their work has resulted in raising the Leonard Formation of King to series rank, with the Hess Formation as the lower unit in eastern outcrops. The Cathedral Mountain Formation, essentially equivalent to King's Leonard Formation, is the upper unit of the Leonard series. King's facies concept of the Hess and Cathedral Mountain (Leonard) Formations is still considered valid.

Hess Formation.—The Hess Formation, within the study area, consists of 1100 feet of thickly bedded to massive, light to medium-gray limestone and dolomite which cap the southeastern escarpment of the Glass Mountains. The dominant lithology is dolomite and dolomitic limestone, however, siliceous shale, quartz pebble conglomerate and calcitic limestone are locally dominant

in scattered areas throughout the facies. Shale and marl are relatively more dominant and more thinly bedded as the section increases in thickness in the eastern Glass Mountains. The facies thins to the west and massive limestone becomes the dominant lithology.

The Hess fauna is impoverished, although crinoidal debris occurs throughout. Locally fusulinids are extremely abundant. Sponge-algal reefs with abundant accessory organisms occur near the upper boundary of the formation.

Cathedral Mountain Formation.—At Split Tank, the Cathedral Mountain Formation consists of 250 feet of thick-bedded clastic limestone, but the section thickens to the west with an increase in sandstone. The dominant lithology of the Cathedral Mountain Formation within the map area is a bioclastic, medium gray to dark brown limestone which contains varying amounts of crinoidal debris. Marked lateral lithologic variation within the study area is related to the occurrence of small patch reefs in the lower part of the formation. Pebble conglomerate beds which were derived from eroding pre-Permian rocks to the southeast are scattered throughout the formation.

A buff-brown, siliceous, shaly siltstone 180 feet thick, separates the Hess and Cathedral Mountain Formations in the study area. This siltstone contains quartz silt and thin beds of gray limestone. Abundant burrows and trails and an abundant siliceous sponge fauna occur within this shaly unit.

Contact between the Cathedral Mountain and Hess Formations has been interpreted as conformable but it may be locally unconformable (P. B. King, 1931, p. 62). At Split Tank, lithology of both the upper Hess and lower Cathedral Mountain beds changes abruptly in association with numerous small patch reefs which measure up to 200 feet across and up to 100 feet high. A marked increase in organisms and bioclastic material is associated with these structures.

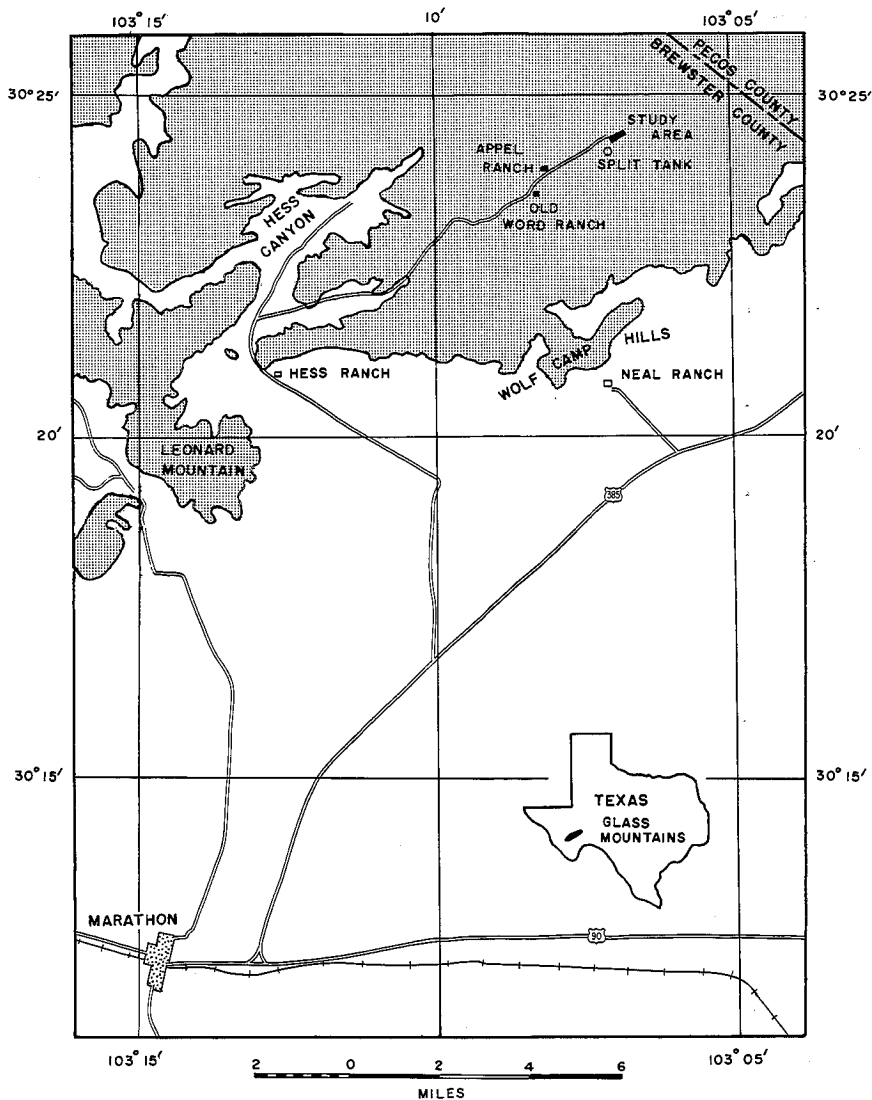
Detailed examination of these patch reefs, their fauna, paleoecology and influence on sedimentation of the environment are the subjects of this study.

PLAN OF WORK

The Appel (formerly Word) Ranch is located in the Glass Mountains, approximately nineteen miles northeast of Marathon, Texas (Text-figure 2). Split Tank is about one mile northeast of the ranch house and is shown on P. B. King's (1931) map. The area has been collected for numerous systematic studies in the past, R. E. King (1931), Knight (1941), Yochelson (1956, 1960), Batten (1956, 1958), Finks (1960), Cooper and Muir-Wood (1960). A strike valley in the Leonardian and lower Wordian strata here exposes the transition beds between the Cathedral Mountain and Hess Formations where small patch reefs occur. Rolling topography of about 200 feet relief provides excellent exposure and accessibility enabling the writer to study rocks of this transition in great detail.

A small area, 800 feet wide and 2200 feet long, which offered the best exposure was selected. Size of the area was purposely limited so as to allow close examination of even the most subtle changes.

Exposures are sufficient to allow tracing of individual beds across the area even though the zone is one of marked lateral variation as a whole. A plane table map was prepared using these beds as marker horizons. Closely spaced



TEXT-FIGURE 2.—Index map showing study area and outcrops in surrounding region. (From Cooper and Grant, 1966, U. S. Geol. Survey Bull. 1244-E, pl. 1).

traverses were made across the area (Plate 15), sampling all lithologic changes at small intervals. At the same time, descriptions were made of lithology, stratification characteristics, appearance of weathered outcrops, and the faunal elements; lateral and vertical changes in these properties were noted. Horizontal distances between individual samples rarely exceed 35 feet and are usually less than 10 feet. Observable lithologic and faunal changes were

sampled and described. Obvious facies boundaries were mapped and interpreted while in the field. Sample traverses were spaced from 4 feet to 100 feet apart as was dictated by the lateral facies changes. Locations of samples and traverses were plotted on the plane table base map (Plate 15).

A total of four months was spent in the field during the summers of 1965 and 1966. This schedule allowed the author to sample and examine the various facies both in the field and laboratory and follow by reexamining and resampling the following season.

Over 300 thin-sections were prepared for petrographic and paleontologic study. These thin-sections were prepared from each lithologic and biologic facies. Identification and distribution of the fossils and organic relationships between the different elements of the fauna and between the fauna and the sediment were determined in the field and laboratory. Thin-sections, polished slabs, and acetate peels were prepared from non-silicified samples. Samples containing silicified fossils were similarly prepared and in addition were etched in hydrochloric acid to remove matrix from the fossils. Identification and paleoecologic interpretations were greatly aided by the excellent preservation for which these fossils are famous.

In addition to the identification of the carbonate minerals, thin-sections were also studied for purposes of fabric analysis and mineralogy and were classified according to a system proposed by Folk (1962).

Paleoecologic conclusions were drawn from the combined information gathered from the examinations described above. Relationships of organism to organism and organism to sediment were determined from as many avenues of study as possible. From these determinations, the conditions existing in this patch reef environment were interpreted.

PREVIOUS WORK

Previous works related to the present study can be grouped into three categories: 1) regional geology and stratigraphy, 2) systematic paleontology, and 3) reef faunal and facies studies. A summary of these studies provides an unequaled compilation of geologic knowledge and understanding of a particular system, area, and fauna.

Early stratigraphic and structural studies of the Glass Mountains and adjacent areas were conducted primarily by Udden and P. B. King. Their studies resulted in publications on the Glass Mountains (Udden 1917, P. B. King 1931), Trans-Pecos Texas (P. B. King 1934), Marathon Region (P. B. King, 1937), Guadalupe Mountains (P. B. King 1942, 1948), and Sierra Diablo (P. B. King, 1965). Skinner (1946) correlated Permian strata within southeastern New Mexico and West Texas. Ross (1963, p. 33) summarized nomenclatural history of West Texas Permian units, but recently Cooper and Grant (1966) subdivided several of the original units and proposed a more detailed stratigraphic nomenclature.

Recent papers on systematic paleontology of Upper Carboniferous and Permian fossils have proven to be excellent references for identification of organisms of the reef and interreef communities. Because of the unusual preservation of the Permian fossils in the Glass Mountains, several papers have described faunas collected from the same area or areas adjacent to that of the present study. Most significant of these systematic papers for the present study

are the following: Algae, Johnson (1942, 1951); Brachiopoda, R. E. King (1931), Stehli (1954), Cooper and Muir-Wood (1960); Cephalopoda, Plummer and Scott (1937), Miller and Furnish (1940); Crinoidea, Moore and Plummer (1940); Fusulinidea, Ross (1963); Gastropoda, Knight (1941), Batten (1956, 1958), Yochelson (1956, 1960); Pelecypoda, Newell (1937, 1942); and Porifera, Finks (1960).

Numerous reef studies provided excellent models from which the author was able to determine the most suitable approach for the present detailed investigation. Although most of these works concerned structures of ages other than Permian, techniques of examination, faunal association, descriptions of facies characteristics, and interpretations of these studies were valuable in the recognition, examination, description, and interpretation of this patch reef association. Among the most significant papers are those by Fairbridge (1950) on Recent and Pleistocene reefs of Australia; Hadding (1950) on Silurian reefs of Gotland; Henson (1950) on Cretaceous and Tertiary reefs of the Middle East; Lowenstam (1950) on Niagaran reefs of the Great Lakes Region; Newell *et al.* (1953) on Permian reef complex of Texas and southeast New Mexico; Ingels (1963) on a Silurian reef of Northeastern Illinois; Klován (1964) on a Devonian reef of Alberta; and Pitcher (1964) on Ordovician reefs of eastern United States and Canada.

Acknowledgments

The author expresses his appreciation to many individuals who have aided in this study, but in particular: Dr. J. Keith Rigby, whose advice, suggestions, and preliminary base map helped immeasurably in examination and interpretation of the environment and in the preparation of this publication; Mr. Carl Appel, owner of the Appel Ranch, and his family who made the field study a much more pleasant experience and whose constant interest lent encouragement to the author; Mr. R. P. Hoeger, who aided in plane tabling the study area; and to my wife, Leslie, who typed the many rough drafts.

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HESS FORMATION

The Hess Formation in the central Glass Mountains can be described in general as a monotonous series of homogeneous, thickly bedded to massive, light-gray crystalline dolomite and dolomitic limestone. The formation is more varied in uppermost beds where several sedimentary and biologic facies related to small patch reefs can be differentiated.

Hess Dolomite and Dolomitic Limestone

Approximately the lower 950 feet of the Hess Formation, as exposed near Split Tank, consists of monotonous, sucrosic dolomite which contains few fossils except for scattered fusulinids and crinoidal fragments. Brachiopods, gastropods, and cephalopods are present but are rare and scattered.

Randomly spaced tongues of pebble conglomerate occur throughout the section. Flooding of these conglomeratic tongues into a carbonate environment has been discussed by Adams (1965, p. 2146) who suggests that periodic

block faulting of eroding land masses adjacent to the basin produced conglomeratic sediments. Well-rounded pebbles of these conglomeratic beds were derived from Ordovician and Devonian sedimentary formations which are currently cropping out immediately to the southeast. This same area of Early Paleozoic exposures was the location of the eroding Marathon Folded Belt at the time of the Hess deposition.

Crinoidal fragments occur throughout the Hess Formation, both as scattered floating fragments and as concentrations in lenses, such as at locality 908, Plate 15 (E-5). The columnals appear as white areas with rhombic cleavage in a light-gray, finely crystalline dolomitic limestone. Most fragments are within coarse arenite to fine rudite grain size.

Fusulinids occur in similar manners, both scattered throughout the section and concentrated into lenses. Scattered fusulinids in the dolomitic limestone are irregularly oriented. On the weathered surface they appear as molds or imprints, but within the rock they are less altered. Strata containing these imprints generally weather to a meringue-like surface. Crinoidal debris is commonly intermixed with scattered fusulinids, but wherever either is concentrated into lenses, they are mutually exclusive.

Fusulinids occurring in concentrated lenses, such as at locality 909, Plate 15 (E-5), show a distinct orientation parallel to the bedding and each other. They are obviously a well-sorted, lag deposit with a sparry calcite matrix (Plate 4, fig. A). This orientation of well-sorted tests in sparry calcite matrix suggests the area was subject to moderately high energy conditions. Ross (1961, p. 299) reports that similar lenses of fusulinids occur throughout the Hess Formation. Lenses of both crinoidal fragments and fusulinids appear to be current accumulations, but both groups of organisms probably lived within or near the environment of deposition. Crinoidal debris is commonly cited as an indication of normal marine conditions, and fusulinids have been cited as evidence for shallow, normal marine water within a moderately high energy environment (Newell, 1957, p. 431; Ross, 1961, p. 399; and Thompson, 1948).

Dolomitic strata of the Hess Formation were deposited as calcitic sediments on a shallow nearly normal marine shelf which was inhabited by fusulinids, crinoids, small numbers of brachiopods, gastropods, and cephalopods. The shelf was bordered on the northwest by subsiding basins and on the east by the eroding Marathon Folded Belt and extensive shallow shelf areas (Text-figure 1). Clifton, (1944, p. 1016) in examining extensive shelf sediments north of the Glass Mountains, reported the existence of hypersaline environments. Patch reefs developed on shelf margins producing an environment which was somewhat protected from vigorous wave action present in the deeper basins. Stehli (1954, p. 232, fig. 5) recognized a similar environment for the deposition of the Bone Springs Formation in the Sierra Diablo region.

Such a topographic setting is similar to those existing during Permian time in the Guadalupe Mountains region and presently on Bonaire. The mechanism suggested by Newell, *et al.* (1953), and shown to work by Deffeyes *et al.* (1965) explains the formation of the Hess dolomite and at the same time explains the occurrence of a normal marine fauna in dolomitic sediments. Magnesium-rich solutions formed on the extensive shelf areas and the shore environment of the Marathon Folded Belt surrounding the depositional site of

the Hess Formation and migrated basinward through the Hess sediments dolomitizing them.

Hess Limestone and Reef Facies

In late Hess time subsidence of the area and protecting reefs caused the environment to change from that in which dolomite and dolomitic limestone formed. As shown on Plate 15 (B-5 and J-4 through M-3) both the lithology and the diversity of the fauna of the Hess Formation changed markedly from the monotonous and homogenous, sparsely fossiliferous, sucrosic dolomite and dolomitic limestone of the lower Hess, to calcitic clastic limestone where both lithology and fauna display abrupt lateral and vertical variation. This lithologic change, as well as the biologic change is related to the formation of small patch reef structures. Four distinct facies including: interreef facies, bioclastic facies, molluscan facies, and reef core facies have been recognized as related to these patch reefs. Each of these will be described separately on following pages.

Interreef Facies

The term "interreef facies" is applied to those strata which occur with patch reefs but which show little or no effect of this association. They appear similar to sedimentary strata of the same age which occur distant from the patch reef environments. The only indication of biocenters nearby is the scattered occurrence of individual faunal elements of the reef community and a slight reefward increase in bioclastic material. It is stressed that their occurrence is not limited to between reef structures.

The interreef facies consists of dark-gray micritic limestone with fine-grained silicified bioclastic material and clay mud. Clay mud comprises up to 40 percent of the rock, but it usually is much less abundant. Fine-grained fragments of crinoid columnals and bryozoans form most of the bioclastic material, however, fragments of brachiopods, gastropods, and cephalopods are present but are far less common. Clay and siliceous silt are present in varying amounts ranging up to 10 percent of the rock volume. Strata are thin- to medium-bedded and are best developed off the flanks of reef structures such as at localities 920 and 928, Plate 15 (K-3). Interreef sediments weather to smooth, medium-gray surfaces, but on freshly broken surfaces the rock appears dark and commonly emits a petroliferous odor.

Well-rounded siliceous pebbles, identical to those described from the lower Hess dolomite, occur within the interreef facies, but here their occurrence is much more scattered. These pebbles continue throughout the upper Hess and lower Cathedral Mountain Formations, again reaching an appreciable concentration at the contact between the two formations. Only the reef core and reefoid facies of both formations lack pebbles.

Reef-derived bioclastic material is present as rare elements within the interreef sediments but also in tongues which extend outward from reef areas and are interbedded with interreef strata. Normal interreef strata may grade laterally into the bioclastic facies associated with reef structures indicating penecontemporaneous deposition (Locality 928, Plate 15, K-3). Vertically, however, sharp contacts between interreef strata and bioclastic tongues suggest that deposition of bioclastic material was catastrophic, possibly during

storms. This high-energy deposition temporarily replaced normal interreef deposition (Locality 921 and 922, Plate 15, K-3).

Sediments of the interreef facies were deposited in low, protected areas between reef structures. Individual beds, such as at locality 920 and 928, Plate 15 (K-3), have been correlated with contemporaneous reef core sediments and indicate that up to twenty-five feet of relief existed at the time of deposition. This relief can account for the energy difference indicated by sediments of the different facies. Greater relief seems indicated between localities 896 and 952, Plate 15 (M-3), however, much of this apparent sedimentary relief resulted from differential compaction and loading beneath the reef core.

There are now no indications of any organisms which lived in the fine lime muds of the interreef environment. Fossils which are found within the strata are interpreted as having been carried into the environment, perhaps from associated reef knolls and flanks. All individuals are scattered and isolated adult forms, none of which occur in growth position. Many show distinct evidence of transportation, such as single isolated brachiopod valves or broken rugose corallites and bryozoa branches. In all cases, specimens lack preservation of any delicate structures. Fossils found within the interreef beds occur in large numbers in either the reef, reefoid, or flank-bank facies. Storm waves washing over these slightly elevated areas could have dislodged these organisms and carried them off into the adjacent muddy, low-energy interreef environment.

Bioclastic Facies

Sediments of the bioclastic facies occur as: 1) massive bioclastic limestone accumulations which surround reef cores and contain reef core breccia (Locality 883, 937, 940, 941 and 954, Plate 15, L-3 and M-3) and 2) tongues and thin beds of bioclastic material which extend outward from these massive bioclastic deposits (Localities 963, 964 and 965, 0-3 and west of 883 and 894, Plate 15, L-3).

Bioclastic Beds.—Tongues of the bioclastic facies consist of biosparite and biosparudite. Bioclastic material is predominantly fragments of fenestrate bryozoan branches and crinoid columnals. Fragments of brachiopods, corals, gastropods, and lime clasts are present in small amounts. Sparry calcite matrix forms approximately 20 to 30 percent of the rock. Noncalcareous siliceous pebbles, like those previously discussed, occur within the bioclastic facies but are quantitatively insignificant. Their presence simply indicates a terrigenous source still existed and that currents within the study area were still strong enough to transport pebbles of this size.

The nearby growth of organisms supplying bioclastic material to the sediments is suggested by several lines of evidence. Fragments are not rounded to any noticeable extent. Delicate structures are commonly present on bryozoa fragments suggesting that very little transportation occurred. Whole fossils are present and some, such as rugose corals and prorichthofenid brachiopods, appear to be in growth position with their attachment still intact. There seems to be a lack of sorting in the bioclastic material which also indicates an absence of appreciable current action.

Fenestrate bryozoa fragments dominate the preserved fossil record in the bioclastic facies. Their occurrence in great numbers on adjacent reef flanks

explains their abundance in these associated beds. Locally crinoid columnals are quantitatively more significant than bryozoa fragments, but in general this is not the case. Attempts to relate the dominant crinoidal areas to a definite pattern failed, but their occurrence is interpreted as locations of crinoid meadows as suggested by Ingles (1963, p. 419). As Ingles stated, crinoid meadows seem to occur within a moderately high-energy environment on the margins of reef structures. Skeletons of dead individuals would readily become disarticulated in this environment producing the vast quantities of bioclastic material associated with reefs.

EXPLANATION OF PLATE 1

CATHEDRAL MOUNTAIN EXPOSURES

- FIG. A.—Molluscan Facies—Concentration of cephalopods and gastropods in outcrop of micritic limestone in Cathedral Mountain Formation near locality 1025. Area shown in photo is approximately 2.0 feet long.
- FIG. B.—Molluscan Facies—Concentration of bellerophonitid gastropods and several cephalopods in micritic limestone in Cathedral Mountain Formation at locality 439. Area shown is approximately 2.5 feet long.
- FIG. C.—Reefoid Facies—Reefoid accumulation within Cathedral Mountain Formation of *Prorichthofenia* in biomicrudite at locality 459. Area shown is approximately 3.0 feet long.
- FIG. D.—Strata of bioclastic facies draping over reef core and flank facies deposits of Cathedral Mountain Formation near locality 311.

EXPLANATION OF PLATE 2

EXPOSURES OF CATHEDRAL MOUNTAIN TRACE FOSSILS
AND HESS REEF CORE

- FIG. A.—Interreef Facies—Trace fossils (vertical burrows) piercing thin, dark, micritic limestone of the Cathedral Mountain interreef near locality 994. Photo shows area approximately 2.5 feet wide.
- FIG. B.—Reef Core Facies—Weathered surface of micritic Hess reef core near locality 945. Calcareous sponges appear dark, calcareous algae appear medium-gray and travertine appears light. Photo shows area approximately 1.5 feet wide.
- FIG. C.—Reef Core Facies—Alignment of *Amblysiphonella* and *Cystothalamia* in Hess reef core at locality 899. *Girtyocoelia* is also present. Dark calcareous sponges are surrounded by medium-gray algae and light travertine in micritic limestone. Photo shows area approximately 1.5 feet wide.

EXPLANATION OF PLATE 3

CATHEDRAL MOUNTAIN OUTCROPS

- FIG. A.—Molluscan Facies—Articulate valves of pelecypods in outcrop of micritic limestone in Cathedral Mountain Formation at locality 802. Bottom of photo shows area approximately 15 inches long.
- FIG. B.—Reef Core Facies—Silicified algal mat at locality 1006 within micritic Cathedral Mountain Formation reef core. Bottom of photo shows area approximately 15 inches long.
- FIG. C.—Reef Core Facies—Alignment within fenestrate bryozoan reef core within the Cathedral Mountain Formation at locality 555. Bottom of photo shows area approximately 2 feet long.

EXPLANATION OF PLATE 4

PHOTOMICROGRAPHS OF HESS AND CATHEDRAL MOUNTAIN LIMESTONES

All figures X5

- FIG. A.—Fusulinid concentration within Hess dolomites at locality 909. BYU Collection 1359.
- FIG. B.—Calcareous sponge filled with sparry calcite within reef core at locality 155. BYU Collection 1360.
- FIG. C.—Biomicrudite of bioclastic facies located adjacent to reef structures containing dominantly bryozoan fragments. Locality 355, BYU Collection 1361.
- FIG. D.—Biomicrudite of reefoid facies containing spiriferid brachiopod with spirallium intact and finer bryozoan fragments. Locality 762. BYU Collection 1362.

EXPLANATION OF PLATE 5

ETCHED BANK AND REEFOID STRUCTURES

- FIG. A.—Etched reefoid structure consisting of ivanovid algae and fenestrate bryozoa. Locality 471, BYU Collection 1336, (X2).
- FIG. B.—Etched reefoid structure consisting of *Prorichthofenia*, fenestrate bryozoa and calcareous sponges from Locality 707. BYU Collection 1337, (X5).
- FIG. C.—Epiphytic growth of *Prorichthofenia* and fistuliporid bryozoa near Locality 69, BYU Collection 1338, (X1).
- FIG. D.—Epiphytic growth of crinoid, *Derbyia*, *Prorichthofenia*, and fistuliporid bryozoa. Near locality 69, BYU Collection 1338, (X1).

EXPLANATION OF PLATE 6

PHOTOMICROGRAPHS OF HESS AND CATHEDRAL MOUNTAIN CARBONATES

All figures X5

- FIG. A.—Biosparudite of reefoid facies showing bryozoan and crinoidal fragments in sparry calcite. Locality 484, BYU Collection 1341.
- FIG. B.—Biomicrudite of reefoid facies consisting of bryozoan and crinoidal fragments in micritic calcite. Locality 488, BYU Collection 1342.
- FIG. C.—Biosparudite of bioclastic facies containing bryozoan and crinoidal fragments and quartz pebbles. Locality 57, BYU Collection 1343.
- FIG. D.—Biomicrite of reefoid facies containing light phylloid algal plates. Locality 423, BYU Collection 1344.
- FIG. E.—Oolites in micritic and microsparry matrix. Locality 900, BYU Collection 1345.
- FIG. F.—Silicified productid brachiopod spines in micrite of reef core margin. Locality 857, BYU Collection 1347.
- FIG. G.—Bioclastic material in microsparry calcite matrix of reefoid facies. Fragments consist of echinoderm and bryozoan fragments and foraminifera. Locality 479, BYU Collection 1348.

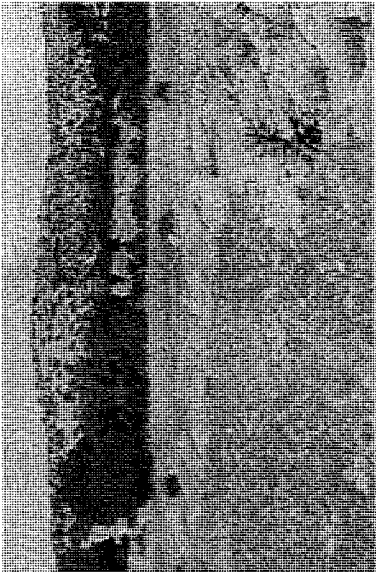
EXPLANATION OF PLATE 7

PHOTOMICROGRAPHS OF HESS AND CATHEDRAL MOUNTAIN LIMESTONES

- FIG. A.—Breccia block of reef core material within biosparudite of reefoid facies. Locality 414, BYU Collection 1349, (X2).
- FIG. B.—Pelletooidal limestone of pelsparudite of reefoid facies. Near locality 405, BYU Collection 1351, (X5).
- FIG. C.—Alternating layers of micrite and sparite with several layers showing graded bedding from the reefoid facies. Near locality 773, BYU Collection 1352, (X2).
- FIG. D.—Biomicrudite of reefoid facies containing fragments of brachiopod and siliceous sponge. Locality 497, BYU Collection 1350, (X5).
- FIG. E.—Breccia blocks of reef core material in biomicrudite of Hess reefoid facies. Locality 881, BYU Collection 1353, (X5).



B



D



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C



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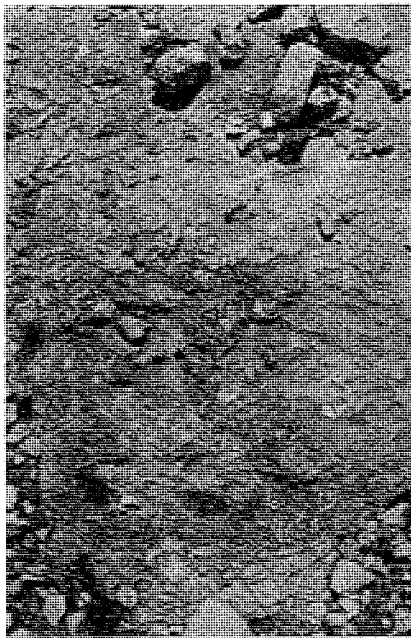
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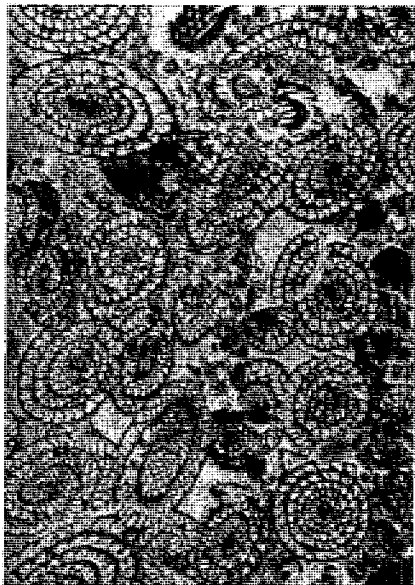
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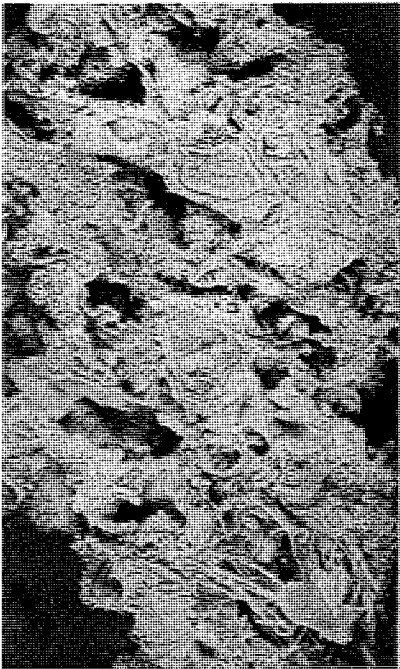
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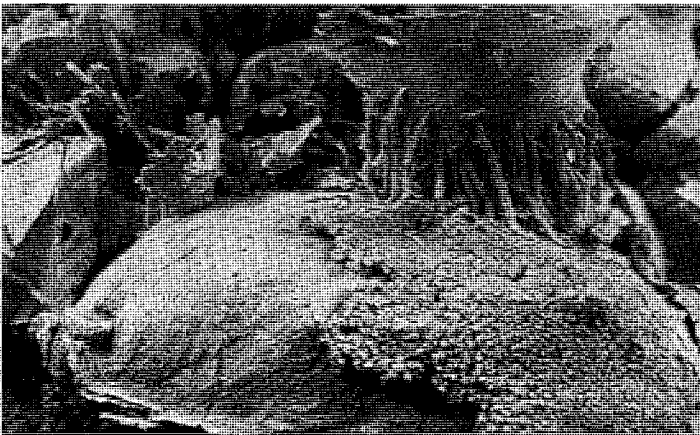
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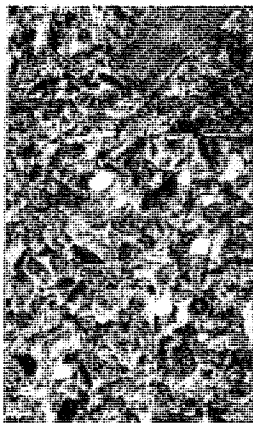
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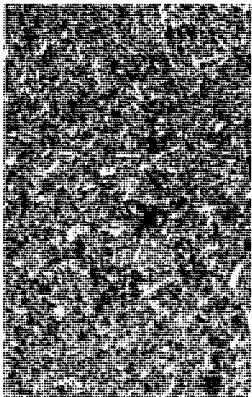
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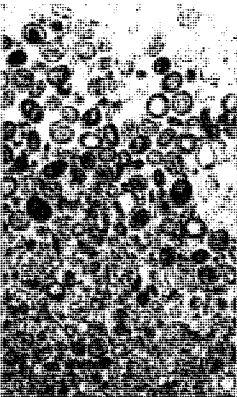
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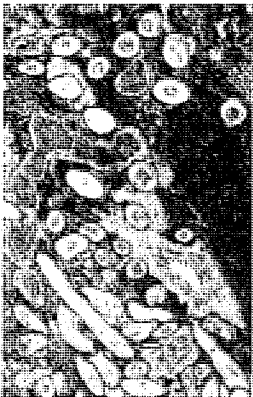
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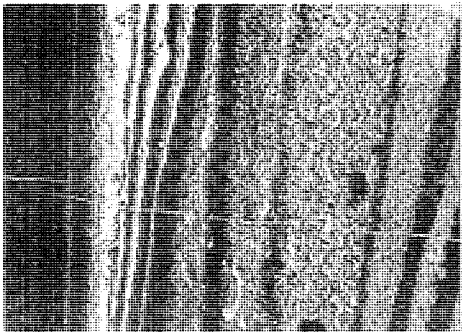
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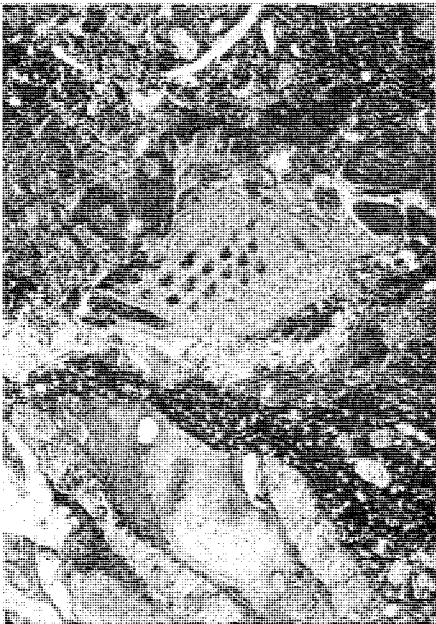
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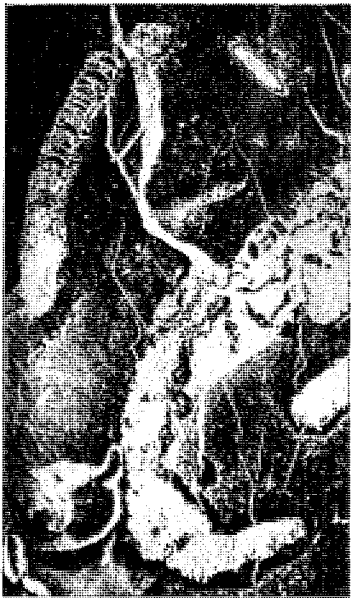
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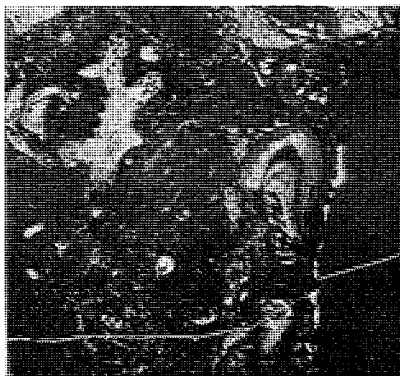
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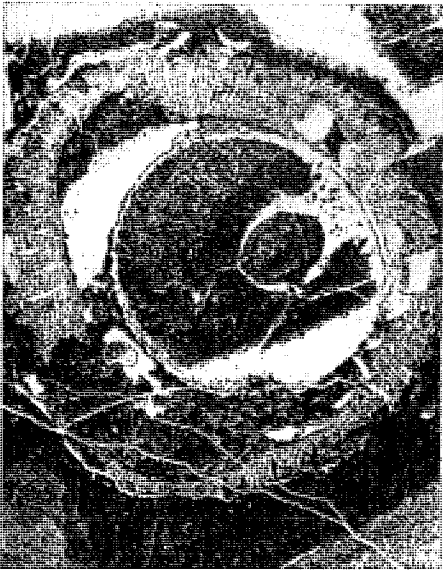
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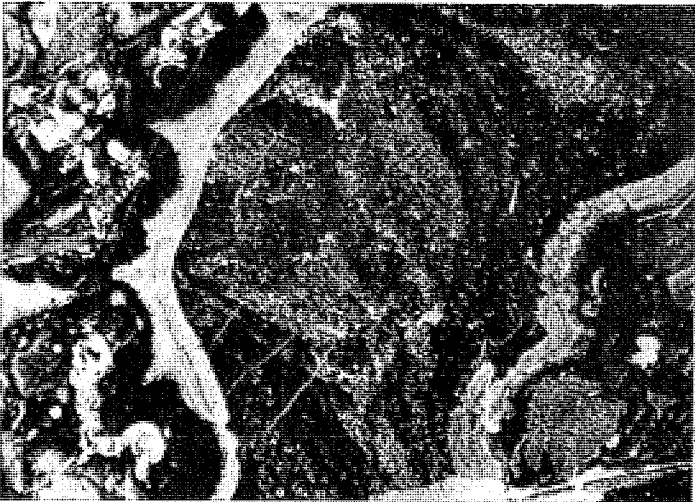
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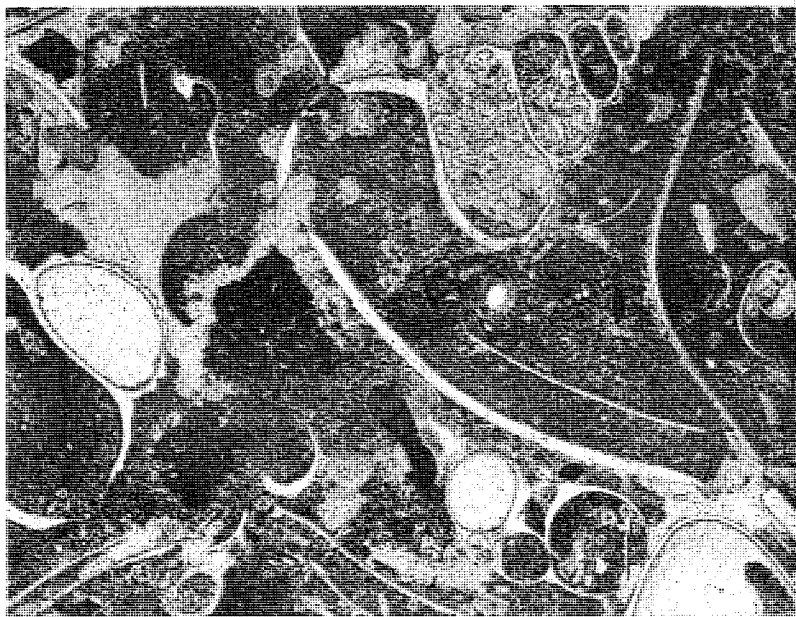
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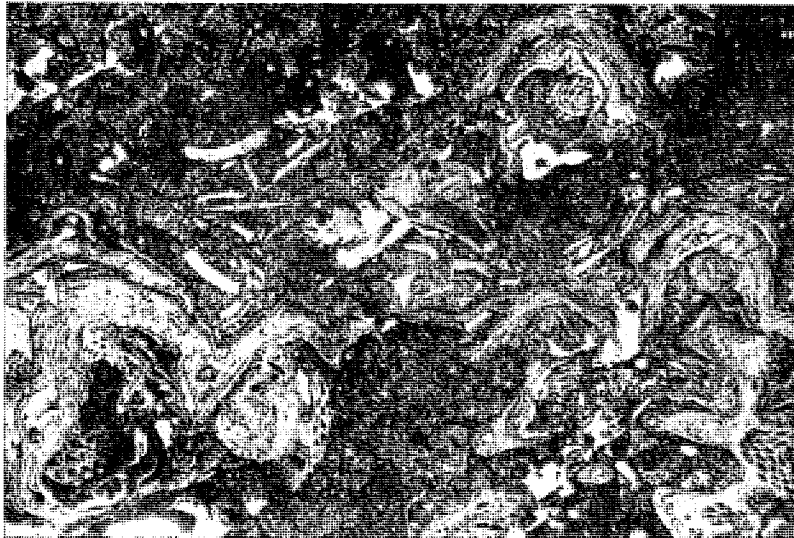
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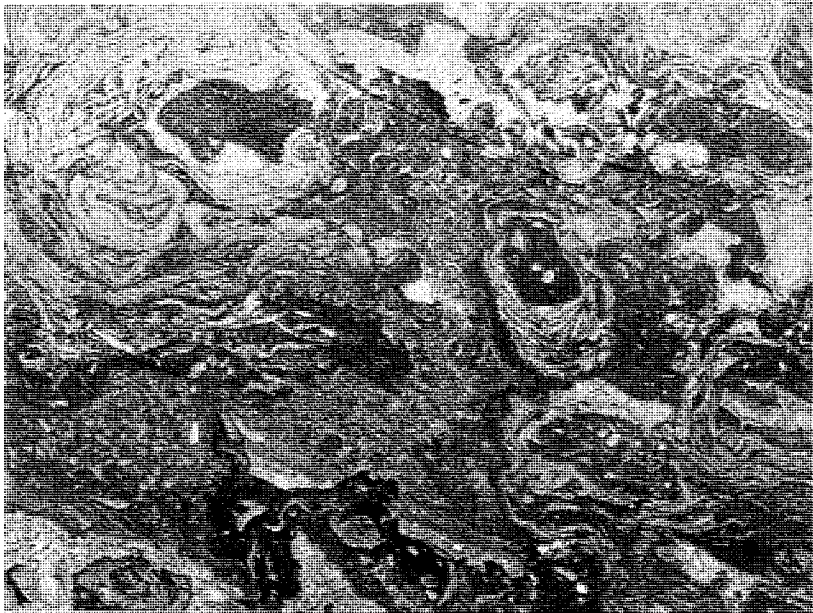
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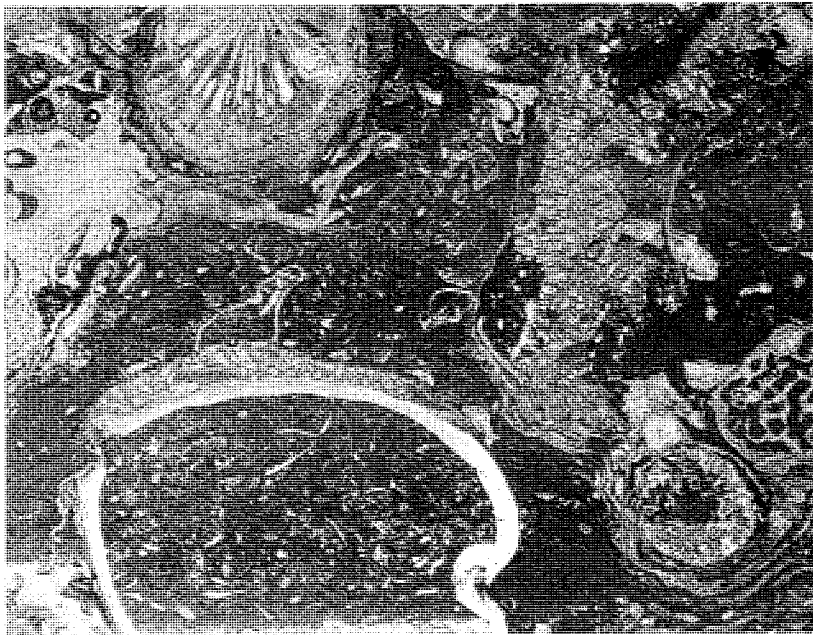
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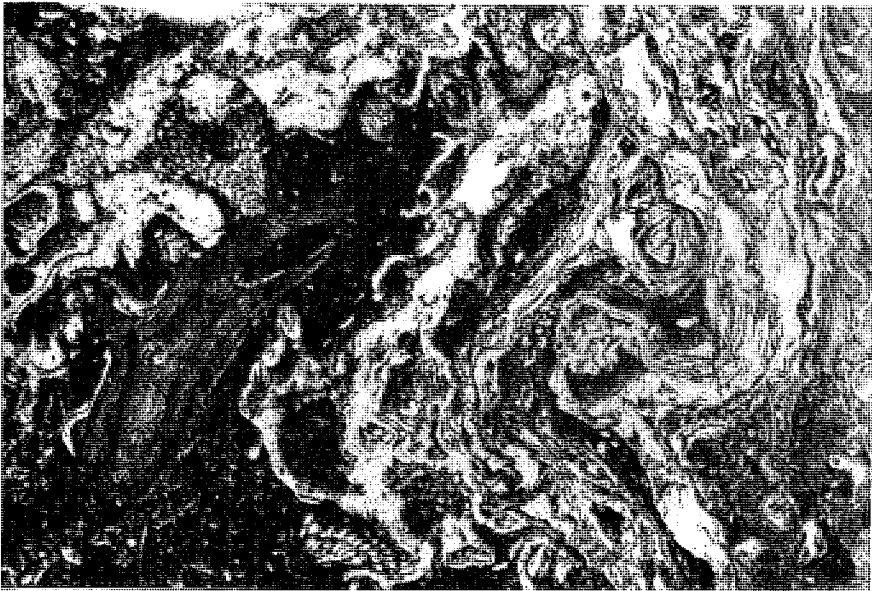
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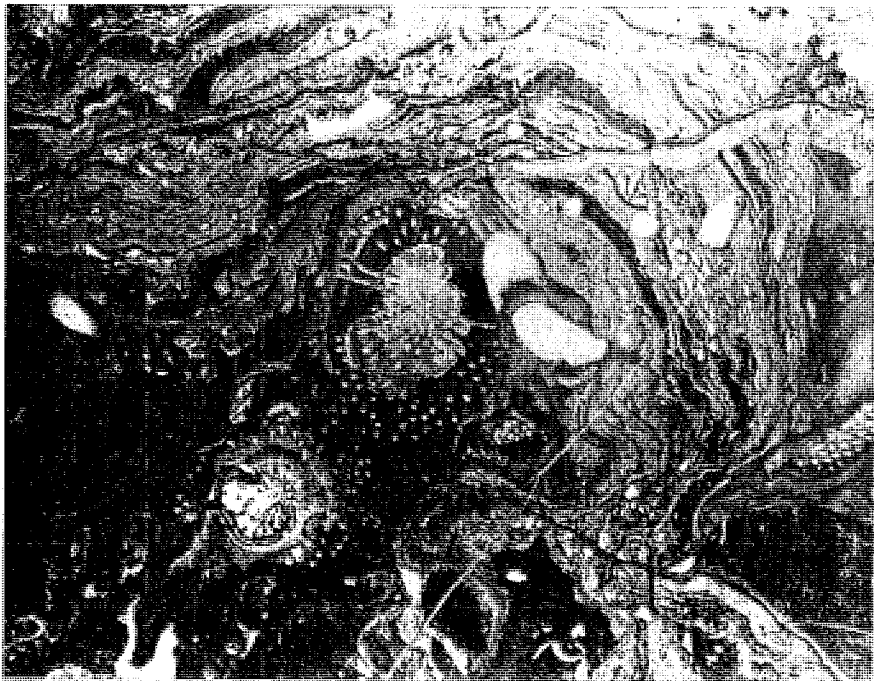
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B

EXPLANATION OF PLATE 8

PHOTOMICROGRAPHS OF CATHEDRAL MOUNTAIN REEF CORE

- FIG. A.—Aligned calcareous sponges bound by laminar algae in Hess reef core. Sponges are being recrystallized to sparry calcite. Locality 888, BYU Collection 1354, (X2).
- FIG. B.—Cathedral Mountain reef core containing fenestrate bryozoa and *Acanthocladia* bound by *Tubiphytes* and fistuliporid bryozoa. *Tubiphytes* and fistuliporid bryozoa are being recrystallized to sparry calcite. Locality 553, BYU Collection 1356, (X5).
- FIG. C.—Calcareous sponge, *Cystothalamia*, filled with sparry calcite in dense micrite of reef core. Possibly bound by algae which is also being recrystallized. Locality 570, BYU Collection 1355, (X5).
- FIG. D.—Cathedral Mountain reef core containing fenestrate bryozoa and *Acanthocladia* bound by *Tubiphytes*. Both are being recrystallized to sparry calcite. Locality 553, BYU Collection 1356, (X5).

EXPLANATION OF PLATE 9

PHOTOMICROGRAPHS OF CATHEDRAL MOUNTAIN LIMESTONES

All figures X5

- FIG. A.—Alteration of micrite matrix to sparry calcite in reefoid facies containing large bryozoan fragments. Locality 495, BYU Collection 1357.
- FIG. B.—Cathedral Mountain reef core with *Acanthocladia* encrusted by *Tubiphytes*. Locality 553, BYU Collection 1356.
- FIG. C.—Reef core material containing *Acanthocladia* encrusted by *Tubiphytes* and fistuliporid bryozoa within the reefoid facies. Locality 117, BYU Collection 1358.
- FIG. D.—*Acanthocladia*, reef frame-builder encrusted by *Tubiphytes*. Locality 553, BYU Collection 1356.
- FIG. E.—*Acanthocladia* and fenestrate bryozoa encrusted by *Tubiphytes* in Cathedral Mountain reef core. Locality 553, BYU Collection 1356.

EXPLANATION OF PLATE 10

PHOTOMICROGRAPHS OF HESS REEF CORE

- FIG. A.—Hess reef core fabric containing calcareous sponge, *Girtyocoelia*, encrusted first by laminar algae, then fistuliporid bryozoa, and again by laminar algae. Algae recrystallizing to sparry calcite. Locality 887, BYU Collection 1339, (X5).
- FIG. B.—Hess reef core fabric showing *Acanthocladia* encrusted first by *Tubiphytes*, then by fistuliporid bryozoa, and lastly by laminar algae. Travertine forms elongate crystal band on core edge. Locality 894, BYU Collection 1340, (X5).
- FIG. C.—Hess reef core with *Acanthocladia* and calcareous sponges bound by *Tubiphytes*, fistuliporid bryozoa, and laminar algae. Travertine forms light marginal coating with void filled by micrite and fine clastic limestone. Locality 894, BYU Collection 1340, (X2).

EXPLANATION OF PLATE 11

PHOTOMICROGRAPHS OF HESS AND CATHEDRAL MOUNTAIN CARBONATES

All figures X5

- FIG. A.—Cathedral Mountain reef core consisting of alternating layers of fistuliporid bryozoa and micritic limestone. Travertine fills voids. Locality 974, BYU Collection 1363.
- FIG. B.—Molluscan facies of Hess Formation containing numerous gastropods in micritic limestone. Locality 900, BYU Collection 1346.

EXPLANATION OF PLATE 12

PHOTOMICROGRAPHS OF CATHEDRAL MOUNTAIN REEF CORE
All figures X5

- FIG. A.—Reef core fabric from Cathedral Mountain Formation showing *Acanthocladia* encrusted by *Tubiphytes* and stromatolitic algae. Sparry calcite fills travertine-lined void. Locality 845, BYU Collection 1332.
- FIG. B.—Cathedral Mountain reef core showing *Acanthocladia* and fenestrate bryozoan encrusted by stromatolitic algae in micrite. Locality 473, BYU Collection 1335.

EXPLANATION OF PLATE 13

PHOTOMICROGRAPHS OF CATHEDRAL MOUNTAIN REEF CORE
All figures X5

- FIG. A.—Algal reef core consisting of phylloid algae, *Tubiphytes*, and stromatolitic algae with micrite fill. Locality 845, BYU Collection 1333.
- FIG. B.—Cathedral Mountain reef core consisting of a rugose coral, spiriferid brachiopod, and siliceous sponges bound by *Tubiphytes*, fistuliporid bryozoa, and stromatolitic algae. Locality 845, BYU Collection 1334.

EXPLANATION OF PLATE 14

PHOTOMICROGRAPHS OF CATHEDRAL MOUNTAIN REEF CORE
All figures X5

- FIG. A.—Reef core of Cathedral Mountain Formation containing *Acanthocladia* encrusted by *Tubiphytes* and stromatolitic algae. Locality 291, BYU Collection 1330.
- FIG. B.—Cathedral Mountain reef core with fistuliporid bryozoa encrusted by *Tubiphytes* and stromatolitic algae. Locality 408-9, BYU Collection 1331.

Material comprising the bioclastic facies was derived from reef or bank structures. Thin beds of bioclastic material which occur isolated from reefs or banks (Locality 922, Plate 15, K-3) are believed to be related to structures which are present downdip in the subsurface or were lost updip through erosion. Some organisms lived on the bioclastic material, but the major portion of fossil material occurring within the bioclastic strata appears to have been derived from the adjacent higher reef flanks.

Tongues of bioclastic material provided a firmer substrate and a slightly raised bar environment which was inhabited by a small fauna. On the basis of numbers of unbroken or partially broken specimens, it appears that this fauna consisted of brachiopods, encrusting bryozoa, rugose corals, crinoids, and gastropods (See Text-figure 3).

Breccia Deposits.—Strata of the bioclastic facies increase in thickness and frequency toward reef cores. This increase in bioclastic material continues until individual strata are lost and massive; thick accumulations occur on the margins of reef cores. Such massive accumulations can be observed at localities 883, 927, 937, 940, and 954, Plate 15, K-3, L-3, and M-3. Massive structure, increase in micritic matrix, and presence of brecciated core material are distinctive of the facies and these areas.

Thick aprons of bioclastic material commonly occur adjacent to reef structures of nearly all ages, Precambrian through Recent. These aprons of fossils and fossil hash accumulated on the margins of reef cores where the environment favored organic activity. Thinner beds of the bioclastic facies were extended outward from this biocenter by waves of higher than normal energy as indicated by introduction of coarser bioclastic sediments into the normally quiet water, interreef environment, and sparry calcite matrix of the bioclastic facies. Lowenstam (1957, p. 226) arrived at a similar interpretation for bioclastic tongues associated with Niagaran reefs in the Great Lakes area.

The more massive breccia zone contains identical bioclastic material, however micritic matrix is far more dominant. Breccia blocks of reef core material, ranging in size from several inches to over two feet in diameter, are included within this biomicroite (Plate 7, fig. E). The size of breccia fragments decreases as one moves away from reef cores. These fragments of reef core material consist of calcareous sponges bound by calcareous algae contained in dense micrite. Sponges are aligned within individual blocks indicating reef growth, but orientation of individual blocks is random. Reef core fragments are not deformed, indicating they were solid at the time of deposition. Bedding surrounding these fragments is deformed, however, indicating that the enclosing sediments were soft. Apparently conditions existed periodically when solid portions of the reef core could be dislodged and carried off onto the apron of bioclastic material.

More shallow water with more vigorous currents allowed an abundant fauna to exist. Crinoid and bryozoan fragments dominate within the sediments, but there are large numbers of brachiopods, rugose corals, encrusting bryozoa, and high-spined gastropods as well. Calcareous sponges of the reef community are also present but are isolated and not in growth position. Whether any of these forms are in their habitat or not is unknown, but it seems that most have not been moved far.

Aprons of the bioclastic facies were deposited on the margins of reef structures. The skeletal material was derived from organisms living on and within the reef and on aprons flanking the reef. During times of increased energy, such as storms, some of this skeletal material was transported into the interreef environment, forming far-reaching tongues of the bioclastic limestone (Localities 883 and 884, Plate 15, L-3). At the same time, the reef core was subjected to vigorous wave action, and areas that had been constructed during quieter periods were broken loose and carried out onto the aprons as breccia blocks.

Molluscan Facies

The molluscan facies occurs as small localized areas usually adjacent to reef core structures (Locality 900, Plate 15, L-3). A photomicrograph of a sample from locality 900, which shows the concentration of mollusks within the facies, is shown in Plate 11, fig. B. Brachiopods occur associated with the mollusks but are rare, scattered occurrences of single specimens of several species. This occurrence suggests that these brachiopods are not in their life habitat. Both high- and low-spined gastropods and small, smooth pelecypods predominate the facies, but other groups are represented. Ostracods, small foraminifera, and fusulinids occur but only in limited numbers.

This dominantly molluscan fauna occurs in a pure micritic matrix. There is a complete absence of fine, broken, bioclastic material which is present in all other reef-associated facies. All fossils are unbroken with delicate structures still preserved. Pelecypods possess both valves and are articulated. Juvenile individuals are also present. It appears that this is not a current accumulation. Faunal elements which do not inhabit a muddy environment are rare. All this seems to substantiate that the molluscan facies represents a localized muddy, quiet water environment. The fauna lived in a protected depression sheltered possibly by the reef core. This is further substantiated by the distribution of similar molluscan facies occurring in the overlying Cathedral Mountain Formation.

Reef Core Facies

Reef cores occur within the upper Hess Formation as micritic limestone masses circumscribed by draping bioclastic deposits. Reef masses range from 20 feet to 125 feet long and up to 100 feet high (Plate 15, M-3). Hess cores display the organically well-knit fabric essential to true reef structures. This fabric can be observed on the outcrop as well as in thin-sections.

A typical weathered surface of an outcrop within reef core facies is shown in Plate 2, figs. B and C. Here frame building, dark-gray, calcareous sponges occur oriented in growth position. They are bound by medium-gray, calcareous algae and encrusting bryozoans. Crystalline travertine appears as a light-gray to white layer surrounding masses of the reef core. Voids between reef masses resulted from the patchy growth of solid reef elements. These voids are filled by fine-grained clastic limestone and are very similar to those illustrated by Newell (1955, p. 303, Plate 6-B) within the reef fabric of the Recent reef on Raroia Atoll. Stratification of this interstitial, clastic limestone shows slumping adjacent to reef limestone, indicating that the core was solid at the time of interstitial deposition (Plate 10, fig. C). Travertine which surrounds reef masses and lines voids was interpreted by Newell (1955, p. 308) to have formed as aragonite shortly after reef growth.

Reef cores within the Hess Formation (Plate 15, L-3 and M-3) measure up to 125 feet wide and nearly 100 feet thick. In general they are pod-shaped or lenticular with maximum areal extent occurring slightly above midway through the reef. Except for slight spreading of the reef onto its flanks, reef growth appears to have been primarily upward as opposed to major lateral growth. This would seem to indicate subsidence of the reef and its growth were nearly equal. Cores are surrounded by bioclastic aprons which apparently extend outward equally in all directions. Initial dips of the bioclastic material appear to have been less than 10° . Reef core facies inter-tongues with bioclastic material (Plate 15, N-3), suggesting that pauses in subsidence allowed reef growth onto adjacent reef flanks.

Lithologically, reef cores consist of well-bound organic structures with a dominantly micritic matrix. Micrite is being recrystallized to sparry calcite in many instances, but this recrystallization is limited. Fine calcareous silt is present within the micritic material, but its volume never exceeds 5 percent. Clay minerals are present in trace amounts. The micritic matrix may have had an organic as well as an inorganic origin. Both high organic activity and warm water conditions would lead to the precipitation of finely crystalline calcium carbonate. Voids within the reef core fabric are commonly filled by fine-

grained clastic limestone which was probably derived from disintegration of the reef structure.

Oolites occur concentrated adjacent to reef cores at locality 900 (Plate 15, L-3). The association of oolites in micritic limestone matrix (Plate 6, fig. E) suggests that oolites formed on nearby carbonate-rich and moderately turbulent surfaces and were transported into quieter micritic areas.

Organisms of reef structure can be classified into three groups: 1) frame builders—rigid organisms occurring in growth position which attach to the substrate and form the organic framework of the reef, 2) binders—organisms which by their encrusting habit bind individual frame builders into a solid unit, and 3) accessory organisms—those which inhabit the reef in preference to surrounding environments and in some way benefit but are minor elements.

Frame building organisms in the Hess reefs are primarily the calcareous sponges, *Girtyocoelia*, *Amblysiphonella*, and *Cystothalamia*, and the bryozoa or bryozoan-algal consortium *Acanthocladia*. Newell (1957, p. 422) noted a similar fauna for Guadalupian reefs but questioned the capabilities of *Acanthocladia* to form wave-resistant structures. Other organisms occur as frame builders, such as siliceous sponges and fenestrate bryozoa, but their importance is small compared to the calcareous sponges. *Amblysiphonella* and *Cystothalamia* have cylindrical to fan-like growth forms. These elongate fan-like skeletons occur oriented parallel to N 15° E at localities 888, 893, 899 and 900 (Plate 15, L-3) This orientation is shown in Plate 8, fig. A and Plate 2, fig. C and believed to be the result of current influence. At locality 945 (Plate 15, M-3) a well-knit organic fabric lacks any orientation (Plate 2, fig. B).

Acanthocladia also acts as a frame builder, second in importance only to the calcareous sponges. Figures B through E of Plate 9 show *Acanthocladia* acting as a frame builder encrusted by *Tubiphytes*.

Acanthocladia has been described as a bryozoan-algal consortium by Johnson (1951) and Rigby (1956, 1957) where zoarial areas are encrusted by the red algae, *Solenopora texana* Johnson. Helen Duncan (1957, p. 789), among others, maintains that *Acanthocladia* represents bryozoan growth entirely.

Binding organisms within a reef structure perform the function of tying individual elements of the reef into one cohesive mass, and through their encrusting habit lend strength to frame-building elements. Binding organisms within Hess reefs consist of fistuliporid bryozoa, and algae, *Tubiphytes*, and another laminar algae, *Apterinella*, an encrusting foraminifera, also acts as a binder, but it is of limited importance because of its rare occurrence.

Typical Hess reef fabric at locality 894 (Plate 15, L-3) is illustrated in Plates 10, figs. A and B. *Girtyocoelia*, a calcareous sponge, occurs in growth position encrusted first by *Tubiphytes*, then by fistuliporid bryozoa, and lastly by laminar algae (Plate 10, fig. A). Both *Tubiphytes* and the laminar algae have been partially replaced by sparry calcite, however, sufficient structure remains to allow identification.

Acanthocladia (Plate 10, fig. B) occurs in vertical growth position at locality 894 (Plate 15, L-3) encrusted first by *Tubiphytes*, then by fistuliporid bryozoans, then by *Tubiphytes* again, and lastly by a laminar algae. Additional thin-sections show a similar faunal succession in reef development. After

establishment of the frame builders, either sponges or bryozoans, *Tubiphytes* first encrusted the reef frame, followed by fistuliporid bryozoans and then by laminar algae. In several instances, fistuliporid bryozoan encrustations were followed by a second occurrence of *Tubiphytes* and then laminar algae, suggesting a temporary reversal in conditions. Laminar algae represents the final organism in every thin-section examined.

Cystothalamia occurs at locality 888 (Plate 15, L-3) in a typical reef core association and is illustrated in Plate 8, fig. A. Here several individuals occur aligned in growth position bound by the darker-appearing calcareous algae, *Tubiphytes*. A small gastropod occurring within the reef core is also encrusted by *Tubiphytes*.

The best exposed reef core in the Hess Formation is located in the vicinity of L-3, Plate 15. Here interreef strata southwest of locality 880 can be traced laterally reefward and observed grading into coarser biosparudites of the bioclastic facies at locality 880. Beds of biosparudite such as at localities 880, 886, 896, 932, and 939 form the substrate upon which reefs developed. Loading of reef cores on these bioclastic beds has resulted in their downwarping. Strata overlying locality 896 correlate with strata at locality 942.

Biosparudites of the bioclastic facies (Localities 884 and 932) gradually become more micritic until adjacent to reef cores, massive deposits of biomicrudite are dominant (Localities 881, 890, and 940). Breccia blocks of reef core material are contained within this biomicrudite. Blocks 2 feet in diameter occur at locality 891 but rarely exceed several inches in diameter in the vicinity of locality 880. Blocks decrease in size away from reef cores. A fauna of gastropods, brachiopods, crinoids, fenestrate bryozoa, and rugose corals inhabited these rudaceous deposits.

The reef core overlies biosparudites (Locality 897) and intertongues with biomicrudites (Locality 891) of the bioclastic facies. It is lenticular in shape, extending laterally 125 feet at its maximum growth and reaching 100 feet thick. Cores consist of dense, organically knit micritic limestone (Plate 8, fig. A and Plate 2, figs. B and C). Organic structures comprise approximately 25 to 30 percent of core material. Fine, dense micrite fills interstices of the reef fabric. At locality 899 (Plate 2, fig. C) the calcareous sponges *Amblysiphonella*, *Cystothalamia*, and *Girtyocoelia* occur bound by calcareous algae forming a tight reef fabric. This same fauna consistently occurs throughout the reef core with no apparent change. Nearly parallel orientation of sponges occurs on core margins (Localities 888, 893, 899, and near 900) but toward the centers of reef cores, reef fabric lacks orientation (Locality 945 and Plate 2, fig. B).

Accessory organisms inhabit the reef in preference to adjacent environments but add little to the reef fabric except bulk. Hess reef accessory organisms consist of fusulinids, gastropods, spiriferid brachiopods, ostracods, and rugose corals. They occur encrusted by algae and bryozoa in growth position, tipped from growth position, or lodged in voids within the reef fabric.

Although accessory organisms were not instrumental in reef construction, they are useful in its paleoecologic interpretation. Corals, fusulinids, and spiriferid brachiopods are stenohaline, indicating salinity was normal marine (Newell, 1957, p. 434). Elements of the reef core fauna are also valuable as paleoecologic indicators. Cloud (1952, p. 2140) suggests that patch reef faunas indicate quiet water. Elias and Condra (1957, p. 51) believe the

occurrence of fistuliporid bryozoa without fenestrate bryozoa, as in Hess reefs, indicates near littoral depths. Wells (1957, p. 773) states that Paleozoic rugose corals probably lived in depths close to five meters. Okulitch and Nelson (1957, p. 765) conclude that calcareous sponges in Leonardian time inhabited shallow rather turbulent water. Finks (1960, p. 22-23) states that "a fauna dominated by calcisponges, with a subordinate element of siliceous sponges" is confined to shallow water. Newell (1957, p. 435) explains concentrated accumulations of calcareous sponges, such as those in Hess reefs, as the result of habitation of specialized environments. He believes that calcareous sponges lived in extremely shallow water, probably the shallowest water on reef crests.

Summary.—During late Hess time, calcareous sponges, *Acanthocladia*, and algae constructed low patch reefs on a normal marine shelf. Shelves were subject to less vigorous waves than basins because of shallower water and the occurrence of patch reefs. Calcareous sponges inhabited reef crests which rose to within 5 to 10 feet of sea level (Newell, 1957, p. 435). Maximum relief observed between reef crests and contemporaneously deposited interreef strata is 25 feet (Localities 920 and 928, Plate 15, K-3). This would indicate that seas over the shelf reef environment were 30-35 feet in depth. Water was warm, clear, and of normal marine salinity. Reefs were subjected to moderately turbulent wave action and supplied vast quantities of bioclastic material to surrounding clastic aprons. Reef growth and subsidence of the shelf were nearly equal. Subsidence, in late Hess time, lowered the shelf and resulted in destruction of the protected shelf environment. Seas deepened and turbulence increased leading to the extinction of reef growth. Reef and interreef structures were scoured and channeled producing a locally unconformable contact between the Hess and Cathedral Mountain Formations. Large amounts of terrigenous quartz silt was introduced into this previously carbonate environment.

Reefs were inhabited by accessory organisms that took advantage of shallower, more vigorous water and firm substrate. Storm waves periodically swept the reef crests dislodging and transporting accessory organisms from the reef as well as moving segments of the reef structure. Both occur in bioclastic aprons which surround the reef cores. Breccia blocks of reef core material in contemporaneous sediments, deformed layering of sediments filling voids within the reef, and slump features in sediments adjacent to the reef cores all indicate that reef cores were lithified upon or soon after deposition.

HESS - CATHEDRAL MOUNTAIN CONTACT

P. B. King (1931, p. 62) described the contact between the Hess Formation and the recently defined Cathedral Mountain Formation as generally conformable but locally unconformable; a description which also applies to the contact within the study area where beds are conformable except between localities 912 and 919 (Plate 15, G-5 and I-5). Here the unconformable contact is both erosional and angular where younger beds are draped over the irregular surface. Such a surface as this could exist over an area of reef growth within shallow water. Local storm wave scouring and channeling is typical on shallow shelves. An angular discordance between the two formations of up to 20° is present in the areas between localities 915 and 918 (Plate 15, H-5 and I-5). A reddish brown, argillaceous siltstone overlies this

unconformable contact and overlaps the conformable portion to the southwest (B-4 to J-3). The siltstone and Hess limestone are separated by a sharp sedimentary contact.

CATHEDRAL MOUNTAIN FORMATION

The Cathedral Mountain Formation at Split Tank consists entirely of reef-associated sedimentary strata. Well-rounded pebbles of chert continue to occur throughout the section but are widely scattered except for basal concentrations (Localities 405, 424, and 425, Plate 15, B-5 and C-5). These pebbles, like those of the Hess Formation, appear to have been derived from the Maravillas and Caballos Formations which cropped out within the Marathon Folded Belt to the south or southeast.

The Cathedral Mountain Formation, in marked contrast with the Hess Formation, lacks any dolomitic sediments, and abrupt lateral variation is more evident. Silicification of fossil material, absent in Hess sediments, is the dominant mode of fossilization in the Cathedral Mountain Formation outside the reef cores.

The only other noncalcareous deposit of importance is an argillaceous siltstone at the base of the formation. Maximum thickness of the siltstone unit occurs near locality 913 where it is nearly 180 feet thick. The siltstone consists of well-rounded quartz grains ranging from 0.1 to 0.5 mm in diameter. Quartz grains comprise approximately 60 percent of the sediment with the remaining 40 percent being predominantly argillaceous grains. Sponge spicules, fragments of brachiopods, ostracods, foraminifera, and radiolarians comprise from 5 to 10 percent of the sediment.

This siltstone weathers to a light reddish brown, fine sandy soil. Beds of fine-grained clastic limestone, approximately one foot thick, are interbedded with this siltstone (Localities 914 and 917, Plate 15, H-4 and I-4). These limestone beds weather to a light-gray but are dark-gray on freshly broken surfaces. They emit a weak petroliferous odor when broken. They also contain up to 10 percent argillaceous material.

A large fauna of siliceous sponges occurs in this siltstone zone. Finks (1960) described members of this fauna; some of which were collected from the present study area (Finks, 1960, Localities USNM 702 and 702b). Most commonly occurring sponges are: *Scheiia*, *Chaunactis*, *Hapliston*, *Pemmatites*, *Anthracosycon*, *Actinocoelia*, *Defordia*, and *Coelocladia*. Finks (1960, p. 22-23) indicates that faunas consisting entirely of siliceous sponges are confined to deeper water or basin environments. The large occurrence of siliceous sponges shown in text-figure 3 in the interreef facies is related to this silt zone. Limestone beds interbedded with the siltstone are identical to those occurring within the interreef facies of the overlying Cathedral Mountain Formation.

Productid and spiriferid brachiopods, rugose corals, high- and low-spined gastropods, and burrowing pelecypods occur both as whole fossils and fragments in the siltstone sequence. Generally they occur in clusters, suggesting current accumulations which were concentrated in depressions on the sea bottom. All specimens show definite signs of transportation, and none occur in growth position.

Burrows and trails occur throughout the reddish siltstone sequence. They are unique to this silt and are believed to have been restricted by grain size to this firmer silt-bottomed environment. There is great variation among the burrows, however, they can be grouped into: 1) those perpendicular to bedding and 2) those parallel to bedding.

Plate 2, fig. A shows burrows in one of the thin limestone units within the siltstone. Although the majority of the burrows are within the siltstone, some also occur in the interbedded limestones. Vertical burrows, such as those in Plate 2, fig. A, measure from 3 to 5 inches long and up to two inches wide. Approximately two-thirds of the burrows' diameter consists of an inner core surrounded by an outer, more tightly cemented rind (Plate 2, fig. A). Some vertical burrows are tubular with the core and rind extending throughout while others, usually smaller, are cup-shaped with the outer rind blocking the lower end of the burrow. The former have been interpreted as resulting from the activity of burrowing pelecypods or gastropods. Cup-shaped burrows are similar to *Kulindrichus* which is interpreted as housing burrows of sea anemones (Häntzschel, 1962, p. W 201).

Trace fossils of the second group consist of trails, 0.5 to 1 inch in diameter, which occur parallel or nearly parallel to bedding. Trails are slightly oval in cross-section and lack internal structure. They occur, in a pattern similar to *Scoyenia* (Häntzschel, 1962, p. W 215), randomly wandering throughout certain areas of the silt sequence and are believed to be feeding trails of gastropods.

Cross beds or ripple marks were not observed within the siltstone. Absence of such structures is thought to be related to high organic activity rather than extremely low-energy conditions. Currents capable of transporting large productid brachiopods swept the area for fossils of these forms occur.

As subsidence continued, increased depth eventually resulted in the destruction of the existing patch reef environment in the immediate region. Storm waves scoured and channeled the upper Hess limestone and reefs. Argillaceous quartz silt was introduced into a previously carbonate environment. This silt was possibly derived from a land area adjacent to the basins which was uplifted and related to late Marathon movements. Siliceous sponges, characteristic of basin and deeper shelf environments, migrated into this now deepened environment, and burrowing organisms churned the sediment destroying most sedimentary features. Depth of water is estimated in the vicinity of 100 to 150 feet. At periods of decreased detrital influx, dark clastic interreef limestone was deposited. Brachiopods, gastropods, and corals were transported into the silty environment from nearby banks, probably situated farther shoreward.

Limestones associated with reef growth have been divided into facies as follows: 1) interreef facies, 2) bioclastic facies, 3) flank-bank facies, 4) reefoid facies, and 5) reef core facies.

Interreef Facies

The interreef facies consists of dark-gray, micritic, limestone which emits a weak petroliferous odor when freshly broken. It weathers to a light-gray. Fine-grained, silicified, bioclastic material comprises up to 5 percent of its volume, and argillaceous content comprises 5 to 10 percent. Individual strata

range from a few inches to slightly over a foot thick. Most covered areas (Plate 15) are believed to be underlain by interreef strata which were buried through weathering and erosion of adjacent beds.

Interreef deposits dominate the Cathedral Mountain Formation and appear to represent normal deposition for areas unaffected by reef growth. In regions removed from the study area, contemporaneous fine-grained micrite and biomicrite, identical to that of the interreef facies at Split Tank, occur as the normal sediments.

Fossils occurring within the interreef facies appear to have been transported, possibly from nearby reefs or banks. All show signs of transportation. Pelecypod valves occur singly and lying with long dimensions parallel to bedding planes. Richthofenid and productid brachiopods lack spines, rugose corals occur parallel to bedding planes, and heads of encrusting fistuliporid bryozoa lie tipped at odd angles to bedding. Storm waves probably swept topographically higher organism-rich areas, and individuals were carried off reefs and banks settling into interreef calcareous muds.

The interreef facies represents deposition within a low-energy environment which existed on a somewhat protected, shallow, shelf area. Seas were probably less than 75 feet deep. By no means was the environment restricted to area between reefs, but instead, reefs locally developed upon this shelf displacing the interreef environment. The bottom was covered with soft calcareous muds which provided an inhospitable environment for both infaunal and epifaunal organisms. Fine sedimentary layering preserved in many areas indicates an absence of burrowing organisms. There is little evidence, however, that this was an euxinic environment.

Bioclastic Facies

Bioclastic sediments occur in two ways in the Cathedral Mountain Formation: 1) as massive accumulations of biomicritic and biomicrudite circumscribing reef structures and 2) as medium- to thick-bedded units of biosparite and biosparudite extending outward from the more massive deposits. Massively bedded accumulations of micritic material are similar to those described from the Hess Formation. Localized reef-like masses within these deposits are considered to be more closely related to reefs ecologically, and consequently these masses are described as the "Reefoid Facies."

Breccia blocks of reef core material occur in both the massive and stratified deposits. Areas of breccia concentration within the bedded bioclastic facies are indicated on Plate 15, localities 160 (C-4), 579 (G-2), and 982 (G-4).

Beds of biosparite and biosparudite up to two feet in thickness drape over and intertongue with interreef strata (Plate 1, fig. D; Locality 302, Plate 15, F-3). Such beds extend outward from reef areas as much as 250 feet (Locality 868, Plate 15, J-1). Individual beds of the bioclastic facies which are related to several reef structures can be traced across large segments of the map area with some lateral variation (Locality 806, Plate 15, H-2). Where such beds are traced toward reef structures, there is an increase in both thickness of the unit and size of the bioclastic material.

The bioclastic facies of the Cathedral Mountain Formation is characterized by a high percentage of fossil fragments contained in a medium-gray to dark-brown, sparry calcite matrix. Bioclastic fragments consist primarily of bryozoan

fragments and crinoid columnals. Appreciable amounts of fragmental brachiopods, gastropods, corals, echinoid spines, and pelecypods are also present. Sparry calcite cement fills interstices between fossil fragments. As reef cores are approached, however, micritic matrix becomes more abundant at the expense of sparry calcite, and sparry calcite is lacking adjacent to reef cores. Likewise, the well bedded bioclastic strata become thicker, more closely spaced, and massive toward reef cores. Figure C of Plate 6 illustrates typical biosparudites of the bioclastic facies. Fig. C of Plate 4 shows coarser biomicrudites which occur near reef structures and the associated increase in size of bioclastic material as well as the amount of micritic matrix. Figure G of Plate 6 shows bioclastic material in microsparite matrix. However, it seems that the sparry calcite in this case is probably the result of recrystallization of originally micritic calcite. Both unrecrystallized portions of micrite and widely separated fragments of fossils indicate that a micritic matrix was deposited simultaneously with bioclastic material and later recrystallized to sparry calcite.

Presence of micrite or sparite as interstitial material in bioclastic sediments is the result of the energy conditions under which the sediments were deposited. Micritic calcite indicates low-energy conditions which allowed deposition of both fine calcareous mud and coarser bioclastic fragments simultaneously. Such conditions existed adjacent to reef structures where massive deposits of bioclastic sediment with micritic matrix accumulated as the result of organic and physicochemical processes.

Bioclastic material with sparry calcite filling interstices indicates that coarse fossil fragments were deposited in high-energy environment while finer calcareous mud was carried away in suspension. Storm waves swept across reef crests and upper surfaces of massive bioclastic aprons transporting both fragments and calcareous mud into the interreef environment. The coarser fraction settled out forming bioclastic tongues, and later voids between fragments were filled with sparry calcite.

At localities 489 and 773 (Plate 15, E-2 and L-1 respectively) alternating high- and low-energy conditions allowed deposition of interlaminated thin layers of micrite and sparite (Plate 7, fig. C). Graded bedding from moderately coarse biosparudite to fine-grained micritic mud can be observed in several layers. Both sample localities are located topographically below reef mounds. Such layering resulted from storm waves sweeping reef crests and depositing debris off the reef. Lowenstam (1957, p. 226) reports similar deposits within interreef areas of Niagaran reefs and interprets them as storm deposits.

The greater proportion of bioclastic material occurring within this facies is not believed to be entirely in place. In general, the material is moderately well-sorted and fossils are fragmented or disarticulated. Echinoderm and fenestrate bryozoan fragments are the dominant bioclastic material.

Fenestrate bryozoan fragments are the principal sediment producers, but locally, crinoid columnals are more abundant. Fragments are subangular and generally rudaceous in grain size. No fenestrate bryozoa were observed as whole colonies within the bioclastic facies. They do occur in abundance, however, within the flank-bank facies and upper portions of the reef core facies. Of the echinoderm fragments crinoid columnals are the principal contributor to sedimentary bulk. Generally all columnals and calyx plates are disarticulated. Second among echinoderms as a sediment producer are echinoids. Their spines

and coranal plates are also generally disarticulated and scattered. It was found, however, in etching blocks of silicified material collected near reef cores that when either crinoid or echinoid plates were found, nearly the whole calyx or carona could be reconstructed from material etched from that single block. This, plus the occurrence of several complete crinoid calices and echinoid caronas at localities 674, 746, and 1008 (Plate 15, O-3, M-1, and H-2) which are on reef core margins, suggests that many of the echinoderms lived on these aprons of biocalcarenitic material. Currents disarticulated their skeletons upon death, and during storms these fragments were carried off the aprons. Ingles (1963, p. 419) reports similar crinoid meadows on the leeward side of the Silurian Thornton reef near Chicago, Illinois.

Other whole fossils occur within the bioclastic facies and are believed to represent both organisms which were transported into the area with bioclastic material and organisms which inhabited these coarser, firmer biocalcarenitic tongues. Dominant among the whole fossils are brachiopods, principally the spiriferid forms *Hustedia*, *Neospirifer*, and *Composita*. More rare are the productid brachiopods, high- and low-spined gastropods, arborescent bryozoa, and rugose corals. Stach (1936, p. 65) noted a similar distribution of arborescent bryozoa which he interpreted as indicative of deeper, more sheltered water. The bryozoan fauna consists almost entirely of arborescent forms with a notable absence of fenestrate or encrusting forms. Small clusters of richthofenid brachiopods are present, but they are believed to have been derived from the flank-bank environment.

Ecology.—High organic growth, on and adjacent to reef cores, provided a source for vast quantities of bioclastic material. Normal currents crossing reef areas carried both this debris and fine micritic muds off reef crests depositing the sediments in aprons circumscribing the reef structures as suggested for Silurian reefs of the Illinois-Indiana area (Lowenstam, 1957, p. 226). From time to time, storms of higher-than-normal energy washed over these same reef areas breaking reef elements loose. This material was then transported into the nearby interreef environment forming bioclastic sand and gravel bars. Micritic muds were washed away into the adjacent interreef area or out into the bordering basins.

These bioclastic bars provided a slightly raised, firmed substrate upon which spiriferid and productid brachiopods, gastropods, a few rugose corals, and arborescent bryozoa lived. Localized crinoid meadows flourished on these bars, once they were established, but in general crinoids appear to have been mainly restricted to bioclastic aprons adjacent to reef cores. Apparently fine calcareous muds of the interreef environment restricted organic activity while the firmer substrate of the sands provided an environment capable of allowing filter-feeding organisms to survive. In some instances banks and bioherms developed upon these bioclastic bars. Generally, however, life was sparse—and the bars were relatively uninhabited. The environment was little different from that of the interreef facies except for the firmer substrate.

Molluscan Facies

Sediments containing a rich concentrated molluscan fauna in fine, dark gray, micritic limestone are differentiated as the molluscan facies. Absence of

bioclastic material, especially bryozoan and crinoidal fragments, is unique to this facies. The molluscan facies occurs in lenses adjacent to reef structures. Ammonoid and nautiloid cephalopods, bellerophontid gastropods, high- and low-spired gastropods, scaphopods, and large pelecypods occur in relatively large numbers within these massive micritic areas. Rugose corals also occur in small numbers associated with this molluscan fauna.

Cephalopods (Localities 1003, D-5; 980, F-4; and 1026, H-2) occur in irregular orientation and appear to have been washed into the sediments in which they are found. Figure A of Plate 1 shows a typical concentration of cephalopods within the weathered micrite. Spines of *Cooperoceras* are unbroken, but on a buoyant conch such as *Cooperoceras* this would not necessarily indicate lack of transportation. Cephalopod concentrations adjacent to bioherms are mentioned by Miller and Furnish (1937, p. 56) who concluded that such concentrations were current accumulations in quiet water behind biohermal mounds.

Bellerophontid gastropods possess anal notches which have been interpreted (Chronic, 1952, p. 107) as indicative of a life slightly below the surface in a muddy environment. Other gastropods inhabited biocenters and lived as carnivores on brachiopods and pelecypods. Gastropods likewise occur at all angles within the micrite which suggests settling into mud without current controlling their orientation. Bellerophontid and naticopsid gastropods are more abundant within the molluscan facies (Localities 439, 1003, and 543; C-5, D-5, and G-2 respectively) than any other place within the reef associated environments. All forms are smooth and unornamented and could be easily rolled by moderate currents. Figure B of Plate 1 illustrates a more gastropod-rich zone within the molluscan facies. Here naticopsid and bellerophontid gastropods are dominant, but several cephalopods and pelecypods are also present.

Scaphopods are dominant at locality 970 (Plate 15, F-4) but are present in less noticeable numbers throughout most of the molluscan facies. At other localities some appear to be in life position. At locality 970 several groups of scaphopods occur oriented parallel to others within their cluster, but orientations of individual clusters are not parallel. They occur slightly inclined in the strata suggesting possible life positions, but this could also be the result of current action. The scaphopods do, however, represent a group that are probably within their life environment.

Large allorismid pelecypods occur at localities 478 (E-2), 1026 (H-2), 802 (H-1), and 786 (L-1) with both valves articulated in life positions. Figure A, Plate 3, illustrates the typical concentration and position of these pelecypods as they occur in the outcrop. They were apparently burrowers in the fine micritic mud in when they occur. These same pelecypods occur within reef cores in growth position but appear to be bound in place by algae. All other occurrences of pelecypods within the study area outside these two facies are single valves.

The molluscan facies represents a quiet water, muddy environment which existed in the current shadow of reef structures. Faunal elements consist of both *in situ* and transported forms. Scaphopods represent a slightly reworked life assemblage. They were probably aligned after death or perhaps by a small turbidity flow which may have caused their death and burial. Pelecypods and

some gastropods represent a life assemblage of burrowers. Cephalopods and some gastropods are current accumulations of individuals which inhabited adjacent reef crests and flanks.

Flank-bank Facies

"Flank-bank" refers to concentrations of unbroken fossil material occurring on the margins of reef cores or as isolated accumulations on bioclastic beds unrelated to reef growth. Those concentrations adjacent to reef (Plate 15, F-3) are here referred to as "flank" deposits and those unrelated to reefs (SE of Locality 69, Plate 15, C-3) are termed "banks." It is stressed that such accumulations are in their life habitat and largely in growth position; however, they lack organic binding. In some instances (SE of Locality 69, Plate 15, C-3) organisms did cement onto and encrust other organisms present, but it was neither critical for the construction of the bank nor for the survival of the organism such as is necessary in reef growths.

The flank-bank consists of dark-brown to very dark-gray clastic limestone which contains large numbers of brachiopods, bryozoa, corals, and echinoderms. Calcareous sponges, gastropods, and fusulinids also occur but less abundantly. Strata are thickly bedded to massive. Silicification has proceeded to its maximum extent here, replacing even matrix in some flank deposits. Organic material comprises up to 40 percent of the rock, with fossils in contact with each other. Micritic and fine bioclastic limestone matrix fills interstices within the rock. Flank deposits intertongue with and drape over reefoid and reef core facies deposits (Plate 15, F-3). Bank deposits are mound-shaped and generally overlie strata of the bioclastic facies. Bioclastic beds commonly grade laterally into flank-bank deposits indicating penecontemporaneous formation (Localities, 69 (C-3), 272 (F-3), and 149 (B-3), Plate 15). At locality 153 (Plate 15, B-4) interreef strata successively grade laterally into strata of the bioclastic facies, flank-bank facies, and reefoid facies. This gradation indicates organisms of the flank-bank facies inhabited firmer and slightly more elevated regions. Maximum relief between interreef sediments and reef crests, however, never exceeded 10-15 feet (Plate 15, Locality 280, F-3).

Organic accumulations of the flank-bank facies may consist entirely of one phylum, such as the bank deposit near locality 440 (Plate 15, C-2) which is composed wholly of brachiopods or contain a wide variety of organisms (flank deposit, F-3, Plate 15). Bank deposits are generally monospecific, whereas flank deposits contain varied faunas. A bank southeast of locality 69 (Plate 15, C-3) consists almost entirely of brachiopods, however, bryozoa and several gastropods are present. Figures C and D, Plate 5, show epiphytic relationships within this bank. The brachiopod *Derbyia* can be seen in Figure D, Plate 5, attached to a segment of a crinoid column at its posterior margin. The occurrence of several articulated columnals in a vertical position suggests the crinoid was living at the time of attachment of *Derbyia*. A similar relationship is described by Unklesbay and Niewolhner (1959) between *Productella* and a Mississippian crinoid. *Derbyia* is in turn encrusted by a fistuliporid bryozoan. *Prorichthofenia* is attached to both *Derbyia* and a fistuliporid bryozoan. Contemporaneous growth of *Prorichthofenia* and the bryozoan resulted in the brachiopod cementing spines over the bryozoan and the

bryozoan encrusting spines of *Prorichthofenia* (Plate 5, fig. C). Productid and spiriferid brachiopods predominate in bank accumulations.

Banks rarely exceed five feet high and ten feet long. Flank deposits form more extensive accumulations (Plate 15, F-3 and M-2) and vary in size from small marginal deposits (Locality 140, Plate 15, B-4) to extensive draping accumulations up to 100 feet long and 50 feet high (F-3). Bryozoa, except for limited occurrences of encrusting bryozoa, are noticeably absent from bank deposits. In contrast, thumb-shaped *Domopora*-like bryozoa and numerous fenestrate and arborescent bryozoa are quite abundant within flank deposits.

Stach (1937) attributes variation in distribution of bryozoans, based on zoarial shape, to depth of water and interprets fenestrate bryozoans as representing more vigorous water. If one is to follow his conclusions, reef flanks represent a moderately vigorous environment on the margins of even more turbulent reef crests. Such a relation is also indicated by field relations.

The coral, *Cladochonus*, occurs dominantly in flank facies deposits. Other rugose corals occur here in large numbers but also are present in other facies. *Cladochonus*, like fenestrate bryozoans, appears to be an indicator of vigorous wave-action.

The bulk of skeletal material occurring in the flank facies deposits is productid or richthofenid brachiopods and bryozoa. Spines of brachiopods are often entangled, suggesting that they are in growth position. Cooper (1937, p. 44) describes Devonian productid brachiopods in a similar relation and concludes that the association is a life assemblage which found no hardship in such crowded conditions.

Spiriferid brachiopods are rare in all but basal and marginal portions of flank deposits, and similarly become less abundant in larger bank deposits. There seems to be a faunal succession in which productid and richthofenid brachiopods replace spiriferid brachiopods. At locality 150 (Plate 15, B-4) a faunal succession is evident where basal bioclastic limestone contains a dominant spiriferid brachiopod fauna which is replaced upward by productid brachiopods and later by productid and richthofenid brachiopods and bryozoa (Bain 1966). Similarly, flank deposits at locality 706 (Plate 15, M-2) show a faunal succession of crinoidal debris to spiriferid brachiopods, productid brachiopods, bryozoa, and lastly to a reefoid community of fenestrate bryozoa, *Prorichthofenia*, and calcareous sponges (Plate 5, fig. B).

The flank-bank environment existed on firmer substrate, usually resulting from the accumulation of coarse textured bioclastic material. Such bioclastic deposits accumulated on the margins of reefs and as bars extending into the interreef area. This bioclastic gravel provided a firm substrate upon which a predominantly brachiopod fauna was able to exist. Where the population did not become too dense, spiriferid, productid, and richthofenid brachiopods existed together. In several instances, however, spiriferid brachiopods declined and disappeared, presumably due to competition with productids and richthofenids. Where the surface of deposits rose into a zone of more vigorous wave action, such as at localities 289 (F-3) and 88 (B-4), Plate 15, fenestrate, arborescent, and thumb-shaped bryozoa existed. Field evidence indicates that maximum relief from bioclastic strata to reef crests appears to have been less than 15 feet and most probably rose only one to two feet above the interreef bottom. Depth of water over this area then must have been relatively

shallow for there to have been a pronounced faunal difference with only minor change in relief. Waters must have been well-oxygenated to allow growth of the abundant bank fauna.

Reefoid Facies

The term "reefoid" is used by the writer to refer to massive accumulations of limestone which circumscribe reef cores. They appear reef-like on the outcrop and also contain localized organically bound reef-like structures. They are not considered reef cores because of their limited size, generally less than a few feet in diameter, or because they lack a well-bound fabric but still appear to have been wave-resistant. The facies is composed principally of medium-gray biomicrite and biomicrudite. Fragments of bryozoa and crinoid columnals dominate bioclastic material with brachiopods, gastropods, and sponge fragments also present (Plate 4, fig. D; Plate 6, figs. B and F; and Plate 7, fig. D). Within the reefoid facies bioclastic fragments comprise less than 20 percent of the rock. Locally pelletal limestone (Plate 7, fig. B) reaches noteworthy concentration, but these areas are few and scattered (Locality 405, Plate 15, B-5). Reefoid facies grade laterally into the bioclastic facies with massive, micritic limestone passing into well-bedded, bioclastic limestone in which micrite is lacking, and sparry calcite is the cementing agent (Plate 6, fig. A). The sediment source of both facies is obviously the same, and differences observed are the result of conditions under which they were deposited.

The vast quantities of micrite which occur within the reefoid facies are attributed to both organic and inorganic processes. Turbulent warm water precipitates finely crystalline calcite which could form micrite. Cloud (1952, p. 2146) interpreted the great quantity of fine-grained limestone in reef structures to be the result of such physicochemical precipitation. Organic activities, especially that of algae, tend to cause the precipitation of calcium carbonate. Newell (1955, p. 305) attributes the precipitation of most finely crystalline limestone in Permian reefs to these two processes. Much of the micrite is believed to have originated from the breakdown and crystallization of algae and algal fragments. Reefoid micrite containing what appears to be phylloid algal plates is shown in fig. D, Plate 6. Cloud (1962, p. 94) similarly concludes that much of the fine calcareous mud associated with reef growth in the Bahamas resulted from alteration of algal material, although the Bahama muds apparently began from fine debris. Stockman *et al.* (1967, p. 647) believed fine calcareous mud in the Florida Bay to have formed from the disintegration of plants and animals.

Breccia blocks, ranging in size from less than an inch to over two feet in diameter, occur as concentrated lenses peripheral to most reef cores (Plate 15, C-3, F-4, B-4, and H-1). Some concentrations of breccia are isolated from visible reef cores and can only be explained as related to possible structures which are in the subsurface or were up dip and lost through erosion (Plate 15, Locality 160, C-4; Locality 210, D-4). Occurrence of fine micritic core blocks in coarser reefoid bioclastic sediment are illustrated in fig. A, Plate 7. Ingles (1963, p. 430) notes the occurrence of blocks of reef rock associated with the Thorton Reef and has concluded that they too were torn up and transported by storm waves.

Pelecypods, brachiopods, bryozoa, a few sponges, corals, large concentrations of crinoids, and an undeterminable flora of algae comprise the organisms present in the reefoid environment as individuals and groups of individuals throughout the facies. They also occur in reef-like associations. Gastropods and scaphopods form a facies of their own within the reefoid facies by their concentration in localized areas. Small reefoid structures occur at localities 459 (D-2), 471 (E-2), 707 (M-2), 800 (H-1), and 978 (F-4) to list a few. *Prorichthofenia* is one of the major frame builders of these reefoid structures. Plate 1, fig C (Locality 459, D-2, Plate 15) illustrates one such mass of shells, most of which are in growth position. *Leptodus* occurs in large numbers at locality 800 where it builds a reefoid structure not unlike that of modern oyster banks. Newell (1955, p. 307) noted similar occurrences of *Leptodus* and *Prorichthofenia* within the Guadalupian reef complex. Ivanovid-type algae and fenestrate bryozoa form reefoid structures at localities 471 (E-3) and 978 (F-4), Plate 15 and Plate 5, fig. A. A branching algal framework is bound and interstitially filled by fenestrate bryozoa. Contemporaneous growth of both organisms is indicated by deformation of growth forms of each by the other. Most reef-like and substantial of all reefoid structures occur at locality 707 where *Prorichthofenia*, fenestrate bryozoa, and the calcareous sponge, *Amblysiphonella*, have intergrown to form an organically well-knit structure (Plate 5, fig. B).

Crinoids flourished on aprons of the reefoid environment. Their vast number is attested to by the great amount of bioclastic material which was derived from these crinoid meadows. Complete calices with articulated arms were collected from localities 674 (O-3), 746 (M-1), and 1008 (H-2). Communities of crinoids apparently grew down slope from reefoid aprons onto upper portions of the bioclastic facies.

Rugose corals, spiriferid, productid, and richthofenid brachiopods, various pelecypods, and several high-spined gastropods inhabited the elevated areas of the reefoid facies. Their occurrences are isolated and without pattern.

Ecology.—Shoals of bioclastic material surrounding reefs provided an environment in which varied communities of organisms flourished. Weak to moderate turbulence allowed the construction of reefoid masses by some organisms. Such structures would have been destroyed in a more vigorous environment since most were not wave-resistant. Crinoid communities flourished in this semiquiet water and supplied vast quantities of bioclastic material. Molluscan faunas prospered in muddy depressions upon reefoid shoals between reefoid and crinoid growth. Micrite was precipitated through biologic and physiochemical processes and filled available voids. An undeterminable amount of micrite was also derived from the alteration of algal material. Turbulence was moderate to low; salinity was normal, and depth probably did not exceed 60 feet over the shoals.

Reef Core Facies

Reef cores of the Cathedral Mountain Formation occur as light- to medium-gray, dense micritic masses which weather to mottled gray, meringue-like surfaces. Cores range from ten feet in diameter (Locality 155, Plate 15, B-4) to 125 feet long and 75 feet high (Plate 15, H-1). Massive accumulations of

biomicritic limestone generally circumscribe the cores (Plate 1, fig. D), but bioclastic material is lacking from reef cores.

Silicification penetrates only slightly below the surface and in general is limited. Silicified fossil material commonly displays orientation as at localities 555 (G-2), 591 (G-1), and 796 (L-2). Lamination of silicified fenestrate bryozoa at locality 555 is shown in Plate 3, figure C. At other localities, algal mats have been silicified, and their well-knit structure is clearly displayed on weathered surfaces (Plate 3, fig. B). Scattered fossils, such as rugose corals, pelecypods, and brachiopods within reef cores are likewise silicified.

Frame-building organisms of reef cores are primarily fenestrate bryozoa and the bryozoan-algal consortium, *Acanthocladia*. They occur singly or associated in the majority of reef cores. Fenestrate bryozoa occur as the sole framebuilder in a tightly knit structure at locality 555. Only a minor amount of algae is present with most binding done by the bryozoan itself. Bonham-Carter (1964, p. 518) described similar fenestrate reef cores from the Pennsylvanian of Ellesmere Island. Of secondary importance as framebuilders are calcareous and siliceous sponges and fistuliporid bryozoans. Newell (1957, p. 434-435) noted a similar decline in importance of calcareous sponges as framebuilders in Guadalupian reefs and concluded that calcareous sponges inhabited an extremely shallow environment which was destroyed by subsidence.

Stromatolitic algae, fistuliporid bryozoa, and *Tubiphytes*, an alga, act as binding organisms within reef cores. Stromatolitic algae and fistuliporid bryozoa and stromatolitic algae combine to form a reef structure at locality organic limestone. At locality 974 (Plate 15, F-4) layers of fistuliporid bryozoa alternate with layers of micritic limestone to construct a zone nearly two feet thick of mat-like reef growth (Plate 11, fig. A). Fistuliporid bryozoa and stromatolitic algae combine to form a reef structure at locality 408 (Plate 15, B-4). Here fistuliporid bryozoa heads are covered by thinly laminated stromatolitic algae (Plate 14, fig. B). Similar dominantly stromatolitic algal mats also occur at localities 845 (I-3), 809 (H-1), and 775 (L-2).

Either stromatolitic algae or fistuliporid bryozoa or occasionally both, generally encrust and bind fenestrate bryozoa and *Acanthocladia* (Plate 12, figs. A, B; Plate 13, figs. A, B; Plate 14, fig. A). Stromatolitic algae are the principal binding organisms and comprise the dominant portion of reef cores. Fistuliporid bryozoa become prominent as binders in several cores, but their importance is secondary to that of stromatolitic algae. The alga, *Tubiphytes*, functions as a binding organism in most reefs and is the primary binder at locality 553 (G-2). Thin-sections of core material with fenestrate bryozoa bound by *Tubiphytes* are shown in Plate 8, figures B and D, and Plate 9, figures B and E, show *Acanthocladia* similarly bound.

There does not appear to be any definite succession of binding organisms such as was evident in the Hess reefs. Occurrences of all three binders, such as in figure B, Plate 13, show that all three encrust each other with no definite order. One siliceous sponge is first encrusted by *Tubiphytes* while another is encrusted by stromatolitic algae. Fistuliporid bryozoans cover both and are later encrusted by both. Stromatolitic algae most often are the final binding organisms.

Accessory organisms within Cathedral Mountain reef cores are few and scattered. Most common accessory forms are brachiopods, primarily *Prorich-*

thofenia, rugose corals, high- and low-spined gastropods, rare scaphopods, pelecypods, calcareous sponges, and fusulinids. Many accessory forms are bound into the reef fabric (Plate 13, figs. A, B; and Plate 12, fig. A). Fusulinids and smaller foraminifera occur dominantly on reef core margins and tops. A similar distribution was noted by Newell (1957, p. 423) in patch reefs on the Bone Springs limestone. Large, epifaunal pelecypods occur bound within most reef cores. They apparently inhabited reef crests taking advantage of turbulent water and were encrusted by reef growth. Brachiopods and corals probably also inhabited the more vigorous reef crests because of a better food and oxygen supply. Gastropods probably fed on algae in the reef. Calcareous sponges occur as both limited frame-builders and accessory organisms. Newell (1955, p. 305) concludes that the productivity of Permian reefs was limited below 50 to 60 feet. Cloud (1942, p. 370) states that stromatolitic algae indicate depths less than 90 feet.

No single reef can be cited as typical of reef development within the Cathedral Mountain Formation because of variation in size, complexity, and fauna. For this reason, several structures are briefly described to present the characteristics of various types of reef cores.

In the area of F-3 of Plate 15, a small reef core, measuring 20 feet long and 15 feet high, is constructed by fenestrate bryozoa and stromatolitic algae (Localities 316 and 317). Dense micritic limestone fills voids within the core fabric and comprises over 60 percent of the core. Extensive flank facies deposits occur adjacent to this reef structure forming massive aprons 50 feet to either side (Localities 297 and 348). Bedded organism-rich flank deposits extend up to 75 feet beyond these aprons at locality 280. The flank fauna is dominated by intergrown productid, richthofenid brachiopods, fenestrate, and thumb-shaped and arborescent bryozoa (Localities 305-309 and 13-17). Strata of the flank facies grade laterally into biosparudites of the bioclastic facies (Locality 304). The flank facies rests upon bioclastic strata (Localities 294 and 347) and is also overlain by beds of the bioclastic facies (Localities 18, 300, 310, and 321) as shown in Plate 1, fig. D. Bioclastic strata can be traced over 500 feet from the reef structure (Locality 323).

The molluscan facies occurs northeast of the core at localities 360 and 361. Here bellerophonitid gastropods, cephalopods, and pelecypods occur in a dense, micritic limestone area which measures 20 feet long and 15 feet high.

The reef core located in the vicinity of G-2 of Plate 15 lacks flank facies deposits. Instead, the reefoid, reef core, and molluscan facies are well-developed. A reef core, measuring 80 feet long and 50 feet high, is constructed primarily by bryozoa and algae. *Acanthocladia* encrusted by *Tubiphytes* dominates the reef core fauna at locality 553 (Plate 9, figs. B through E). *Tubiphytes*, in this association, comprises approximately 40 percent of reef fabric, *Acanthocladia* 20 to 30 percent, and micritic matrix the remainder.

Stratigraphically higher in the reef core, fenestrate bryozoans dominate with the fabric, occurring alone and lacking any additional binder (Locality 555). Figure C of Plate 3 illustrates the weathered surface of the core at locality 555. Fenestrate bryozoa occur oriented and form a well-knit structure.

The reef core intertongues with reefoid and molluscan facies deposits at localities 542, 544, 545, 564, and 565. Mollusks, dominantly cephalopods,

are present in lenticular masses of micrite southwest of the reef core at localities 533 and 534 and to the northeast at localities 563 and near 580. Breccia fragments of reef core material occur at localities 539, 540, 542, and 579. Bioclastic deposits intertongue with (Locality 529) and extend out from the reef structure (Localities 521-525 and 571-573) up to 180 feet (Locality 286). They grade laterally into interreef strata (Locality 516).

Two reef cores in the vicinity of I-3 of Plate 15 are small, lenticular masses of micrite. The smaller core at locality 845 measures 20 feet long and 10 feet high. The larger core at localities 857 and 859 is 60 feet long and 20 feet high. Both cores are constructed dominantly by stromatolitic algae which comprises up to 75 to 80 percent of the core fabric. *Fistuliporid* bryozoa and *Tubiphytes* act as binding organisms but are less common than stromatolitic algae. Fenestrate bryozoa and *Acanthocladia* occur as frame-builders, but their contribution to reef construction is minor compared to stromatolitic algae. Figures A of Plates 12 and 13 show this preponderance of stromatolitic algae. A faunal succession appears to exist at locality 845. Fig. B of Plate 13 shows the primary encrustations of either *Tubiphytes* or *fistuliporid* bryozoan over siliceous sponges followed by stromatolitic algae.

Rugose corals, siliceous sponges, and brachiopods are present within the reef core fabric. Figure B of Plate 13 shows that even accessory organisms, such as these, were incorporated into the well-knit reef core fabric. *Fistuliporid* bryozoans occur at locality 845 (Plate 13, fig. B) but are greatly decreased in importance compared to other structures, such as at locality 974 (Plate 15, F-4) where it builds extensive mats (Plate 11, fig. A).

Voids within reef fabric are filled with dense, micritic limestone. Oolites, fusulinids, foraminifera, and algal plates occur scattered throughout this micrite. Foraminifera, fusulinids, and oolites reach higher concentrations on reef core margins (Locality 857).

Massive accumulations of reefoid limestone surround the core at locality 845 but are missing over localities 857 and 859. Reefoid deposits pass laterally into biosparudites of the bioclastic facies. A small micritic mass at locality 851 contains pelecypods and gastropods.

Ecology.—Following the destruction of the Hess reef environment, terrigenous silt and clay was deposited in a thick basal unit over Hess reefs and limestone. Siliceous sponges migrated shelfward into this habitat and remained as a flourishing fauna until conditions stabilized for reef growth. Reefs developed on the margin of the subsiding shelf as sedimentation raised the bottom to within the zone of reef growth and produced a protected limestone environment shelfward. Interreef deposition continued on the shelf in areas unaffected by reef growth. Crinoid communities became established and supplied vast quantities of bioclastic material to the area. Banks and reefs grew on these coarser and firmer bioclastic deposits and provided additional environments for more organisms.

The siliceous sponge fauna dwindled, and only a few remained to inhabit the reef environment. A fauna, somewhat different than that of Hess time, consisting of fenestrate bryozoa, *Acanthocladia*, stromatolitic algae, *Tubiphytes*, and *fistuliporid* bryozoa, constructed reefs. Calcareous sponges are present in limited numbers in these deeper habitats, but their ability to construct reefs was limited. Fenestrate bryozoa and *Acanthocladia* became the dominant frame-

builders, and structures were bound principally by stromatolitic algae, fistuliporid bryozoa, and *Tubiphytes*. The preponderance of stromatolitic algae is different from Hess reefs. Reef crests probably grew to within 55 or 60 feet of sea level.

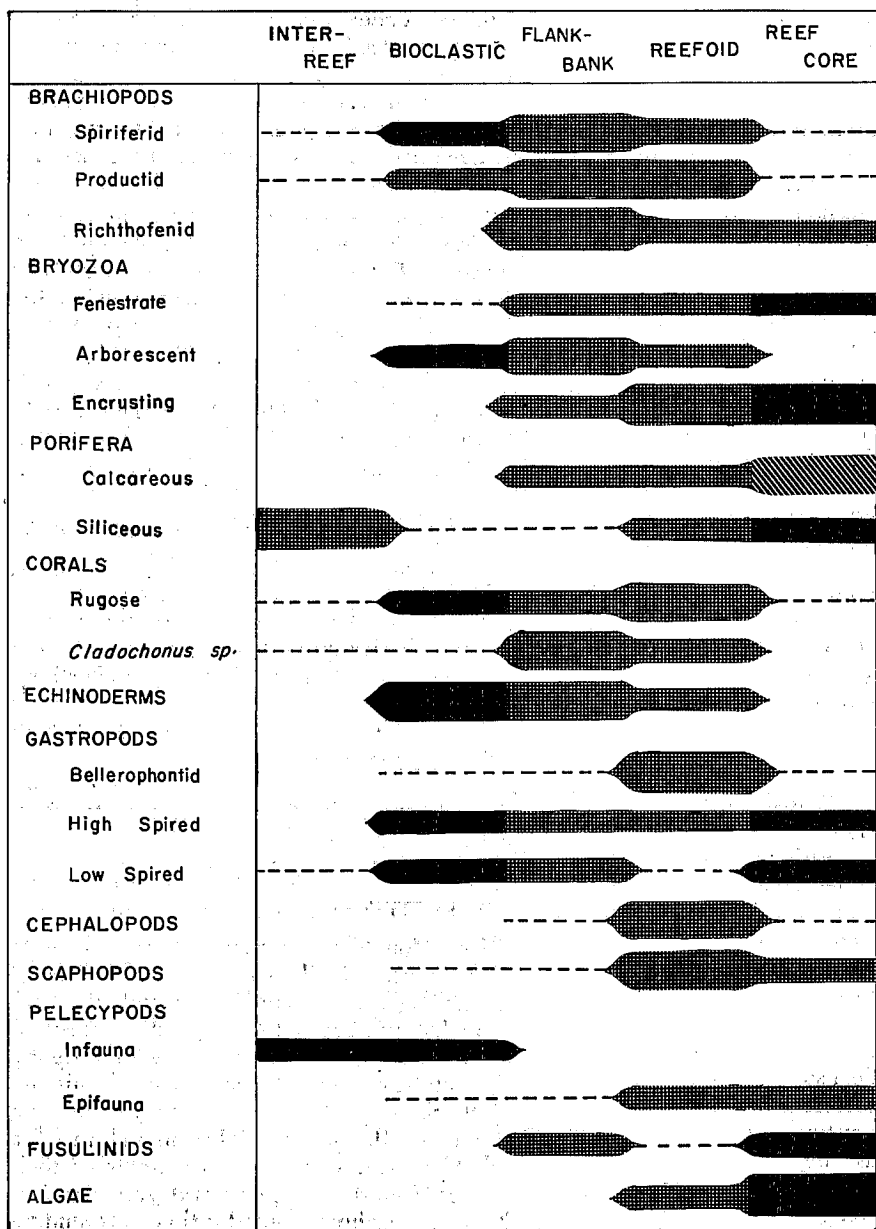
Interreef areas were subject to very weak currents but were not stagnant. From these interreef areas, such as at locality 515 (Plate 15, F-2), one rises toward reef structures over storm-deposited bioclastic tongues of limestone (Locality 521, F-2) inhabited by sparse faunas of brachiopods. Banks of brachiopods and fenestrate bryozoa locally inhabited the higher, more extensive tongues. Nearer the reef, bioclastic deposits were more numerous and thicker and the fauna increased in size and variety. Here on the edges of massive aprons of bioclastic material, localized crinoid communities appeared. Disarticulated crinoid columnals are everywhere (Locality 526, G-2). Crinoid and bryozoan faunas became more numerous on the higher parts of the aprons. Small, weakly constructed, reefoid masses rose above the bottom and were washed by moderately strong currents. Some areas, sheltered from current action by reef growth, contained muddy sediments and an abundant molluscan fauna (Locality 533, G-2). Large, varied communities of brachiopods, gastropods, bryozoans, and pelecypods formed shell banks on the uppermost margins of the bioclastic aprons. Reef cores are located at the top of these bioclastic aprons and stood as solid, lithified structures in moderate to strongly turbulent water (Locality 555, G-2). Dislodged and transported blocks of reef rock are evidence of storms and are scattered out onto bioclastic aprons (Locality 539, G-2). Algae encrusted fenestrate bryozoa and *Acanthocladia*. Brachiopods, pelecypods, gastropods, sponges, and corals were also present in limited numbers. Seas were of normal salinity, moderately turbulent, and no deeper than 75 feet.

FAUNAL DISTRIBUTION AND ASSOCIATION

Faunal distribution within the reef environment is illustrated in Text-figure 3 as: 1) not present, 2) rare, 3) common, and 4) abundant.

Although most brachiopods occur together, the ecologic niche of each varies considerably from others because of great disparity in growth forms. Spiriferid brachiopods inhabited any firm substrate where moderate currents were active. They seem to have avoided habitats where encrusting organisms were abundant. Although commonly occurring with productid brachiopods, they seem to have been unable to survive under crowded conditions with productids. Where the two occur together in large numbers, spiriferid brachiopods always become less abundant toward the upper portion of the deposit. In competition with richthofenids and productids, spiriferids always suffered. Productid brachiopods inhabited similar environments where encrusting forms are not abundant but favored more vigorous conditions, such as the flank-bank and reefoid environments. Richthofenid brachiopods, because of their cementing nature, were able to do well in more populated environments with moderate to vigorous waves. The flank-bank environment seems to have been most suitable, but reefoid and reef core habitats also provided sufficient surfaces for attachment.

Stach (1936) describes distribution of bryozoa based on their zoarial shape and relates encrusting forms to littoral to sublittoral depths, fenestrate



TEXT-FIGURE 3.—Diagram showing distribution of organisms in reef-associated facies. Diagram shows occurrence as: not present, rare, common, and abundant. Patterns indicate as follows: stippled—Cathedral Mountain Formation; diagonal lines—Hess Formation; and solid black—both Cathedral Mountain and Hess Formations.

to depths affected by strong waves, and arborescent forms to deeper, quieter water. Distributions of bryozoa observed within this reef environment do not agree completely with those of Stach. Encrusting bryozoa did occur in extremely shallow, vigorous, Hess reef crests but also ranged to deeper, less vigorous Cathedral Mountain banks and reefs. Arborescent forms occurred in greatest abundance in moderately turbulent environments but avoided the vigorous reef crests. Fenestrate bryozoa occurred in the most vigorous areas as suggested by Stach.

Finks (1960) interprets calcareous sponge faunas as indicators of shallow water and siliceous sponges as indicators of deeper water. Observations of this study agree with his interpretation. Calcareous sponges inhabited Hess reef crests while siliceous sponges occur in appreciable numbers only in the basal siltstone of the Cathedral Mountain Formation which was deposited in relatively deep water.

Rugose corals are ubiquitous but were most numerous in shallower, moderately vigorous water. They do not occur as a dominant fauna anywhere in the study area. *Cladoconus*, a dendroid tabulate coral, has a more restricted occurrence and seems to have inhabited only moderately vigorous environments.

Echinoderms, both crinoids and echinoids, occur together on upper slopes of the bioclastic and most of the reefoid accumulations. They preferred weak to moderate current action and avoided vigorous reef crests.

Mollusks occur throughout the area in rocks representing all the various environments. Cephalopods, neritic in life habit, appear to have preferred waters near reef crests. Burrowing forms, such as pelecypods and gastropods, inhabited muddy depressions on reefoid shoals adjacent to reefs. Pelecypods and gastropods also lived in the siltstone associated with siliceous sponges. Epifaunal pelecypods and gastropods inhabited reef crests.

Fusulinids occupied shelf areas during early Hess time and occur with other foraminifera on the margins of Cathedral Mountain reef cores. Both environments were moderately agitated and shallow.

ALTERATION AND RECRYSTALLIZATION

The silicified fauna of the Glass Mountains is famous for its delicate preservation. Silicification is not characteristic of all facies nor has it affected all fossil groups equally. Silica replacement is generally restricted to facies consisting of bioclastic sediments and has proceeded to the greatest extent in biosparites and biosparudites. Its occurrence is also restricted within tightly packed reefoid micritic limestone. Flank-bank and bioclastic facies fossils are silicified to the greatest extent. Both porosity of sediment and the draping attitudes of strata within these facies aided silicification. Solutions rich in silica were able to migrate freely through these sediments, and as a result of their draping structure, trapped waters were forced up dip toward reef cores as sediments were compacted, resulting in maximum silicification surrounding cores.

Silica did not replace all elements of the fauna equally. Some of this preferential alteration seems to be related to the facies in which various fossils occur, but there are indications that simpler forms, such as brachiopods, corals,

sponges, and fusulinids, are highly silicified while higher forms, such as mollusks and echinoderms, are generally less extensively silicified.

Sparry calcite occurs as primary filling or as a product of secondary recrystallization. Figure A of Plate 9 shows micritic limestone matrix of the reefoid facies being altered to sparry calcite. Its primary occurrences are those of interstitial filling in coarser sediments of the bedded deposits of the bioclastic facies. It is also present within voids in reef fabric (Plate 12, fig. A) and filling fossil body chambers (Plate 4, figs. B, D; Plate 8, fig. C; and Plate 11, fig. B).

Occurrences of sparry calcite attributed to secondary recrystallization are present within reef cores where micrite is converting to more coarsely crystalline sparite. Reefoid biomicrudites are similarly converting (Plate 6, fig. G). Fossil structures are being recrystallized into sparry calcite as shown in Plate 8, figs. A through D. A progressive recrystallization of skeletal structures to fibrous calcite, to microspar, and finally coarse sparry calcite is evident. This recrystallization affects primarily algal, sponge, and bryozoan structures.

DEPOSITIONAL HISTORY AND ECOLOGY OF THE LEONARDIAN SERIES OF THE GLASS MOUNTAINS

The depositional history of the Hess and Cathedral Mountain Formations within the study area was one of progressive deepening of a shallow shelf.

For five-sixths of Hess time, shallow seas covered an extensive shelf which bordered the subsiding basin margin. The sea was probably no deeper than 10 to 15 feet. Carbonates formed on these shelves were probably converted to dolomite by refluxing magnesium-rich ground water. The shelf was inhabited by fusulinids, crinoids, and a limited fauna of brachiopods, gastropods, and cephalopods. Weak to moderate turbulence existed; salinity was nearly normal, and carbonates were precipitated by physiochemical processes.

In late Hess time the rate of basin margin subsidence increased and progressively deepened adjacent shelf areas, deepening up to 30 or 35 feet within the study area. Reefs were established on the shelf margin and produced a moderately well-protected environment over the shelf. Crinoid communities inhabited this shallow shelf, and currents concentrated their columnals and calyx plates into gravel bars. These firmer and slightly elevated bars provided a more stable substrate upon which reef communities grew. *Acanthocladia*, calcareous sponges, fistuliporid bryozoa, and algae constructed solid reef structures to within 5 or 10 feet of sea level which were flanked by massive aprons of bioclastic material. Brachiopods, corals, gastropods, pelecypods, and large communities of bryozoa and crinoids inhabited the bioclastic aprons which surrounded reef cores. Molluscan faunas lived in muddy depressions upon reefoid masses adjacent to reef cores.

Subsidence continued, marking the end of Hess time, and the barrier of patch reefs was lowered, resulting in local destruction and eastward displacement of the protected environment. Within the study area, moderate to strong currents washed and scoured reef structures producing an unconformable surface over which basal Cathedral Mountain sediments were deposited. As the area subsided, mud and silt from uplifted land areas were transported into this previously carbonate environment. With increasing depth of the

shelf, a fauna consisting dominantly of siliceous sponges migrated shelfward and inhabited this silty bottom. Burrowing organisms, probably pelecypods, gastropods, crustaceans, and anemones, have also left evidence of their existence.

Following the flood of terrigenous clastic sediment, reefs were established on the shelf margin. Protected shelf areas were covered with sediments, and eventually bottoms rose to depths capable of supporting high organic activity. Crinoids and bryozoa supplied bioclastic gravels which were concentrated by currents. Reef growth again developed on a firm substrate, but unlike earlier Hess reefs, in these calcareous sponges were absent. Reef construction was performed primarily by *Acanthocladia*, fenestrate bryozoa, and algae. Stromatolitic algae act as the dominant binding organisms; locally forming reefs nearly by themselves. Reefs rose 15 feet above the sea floor and provided shoals upon which a large varied fauna existed. Massive draping aprons of bioclastic sediment circumscribed reef cores and supplied a favorable habitat where brachiopods, bryozoa, and calcareous sponges constructed small reefoid structures. Brachiopods, gastropods, pelecypods, and fusulinids inhabited reef crests as accessory organisms. Cephalopods apparently preferred waters near reefs and upon death were buried in sediments nearby. Echinoderms and bryozoa grew in clustered communities on reef flanks below reef crests, and sheltered pockets of muddy sediment were inhabited by a rich molluscan fauna. Water was probably no deeper than 55 to 60 feet over reef crests. Salinity was normal and turbulence moderate.

In later Cathedral Mountain time, the shelf continued to subside, and reef environments were locally destroyed but formed again farther shelfward.

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EXPLANATION OF PLATE 15

Map showing sample localities, traverses, and facies within study area at Split Tank in the Glass Mountains, Texas.