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Cover: Virgin anticline near St. George, Washington County, Utah.

### The Petrology of Three Upper Permian Bioherms, Southern Tunisia\*

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ABSTRACT.—The only known marine Permian rocks exposed in northern Africa are those in southern Tunisia at Djebel Tebaga. They crop out in the core of an anticline 25 kilometers northwest of the community of Medenine. Permian rocks of Guadalupian age dip 30° to 40° to the southeast and form strike ridges that are angularly overlain in the western end of the outcrop belt by nearly flatlying Cretaceous rocks. The Permian rocks there represent a reef complex with large carbonate masses interfingering laterally into greenish and brownish gray shales. Many small bioherms occur in the shale beds between larger carbonate masses. Three well-exposed, well-preserved bioherms, one each from three locations: the Saikra Biohermal Complex, the Upper Biohermal Complex, and the Middle Shaly Facies, were studied in detail.

The largest bioherm, Bioherm 2, from the Upper Biohermal Complex, is 55 meters long, 32 meters wide, and 4 meters thick. Bioherm 3, the smallest, is from the Middle Shaly Facies and is discoidal, 6 meters in diameter, and about 3 meters thick. Bioherm 1 is from the Saikra Complex. The in situ skeletal framework of the bioherms comprises complexly overgrown colonies of solenoporacean, codiacean, and dasycladacean algae, Osagia, Tubiphytes, tabulate corals, and cyclostome, cryptostome, and trepostome bryozoans. The matrix in all three bioherms is dominantly micritic. Vertical biostratigraphic zones observed in Bioherm 1 indicate that codiacean algae, then tabulate corals, and finally solenoporacean and codiacean algae sequentially dominated in the bioherm during deposition.

Biologic evidences suggest the bioherms were deposited in warm, shallow waters with moderate circulation. Lithologic evidences indicate that initial colonization of the localities took place on a substrate of skeletal debris, and that growth continued during prevailingly quiet water conditions, punctuated by shorter episodes of agitation. Formation of abundant stylolites in Bioherm 3 aided extensive dolomitization which masks elements of the skeletal reef framework. Recrystallization and micritization partially obscure the primary depositional fabric in Bioherms 2 and 3.

#### INTRODUCTION

The Djebel Tebaga region of southern Tunisia (fig. 1) exposes the only known Permian outcrops in Tunisia and the only known marine Permian rocks of northern Africa. Djebel Tebaga is located 25 kilometers northwest of Medenine, southern Tunisia, and is in the core of an anticline. Permian rocks in the anticline form strike ridges trending about N.  $70^{\circ}$  E., with beds dipping  $30^{\circ}$  to  $40^{\circ}$  to the southeast. At the west end of the outcrop belt, Permian rocks are unconformably overlain by nearly flatlying Cretaceous rocks which form a prominent escarpment at the edge of the Dahar Plateau.

The Tebaga outcrops are evidence of the westernmost extension of marine shelf deposition in the Mesogean Tethys (Baird 1968). The Djebel Tebaga rocks were deposited on the shelf at the edge of a Permian basin in which Upper Permian strata attain great thickness. A well drilled in the area encountered nearly 4000 meters of Upper Permian rocks (Baird 1968). The age of the Djebel Tebaga marine beds is Guadalupian, probably Wordian and Capitanian (Newell et al. 1976).



FIGURE 1.-Index map of southern Tunisia showing the location of Djebel Tebaga 25 kilometers northwest of Medenine.

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Numerous small bioherms exposed in the area are composed in large part of algae, corals, and bryozoans, all in a fine-grained matrix. These small bioherms occur along the flanks of larger reef masses. Many of them are well preserved and nearly exhumed in three dimensions from overlying and laterally equivalent strata. This study is concerned with the petrology of three of these bioherms.

Bioherm 1 is exposed on the south slope of a small stream valley on the south flank of Djebel Souinia, north of the village of Saikra (fig. 2). The bioherm is part of the Saikra Biohermal Complex, bed 15 of section G, of Newell, Rigby, Driggs, Boyd, and Stehli (1976). Bioherm 2 caps a low hill at the northwestern edge of the village of Halk el Djemel (fig. 3). It is included in the Upper Biohermal Complex of Newell et al. (1976) and lies in bed 23 of their section B. Bioherm 3 is exposed to the east of the road in Merbah el Oussif (fig. 3). It lies in the Middle Shaly Facies, bed 26 of section E, of Newell et al. (1976).

#### Field and Laboratory Methods

Each bioherm and the immediately surrounding strata were mapped and sampled by utilizing a metric grid system. A Brunton compass was used to orient the grids. A baseline for the grid was measured and painted along the greatest horizontal dimension of the bioherm, and traverse lines were constructed at regular intervals perpendicular to the base. Sections were measured and samples were taken along each of these closely spaced perpendicular traverses. Sample locations were plotted on the grid (figs. 4, 5, and 6). An additional smaller bioherm was included within the grid boundary at each of the three localities because of close proximity to the principal bioherm.

The grid baseline for Bioherm 1 was 50 meters long, and perpendicular traverse lines were established at 5-meter intervals along the baseline. These perpendicular sample traverses ranged from 8 to 15 meters long (fig. 4). The grid baseline for Bioherm 2 was 55 meters long. Perpendicular sample lines, from 18 to 36 meters long, were constructed at 5-meter intervals across Bioherm 2 (fig. 5). Bioherm 3 is somewhat smaller, and a baseline only 7 meters long was necessary. Perpendicular traverses were from 3 to 15 meters long (fig. 6). Complex topography and almost complete exhuming of Bioherm 3 necessitated plotting sample locations on topographic profiles of each traverse to show vertical as well as lateral position. Each traverse profile on Bioherm 3 was also photographed to show topographic position.

In addition to Bioherm 3 and the smaller bioherm several meters north of it, a third small associated bioherm, 17 meters to the west across the Merbah el Oussif road, was mapped and sampled.

Samples from the three large bioherms were about 10 centimeters in diameter and as nearly equant as possible. Density of sampling varied from bioherm to bioherm. Samples were taken about 1 meter apart, both vertically and horizontally, at Bioherm 1; about 2 meters apart at Bioherm 2; and approximately 1 meter apart at



FIGURE 2.—Detailed index map indicating location of Bioherm 1 north of the village of Saikra. A trail leading north passes to the west of Bioherm 1 and is shown as a dotted line.



FIGURE 3.—Detailed index map showing locations of Bioherm 2 at the northern outskirts of Halk el Djemel and of Bioherm 3 in Merbah el Oussif.



FIGURE 4.—Map of Bioherm 1 showing sampled locations and associated strata. Stippled area underlying Bioherm 1 represents a limestone with fabric similar to the bioherm but which weathers to a spheroidal surface. Youngest beds are at the top of the map.

Bioherm 3. A cassette tape recorder was utilized to record field observations. was examined using both petrographic and binocular microscopes.

A 2-by-3-inch billet was cut in laboratories at Brigham Young University from each sample of alternating traverses, a thin section was made of each billet, and each Point counts of thin sections from Bioherms 1 and 2 were made to determine relative population densities. Projection prints with 4-power enlargement were made of each



FIGURE 5 .- Map of Bioherm 2 indicating sampled locations and associated strata. Youngest beds are at the top of the map.

thin section. A 2-centimeter gridwork was printed on an acetate transparency and was used to overlay each projection print. The point count was then effectuated by identifying the material beneath each grid intersection and counting its frequency of occurrence.

Table 1 gives results of point counts of thin sections from Bioherms 1 and 2. The data are averaged for each biostratigraphic zone of Bioherm 1 and for the areas north and south of the grid baseline for Bioherm 2.

#### **Acknowledgments**

I thank Dr. J. Keith Rigby, chairman, and Dr. H. J. Bissell of my thesis committee for their unselfish assistance. Dr. Donald W. Boyd and Dr. Norman D. Newell, as well as Dr. Rigby, provided much help with field work, for which I am grateful. To the University of South Carolina International Study Project, for providing transportation to and from Tunisia and defraying field expenses, and to the Union Oil Company of California, for also providing funds, I express my thanks.

In January 1976 Dr. John L. Wray of the Marathon Oil Company identified the algae from selected thin sections of the bioherms. In the same month Dr. J. R. P. Ross of Western Washington State College identified several bryozoans from thin sections of the bioherms. Their help with identification of these organisms is appreciated.

Finally, I extend appreciation to my wife, who patiently endured my absence and willingly gave her time during preparation of the manuscript.

 TABLE 1

 CONSTITUENT PERCENTAGES OF BIOHERMS 1 AND 2

	BIOHERMI				BIOHERM 2	
Constituents	Zone i	Zone 2	Zone 3	Zone 4	North	South
Osagia	14%	17%	14%	13%	5%	22%
codiacian algae	28	8	8	3	10	16
solenoporacean algae	0	0	1 -	20	15	22
Tubiphytes	1	5	l	3	2	3
Permosoma	4	33	8	3	17	10
fine tabulate coral(?)	2	3	25		10	L
bryozoans	2	1	4	0	0	0
matríx	43	35	25	45	27	31
sparry calcite	2	9	4	2	4	10

#### Previous Work

Douvillé, Solignac, and Berkaloff (1933) published a stratigraphic section and a faunal zonation of Berkaloff's Permian discovery at Djebel Tebaga. They decided that the outcrops contained both Middle and Upper Permian rocks. The folowing year Douvillé (1934) described the fusulinid fauna from the outcrops. The stratigraphy and structure of these rocks and Mesozoic rocks of the adjacent mountains were studied and reported by Gilbert Mathieu (1949). His paper has provided a stratigraphic and structural framework for later authors. Henri and Geneviève Termier published a series of general descrip-



FIGURE 6.—Map of Bioherm 3 showing sampled locations and bioclastic limestone north of bioherm. Youngest beds are at the top of the map.

tions of sponges, algae, corals, brachiopods, echinoderms, trilobites, gastropods, and pelecypods of the Djebel Tebaga (1955a, 1955b, 1957a, 1957b, 1958, 1959, 1973, 1974a, 1974b, 1975a, 1975b). They consider the age of the Permian beds to be between the end of Kazanien and the beginning of Pamirien time (1974c). Glintzboekel and Rabaté (1964) described the microfossils and microfacies of the Djebel Tebaga outcrop, plus those of a well at Bir Soltane to the southeast. Skinner and Wilde described fusulinids from the section (1967). In a guidebook for a field trip by the Petroleum Exploration Society of Libya, D. W. Baird (1968) summarized previously published literature dealing with the stratigraphy, structure, geomorphology, paleontology, and tectonics of Djebel Te-baga. Henry and Carol Faul more recently briefly described the area and their fossil collecting (1974). Newell, Rigby, Driggs, Boyd, and Stehli (1976) described their stratigraphic and paleontologic reconnaissance of the area. They describe the Djebel Tebaga section as a reef complex and suggest that this interpretation may aid in understanding complex and abrupt facies relationships.

#### **BIOHERM** 1

#### Geometry

Bioherm 1 is exposed to the steep north-facing slope of a small stream valley on the southwest slope of Djebel Souinia (fig. 7). It comprises two closely spaced masses which together measure about 46 meters across, parallel to the strike of beds underlying and overlying it. The bioherm has a maximum thickness of approximately 6 meters. Elongate shapes of the masses are shown in figure 4. The western end of the bioherm is blunt whereas the eastern end thins to a point and wedges out between bedded, fine-grained clastic rocks.

#### Local Stratigraphy

Stratigraphic relationships of Bioherm 1 are shown in figure 4. A bedded bioclastic limestone, 1 to 2 meters thick, lies from 2 to 4.5 meters below the bioherm and has an average strike of N. 70° E. and a dip of about 40° to the southeast. The moderately resistant biohermal mass is underlain by slope-forming limestone. This reA. F. DRIGGS



FIGURE 7.—View east toward Bioherm 1 and associated strata exposed on the southwest flank of Djebel Souinia. Bioclastic limestones associated with Bioherm 1 strike N. 70° E. and dip approximately 40° to the southeast.

cessive unit has a fabric and composition similar to that of the overlying bioherm but differs from it in weathering to a spheroidal surface, with knobs ranging from 5 to 15 centimeters in diameter (fig. 8). This same knobby weathering appearance is also found between the two resistant masses which comprise Bioherm 1. The less resistant argillaceous limestone extends laterally beneath the bioherm and at least several meters beyond its margins.

A greenish gray shale which weathers to form a slope is laterally equivalent to the bioherm. A 2-meter-thick bed of algal oncolites extends westward from about 20 meters west of the bioherm and is roughly equivalent to the top of the bioherm. A shale, 1 meter thick, overlies the bioherm. A series of alternately thick- and thin-bedded bioclastic limestone up to 2 meters thick occurs above the shale and overlies the western half of the bioherm. This limestone abuts the western flank of a small bioherm which overlies the eastern half of Bioherm 1 (fig. 4).

#### Associated Bioclastic Limestone

Beds of grain-supported bioclastic limestone, according to the classifications of Dunham (1962) or Folk (1962),



FIGURE 8.—Spheroidally weathered limestone near locality E2 of Bioherm 1.

overlie and underlie Bioherm 1. They are thin to thick bedded and are brownish gray. Clastic grains include several genera of fusulinids (fig. 9E), algal plates and pelletoids, crinoid fragments, small gastropods, fragments of bryozoans and corals, codiacean and dasycladacean algae, and quartz grains. Algae coat many grains and also occur as free filaments. Abrasion of the skeletal grains prior to deposition was minimal.

Finely textured, sparry calcite fills interstitial areas. Many patches of spar are murky and probably contain mud or algal debris.

Sorting of the debris is generally poor. Grains range from less than 0.1 millimeters to about 8 millimeters in diameter. Small, subangular quartz grains, which have calcite overgrowths, are present in most samples but are not abundant. Their diameter is about 0.2 millimeters. In the sample taken at position J7 (fig. 4), grains of similar size differentiated into weak layers with moderate sorting in each layer.

Stylolites are found in sample J6. In most samples small quantities of dark dead oil occur in small patches and along grain boundaries.

FIGURE 9.—Bioclastic limestone fabric, mottled biohermal matrix, micritization, and Ivanovia outcrop view. A.—Small bores in Permosoma which are now filled with micrite, site B5, Bioherm 1, X10. B.—Solenoporacean algae riddled with micrite-filled bores at locality D9, Bioherm 2, X5. C.—Matrix at site G3, Bioherm 2. Mottling is probably algal material, X5. D.—Phylloid algae Ivanovia in outcrop near sample locality D8 of Bioherm 1. E.—Fusulinid-rich bioclastic limestone, locality B1, Bioherm 1, X10. F.—Small micrite-filled bores in solenoporacean algae, site C5 of Bioherm 1, X10.



#### Matrix of Bioherm 1

Mud-dominated matrix fills the space not occupied by in situ skeletal remains throughout Bioherm 1 (table 1). Such matrix contains varying quantities of micrite, skeletal fragments, pellets, and detrital(?) grains, but the latter two are minor constituents.

A wide variety of skeletal fragments is present. Bivalves occur, both as articulated individuals and as individual or fragmented single valves. Fragments of algal plates, codiacean algae, bryozoans, and solenoporacean algae also appear with varying abundance, depending upon the proximity of the sampled locality to each biofacies.

Sorting of the fragments is generally poor to medium. Fragment sizes range from less than 0.1 millimeter to over 5 millimeters. Such a size range in the biohermal matrix compares well with the grain sizes of the bedded limestones which overlie and underlie the bioherm.

In the samples which show concentrations of coarse debris, fragments are oriented with the long axes parallel with the bedding plane in the matrix. Sample E4, for example, shows elongate clasts of codiacean algae, solenoporacean algae, and bivalves parallel to bedding. In samples with sparse, coarse debris in the matrix, bioclastic fragments are generally quite small and show no marked orientation.

Subspherical pelletoids with diameters of approximately 0.5 millimeters are present in the sample from locality B4 but are not common in the bioherm. They are possibly of algal origin in view of the abundance of algae in the bioherm.

Finely crystalline grains of possible detrital origin are evident near the top of the bioherm at localities E11 and E12 and make up less than 1 percent of the rock.

Most of the fragments in the matrix, in particular the codiacean and solenoporacean algae, bivalves, bryozoans, and algal plates, could have originated from elsewhere within the bioherm. As stated previously, the close proximity of a particular in situ biofacies increases the ratio of skeletal fragments from that facies in adjacent rocks. Crinoid fragments, however, are present in the matrix even though crinoids are not part of the in situ framework of the bioherm. Some skeletal fragments may have been transported to the bioherm from adjacent areas.

#### Organism Relationships within Bioherm 1

Corals, bryozoans, and a variety of algae make up the skeletal framework of Bioherm 1 (table 1). Small brachiopods are found in the matrix but are not part of the framework.

The most abundant corals belong to the genus *Permo*soma Jaekel (1918). Termier and Termier (1957) have described specimens of the genus from Djebel Tebaga (fig. 10F). This coral resembles *Michelinia* De Koninck (1841), for it is colonial and has corallites that are generally hexagonal. It differs from *Michelinia*, however, in possessing columellae (fig. 10F). *Persoma* assumes both encrusting and massive forms.

An undescribed fine tabulate coral(?) is abundant in the bioherm and throughout the Permian outcrop belt. The tubules in the colony are round and slender, 0.3 to 0.4 millimeters in diameter, and are evenly spaced. Tabulae are complete and widely spaced (fig. 10E). Colonies of this coral(?) most commonly form encrustations but may also be massive.

Cyclostome, cryptostome, and trepostome bryozoans are locally abundant but contribute only minor volumes to the total bioherm mass (table 1). Figure 10B shows a fistuliporid cyclostome from locality G8. Autopores, mesopores, and numerous acanthopores are evident in twigs of a stenoporid trepostome from locality G1 (fig. 10D). J. R. P. Ross (pers. comm. January 1976) also identified fistuliporid and rhabdomesonid bryozoa from material sent to her from locality G1.

Varieties of red and green algae are important in the skeletal framework (table 1). Of the red algae the solenoporaceans are most abundant. J. L. Wray (pers. comm. January 1976) identified the genera Solenopora (fig. 11B) and Parachaetetes (fig. 11A) in material submitted to him for study from Bioherm 1. Solenopora is distinguished by its irregular tissue in which cross partitions are widely spaced. Parachaetetes, by contrast, has regular tissue and strong regular cross partitions and has a gridlike appearance in thin section (Johnson 1963). Figure 11A illustrates the growth forms which these Permian solenoporaceans assume. These branching thalli comprise a major portion of the skeletal framework of Bioherm 1.

Codiacean green algae are represented by *Hikorocodium* and *Ivanovia*. *Hikorocodium* is characterized by tubular or tubular branching thalli composed of threadlike filaments which branch outward from a central stem (Endo 1951, p. 126), (fig. 10 C). *Ivanovia* form potato-chip-like plates or blades containing cylindrical cells radiating out from a central column. The cylindrical cells intersect the surface of the thallus at right angles (fig. 11F).

Dasycladacean algae are found in the uppermost part of the bioherm, at location B7 of figure 4, and in associated bioclastic limestone (location J7 of fig. 4). Dr. John Wray (pers. comm. January 1976) has tenatively identified *Macroporella* and *Epimastopora* in samples of bioherm submitted to him for study. *Macroporella* is cylindrical with a thick central stem. Branches extend from the stem in irregular whorls (Johnson 1963). *Epimastopora* resembles *Macroporella* but has a cylindrical thallus and long primary branches that form regular, closely spaced whorls (Johnson 1963).

Laminar filamentous algae are found in essentially every sample and probably belong to the genus Osagia. Osagia is a tubular alga which forms a symbiotic relationship with

FIGURE 10.—Representative fossils of the bioherms, including algae, bryozoans and corals. A.—Tubiphytes from location E2, Bioherm 3, X15. B.—Fistuliporid bryozoan from location G8, Bioherm 1, X10. C.—Hikorocodium from locality C1, Bioherm 1, showing various growth forms, X5. D.—Trepstome bryozoan showing autopores, mesopores, and acanthopores, location G1, Bioherm 1, X10. E.—Fine tabulate coral(?) showing longitudinal and tangential cross-sections of tubules. Tabulae can be seen in several tubules. Specimen from locality J2, Bioherm 1, F.—Permosoma from site G2, Bioherm 1. Columellae and tabulae are seen in several corallites, X5.



the encrusting foraminifera Nubecularia (Johnson 1963). Osagia characteristically forms laminae on the surface of other organisms. Girvanella, another tubular to boring algae, is also present in laminations as small tubes about 20 microns in diameter.

The gray encrusting alga, *Tubiphytes* Maslov (1956), is common in the bioherm (table 1) and forms warty encrustations on the organisms. Figure 10A shows a free individual. Johnson (1963) compared *Tubiphytes* to the genus *Rettphycus* from the Mississippian of Alberta.

Small rostrate brachiopods are common in the matrix, but their generic identity is unknown. They apparently were not anchored to the substrate and do not form part of the skeletal framework.

Four biostratigraphic zones can be recognized in Bioherm 1 (fig. 12). Table 1 gives average percent composi-tion for each zone. The first organisms to pioneer the bioherm locality occur in zone 1 and are tubular to branching tubular algae of the genus Hikorocodium. Lesser numbers of corals, bryozoans, and other algae also lived in the zone. In a second zone Hikorocodium decreases in importance whereas Permosoma, other corals, bryozoans, and other algae become significant. Zone 3 is limited laterally to the western two-thirds of the bioherm where algae and new tabulate coral (?) dominate. Hikorocodium and Permosoma occur but are less important. Zone 4 caps the eastern two-thirds of the bioherm and zone 3 the western third. Zone 4 is characterized mainly by Ivanovia, solenoporacean algae, and encrusting algae, with some minor corals and codiacean algae. Osagia is common in all zones (table 1), and accordingly it is not mentioned specifically in any of them on the map.

Organisms in the bioherm commonly attach to other forms or overgrow them, and the encrusting organism conforms to the surface contours of its support. Some fossils have greater tendencies to overgrow than do others. They are, listed in decreasing tendency to overgrow, Osagialike encrusting algae, fine tabulate corals(?), other algae, and Permosoma. There does not seem to be a correlation between the abundance of an organism at a locality and its tendency to overgrow neighboring organisms. For example, at location B4 (fig. 4) Permosoma is more abundant than Hikorocodium, but there Hikorocodium generally has overgrown Permosoma.

In zone 1, as in the other three zones of the bioherm, Osagia overgrows all the other groups. In samples from locality G1, the new fine tabulate coral(?) has overgrown Hikorocodium (fig. 11C). At the same location Permosoma has encased Hikorocodium. Hikorocodium in turn has encrusted a small brachiopod.

Figure 11E illustrates a complex overgrowth relationship from zone 2, locality G5. A codiacean alga has overgrown *Tubiphytes*, which has encrusted the new fine tabulate coral(?) which, in turn, has encased *Permosoma*. At site G4 *Permosoma* has overgrown a fine tabulate coral(?) whereas several centimeters up section the fine tabulate coral (?) has overgrown *Permosoma*.

A sequence of encrustation involving six organisms at site G9, zone 3, is shown in figure 11D. The fistuliporid bryozoan first occupied the area and was overgrown by *Hikorocodium*, then by another codiacean algae, then by a second generation of the same fistuliporid genus, then by *Permosoma*, and finally by *Osagia*(?). Zone 3, from which the sample was taken, is characterized by abundance of the undescribed fine tabulate coral(?), which has overgrown brachiopods, *Hikorocodium*, and *Permosoma* at various locations.

At the top of the bioherm, locality E 12, Osagia has encrusted Solenopora sp. (J. L. Wray, pers. comm. January 1976). Figure 11F shows a colony of the undescribed fine tabulate coral (?) which has overgrown a blade of *Ivanovia*.

#### Diagenesis

Recrystallization is important in the fabric of Bioherm 1 and has affected both the fossils and the matrix. Corals and solenoporaceans are the most strongly recrystallized fossils, but encrusting algae, tubular algae, bryozoans, and bivalves are affected as well. Recrystallized calcite has commonly replaced the skeletal structure of corals and bryozoans with a coarse mosaic. Some algae, such as Osagia and Tubiphytes, have resisted recrystallization, though surrounded by recrystallized matrix. Patches of matrix tend to recrystallize to sparry calcite.

Some fossil structures, such as tented algal plates and bivalve interiors, provide shelters in which enclosed matrix has recrystallized. Figure 13A shows an oriented sample containing a bivalve shell. Matrix in the upper part of the shell has recrystallized, and that in the lower part has remained essentially unaffected.

Many samples contain abundant microfractures that expand in delicate spidery networks. They are filled with sparry calcite and locally contain traces of a black material, possibly dead oil, as at locality B2 (fig. 13C). The fractures, perhaps, served as pathways of fluid movement.

Stylolites are not abundant in Bioherm 1. Where they occur, their amplitude is small. They are commonly filled with stained, dark brown or black material.

Fossils in the bioherms are commonly enclosed within a micritic envelope. Normally, the contact between the micrite and the fossil is irregular. Bathurst (1971) described the process of micritization, a process which may explain the genesis of micritic envelopes. As explained by him, boring endolithic algae perforate the exterior of fossil grains. Upon the death of the alga, the bore is filled with micrite. After several generations, the interweaving bores merge to form an envelope of micrite. Micritization affects

FIGURE 11.—Overgrowing relationships within the bioherms and varieties of algae A --Characteristic growth form of Parachaetetes, encrusted with Osagia, locality G5, Bioherm 2, X5. B.—Solenopora encrusted by Osagia at site E12, Bioherm 1, X10. C.—Fine tabulate coral(?) overgrowing Hikorocodium, location G1, Bioherm 1, X5. D --A complex overgrowth relationship Osagia overgrowing Permosoma, overgrowing a fistuliporid bryozoan, overgrowing a codiacean alga, encrusting Hikorocodium at locality G9, Bioherm 1, X5. E.—Hikorocodium overgrowing Tubiphytes, encrusting fine tabulate coral(?), overgrowing Permosoma at site G5, Bioherm 1, X5. F--Fine tabulate coral(?) encrusting Ivanovia at locality C6, Bioherm 1, X10.





FIGURE 12.-Biostratigraphic zones of Bioherm 1. Zone 1 overlies the northernmost bioclastic limestone.

many fossils in the bioherm. Figure 9A shows micritefilled bores on the interior and a micrite envelope around the coral *Permosoma* at location B5. Solenoporaceans seem to be particularly susceptible to micritization. Figure 9F shows micritization of a solenoporacean at location C5.

#### **BIOHERM 2**

#### Geometry

Bioherm 2 is 55 meters long, aligned east-west. The western half bulges slightly and is 32 meters wide and approximately 4 meters thick. Figure 5 is a map of the bioherm showing its shape, facies, and sample traverses. The bioherm caps a low hill, exposing the elongate disklike structure. The only appreciable relief on the surface of the bioherm is over several low mounds centered, respectively, at sample locations G7, H13, and H14. The mounds are about 5 meters broad and rise up to 1 meter above the surrounding lower biohermal surface.

#### Local Stratigraphy

Stratigraphy of Bioherm 2 is shown in figure 5. A bedded bioclastic limestone occurs from 0.5 to 5 meters below Bioherm 2. This limestone is 1.5 meters thick beneath the eastern margin of the bioherm, thickening to approximately 5 meters at the western margin; it dips about  $15^{\circ}$  to the south and strikes N. 60-70° E. A small bioherm 7 meters long and 2 meters thick is encased in this limestone near the northernmost extremity of Bioherm 2. Four beds of bioclastic limestone are laterally equivalent to the bioherm and interbed with the shale. Figure 5 shows that three of these four limestones abut against the bioherm. The uppermost of the beds, from which the

sample at locality M3 was taken (fig. 5), laps onto the bioherm. It is equivalent to a 3-meter-thick sequence of finely-bedded shaly sandstones several meters west of the bioherm. Patches of bedded bioclastic limestone approximately 50 centimeters thick stratigraphically rest upon the upper surface of the bioherm.

#### Associated Bioclastic Limestone

Beds of brownish gray, grain-supported bioclastic limestone overlie, abut, and drape onto Bioherm 2. Similar beds are associated with Bioherm 1. The limestones are thinly to thickly bedded.

Grains present include fusulinids, other small foraminiferal genera, fragments of bryozoans, solenoporacean and codiacean algae, gastropods, algal pellets, bivalve tests, and rare quartz grains. Algae are abundant both as grain coatings and as free filaments.

Sparry calcite and lime mud fill interstices between grains in the bioclastic limestone; this spar is murky and consists of finely crystalline calcite with lime mud and algal material. Sparry calcite probably represents recrystallized lime mud (fig. 13E). Sorting is poor. Pods of smaller grains are present. A

Sorting is poor. Pods of smaller grains are present. A few small quartz grains with calcite overgrowths are seen in the samples. Skeletal grains range from less than 1 millimeter to over 8 millimeters in diameter.

Patches of dead oil, though present, are rare.

#### Matrix of Bioherm 2

As in Bioherm 1, fine mud, fossil debris, and algal material fill voids in the in situ skeletal framework (table 1). In many samples, for example, sample G3 (fig. 9C),

FIGURE 13.—Stylolites, microfractures, and recrystallization fabrics. A.—Micritic matrix in the uppermost area of brachiopod interior has recrystallized to sparry calcite, locality G2, Bioherm 1, X5. B.—Recrystallization of micritic matrix to sparry calcite in the top of a gravity trap, site J4, Bioherm 2, X5. C.—Microfracture stained by dead oil, locality B2, Bioherm 1, X5. D.—Smallamplitude stylolytes, some with oil stain, from site G5, Bioherm 3, X5. E.—View of micritic matrix in lower middle of photomicrograph and sparry calcite recrystallized from micrite in upper middle of photomicrograph, locality D2, Bioherm 2, X10. F.—Skeletal elements of *Hikorocodium* have recrystallized at locality C3, Bioherm 3, X5.



the matrix is mottled brown or gray probably because of the presence of algal and fine organic debris.

The ratio of skeletal fragments to matrix increases within biologic sediment traps in the in situ skeletal framework. In thin section they appear as pockets of closely packed skeletal fragments and matrix bounded by in situ organisms. The fragments range from less than 1 millimeter to about 5 millimeters in diameter. Bioclastic limestone beds in association with the bioherm contain fragments of similar sizes.

Skeletal grains in the matrix include fusulinids, fragments of corals, codicean and solenoporacean algae, bivalves, bryozoans, and crinoids. Many of these grains possibly were derived from other parts of the bioherm, and the crinoid and fusulinid debris may have come from interbiohermal sea floor. A few algal pellets can be found in the matrix but are not abundant.

The matrix in the western extremity of the bioherm has recrystallized to a greater degree than similar matrix to the east. However, at only one locality, J7 (fig. 5), had recrystallization seriously altered the fabric. At that locality sparry calcite partially replaces the skeletal framework.

#### Organism Relationships within Bioherm 2

Fossil groups present in Bioherm 1 are also found in Bioherm 2, together with several additional genera. Some growth forms of the codiacean algae *Hikorocodium* occur, but their specific identification is uncertain. At location B5 (fig. 5) a *Permosoma*-like coral occurs. Corallites of this coral are smaller than those noted in *Permosoma* by Termier and Termier (p. 771, 1957a), and they flare upward and outward from the center of the finger-shaped corallum. Tabulae are rare, and no columellae can be seen in the several specimens from the locality.

Bioherm 2 is broad and discoidal; it had relatively little paleotopographic relief. Its present topographic expression is also low; accordingly, vertical biostratigraphic zones are difficult to establish. However, lateral variations in the fossil population within the bioherm are easily documented (table 1). Varieties of algae dominate throughout most of the bioherm, but corals dominate in scattered localities, as for example at locations B1, B4, B5, D3, D4, D8, F1, F4, G2, and G4 (fig. 5). Few bryozoans are present although a fistuliporid colony was collected at locality G4 (fig. 5).

Algae, corals, and bryozoans overgrew each other, as in Bioherm 1. Encrusting algae and a fine textured tabulate coral(?) most commonly attached to or encrusted other forms. Osagia is common in the bioherm and contributes significantly to the skeletal framework (table 1). Osagia characteristically overgrows or laminates other forms, and most organisms in the bioherm are partially coated with it.

The fine tabulate coral(?) frequently overgrows other forms. It assumes a long, sinuous growth form and overgrows a variety of other organisms at one locality. For example, at sample location D3 (fig. 5) it encrusts *Hikorocodium*, a crinoid fragment, and an unidentified alga.

#### Diagenesis

Recrystallization affects both the skeletal framework and the matrix of Bioherm 2. Solenoporaceans have been most extensively recrystallized. The structure of *Para*- chaetetes commonly has been altered until only a coarse mosaic of calcite crystals, confined within the original skeletal boundary, remains. Less commonly, the structural elements of corals, bryozoans, and tubular algae are destroyed by recrystallization. Encrusting Osagia algae and Tubiphytes have resisted recrystallization.

As in Bioherm 1, patches of micrite have recrystallized. Voids between elements of the skeletal biohermal framework formed traps for deposition of lime mud. These openings were interior voids of brachiopods, tubular algae, or corallites; some may have been spaces between individual organisms. Matrix in the uppermost areas of these traps is normally recrystallized. Micrite at the top of a gap in the skeletal framework at location J4 has recrystallized to sparry calcite (fig. 13B). Micrite occupying the interior of brachiopods and other fossils appears to have been protected from recrystallization.

Stylolites are not common in Bioherm 2. At locality H14, however, stylolites with amplitudes of several millimeters are associated with patches of dolomite crystals. They may have provided avenues for those fluids that aided dolomite formation. Microfractures are numerous only locally, such as at locality D8.

Micritization has taken place in many fossils. *Permo*soma, Hikorocodium, crinoids, and brachiopods have all been affected at various locations within the bioherm. Of all the organisms present, the solenoporaceans are most commonly micritized. At locality D9, for example, a solenoporacean has been intensely bored (fig. 9B). Micrite fills the bores; micritic envelopes surround the organisms. At locality B5 *Permosoma* is riddled with bores approximately 1 millimeter in diameter filled with micrite where not recrystallized.

In essentially each thin section studied, the matrix is mottled. The mottling is brown or gray and is probably caused by variation in algal material. Figure 9C shows this mottling at site G3.

#### **BIOHERM 3**

#### Geometry

Bioherm 3 is exposed in Merbah el Oussif on the dip slope of a small south-facing ridge on the southwestern flank of Baten beni Zid. Essentially all the encasing shale has been eroded, exposing three dimensions of the bioherm. It is roughly discoid; its diameter is 5 to 6 meters and its thickness is 2.5 to 3.5 meters (fig. 6). Mounds and indentions make its topography irregular.

#### Local Stratigraphy

Figure 6 shows the uncomplicated stratigraphy of Bioherm 3. It rests on thick, slope-forming, green brown shale. A blocky weathering bioclastic limestone 50 centimeters thick, striking N. 55° E. and dipping 25° southeast, laps against the northeast and southwest margins of this bioherm. Bioclastic limestone overlaps several very small bioherms 10 meters to the north. Brown shale overlies the limestone and encases the bioherm. Another bioherm approximately the same size but not as well exposed as Bioherm 3 is situated 17 meters to the southwest (fig. 14). The same limestone which laps against Bioherm 3 abuts the western margin of this southwestern bioherm.



FIGURE 14.-View northeast toward small bioherm 17 meters southwest of Bioherm 3.

#### Matrix of Bioherm 3

A greater percentage of the matrix in Bioherm 3 has recrystallized than in Bioherms 1 and 2. Though most in situ organisms have been recrystallized, the primary sedimentary relations between the skeletal bioherm framework and the matrix are sharply defined. Some areas in thin section are pigmented dark brown in mottled patches, and normally these patches have recrystallized to very small anhedral dolomite crystals or to mosaics of clear dolomite.

Skeletal fragments in Bioherm 3 are small, ranging from a fraction of a millimeter to 1 millimeter in diameter. Algal pellets, small gray biologically unidentifiable fragments, crinoid pieces, fusulinids, and bivalve tests make up the fragmental debris. As in other bioherms, these fragments commonly accumulated in patches. The micritic fraction of the matrix in these patches tends to be recrystallized.

Small amplitude stylolites are abundant in the matrix and are partially filled with black material. Recrystallized patches of darkly pigmented areas are normally interconnected by stylolites.

Many fractures criss-cross the rock, and the matrix surrounding them is commonly bleached to a depth of twice the width of the fracture. They also contain traces of dead oil. Some younger fractures displace other fractures and patches containing dead oil.

#### Organism Relationships within Bioherm 3

Dolomitization and other diagenetic changes have masked most biologic structures in Bioherm 3. Of those preserved, Osagia-like encrusting algae, Hikorocodium-like tubular algae, and *Tubiphytes* are most abundant. At nearly every sampled locality relict fossil grains are laminated with Osagia(?). In this bioherm, as in others described, Osagia has resisted major recrystallization and dolomitization changes. *Tubiphytes* has also not experienced advanced diagenesis. This genus is easily recognizable in the framework because of resistance to change. The threadlike filaments and the thallic outline of *Hikorocodium* are often preserved well enough to allow reasonably certain identification.

Other groups certainly inhabited the bioherm, but dolomitization has made their identification uncertain. At sample localities E2 and E6 (fig. 6) the fine tabulate coral(?) described in connection with Bioherm 1 is present. A coral, perhaps *Permosoma*, occurs at sites E4 and E7.

Bioherm 3 is the smallest of the three bioherms described here. Forms of algae dominate at each sampled locality in it. Consequently only a single biostratigraphic zone was recognized. As indicated above, other groups, like corals and bryozoans, are present but are not abundant.

Osagia characteristically overgrew other forms and produced laminations. In the bioherms these laminations are preserved, but the grains they enclosed have commonly been altered and grain origin obscured. At locality E4 (fig. 6) a coral overgrows *Hikorocodium*. Overgrowing relationships in the fabric of Bioherm 3 are difficult to decipher because of loss of detail produced by dolomitization and other diagenetic changes.

Shale that encased the bioherm has been eroded exposing small brachiopods anchored to the paleosurface of the bioherm. They were apparently killed when fine sediments comprising the surrounding shale engulfed the bioherm.

#### Diagenesis

The primary depositional fabric of Bioherm 3 has been masked by extensive diagenesis. Dolomitization and recrystallization are mostly responsible for the present texture. Abundance of stylolites may partly explain the pervasive dolomitization and recrystallization.

Low-amplitude stylolites are abundant in most samples from Bioherm 3. In sample C6, for example, stylolites connect patches of dolomited crystals, and at locality E1 stylolites connect patches of sparry calcite. Stylolites within the bioherm are commonly filled with reddish brown stained material and frequently contain dead oil. They probably served as avenues for fluid migration which induced dolomitization and recrystallization. Figure 13D shows typical stylolites at locality G5.

Most of the skeletal framework has been dolomitized, and organisms now appear as ghosts in micrite, with interior structural elements obscured or destroyed. Encrusting relationships are consequently difficult to unravel. *Tubiphytes* and some encrusting algae, possibly *Osagia*, have resisted dolomitization. Figure 10A shows *Tubiphytes* at locality E2. Reddish patches in the micrite of Bioherm 3, probably concentrations of iron-stained dolomite, are resistant to etching with hydrochloric acid.

Organisms which have resisted dolomitization have been recrystallized to sparry calcite. Figure 13F shows a recrystallized alga, *Hikorocodium*(?). The details of cell structure have been destroyed, but the central cavity can be discerned by a change in the mosaic pattern of sparite. Patches of matrix within the bioherm have recrystallized to spar. These patches frequently have sharp contacts with adjoining matrix, as though recrystallization had followed an earlier, possibly primary, depositional fabric.

Microfractures in the bioherm are common, but not as abundant as in Bioherm 1, and commonly contain traces of dead oil. At locality C8 (fig. 6), a black stain extends radially from a fracture into surrounding rock. In another sample, the matrix surrounding a fracture has been bleached.

Some recrystallized organisms have micritic envelopes, and others have been totally micronized. At locality C3, for example, the alga *Hikorocodium*(?) shows micritization. On the whole, micritization in Bioherm 3 has been obscured because of overprinting of dolomitization.

#### COMPARISON OF THE BIOHERMS

Figure 1 shows the geographic relationships of Bioherms 1, 2, and 3. Bioherm 1 is part of the Saikra Biohermal Complex of Newell et al. (1976), near the eastern end of the Djebel Tebaga inlier. In the western part of the Permian exposures, Newell et al. (1976) have described an Upper Biohermal Complex, a Middle Shaly Facies, and a Lower Biohermal Complex. Bioherm 2 is located in the Upper Biohermal Complex, and Bioherm 3 lies stratigraphically lower in the Middle Shaly Facies. The stratigraphic relationship of Bioherm 1, in the east, to Bioherms 2 and 3, in the west, are not known at present because structural complications intervene.

Bioherms 1 and 2 are considerably larger than Bioherm 3. Bioherm 2 (fig. 5) is longer and broader than Bioherm 1 (fig. 4) but is not as thick. Bioherm 3 (fig. 6), having been nearly completely exhumed from associated strata, is the best exposed of the three structures.

Bedded bioclastic limestone underlies, abuts against, and laps onto Bioherms 1 (fig. 4)) and 2 (fig. 5). Bioherm 3 is also underlain by a bioclastic limestone (fig. 6) but is laterally buried by shale. The fabric and skeletal debris of these limestones are quite similar. Greenish gray shales largely encase all three bioherms. Other small bioherms, exposed in the immediate vicinity of each of the three bioherms studied in detail, are also encased in greenish gray shales.

All three bioherms contain a prolific biota. Most of the groups found in Bioherm 1 are also present in Bioherm 2 (table 1) although they are 7.5 kilometers apart. No trespostome bryozoans, however, were observed in samples from Bioherm 2 whereas they are common in Bioherm 1 An undescribed coral not found in Bioherm 1 occurs in Bioherm 2.

Both quantity and variety of algae are greater in Bioherm 2 than in Bioherm 1. For example, several codiacean algae resembling *Hikorocodium* appear in Bioherm 2, and *Osagia* is almost ubiquitous, contributing substantially to the total mass of Bioherm 2 (table 1).

Forms of algae, principally *Hikorocodium* and *Osagia*, dominate at every locality in Bioherm 3 in contrast to Bioherms 1 and 2, where corals and bryozoans are more important. The latter groups may have been present in Bioherm 3 but certainly played minor roles in the growth of the carbonate lenses.

Biostratigraphic or paleoecologic zones can be established in Bioherm 1 (fig. 2), but several problems were encountered when attempts were made to similarly zone Bioherms 2 and 3. Paleotopographic relief—and hence numbers of microniches—seems to have been quite low on Bioherm 2. Its thickness (4 meters) is small, compared to its length (55 meters) and width (32 meters). Consequently, vertical biologic zones were not established even though lateral variations in populations occur (table 1). Bioherm 3 is significantly smaller than the other studied lenses, and its fossil community is dominated by two varieties of algae. Little vertical variation in population structure occurs there.

A variety of diagenetic processes have operated in all three bioherms, but to varying degrees. Bioherm 3 has undergone pervasive dolomitization which has more or less masked the primary depositional fabric. Dolomitization in Bioherms 1 and 2 is minimal.

In situ organisms, as well as lime mud matrix, in all three bioherms are affected by recrystallization to sparry calcite. Recrystallization is locally extensive in Bioherms 1 and 2. Only at rare, scattered localities are structural elements of fossils of Bioherms 1 and 2 replaced by a coarse mosaic of sparry calcite, but at nearly every locality in Bioherm 3 fossils are affected.

Bioherm 3 contains an abundance of low amplitude stylolites, but similar stylolites are nearly absent in Bioherms 1 and 2. On the other hand, microfractures are relatively numerous in Bioherm 1 but are not important in Bioherms 2 and 3. Bioherm 3 was subjected to pressures and reacted by forming stylolites early before lithification. In contrast, Bioherm 1 yielded to pressures after lithification and formed microfractures. Small quantities of dead oil line fractures and stylolites in all three bioherms, probably because of oil migration after burial and lithification.

#### CONCLUSIONS

The presence of abundant fossil algae in the bioherms allows fairly reliable paleoecologic conclusions to be reached by analogy with the ecology of recent relatives of the ancient algae. Modern algae require moderate-intensity light to flourish. Consequently, these bioherms are considered to have formed in shallow water. Codiacean algae in the bioherms, like their modern descendants (Johnson 1961, p. 73), probably required moderately warm water to occur as abundantly as they do in the bioherms (table 1).

Several lithologic evidences suggest that, though the water in which the carbonate lenses accumulated was shallow, energy conditions were low except for several relatively brief periods of increased agitation. The matrix in each bioherm is micritic (table 1), generally containing less than 10 percent fragmental debris, Highly agitated waters would have washed the fine lime mud away and would have degraded the skeletal framework. The skeletal framework of the bioherms shows little or no evidence of degradation; neither do marginal talus fans border the bioherms. According to these evidences, the prevailing energy regime was probably low. However, bioclastic limestones associated with each bioherm (figs. 4, 5, and 6) are evidence that agitated water conditions occurred several times during growth of the structures, the first having occurred just prior to colonization of the sites.

Apparently, the organisms which colonized the bioherm preferred to occupy a fragmental, rather than a muddy, substrate. It is interesting to note that, though quiet water conditions seem to have perpetuated development of the bioherms, agitated water conditions and deposition of a fragmental substrate probably made possible colonization of the bioherm sites.

As the bioherms developed, they extended laterally rather thaan increasing their height. The length:breadth: thickness ratios for Bioherms 1, 2, and 3 are approximately 7:2:1, 14:8:1, and 2:2:1, respectively.

Competition among biologic groups for food and space in the bioherms was great, as evidenced by the frequency with which organisms overgrew other forms. Figure 11D shows a complex series of overgrowth in which six organisms successfully overgrew each other at locality G9 (fig. 4). At the same locality second generation fistuliporid bryozoans attached to earlier fistuliporids of the same genus.

Dolomitization and recrystallization in Bioherm 3 are much more pervasive than in either Bioherms 1 or 2. Stylolites are abundant in Bioherm 3 but rare in Bioherms 1 and 2. Styolites probably played a major role in the dolomitization of Bioherm 3 by supplying avenues of fluid migration. The implication is that dolomitization probably occurred before complete lithification because stylolites are assumed to form before complete cementation of sediments (Park and Schot 1968, p. 72).

Traces of dead oil occur in stylolites in Bioherm 3, in microfractures in all three carbonate lenses, and between threadlike filaments of Hikorocodium. There was apparently minor hydrocarbon accumulation in fractures in the bioherms, and some oil probably migrated through the lenses.

Bioherms 1, 2, and 3 occur along the flanks of larger biohermal masses which constitute the bulk of the complexes described by Newell et al. (1976). Detailed studies of the petrologic fabric of the larger carbonate masses have not been undertaken by previous workers, probably because dolomitization and other diagenetic processes have masked the fabric in the masses. However, the fabric of the smaller bioherms described in this paper is well preserved and easily studied. The smaller bioherms can be viewed as models of their larger counterparts; their petrologic fabric is probably similar. Information and conclusions given in this paper therefore aid in understanding the depositional history of the entire Djebel Tebaga outcrop belt.

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