Depositional Models for Jurassic Reefal Buildups*

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DEPOSITIONAL MODELS FOR JURASSIC REEFAL BUILDUPS

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ABSTRACT

Studies of Jurassic carbonate reefal buildups from the surface and subsurface of the United States Gulf Coast (including the Smackover Formation), the eastern North American Margin, and the Tethyan reef belt of Europe and northwest Africa show that buildup development occurred in three depositional settings: (1) deep, quiet water below wave base; (2) gently sloping platforms (ramps) subjected to wave agitation; and (3) margins of steeply rimmed, wave-swept platforms. A classification developed for the buildups from these various depositional settings emphasizes the major reef-framebuilding assemblages which, if combined with studies of buildup-related facies, provide a basis for interpretation of depositional setting and paleoenvironmental reconstruction.

Buildups that developed in deep, quiet-water settings below wave base were constructed primarily by siliceous sponges and thrombolite/stromatolite algal(?) structures. Accessory reef-dwelling biotic communities and related lithofacies assemblages indicate that these sponge-algal buildups grew in normal marine waters either on gently sloping platforms, in settings downslope from platform margins, or on basin floor highs.

Buildups that developed on wave-agitated, gently sloping platforms show the greatest range in framebuilding assemblages and are the most common types in the subsurface Smackover Formation. In lower-energy settings, which could range in water depth depending on wave energy, these buildups were constructed by siliceous and calcareous sponges, chaetitids, corals, stromatolites/thrombolites, and calcareous algae. Such buildups apparently represent an intermediate assemblage between the sponge-algal deep-water mounds and the coral-dominated patch-reef mounds developed in more energetic platform settings. The coral-dominated patch reefs contain abundant calcareous biota such as skeletal algae, calcareous sponges, and stromatoporoids. Commonly, reworking of the reef core by waves produced piles of skeletal debris. In regions where salinities and temperatures of marine waters covering the platforms diverged from normal oceanic conditions, biotic-community assemblages were reduced, resulting in stromatolite algal(?) buildups.

Buildups replete with coral, stromatoporoid, calcareous sponge, and skeletal algae framebuilders developed on steepened platform margins facing open oceans. Stromatoporoid assemblages enabled these buildups to be differentiated into back-reef patch reefs and platform-margin reefs.

INTRODUCTION

Jurassic carbonate buildups have only recently been documented from the United

States Gulf Coast, whereas equivalent-age buildups in Europe and North Africa have been studied for over 100 years. This disparity is due primarily to the lack of surface exposures along the Gulf Coast, in contrast to the accessible buildups cropping out around the Tethyan reef belt. The outcrop studies define biotic assemblages, buildup geometries and trends, facies relationships, and paleogeographic settings of buildup development - all of which should be applied to investigations of subsurface Jurassic reefal buildups.

Baria *et al.* (1982) have recently discussed the occurrence of Oxfordian patch reefs that developed on a ramp shelf throughout the Gulf Coast during deposition of the Smackover Formation. Researchers have also reported that patch reefs (Cregg and Ahr, 1982) and a ramp-reef complex (Finneran *et al.* 1982; Scott, this volume) developed as a part of the Knowles Limestone in central East Texas. Exploration drilling and seismic studies provide the only means for gathering information on these buildups. Occurrences and general trends have been inferred from seismic and borehole log correlations, whereas facies trends and paleocommunity analyses require thorough examination of rock material with correlations to well-log signatures. Reefs, probably more than other carbon- ate facies, provide considerable insight in- to depositional setting and general paleooceanography because of their diverse biologic community assemblages. Modern reefs grow in a wide range of water depths, which can be reasonably interpreted from biotic assemblages. This paper shows that Jurassic (and possibly early Cretaceous) reef (or buildup) development also occurred in a variety of depositional settings which are also reflected by their biotic communities. In this paper, we develop a classification for Jurassic carbonate buildups based on the major framebuilding paleocommunity. This classification stresses an interpretation that can be made from limited subsurface rock samples which, through biotic community analyses, can be used to infer subsurface buildup geometries and trends, and paleoshelf setting.

Much of the information on buildup geometries and lithofacies relationships presented in this paper was taken from outcrop studies. The work of Baria *et al.* (1982) and additional microfacies analyses provided the framework for our classification of the Smackover buildups. A general classification for Jurassic buildups, which may also apply to early Cretaceous buildups, incorporates our Smackover model along with data from outcrop studies reported in the literature and our examinations of buildups that crop out in Europe and northwest Africa.

PREVIOUS STUDIES OF SUBSURFACE JURASSIC BUILDUPS FROM THE UNITED STATES GULF COAST

Prior to the work of Baria *et al.* (1982; Fig. 1), relatively little information on Smackover (Oxfordian) buildups appeared in the Gulf Coast literature. The first report on possible buildups in the upper Smackover Formation was provided by Imlay (1940) for widely distributed, coral-rich, fossiliferous beds in southern Arkansas. Similarities with coral-rich deposits from the Jurassic of England, described as fringing reefs by Arkell (1935), prompted Imlay (1940) to speculate that the Smackover shelf was also rimmed with fringing reefs. Wells (1942) discounted the fringing-reef hypothesis, however, based on his study of coral specimens provided by Imlay. Wells (1942) noted that the coral growth forms were more indicative of either a very shallow, quiet-water lagoon or deeper water undisturbed by surf, and that none of the corals described from the Smackover were similar to the massive forms described by Arkell (1935). Wells (1942) further noted that the corals probably grew in thin patches which were scattered across a gently sloping sea floor.

Not until Croft's (1980) study of two cores in the North Haynesville Field, northern Louisiana, was the first description and well-correlation study provided of reef and related facies in the Smackover. Croft (1980) described the reef interval as a coral and coralline-algal framework with multiple

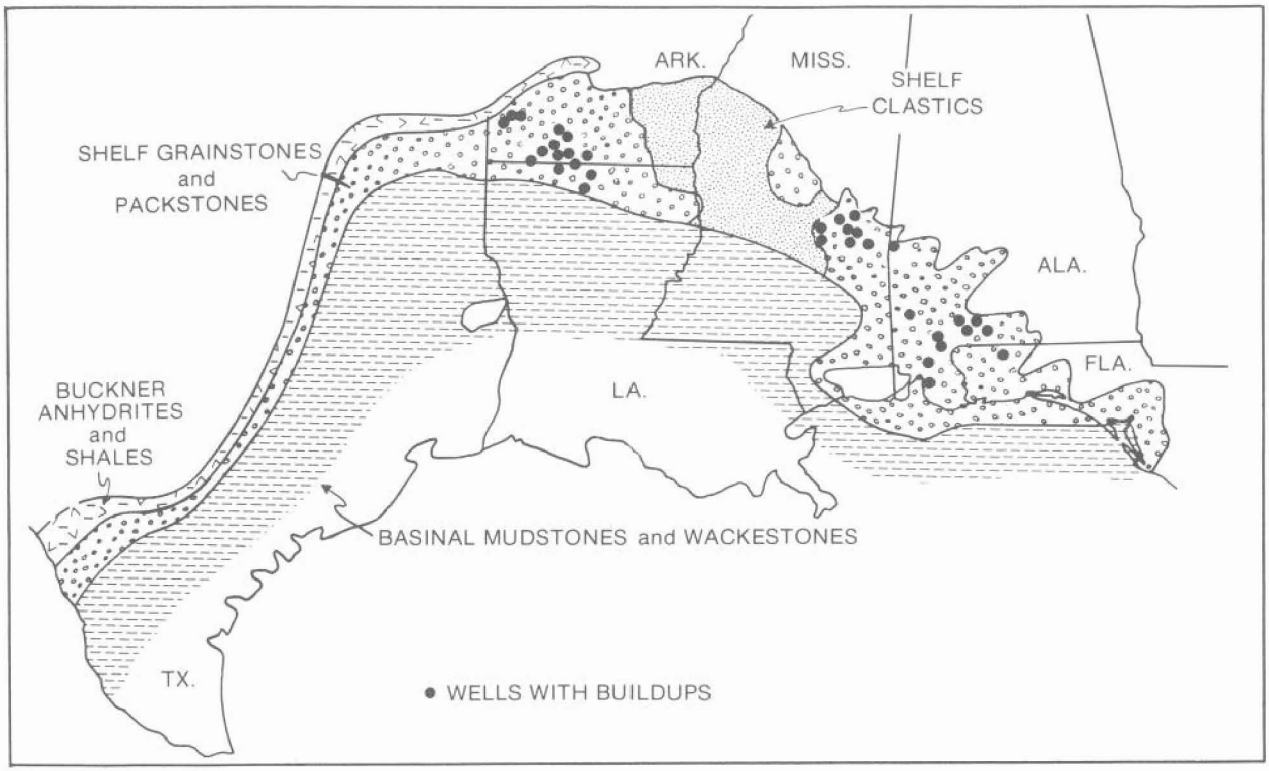


Figure 1. Generalized map of Smackover and Buckner lithologies along United States Gulf Coast (modified after Baria *et al.*, 1982; and Budd and Loucks, 1981). Black circles represent locations of subsurface Jurassic buildups described from conventional cores by Baria *et al.* (1982) and McGraw (1982).

generations of microborings and geopetal sediment; and he recognized that localization of the reef on the southern, seaward-facing edge of a horst was likely caused by penecontemporaneous faulting during deposition on the Smackover shelf. Croft's study, however, dealt primarily with local variations in the non-skeletal carbonate facies and did not address buildup paleocommunities.

Baria *et al.* (1982) concluded, from extensive core and borehole log studies, that reefs were common in the upper Smackover (Fig. 1) and grew on or near the seaward-facing crest of basement- or salt-cored paleostructures. Variations in the reef foundation (Fig. 2) through the trend, the stratigraphic level of reef development, and more importantly, the diversity of biotic assemblages led Baria *et al.* (1982) to suggest that circulation of normal marine waters must have varied along trend over the Smackover platform to account for the dramatic variation in the paleocommunities: more restricted marine conditions existed over the platform in Alabama, Mississippi, and Florida. Baria *et al.* (1982) recognized that similarities existed between the paleocommunities of the skeletal-rich Smackover buildups and the European examples, but did not compare the buildups of the two areas. Crevello and Harris (1982) refined the classification of Smackover buildups to facilitate comparisons with Tethyan buildups. Crevello *et al.* (in press) also examined the reservoir potential and diagenesis of several of these buildups, emphasizing that both depositional and diagenetic variations through the subsurface Smackover trend were important in developing reservoir-quality lithologies.

In buildups of the Knowles Limestone

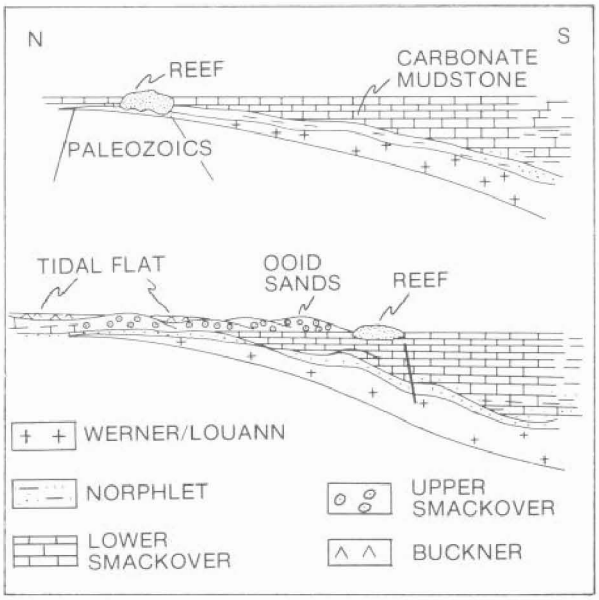


Figure 2. Schematic dip cross section illustrating development of late Jurassic reefs on basement blocks in the lower Smackover Formation of Alabama and Florida (top) and on salt swells in the upper Smackover Formation of Arkansas and Louisiana (bottom) (modified after Baria *et al.*, 1982).

(Finneran *et al.*, 1982; Cregg and Ahr, 1982), most recently determined to be Berriasian to Valanginian in age (Scott, this volume), corals along with stromatoporoids developed a more diverse and important role as reef builders. The Knowles Limestone also marks the development of a seismically and lithologically definable platform margin, in contrast to the gently sloping Smackover carbonate platform (or carbonate ramp).

CLASSIFICATION OF JURASSIC CARBONATE BUILDUPS

Our classification of Jurassic carbonate buildups is based on depositional setting and major fossil assemblages. Baria *et al.* (1982), although noting a variation in biotic constituents through the Smackover trend, broadly classified these facies as reefs because they contained attributes common to many modern and ancient reefs: framebuilding, binding, and encrusting organisms; marine cements; internal sediment; and a boring infauna. A refinement of the classification of subsurface buildups has enabled us to compare our findings with outcrop studies of other Jurassic buildups for which detailed facies relationships and paleogeographic reconstructions exist.

Wilson (1975) compiled several commonly used definitions for buildups based, in general, on their local configuration and composition. A recurring problem encountered in classifying subsurface carbonate buildups, however, is the inability to determine the buildup geometry and the relationship of the buildup to lateral and bounding facies; hence, thick biostromes may be indistinguishable from bioherms, and bioclastic beds may be indiscernible from bioclastic piles. In addition, borehole information is too widely spaced to resolve this problem, although, in some cases, where the buildups are thick and/or laterally extensive, seismic profiling may aid in the interpretation. Classification for subsurface buildups therefore must be based primarily on the biotic assemblages recognized in cores and cutting samples and on similarities with analogues from outcrop studies.

The outcrop and subsurface examples discussed here display some of the major differences in paleocommunities that exist in Jurassic reefal buildups. Our subsurface and outcrop studies as well as literature review suggest that the major framebuilding and binding organisms that contributed to reef development were environmentally sensitive to depositional settings and are useful for classifying the buildups. Accessory reef inhabitants, epifaunal and infaunal dwellers, and encrusting organisms were also important in reef building, but their distribution and recognition are much more complicated. Few studies have been published which adequately document entire Jurassic reef paleocommunities.

Jurassic carbonate buildups have been described from three depositional settings (Table 1): (1) deep, quiet water below wave base; (2) wave-agitated, gently sloping car-

Table 1. Classification, Depositional Setting, and Reef-Building Organisms of Jurassic Buildups

DEPOSITIONAL SETTINGS	DOMINANT REEF BUILDERS	ACCESSORY ORGANISMS	CLASSIFICATION
Deep, Quiet Water *fore-reef slope *deep-water lagoon *deep water of sloping carbonate platform (ramp) *basin floor	Siliceous Sponges (hexactinellids and lithistids) and stromatolites	Brachiopods, Echinoids and Ophioroids, Belemnites and Ammonites, Foraminifers (vagile-benthonic, sessile and planktic forms), Ostracods, Serpulids, Bryozoans, Pelecypods, Calcareous Sponges, *Tubiphytes* sp., Gastropods, Corals	Sponge-Algal Buildup Sponge Buildup Algal Buildup
Wave-Agitated Platform *lagoon behind reef belt *shallow water of gently sloping carbonate platform	Corals, Siliceous (hexactinellid and lithistid) and Calcareous Sponges, Stromatolites Calcareous Algae	Pelecypods, Chaetetids Foraminifers (vagile-benthic and sessile forms), Bryozoans, Gastropods, Brachiopods, Skeletal Algae, Echinoids, Stromatoporoids, Stromatolites, Corals	Coral-Dominated Patch Reef Coral-Stromatoporoid Patch Reef Sponge-Coral-Algal Buildup Stromatolitic Buildup Bioclastic Pile
Platform Margin *open ocean facing	Corals, Stromatoporoids, Calcareous Sponges	Chaetitids, Calcareous Sponges, Calcareous Algae, Pelecypods, Gastropods, *Tubiphytes* sp. Foraminifers (vagile-benthic and sessile forms), Echinoids, Bryozoans, Crinoids	Stromatoporoid, Coral, and/or Calcisponge Buildup

bonate platforms; and (3) platform margins. Buildups that developed on wave-agitated platforms display the broadest range in paleocommunity assemblages, some of which have been recognized in the subsurface Smackover Formation.

Outcrop Examples of Tethyan Buildups

Deep-Water Mounds

Sponge-Algal Mud Mounds.- During the late Jurassic, micrite-rich sponge-algal mounds developed across parts of Central Europe in relatively deep, quiet water. These mounds occur along a trend termed the Malm reef belt, which rimmed the northern margin of the Tethyan Sea (Wilson, 1975). In Germany, the well-documented mounds (late Oxfordian to early Tithonian in age) in the Swabian and Franconian Alb represent the "classic" examples of sponge-algal reefs (Fig. 3) (Wagenplast, 1972; Nitzopoulos, 1974; Zeiss *et al*. 1975; Gwinner, 1976; Flugel and Steiger, 1981). The cores of these mounds consist of a sponge-algal boundstone facies (Fig. 3) with siliceous sponges (Hexactinellidae and Lithistidae) in various growth forms (flat, dish-, tube-, or cone-shaped), algal crusts (thrombolitic forms and stromatolites), and

an accessory population of tubular foraminifers, *Tubiphytes* sp., serpulids, brachiopods, bryozoans, and various molluscs (bivalves, ammonites, and belemnites)(Wagenplast, 1972; Gwinner, 1976; Flugel and Steiger, 1981). Volumetrically, the bulk of the buildup consists of sponges and cyanophycean algal crusts in a matrix of skeletal micrite and pellets.

Adjacent to the buildups are distinct, rhythmically bedded marls and biomicrites containing ammonites, foraminifers, thin-walled bivalves, brachiopods, and sponge spicules. Near the mounds, the marls and biomicrites grade laterally into biointramicrites containing oncolites and calcified fragments of algal crusts and sponges, referred to as tuberoids (Fritz, 1958, in Gwinner, 1976; Flugel and Steiger, 1981). A cross section through a sponge-algal mound (Fig. 3a) shows an abrupt lateral change from the core-mound facies to the tuberolitic debris facies. Apparently, the water overlying the mounds was relatively deep because wave turbulence or other currents did not produce significant accumulations of detritus.

Sponge-algal communities also produced biostromes, but more commonly formed buildups with several meters to 100 meters of seafloor relief (Gwinner, 1976). Gwinner (1976) could not envisage water depths greater than 100 meters for mound development because of the depth limitations placed on the photosynthetic, blue-green (cyanophycean), non-calcareous algae, providing, that is, these crusts and stromatolites were produced by algae. Ziegler (1967, in Gwinner, 1976) based water-depth zone interpretations on ammonite assemblages, placing sponge-algal mud-mound development in about 100 meters of water.

In the late Oxfordian and early Kimmeridgian of the Swabian Alb, the sponge-algal buildups occurred as isolated patches across a deep-water shelf. But during middle and late Kimmeridgian, bioherms often coalesced to form beds in excess of 250 meters thick, covering an area of several hundred kilometers (Gwinner, 1976). Nitzopoulos (1974) and Zeiss *et al.* (1975) suggested that submarine ridges provided the foundation on which many sponge-algal mounds developed. The sponge-algal mounds in this region commonly grade upward into coral-dominated patch reefs during the later Jurassic regression (see the discussion of buildups developed on wave-agitated platforms).

Sponge-algal mound development in downslope and basin-floor settings was also common in a number of other areas: in the Bajocian of Spain (Giner and Barnolas, 1979), in the Liassic of the Central High Atlas Mountains of Morocco, and offshore Nova Scotia in Jurassic and early Cretaceous carbonates (Eliuk, 1978; Jansa *et al.* 1982).

Along the axis of the Moroccan High Atlas Trough, sponge-algal mud mounds (Fig. 4) developed biotic assemblages similar to those of the sponge-algal mud mounds of the Swabian and Franconian Alb. The boundstone core facies of the Moroccan mud mounds (Fig. 4) is dominated by digitate- and branching-algal crusts with sponges, which produced a microframework infilled with pellets, skeletal debris, and micrite. The microframestone changes abruptly into bedded micrites and marls containing brachiopods, echinoid debris, and ammonites. The entire sequence is encased in marls and micrites that Evans and Kendall (1977) interpreted as deep-water deposits. They suggested that structural movement localized the mounds along upthrown ridges of tilted fault blocks.

Buildups on Gently Sloping Wave-Agitated Platforms

Coral-Dominated Patch Reefs.- Examples of late Jurassic patch reefs in outcrop that developed on shallow, wave-agitated platforms commonly contain coral-rich biotopes. Related facies include skeletal, oolitic, and oncolitic lime sands. The coral patch reefs developed on pre-existing seafloor relief that, in parts of the Schwabian and Franconian Alb, was created by the deeper water sponge-algal mounds discussed in the previous section (Gwinner, 1976). Examples cited from the Knoll reef ramps of Germany and the Oxfordian-aged patch reefs of the Paris Basin (Fig. 5; Wilson, 1975) show the change in ma-

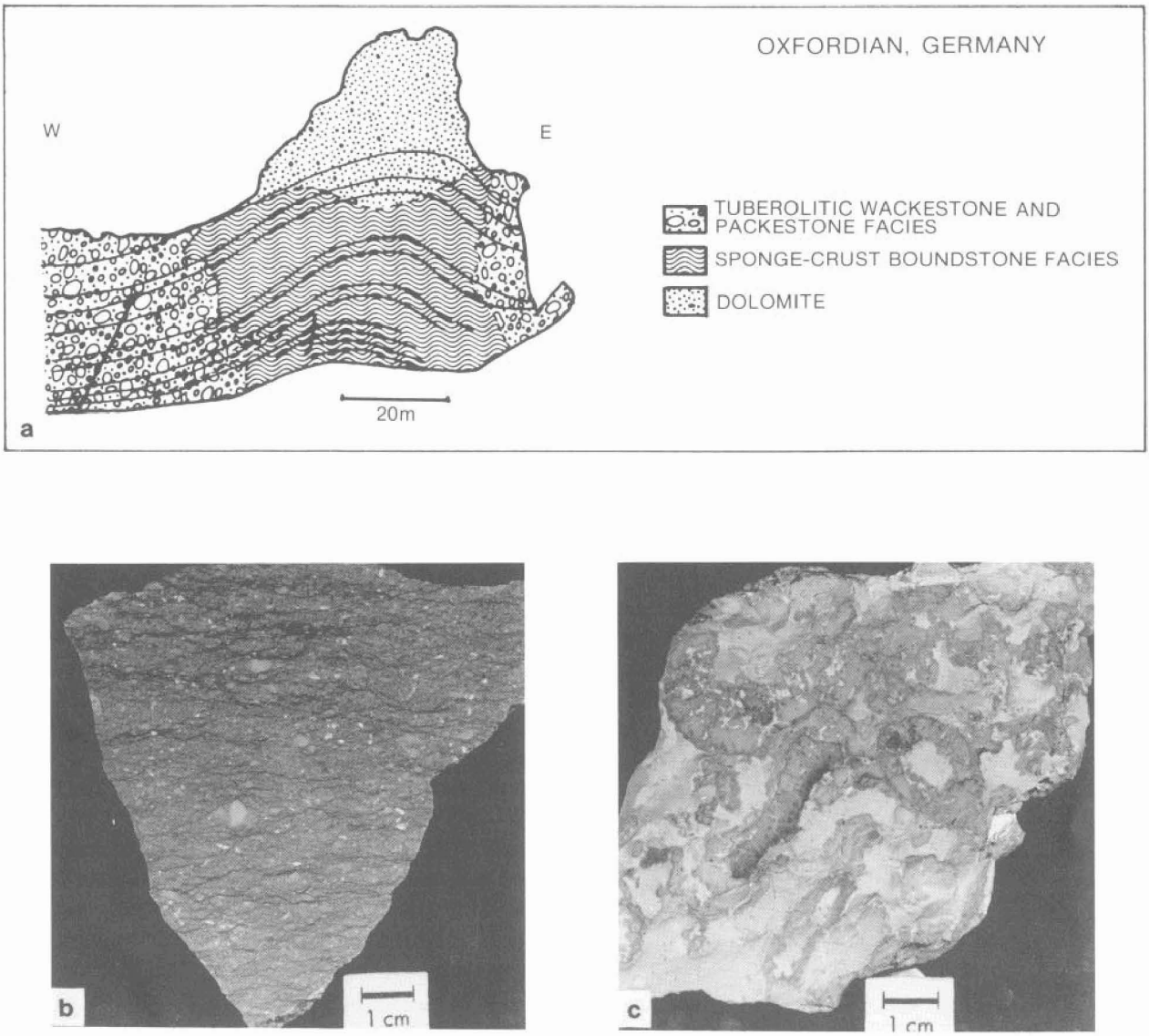


Figure 3. Line drawing of an outcropping sponge-algal mud mound and photographs of polished rock slabs.

a. Distribution of carbonate facies within the Middle-Upper Oxfordian Mullersfelen buildup near Streitberg, in northern Franconia, West Germany (modified after Flugel and Steiger, 1981).

b. and c. Polished slabs of outcrop samples from quarry near Urspring, in northern Franconia, West Germany, where sponge-algal buildup of approximately 80 to 100 meters is well exposed. b. Tuberolitic wackestone-packstone facies with rare sponge fragments from margin of buildup. c. Sponge-algal boundstone from core of buildup with stromatolite/thrombolite crusts and siliceous sponges. Lighter patches are pelleted and bioclastic packstones to mudstones filling between sponge-algal framestone (samples courtesy of E. Flugel and B. Lang).

jor reef-building paleocommunities and growth forms associated with the evolution from sponge-algal mounds to shallower water coral-patch reefs. The base of the patch reef is marked by lamellar (plate-shaped) and cup-shaped sponges, along with lamellar corals that occupied muddy, deeper water and lower energy settings of these buildups. With shoaling conditions, the change to coral-dominated buildups was accompanied by (1) a transition from thrombolitic, pelletal stromatolitic algal crusts to more laminated stromatolitic algal boundstones, and (2) a change from lamellar sponges, corals, and algal stromatolites to massive, fasciculate, dendroid, and encrusting corals, calcisponges, skeletal algae, and chaetitids. The paucity of encrusting and binding red coralline algae and the apparent inability of non-skeletal blue-green algal stromatolites and crusts to colonize strongly wave-agitated environments made these reefs more susceptible to wave erosion. Bioclastic sand and rubble became volumetrically important in the reef matrix and formed extensive flanking beds. Barthel (1977) speculated that the development of a large spur-and-groove system in such an early Tithonian coral reef in Bavaria was enhanced by the lack of reef-binding organisms (discussed below). Wilson (1975) suggested that patch reefs of this type developed on ramps inclined only 1 to 2 degrees.

During Oxfordian time in the Swiss Jura Mountains (Bollinger and Burri, 1970; Fig. 6), a coral-rich horizon formed that was 10 kilometers wide and extended over 50 kilometers along depositional strike. It consisted of numerous patch reefs which were flanked by coalescing beds of bioclastic debris. To the southeast the patch reefs gave way to lower-energy, deeper-water limestones and marls. The carbonates contained an open-marine fauna, including ammonites. Updip from the reefs, oolite, oncolitic, and bioclastic lime sands formed in shoal environments that represented the crest of the ramp-shelf profile.

The cores of the coral patch reefs are, in general, rather small when compared to the extensive volume of the bioclastic limestones originating from this source. Steiger and Wurm (1980) described Oxfordian coral-stromatoporoid boundstone patch reefs from Austria, which they interpreted as having developed in a lagoon behind a barrier reef that was dominated by stromatoporoids rather than by corals. These patch reefs are up to 20 meters thick and 100 meters wide, and are surrounded by flanking bioclastic debris. These debris deposits extend for several hundred meters in all directions away from the reef core and show no obvious distinction into fore- or back-reef talus (Fig. 7).

The volumetric significance of bioclastic flanking beds compared to the size of the patch-reef core is also shown in the Bajocian patch reefs of the Central High Atlas Mountains, Morocco (Fig. 8). These patch reefs

Figure 4. Photographs of outcrops of Liassic sponge-algal mud mounds exposed at Jebels Amalou Tassacatt and Idignt, from Central High Atlas, Morocco.

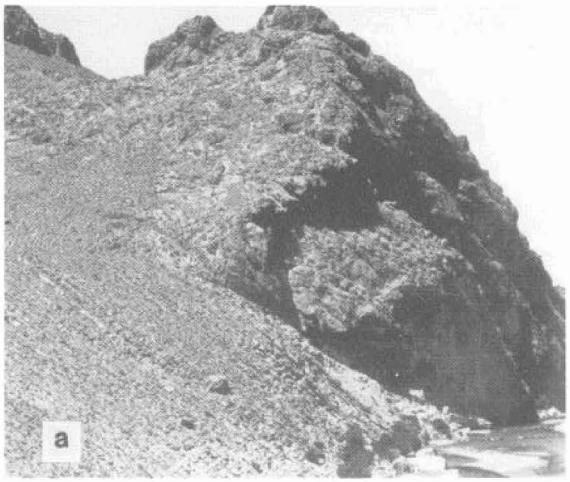
a. Stacked series of sponge-algal mud mounds in well-bedded marls and bioclastic wackestones. Height of mound exposure approximately 50 meters.

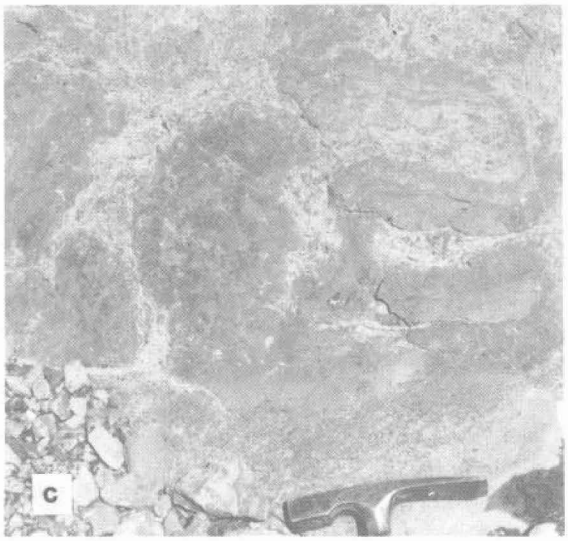
b. Sponge-algal mud mound with abrupt contact to the left of buildup into well-bedded bioclastic mudstones to packstones. Person on right for scale.

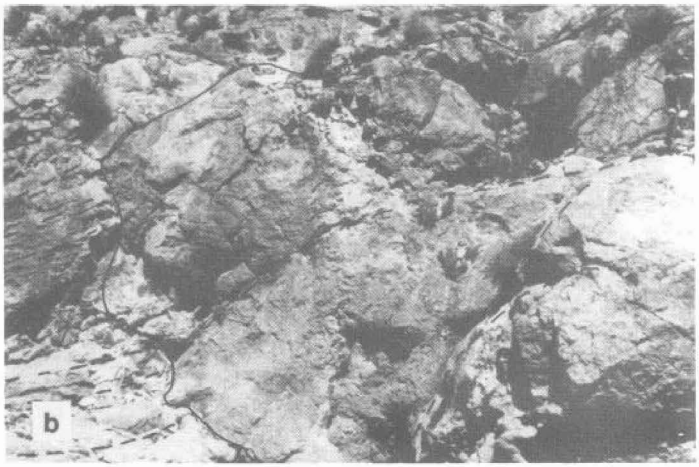
c. Upper surface of a sponge-algal mound. Plan view illustrates algal crust heads surrounded by bioclastic wackestones and packstones. Probable spongiomorph (S-shape) occupies right portion of photograph.

d. Sectional view of sponge-algal mound illustrating laminar crusts (near base) and digitate, branching stromatolites/thrombolites (upper half). Crusts are dark gray versus lighter gray sediments. Note large sediment pocket in upper center of outcrop.

e. Bedding plane view of well-bedded bioclastic wackestone immediately adjacent to sponge-algal mud mound and of brachiopods, ammonite casts, and small thrombolite-crust head (to lower right of scale).







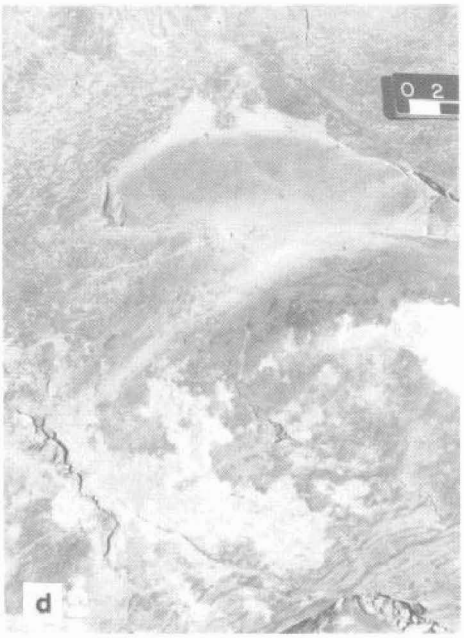


Figure 4

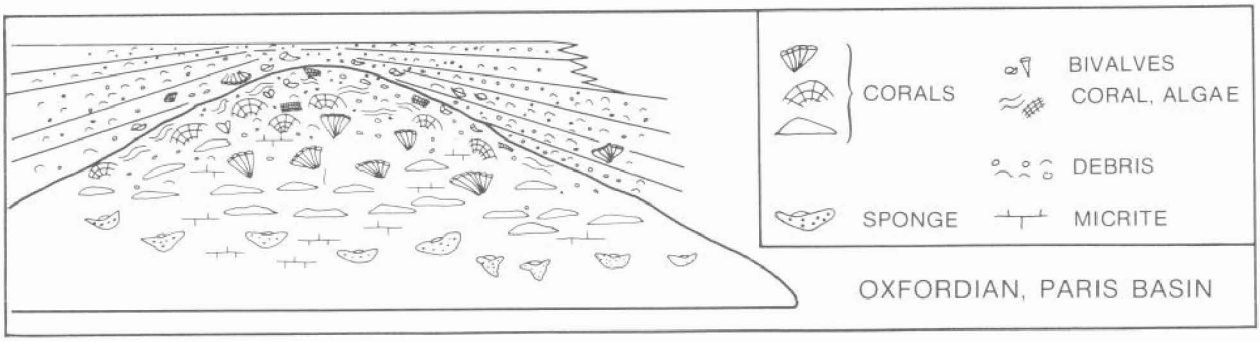


Figure 5. Idealized diagram of Oxfordian patch reef from Yonne Valley in southeastern Paris Basin illustrating changes in major reef-building paleocommunities and sediment type associated with evolution from sponge-algal mud mound into shallow-water coral patch reef (modified after Wilson, 1975).

and flanking beds are up to 40 meters thick: the central core appears to form only a third or less of the entire unit, while the flanking beds extend more than 100 meters away from the core and coalesce with debris from adjacent patch reefs. This horizon, rich in patch reefs, developed at the top of a shallowing sequence across a Jurassic atoll within the High Atlas Trough and covers an area of nearly 40 square kilometers (Warme *et al.* 1975; Stanley, 1981).

Most of the patch reefs that developed on wave-agitated platforms do not show preferred windward margins or orientations. However, Barthel (1977) described an early Tithonian coral patch reef from Bavaria, Southern Germany, that contains a spur-and-groove system which caps a later Kimmeridgian sponge-algal mound. The reef complex is exposed along quarry walls more than 1 kilometer in length and 400 meters in width. Barthel (1977) recognized a succession of reef-building organisms and growth forms as the patch reef grew up to sea level that is similar to that in the coral patch reefs in the Paris Basin (Wilson, 1975). The base of the coral patch reef consists of micritic sponge-algal mounds, overlain by platey corals that

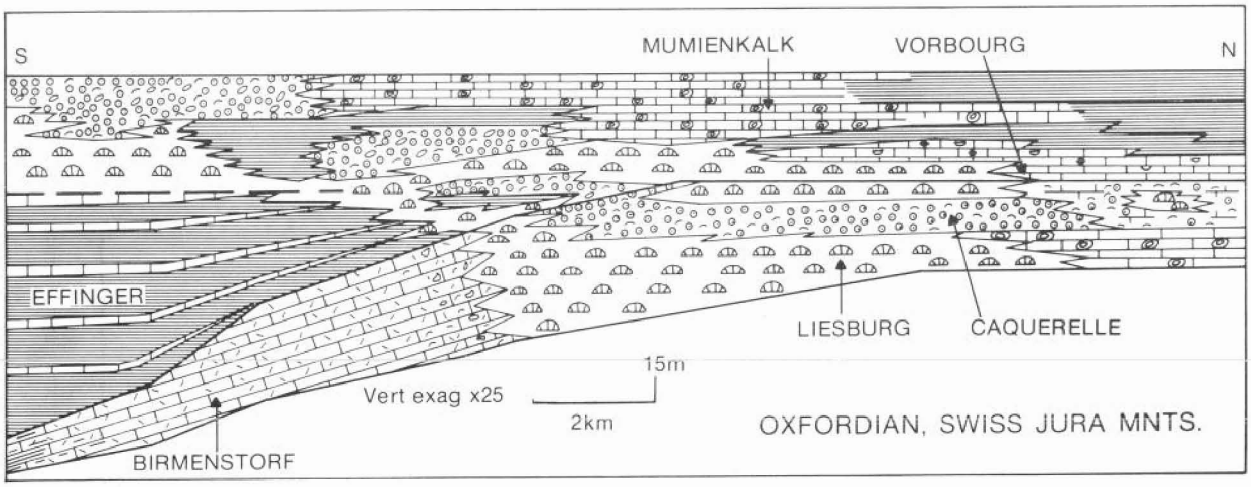


Figure 6. Diagrammatic cross section of Oxfordian strata illustrating facies transitions of a gently sloping, prograding carbonate platform (ramp) in the Swiss Jura Mountains near Basel to Gorges de Pichoux (modified after Bollinger and Burri, 1970; *in* Wilson, 1975).

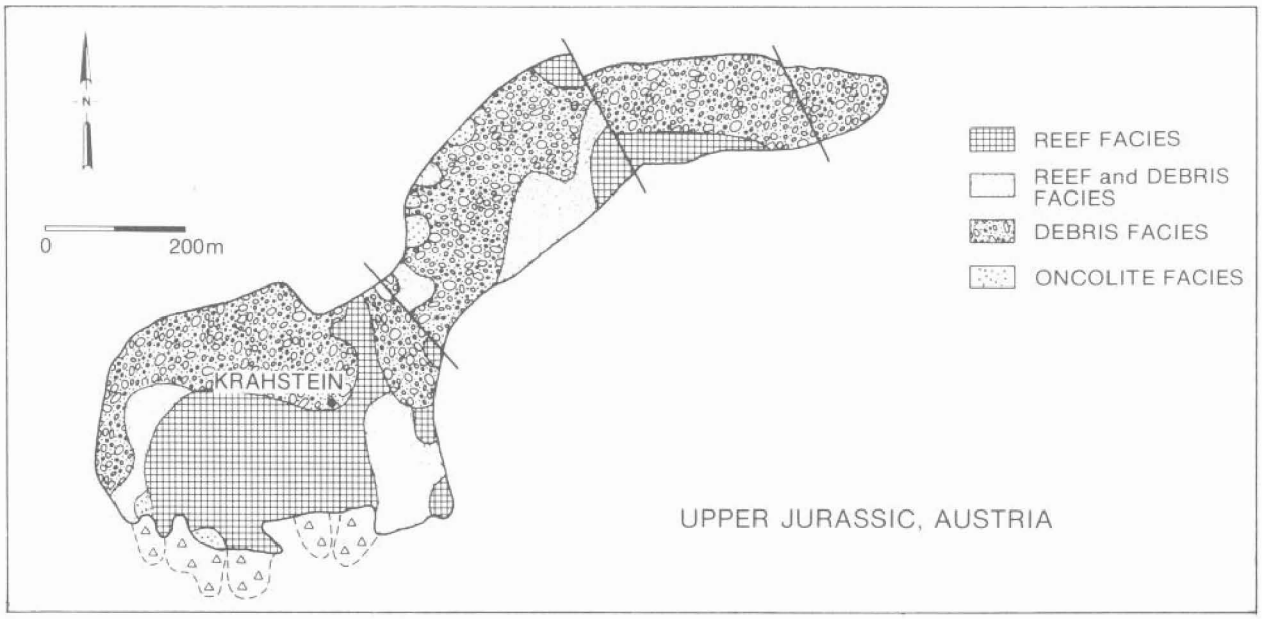


Figure 7. A plan-facies map of Upper Jurassic coral-stromatoporoid patch reefs and debris in the Plassen Limestone cropping out near Krahstein, Northern Alps of Austria (modified after Steiger and Wurm, 1980).

settled on, and bound, the talus deposits in the grooves. The reef-crest margins were colonized by large branching corals more than 1 meter in diameter. Barthel (1977) noted that stromatoporoids were extremely rare and speculated that the lack of binding organisms, such as corals and red algae, was probably responsible for the development of a large spur-and-groove system.

Coral patch reefs are commonly associated with regressive oolite shoals in the Iberian Ranges of Spain and in eastern Portugal (Giner and Barnolas, 1979; Wilson and Exton, 1979). Giner and Barnolas (1979) described Kimmeridgian coral patch reefs as coral boundstones, although their description of the reef biota suggests that the buildups were loosely bound, encrusted coral patch reefs. They described the growth of buildups in a shoaling-upward cycle. In this setting, sponge-rich mounds occurred in quieter water in downslope (or deeper outer platform or intrashelf basin) basinal marls and micrites. Whereas, the coral-rich facies developed in high-energy grainstone belts, usually seaward of oolite and oncolitic shoals (Fig. 9). The reefs range from 2 to 10 meters in height and from 5 meters to, more rarely, 30 meters in width. Although the biota of the reef are not well illustrated, Giner and Barnolas (1979) indicated a vertical zonation with a lower zone of encrusting sponges, few stromatoporoids, and small corals; and an upper zone dominated by coral colonies up to a meter in diameter. Biotic diversity is greater in the upper zone, which contains oysters, gastropods, brachiopods, byrozoans, echinoderms, encrusting solenoporacean algae, and stromatoporoids.

Wilson and Exton (1979) described coral patch reefs, which have a similar succession of facies to those descibed by Giner and Barnolas (1979), from the Lusitanian Basin in Portugal. The patch reefs recognized in Portugal reached a height of 10 meters and occur in large numbers along a common horizon, which is immediately overlain by thick (more than 60 meters) oolitic grainstones (Fig. 10). Patch reefs that commonly coalesced as intermound areas were filled with

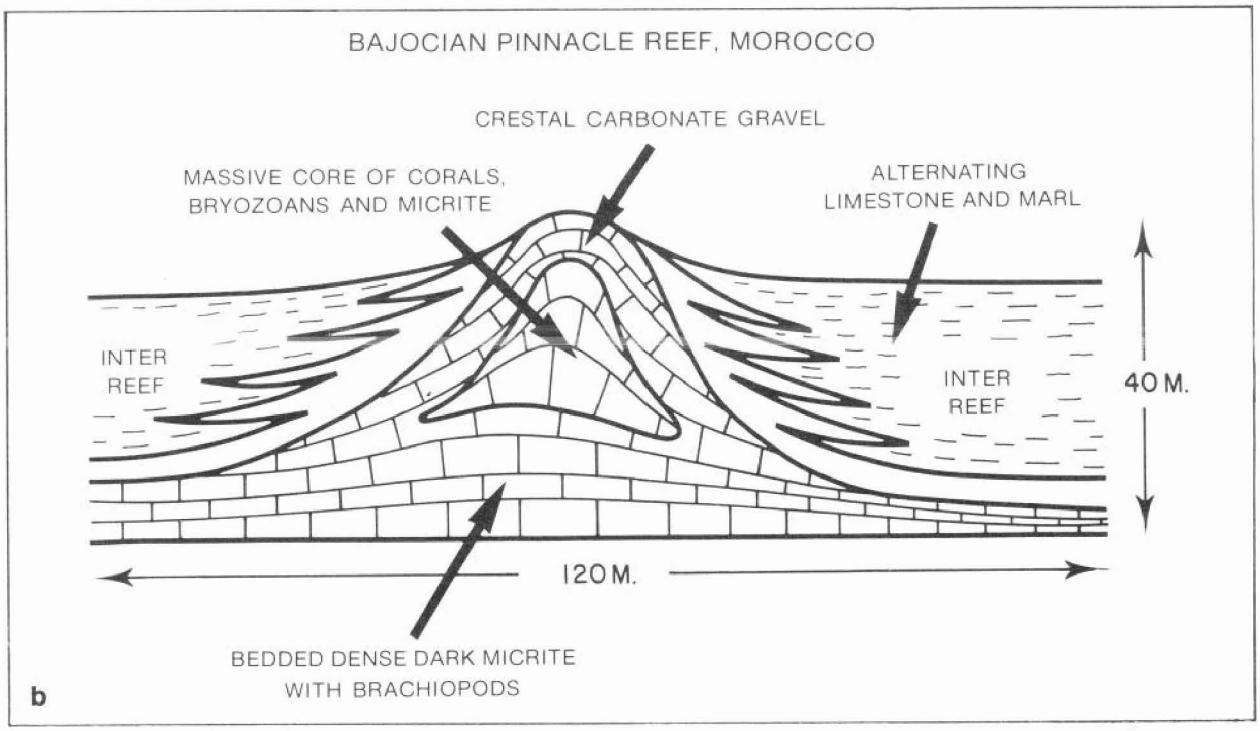


Figure 8. a. A view of a series of Bajocian pinnacle reefs exposed at Jebel Assameur n'Ait Fergane, Central High Atlas, Morocco. Reefs made of a resistant, massive core of scleractinian corals and skeletal wackestone while flanking beds, many which can be seen to coalesce between pinnacles, are mainly coral debris in bioclastic rudstones to wackestones. Well-bedded micrites and marls below the 40- to 70-meter-thick reef horizon represent a shallowing sequence from deep-water sedimentation below wave base to a moderately wave-agitated platform (see Stanley, 1981).

b. Line drawing of Bajocian pinnacle reef shown on Figure 8a (modified from Kendall and Evans, 1973; illustration courtesy of C.G.ST.C. Kendall).

bioclastic debris and patches of boundstone.

Reefs Developed on Platform Margins

Stromatoporoid-Coral Reefs.- Buildups described as barrier reefs occur in Austria (Steiger and Wurm, 1980), on the margin of the Dinaric Platform in Yugoslavia (Turnsek *et al*. 1981), and on the margin of the Panormide Platform of Sicily (Catalano and D'Ar-

genio, 1981). The principal reef framebuilding organisms were stromatoporoids and corals. Two of the barrier complexes can be subdivided into platform edge and back reef based upon the distribution of two stromatoporoid faunal subzones: *Actinostromariid* and *Parastromatoporid*, respectively.

Catalano and D'Argenio (1981) described the Sicilian reef complex (Fig. 11) as an alternation of reef (patch-reef and inter-reef deposits) and fore-reef debris. In the Dinaric reef complex, stromatoporoids dominate and massive and phaceloid corals predominate over solitary ramose forms and chaetitids. However, non-skeletal algae, foraminifers, bryozoans, crinoids, echinoids, brachiopods, molluscs, and *Tubiphytes* sp. are of lesser importance (Turnsek *et al*. 1981).

Extensive linear reef trends are illustrated in both the Sicilian and Yugoslavian examples. The Dinaric complex is approximately 140 kilometers long and about 20 kilometers wide. Fore-reef and slope depositional settings are represented by calcareous breccias consisting of allochthonous blocks of reef limestone and bioclastic detritus. The presence of clean skeletal detritus in the reef areas, marginal to slope settings, suggests that high-wave energies impinged on the reef complex. A smaller reef complex mapped by Steiger and Wurm (1980), in Austria, is approximately 1.5 kilometers in length and is about 300 meters in width (Fig. 12).

Subsurface Examples of Smackover Buildups

Buildups on Gently Sloping Wave-Agitated Platforms

Sponge-Coral-Algal Mounds.- Subsurface examples of sponge-coral-algal buildups in the Smackover Formation (Fig. 13) are displayed best in cored intervals from Walker Creek Field in Columbia County, Arkansas (Arco No. 1 McFadden Well, Fig. 14; Appendix A; Baria *et al*. 1982; Harris and Crevello, 1983), and from North Haynesville Field in Claiborne County, Louisiana (Tenneco No. 1 Seegers-Waller Well, Fig. 15; Appendix B; Baria *et al*., 1982).

The framework of these buildups was constructed mainly by non-calcifying, stromatolitic blue-green algae that apparently were rapidly lithified by micritic marine cements. These algae were volumetrically important constituents of the buildups. In addition, they served a dual role of binding reef sediment and producing a microframework for organisms to inhabit and sediment to infiltrate. The algae developed faint laminar crusts on sediments of encrusted skeletal debris, or developed delicate digitate branches and heads with only a few centimeters of re-

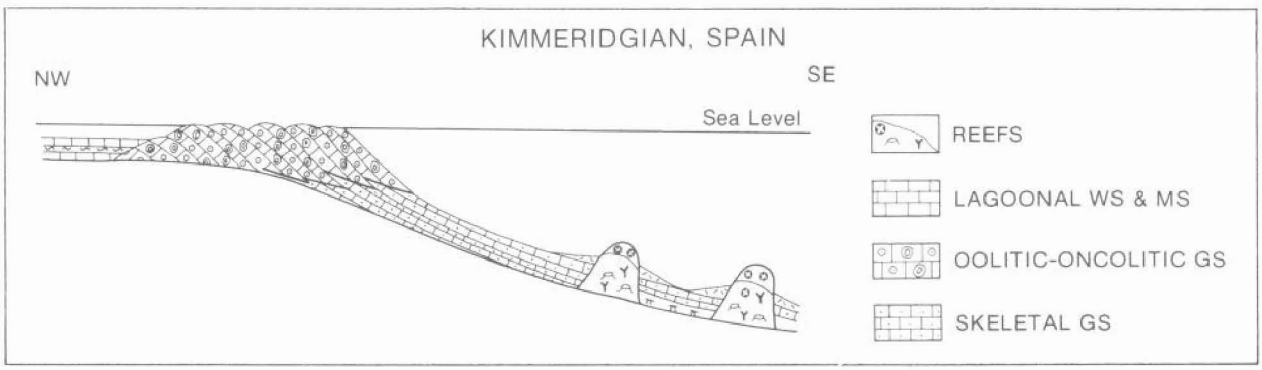


Figure 9. Depositional model for the outcropping lower Kimmeridgian of Spain (modified after Giner and Barnolas, 1979) illustrating a carbonate platform with moderate bottom agitation. Note that individual reefs and bioclastic debris occur on the shelf seaward of oolite shoals and lagoonal muds.

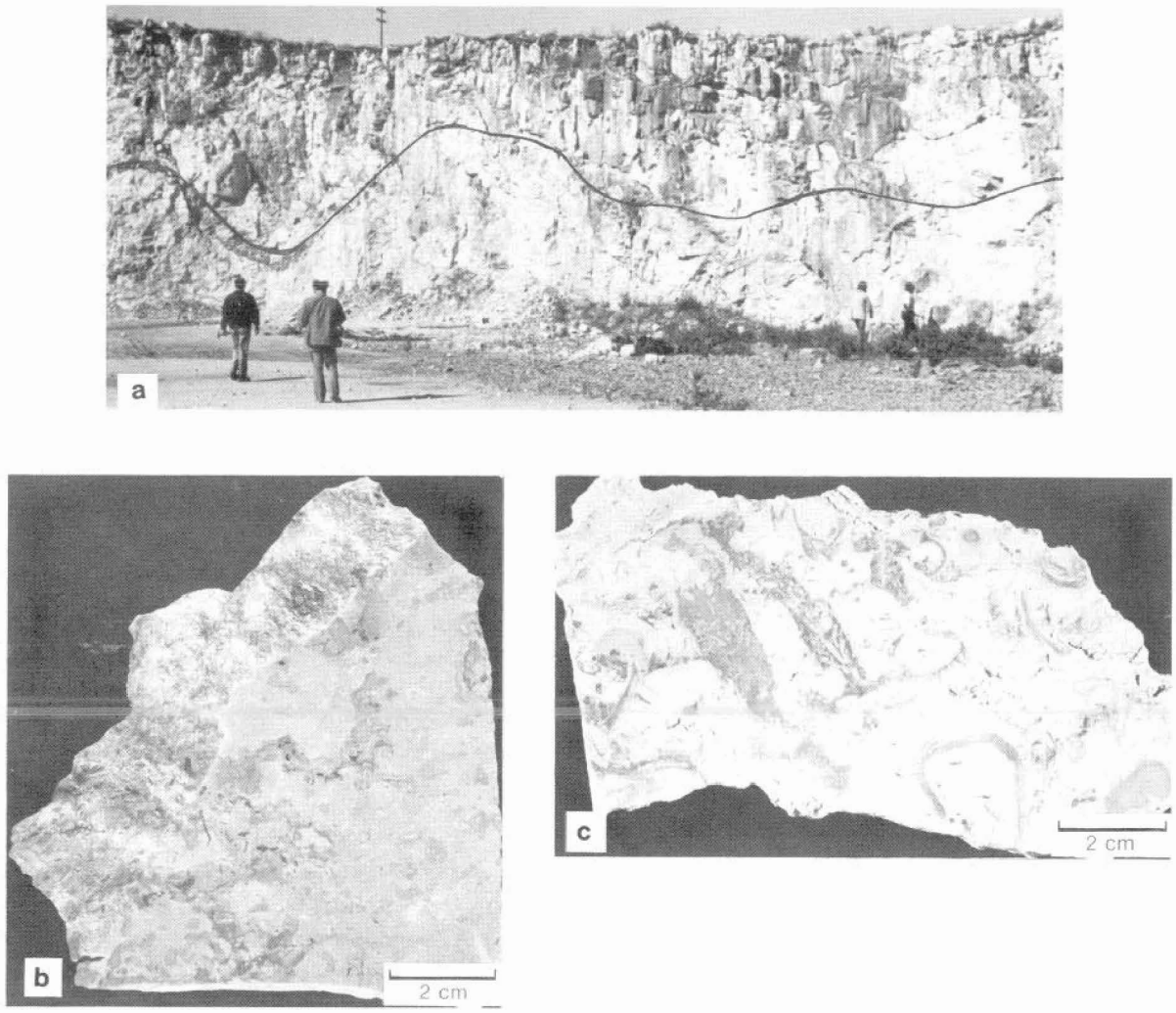


Figure 10. Photograph of outcrop and polished rock slabs illustrate buildup and associated lithologies from wall of working quarry, 2 kilometers south of Arruda, Portugal, exposing Kimmeridgian-age Corallien sequence of the Lusitanian Basin.

a. Reefal carbonates at base of quarry (upper boundary of the interval is highlighted) are overlain by well-bedded ooid grainstone which is regionally up to 60 meters thick. Individual mounds up to 10 meters thick in the quarry and up to 30 meters thick regionally developed over an area that covers 400 square kilometers.

b. Digitate algal-crust boundstone and wackestone. Boundstone (left half of slab) is stained orange-brown, appears lithified and fractured early, with fractures partially filled with wackestone and equant calcite spar; some borings. Wackestone is pelleted and thrombolitic in places, is oncolitic, and contains scattered clam shells.

c. Boundstone of algal-encrusted corals, red algae, and clams; internal cavities filled by wackestone with numerous fractures. Algal coatings are similar to *Lithocodium-Bacinella*. Corals and clams are replaced or filled with equant calcite spar, as is fracture-breccia fabric.

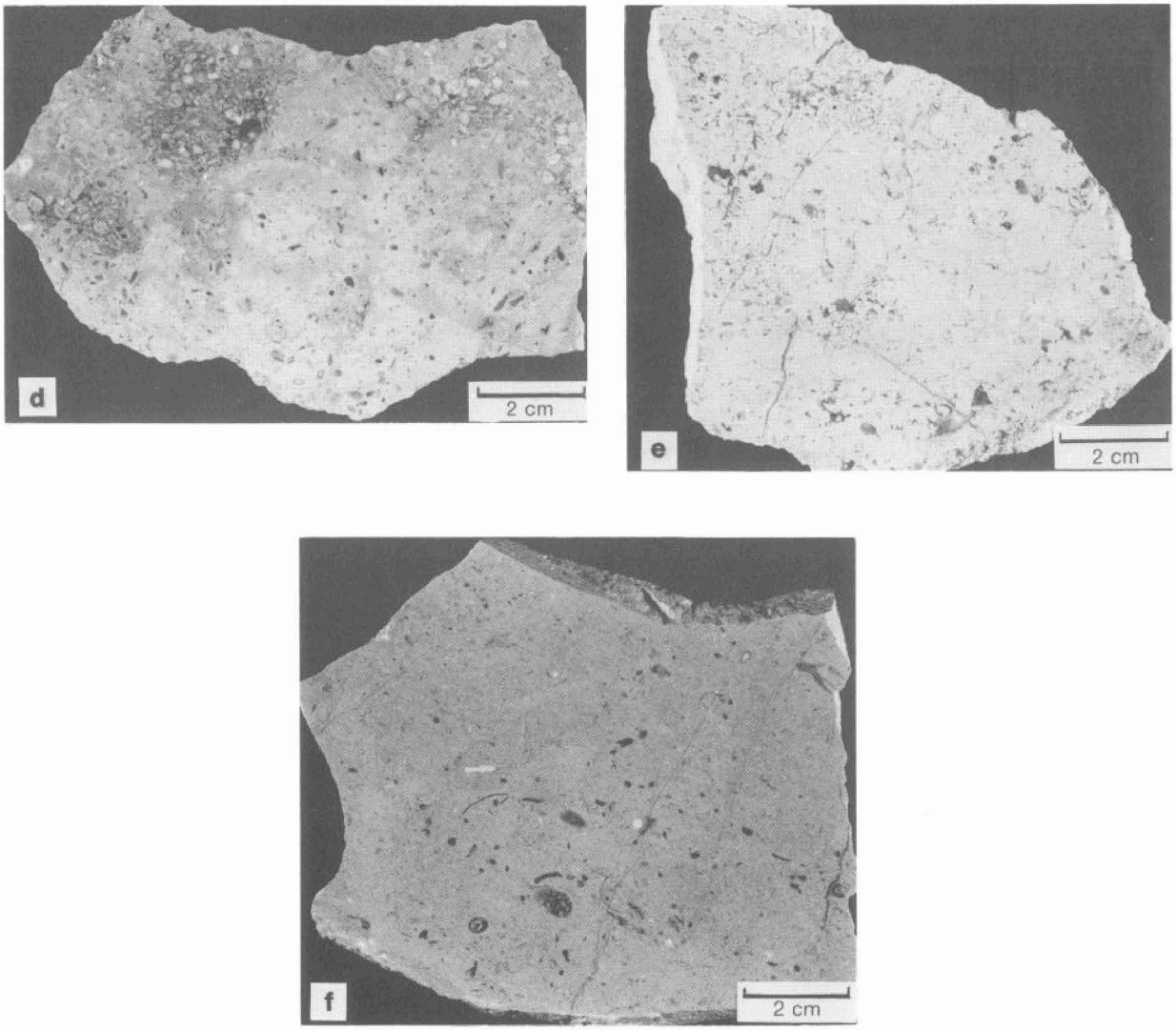


Figure 10. Continued.

d. Oncolite rudstone to packstone overlying buildup contains algal-coated echinoid plates and spines, gastropods, pelecypods, and corals, in addition to uncoated skeletal fragments. Mollusc and coral debris were replaced by blocky calcite spar.

e. Bored and encrusted cyanophycean algal boundstone (stromatolite/thrombolite) from crest of buildup. Framework and/or shelter pores are filled with layered grainstones and packstones of oncolites and bioclasts. Notice mollusc (borings?) scattered in boundstone fabric.

f. Intermound sediments of bioturbated fine packstone to wackestone of micropeloids and pellets with scattered pelecypods, gastropods, echinoderm debris, oncolites, and coral fragments.

lief (Fig. 16).

Commonly, pelleted or thrombolitic (unlaminated stromatolite) fabrics developed and were encrusted with *Tubiphytes* sp., agglutinated and calcareous worm tubes, bryozoans, foraminifers, and calcareous sponges (Fig. 17). All of these organisms seemingly required a substrate more stable than that of a

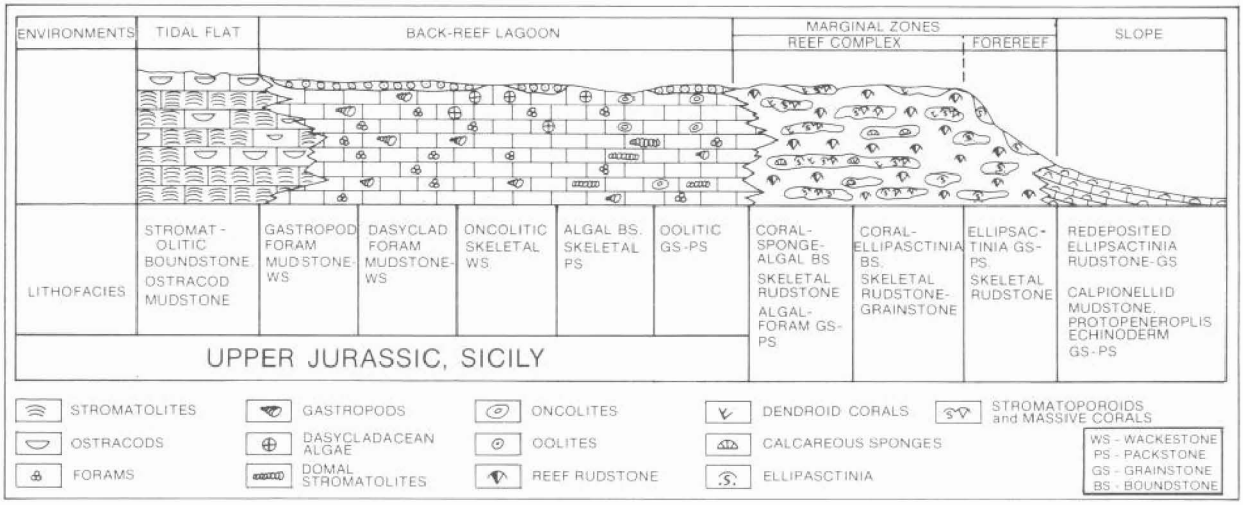


Figure 11. Diagrammatic cross section illustrating depositional settings and facies developed across the Panormide carbonate platform margin of western Sicily during Upper Jurassic (modified from Catalano and D'Argenio, 1981).

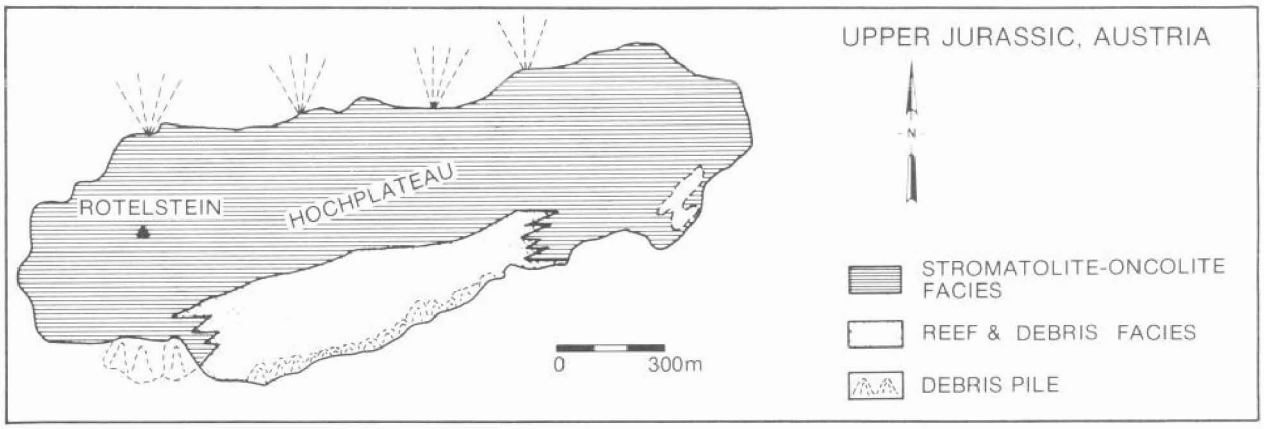


Figure 12. A plan-facies map of an Upper Jurassic stromatoporoid-coral reef margin complex in the Plassen Limestone in the Rotelstein area, northern Alps of Austria (modified from Steiger and Wurm, 1980).

weakly cemented mat. Although synsedimentary fracturing of the reef framework and boring of the algal fabric are rare, multiple cross-cutting relationships of clam and sponge borings into corals and crusts indicate marine lithification of the buildups (Figs.16h, 17a and 17b).

Sponges are also important in the construction of these buildups, particularly in the lower part of the buildup in the Arco #1 McFadden well. Here, laminar and finger-like lithistid sponges and hexactinellid sponges are common, and encrusting calcareous sponges and calcareous finger-like sponges are rare. Chaetitids are scattered through the buildups. A vertical variation in the paleocommunity of the buildup in the Arco No. 1 McFadden well occurs; the upward increase in size and number of corals suggests a shoaling-upward trend (Baria *et al.* 1982; Harris and Crevello, 1983). Calcareous red algae are abundant in the upper parts of the Tenneco No. 1 Seegers-Waller well buildup and are in the bioclastic pile in the Bass Smith

Appendix C), and their abundance suggests a paleocommunity evolution brought on by shallowing conditions.

Corals (primarily *Actinastrea* sp.), the problematical calcareous red alga *Parachaetetes* sp., and the blue-green alga *Cayeuxia* sp. served as the primary framebuilders of the reef. The only significant difference between the buildups described from the Walker Creek and North Haynesville fields is the greater abundance of red coralline algae that cap the buildup in the Tenneco No. 1 Seegers-Waller well (North Haynesville).

Imlay (1940) and Wells (1942) described at least six different genera of corals from the Smackover Formation, none of which was recognized in the core studies of Baria *et al.* (1982). Various types of small head, finger, and branching forms of corals were observed, but the preservation of the coral microstructure was generally poor and identifications could not be made. Partially dissolved and micritized calcareous algal structures also impeded identification of many of the green codiacean and blue-green algae. Echinoid and mollusc debris, including gastropods, cerithids and nerinids, along with whole and fragmented shells of the oyster *Lopha* sp., and unidentifiable bivalves is commonly associated with the buildups.

Immediately beneath the buildup in Walker Creek Field, poorly sorted biointraclastic and peloid packstones and oncolite rudstones are present. These lithologies may represent debris that was shed onto an unstabilized, deeper water sediment flat or channel adjacent to the buildup. Oncolites from this interval display a digitate growth fabric that resembles the framework developed in the buildups. Lithoclasts consist of pelleted, very fine-grained peloidal (micropeloid) packstones to mudstones resembling the blue-green algal fabric and sponge debris. Similar clasts observed in outcrop studies of flanking beds adjacent to sponge-algal mounds in Germany and Austria were termed tuberoids

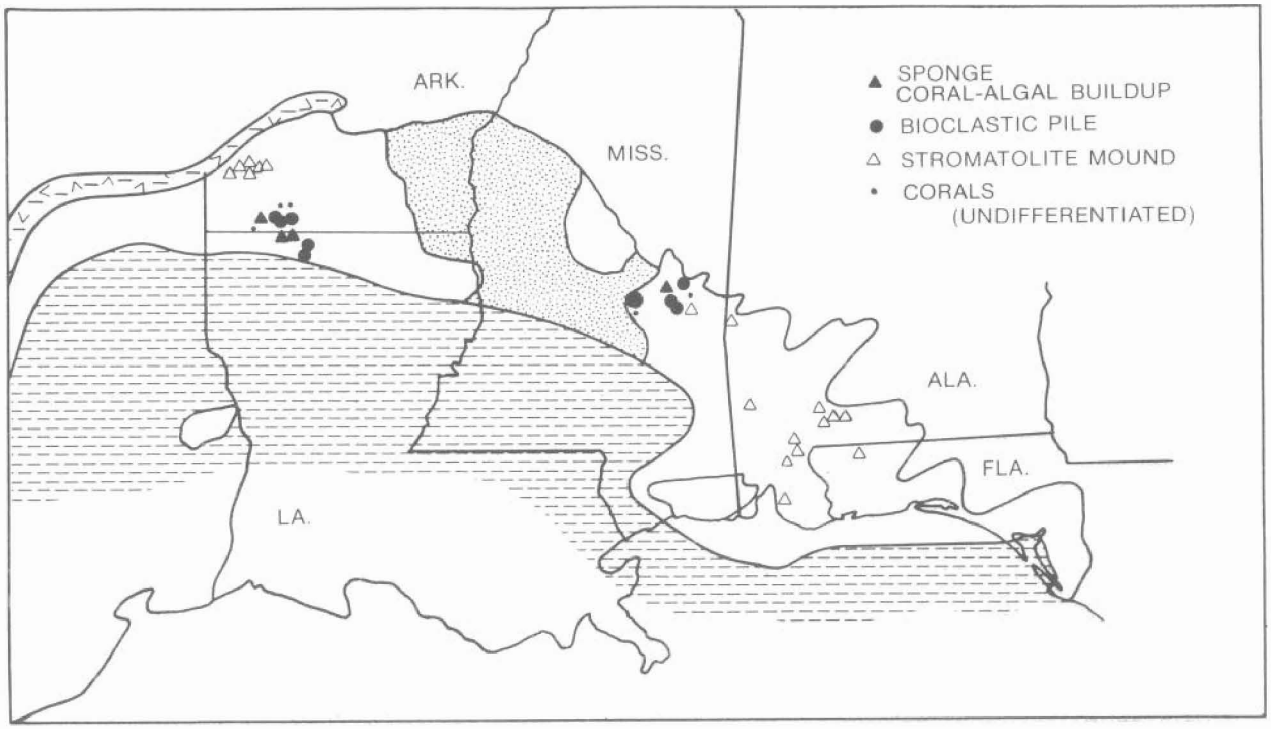


Figure 13. Types of Jurassic buildups recognized in conventional cores from the Smackover Formation; data from Baria *et al.*, 1982 and McGraw, 1982). Lithologies are identified in Figure 1. Corals (undifferentiated) designate isolated occurrences of corals or biostromes.

(Gwinner, 1976; Flugel and Steiger, 1981). In those studies, the tuberoids were interpreted as reworked calcified siliceous sponges and stromatolite crusts.

Underlying the biointraclastic and oncolitic intervals in the Arco No. 1 McFadden well buildup is a quartz sandstone and a poorly sorted ooid grainstone couplet (Appendix A). In contrast, below the buildup in the Tenneco #1 Seegers-Waller well, sediments grade downward to very fine-grained peloidal packstones and wackestone containing scattered oncolites, abundant echinoid debris, and brachiopod *Terebratellia* sp. (Appendix B).

Oncolite, peloidal, and intraclastic packstones and grainstones, containing abundant tuberolitic intraclasts, overlie both buildups. Somewhat greater water turbulence over the buildup in the Tenneco No. 1 Seegers-Waller well is suggested by the presence of a thick sequence of biointraclastic packstones and rudstones. In contrast, the buildup in the Arco No. 1 McFadden well is capped by less than 3 meters of fine- to medium-grained peloid packstones which are overlain by a coarse-grained ooid grainstone.

Bioclastic Piles.- The Bass No. 1-A Smith (Figs. 13 and 18; Appendix C) in Hico Knowles Field in Lincoln Parish, Louisiana, provides a subsurface example of skeletal rubble from the Smackover Formation from which hydrocarbons were produced (Baria *et al.*, 1982; Crevello *et al.*, in press). The skeletal rubble lacks a boundstone fabric and differs somewhat in texture and biotic constituents from the sponge-coral-algal mounds just described. Delicate or more fragile types of reefbuilding organisms, such as hexactinellid and lithistid sponges, are lacking. Also absent are encrusting organisms such as *Tubiphytes* sp., which commonly populated the stromatolite crust and framework. Corals, molluscs, echinoids, calcareous finger-like and en-

Figure 14. Photographs of thin sections in plane-polarized light illustrating microfacies from and associated with the sponge-coral-algal buildup in the Arco No. 1 McFadden well, Walker Creek Field, Arkansas.

a. Micropeloidal (very fine-grained sand- to silt-size peloids) packstone with coated echinoid and texturlarid foraminifer. 10,960 feet (3,340.6 m).

b. Reef-derived skeletal debris in an oolitic and skeletal-peloidal packstone: *Cayeuxia* sp. (lower right); *Ptychochaetetes* sp. (lower left); *Actinastrea* sp., bored and encrusted by calcisponge (upper right); and gastropod and pelecypod fragments. 10,966 feet (3,242.4 m).

c. Coral-bearing thrombolite/stromatolite-*Tubiphytes* boundstone with pelecypods, agglutinated worm tubes in a bioclastic-micropeloidal wackestone to packstone. 10,973 feet (3,344.9 m).

d. Coral-bearing thrombolite/stromatolite-*Tubiphytes* boundstone illustrating the intensely pelleted packstone framework filled in with bioclastic-micropeloid packstone to wackestone (lighter color). Note several generations of microborings and geopetal sediment in upper half of coral. 10,982 feet (3,347.3 m).

e. Boundstone of laminar sponge (lower half) encrusted by calcisponge and bryozoan. *Lopha* sp. (oyster) on left is bored. 10,985 feet (3,348.2 m).

f. Biointraclastic packstone of echinoid debris, intraclasts of micropeloid*iphytes* packstone to wackestone (tuberoids) and oyster debris in dolomicrospar matrix. 10,990 feet (3,349.7 m).

g. Biointraclastic oncolite packstone to rudstone with fragments of echinoids, pelecypods (*Lopha* sp.), calcisponges, chaetitids, reworked thalli of *Cayeuxia* sp., and intraclasts of micropeloid (tuberoids)-*Tubiphytes* packstones. 10,994 feet (3,351 m).

h. Quartzose, intraclastic and oolitic oncolite rudstone, poorly sorted, with perched micrite, grapestones, and oolite intraclasts. Large oncolite (right) is encrusted with serpulid worm tubes and foraminifers. 10,997 feet (3,351.9 m).

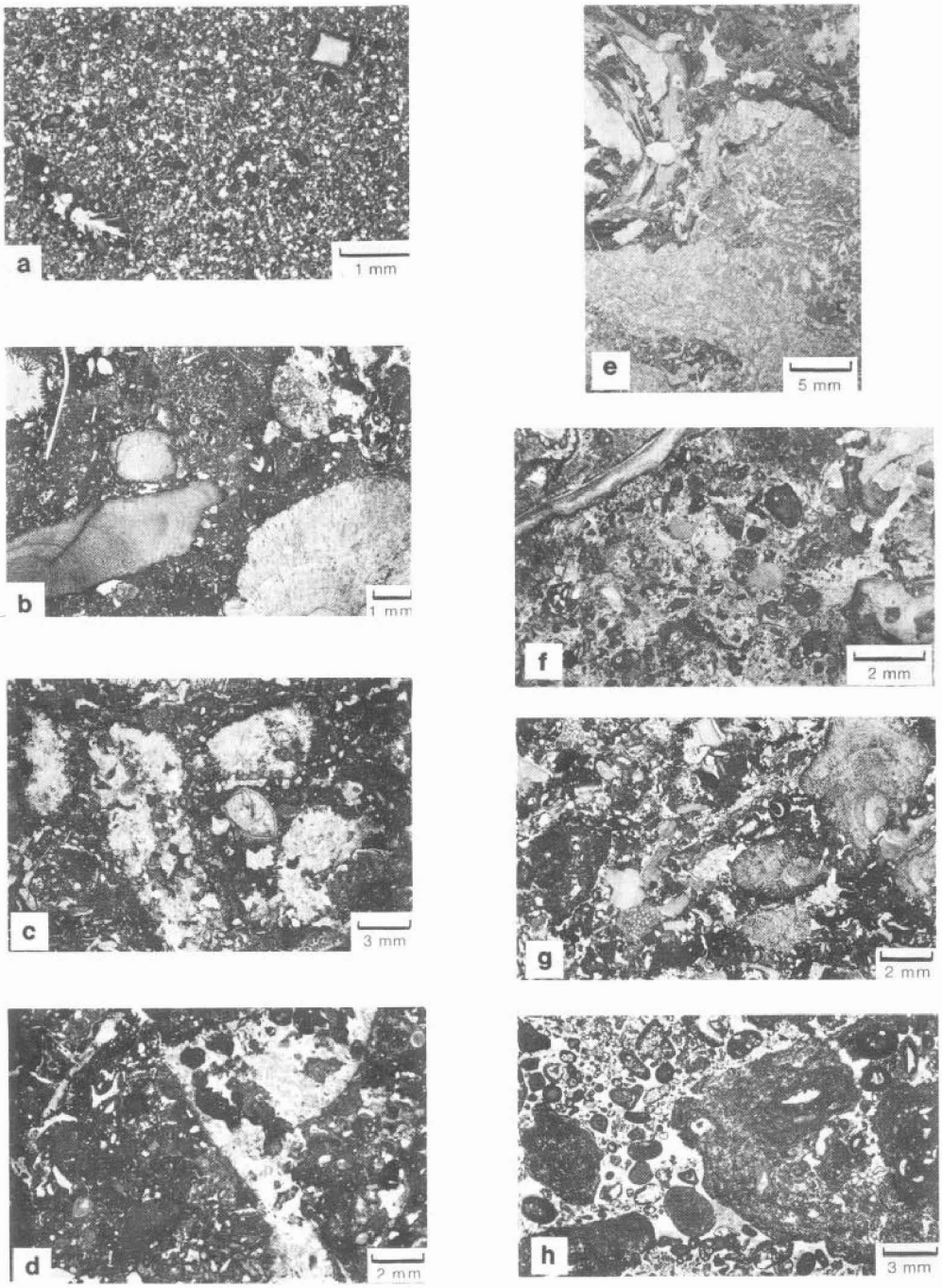


Figure 14

crusting sponges, chaetitids, and various calcareous algae (*Cayeuxia* sp., *Parachaetetes* sp.) and abundant red algae are the dominant constituents of the bioclastic pile.

The combination of (1) fragmented, gravel-supported skeletal debris with bioclastic grainstones and packstones between the clasts (Fig. 18c); (2) the variable depositional sequence of bioclastic rudstones, grainstones, packstones, and terrigeneous silt/sandstones; (3) the lack of reef-building organisms in growth position; and (4) extensive marine cementation - all suggest that the skeletal interval represents locally reworked detritus, possibly flanking beds of a nearby patch reef (Crevello *et al.*, in press). Based on the biotic assemblage and thickness of these deposits, as well as outcrop analogues, we believe this facies forms a pile, perhaps with a nearby reef core, rather than an extensive sheet deposit.

Stromatolite Mounds.- Stromatolite mounds (Figs. 13 and 19) are the only types of buildups encountered, to date, in the Alabama and Florida part of the subsurface Smackover trend (Baria *et al.*, 1982). These buildups are dominated by laminated stromatolites, but pelleted thrombolite growth forms are also common (Fig. 19). The framebuilding and encrusting organisms, common in the other two types of buildups recognized in the Smackover Formation, are minor constituents in the stromatolite mounds. Corals, skeletal algae, echinoderms, oysters, and other organisms in growth position are rare, although their presence verifies that these mounds developed in a subtidal environment. These buildups also developed near ooid shoals as they are covered by peloid and ooid sands. The stromatolite mounds are up to 40 meters thick, which is thicker than the other buildups recognized in the Smackover. Baria *et al.* (1982) suggested that the development of these mounds on subsiding basement fault blocks caused them to be thicker than the buildups in Louisiana and Mississippi. The foundation for the latter buildups was salt-cored structures, which were capped by buildups with thicknesses of less than 20 meters.

Stromatolite mounds were recently reported from Paup Spur Field in Southern Arkansas (McGraw, 1982), about 50 kilometers northwest of Walker Creek Field (Fig. 13).

Figure 15. Photographs of thin sections in plane-polarized light illustrating microfacies from and associated with the sponge-coral-algal buildup in the Tenneco No. 1 Seegers-Waller well, North Haynesville Field, Louisiana.

a. Fine- to medium-grained dolomitic oopeloid packstone to poorly washed and bioturbated grainstone. 10,056 feet (3,065.1 m)

b. Intraclastic rhodolite-oopeloid rudstone to packstone. 10,058 feet (3,065.7 m).

c. Biointraclastic rhodolite rudstone to grainstone with alga thalli of *Cayeuxia* sp. and red alga thalli of probable *Parachaetetes* sp. that is partially micritized and replaced by anhydrite. 10,066 feet (3,068.1 m).

d. Intraclastic floatstone in dolomicrospar matrix. Intraclasts are reworked boundstone (left center) and bioclastic micropeloid (tuberoid) packstones to wackestones (center and right). 10,089 feet (3,075.1 m).

e. Thrombolite/stromatolite boundstone to framestone (lower half) overlain by lamellar sponge with large vertical fractures and hexactinellid sponge (top). Boundstone to framestone crusts consist of faintly laminated, pelleted, or micropeloid texture with rare agglutinated worm tubes. 10,093 feet (3,076.3 m).

f. Coral-bearing *Tubiphytes*-thrombolite boundstone illustrating abundant *Tubiphytes* encrusting boundstone which grew out from coral. 10,095 feet (3,077 m).

g. Biointraclastic and oncolite floatstone in a bioclastic peloid packstone with a dolomicrospar matrix. Bioclasts are calcareous thalli of *Cayeuxia* sp., pelecypods, and *Tubiphytes*. Intraclasts are micropeloid (tuberoid) packstones and wackestones. 10,109 feet (3,3081.2 m).

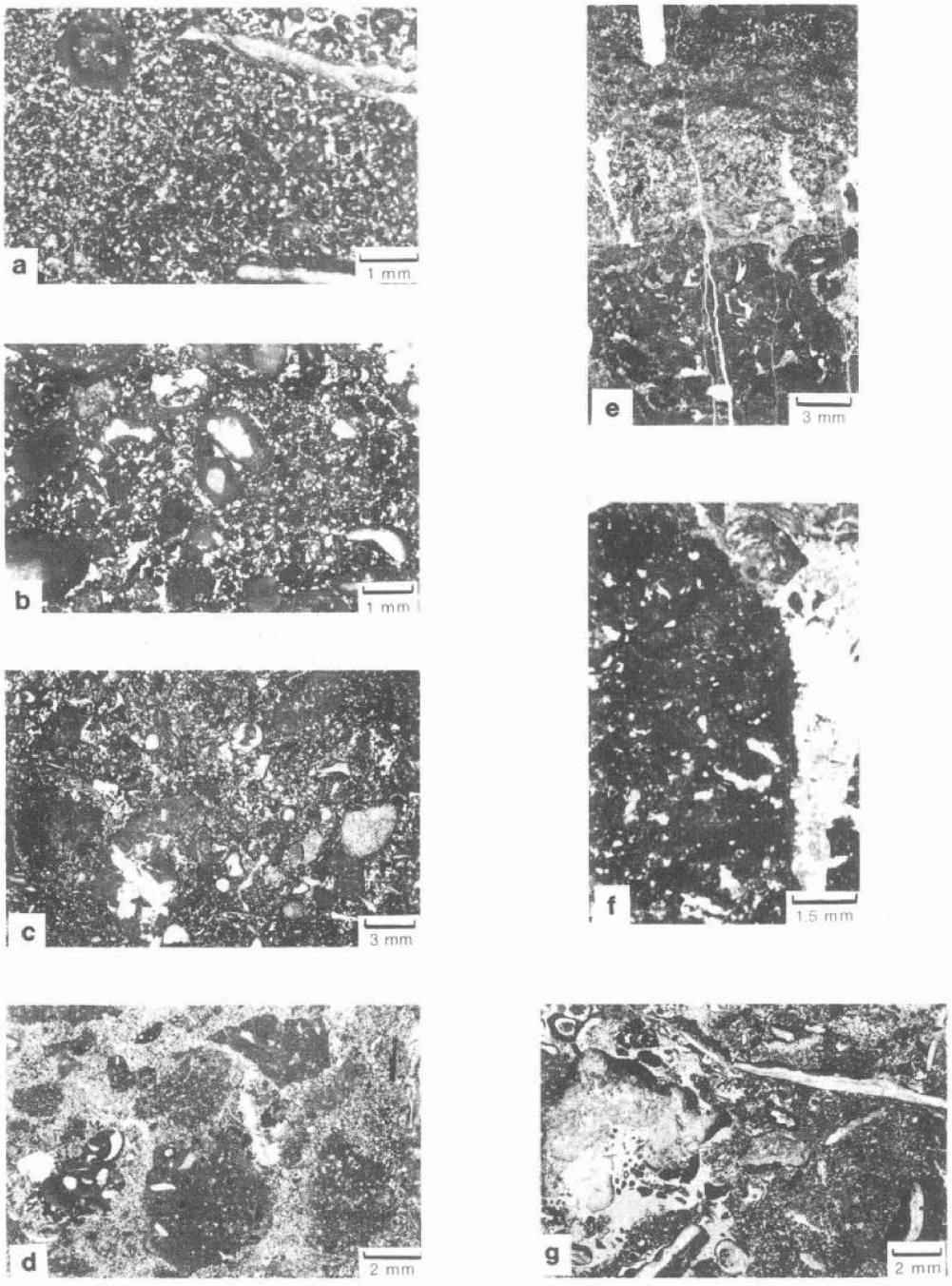


Figure 15

McGraw's (1982) work provides the first documentation of stromatolite mound development in the Smackover of southern Arkansas. In Paup Spur Field, the algal stromatolites are associated with ooid, oncolite, and pellet packstone-grainstone facies, similar to those of the stromatolite mounds reported by Baria *et al.* (1982) from Alabama to Florida. Using borehole logs and cores, McGraw (1982) correlated the algal stromatolite unit, which is commonly less than 8.5 meters thick, for nearly 5 kilometers along depositional strike and 1.6 kilometers in a shelfward direction. The algal facies is overlain by a blanket of ooid grainstones, suggesting mound development immediately seaward of ooid shoals.

DISCUSSION

Platform Setting for Carbonate Reefal Buildups

Platform Profiles

Two figures illustrate the various positions that reefal buildups occupied on carbonate platforms during the Jurassic (and early Cretaceous)(Figs. 20 and 21). The reconstruction of the Smackover platform (Fig. 20) shows the considerable variation in types of buildups along the depositional trend (see also Fig. 13). Whereas, the platform profiles (Fig. 21) show only the variation in types of buildups across the depositional dip: (A) a gently sloping platform (commonly referred to as a carbonate ramp (Ahr, 1973) or knoll reef ramp (Wilson, 1975) as the Smackover platform, (B) a steepened platform margin as presented by Catalano and D'Argenio (1981; Fig. 11) and Eliuk (1978), and (C) a steepened or rimmed platform margin with an intrashelf basin or deep lagoon that passes laterally updip into a gently sloping carbonate platform as profile A. Profiles A and B (Fig. 21) represent platforms several tens of kilometers across: (A) such as a transect from Tongue of the Ocean onto the steepened margin of the Great Bahama Platform or across the subsurface Jurassic Abenaki platform margin offshore from Nova Scotia (Eliuk, 1978); and (B) a transect across the gently sloping Trucial Coast of the Persian Gulf (*in* Budd and Loucks, 1981) or the Jurassic Smackover platform. Profile C (Fig. 21) may be several times larger than A and B (Fig. 21), on the order of ten's to hundred's of kilometers across. Analogues similar in scale and profile may be comparable to a transect from the Atlantic margin of the Great Bahama Bank,

Figure 16. Photographs of thin sections in plane-polarized light of stromatolite and thrombolite boundstone to framestone fabrics.

A.M. (Arco No. 1 McFadden well), S.W. (Tenneco No. 1 Seegers-Waller well), B.S. (Bass No. 1-A Smith well).

a, b, c, and d. Laminated and pelleted stromatolites illustrating boundstone to framestone fabric (a, b, and d) and isolated, upward-expanding crust (c). a. A.M., 10,988 feet (3,349.1 m); b. S.W., 10,092 feet (3,076 m); c. A.M., 10,988 feet (3,349.1 m); d. A.M., 10,985 feet (3,348.3 m).

e. Micropeloidal framestone encrusted with *Tubiphytes* and probable nubeculinellid foraminifer. Note geopetal sediment and shelter porosity developed in the thrombolite framestone. S.W., 10,095 feet (3,077 m).

f. Thrombolite framestone encrusted by serpulid worm and agglutinated worms with sponge spicules in geopetal sediment; micritic marine cement in serpulid and framestone, and late-stage ferroan dolomite pore-filling cement. A.M., 10,985 feet (3,348.2 m).

g. Photograph of close-up view of encrusted stromatolite framestones with algal(?) cysts (middle- and lower-center). A.M., 10,985 feet (3,348.2 m).

h. Microboring of micropeloidal intraclasts and pelecypod in oncolite floatstone. A.M., 10,961 feet (3,340.9 m).

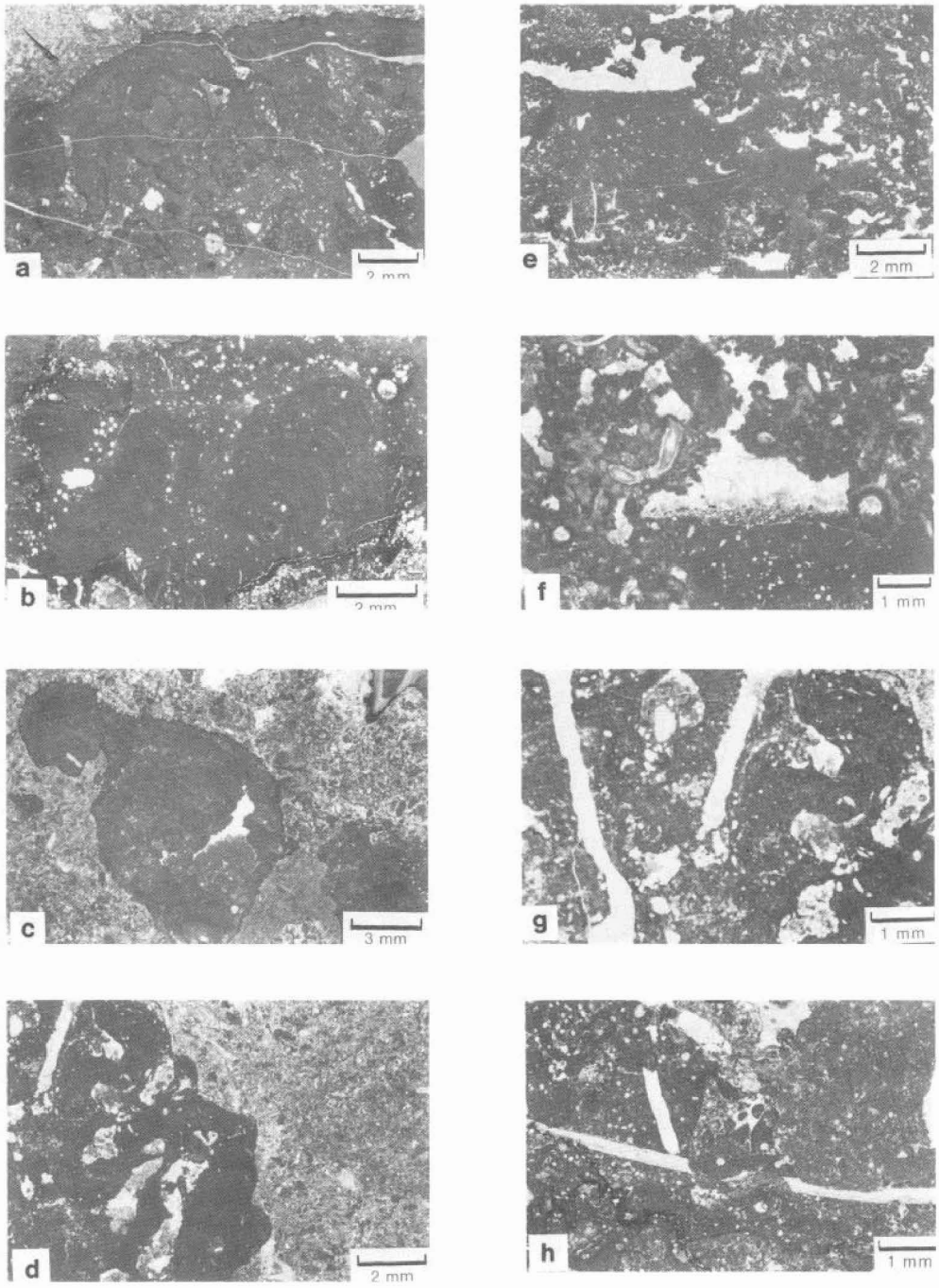


Figure 16

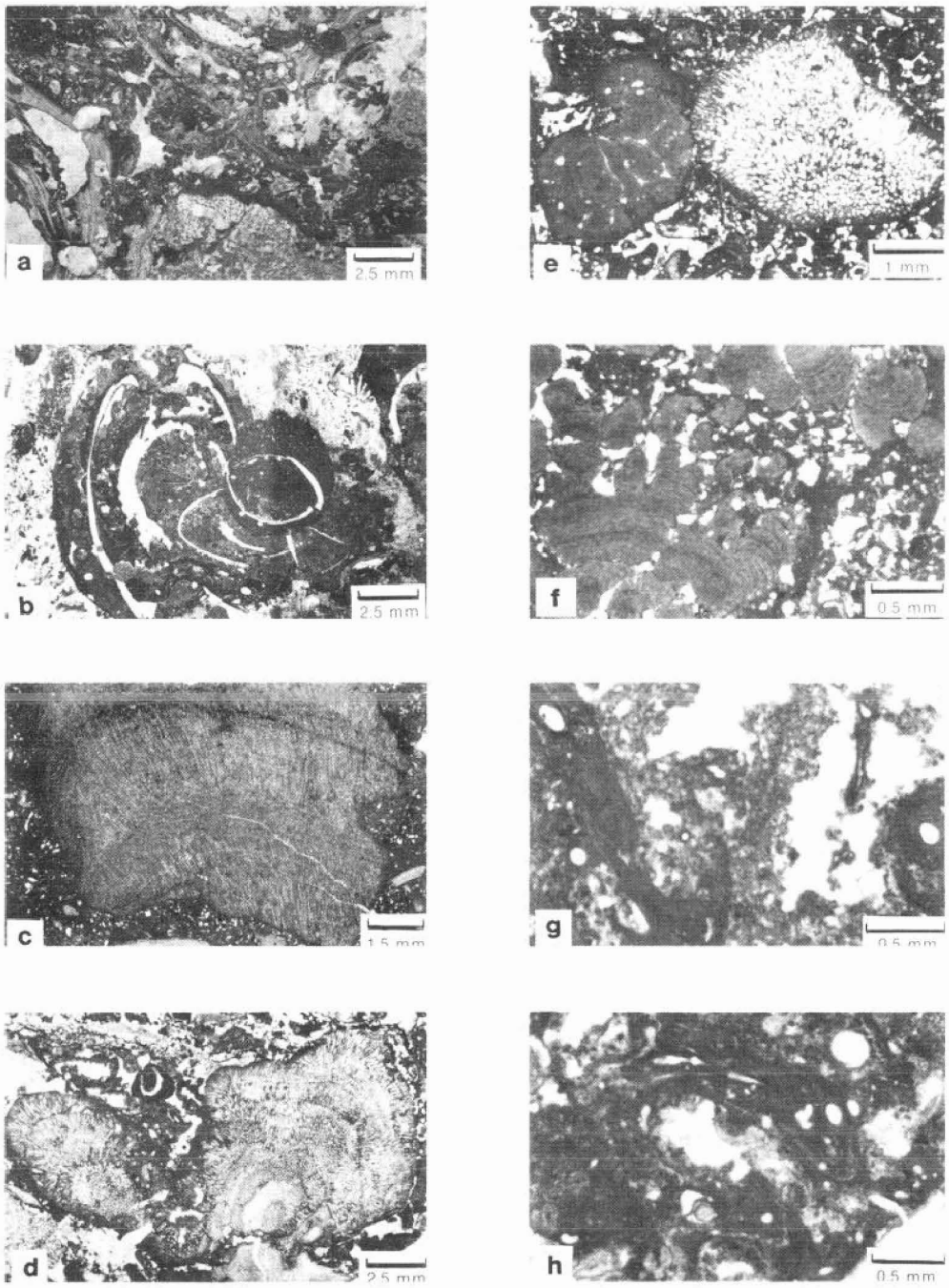


Figure 17

across the intraplatform basins and platforms, and onto the Florida peninsula; or across the Jurassic Friuli Platform to the Lombard Basin of the southern Alps (Winterer and Bosselina, 1981).

Buildup Type and Platform Position

Sponge-Algal Mounds (Type 1).- These mounds are developed downslope from gently dipping platforms and steepened margins (Fig. 21). These mounds occupied areas of lower sediment input, below the fore-reef talus slopes, favoring intergulley or seafloor highs. They have not been documented from shallow, wave-agitated settings, yet the algal frameformers presumably required light for photosynthesis, thus limiting their development to within the photic zone. Such deep-water mud mounds have not yet been reported from the subsurface of the Smackover Formation. However, Jansa *et al.* (1982) interpreted algal-stromatolite buildups occurring in the subsurface Abenaki Formation as indicative of a deeper water neritic environment.

Coral-Bearing Reefs (Types 2a, b, and 3; Fig. 21).- These reefs show marked variations in

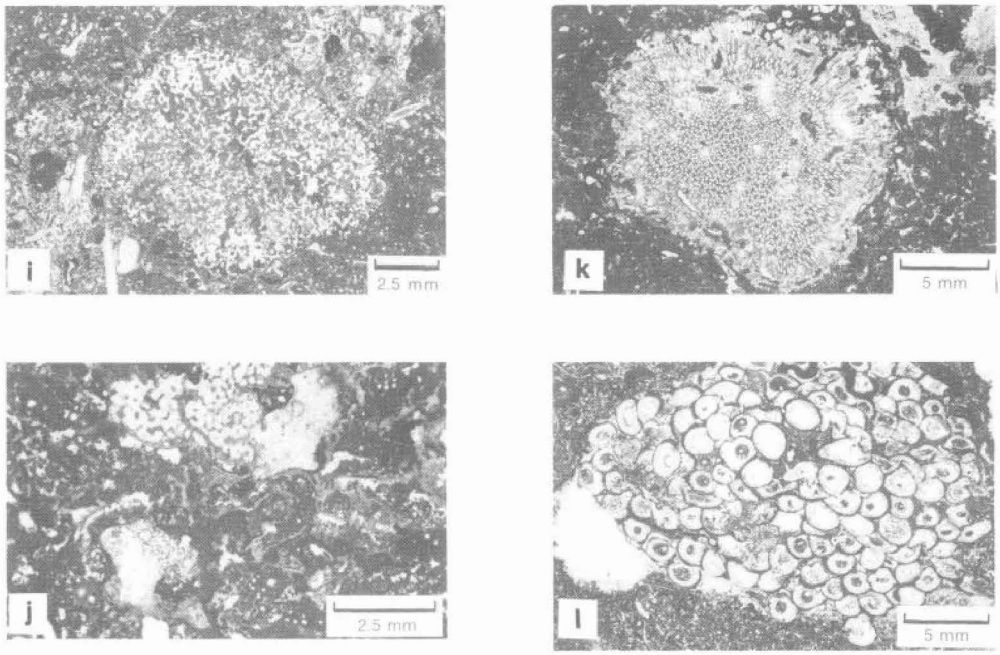


Figure 17. Photographs of thin sections of reef framebuilders and encrusters, and microborings from Smackover buildups.

a and b. Boring in pelecypod and boundstone (a) of sponge-coral-algal boundstone and multiple borings (b) in coral. a. A.M., 10,985 feet (3,348.2 m); b. S.W., 10,106 feet (3,080.3 m). Thallus of calcareous algae: c. *Parachaetetes* sp., B.S., 10,755 feet (3,278.1 m); d. *Cayeuxia* sp., A.M., 10,944 feet (3,350.9 m); e. *Cayeuxia* sp. or *Ortonella* sp. (right) and red alga of probable *Parachaetetes* sp. (left), S.W., 10,066 feet (3,068.1 m); f. Red alga *Parachaetetes* sp. or micritized coralline alga; g. *Tubiphytes morronensis* Crescenti, S.W., 10,095 feet (3,077 m); h. *Tubiphytes* sp., A.M., 10,985 feet (3,348 m); i. Cross section of a lithistid sponge, S.W., 10,106 feet (3,080.3 m); j. Calcisponge and leached codiacean alga thalli, A.M., 10,976 feet (3,345.5 m); k. Chaetitid *(Acanthochaetetes* or *Pseudochaetetes)*, S.W., 10,105 feet (3,080 m); l. Annelid worm tubes encrusted by chaetitid, S.W., 10,116 feet (3,083.4 m).

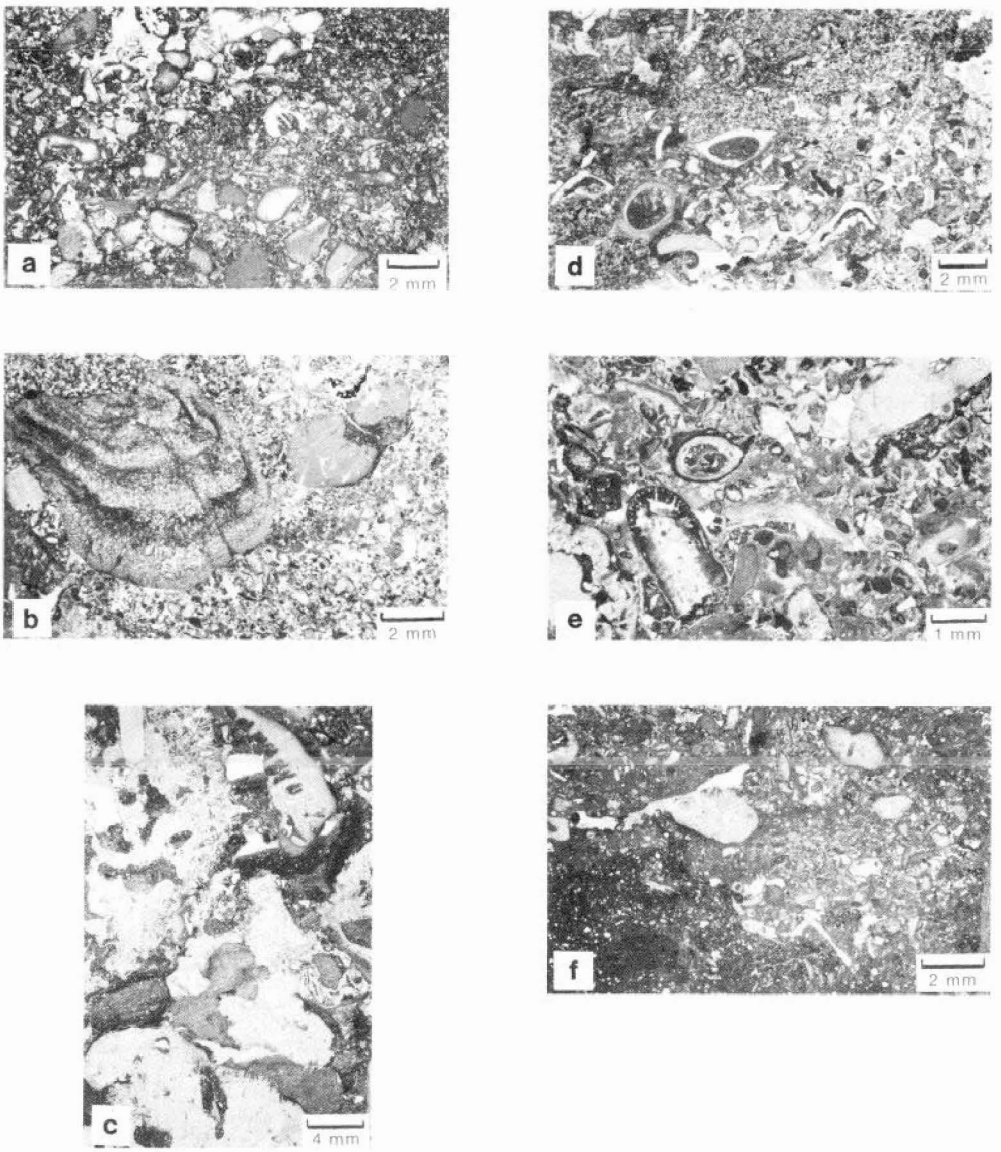


Figure 18. Photographs of thin sections in plane-polarized light illustrating microfacies in the bioclastic pile (reef rubble) from the Bass No. 1-A Smith, Hico Knowles Field, Louisiana.

a. Peloidal bioclastic packstone to rudstone illustrating fragmented and abraded debris of corals, red algae, pelecypods, and echinoids with preserved primary interparticle porosity. 10,733 feet (3,271.4 m).

b. Coral and red algal floatstone in bioclastic grainstone matrix with preserved interparticle and skeletal moldic porosity. Reworked thalli of calcareous red alga (*Parachaetetes* sp.), or possibly micritized coralline alga, on right. 10,739 feet (3,273.2 m).

c. Coral rudstone with multiple generations of sediment flooring shelter cavities; preserved shelter porosity. 10,744 feet (3,274.8 m).

d, e, and f. Peloidal bioclastic packstones and grainstones to floatstones (in bioclastic packstone-grainstone). Skeletal debris consists of annelid worm tubes, echinoid spines and plates, corals, pelecypods, red algae, and codiacean green algae. Note the leached coral (lower right) and the reworked codiacean alga thalli in e. d. 10,748 feet (3,276 m); e. 10,754 feet (3,277.8 m); f. 10,755 feet (3,278.1 m)

their overall biotic assemblages, coral growth forms, and species diversity. Beauvais' (1973) review of Upper Jurassic hermatypic coral deposits listed three principal types of coral formations: bioherms or patch reefs (types 2a, b, and 3) that produced deposits which ranged from a few to 30 meters thick; thin beds or biostromes, which also have organisms in growth position (not discussed in this paper); and bioclastic deposits (type 2c), in which reworked coral and other skeletal debris are often associated with sandy or oolitic sediment, a lack of binding organisms, and poor preservation of the original reef core. In these coral-bearing bioherms (Fig. 21), at least three framebuilding associations, with minor variations, dominate: sponge-coral-algal (type 2a) crust buildups developed on low-energy, less frequently wave-agitated platforms; coral-dominated patch reefs (type 2b) and associated bioclastic piles (type 2c) developed on highly wave-agitated platforms; and stromatoporoid-coral buildups (type 3) developed on steepened platform margins.

Coraliferous buildups that occupied deeper water (type 2a) were micrite-rich and contained lamellar corals, siliceous sponges, and stromatolite boundstones. Their assemblage and laterally equivalent muddy, pelleted, moderately fossiliferous, and oncolite-bearing sediments suggest lower energy settings, probably near the lowermost reaches of storm wave base. In contrast, coral-dominated bioherms (type 2b) with robust and encrusting growth forms of corals, calcareous algae, and calcisponges reflect bioherm development in shallow-water wave-agitated conditions. Associated bioclastic, oolitic, and oncolitic grainstone and packstone facies support the interpretation of a high-energy depositional setting.

The sponge-coral-algal mounds (Fig. 20; type 2a in Fig. 21) of the subsurface Smackover Formation (Walker Creek and North Haynesville Fields) contain nearly equal amounts of siliceous sponges, corals, and algal crusts, in addition to calcareous algae. Insignificant beds of skeletal debris flank these buildups, although the association with bioturbated, poorly sorted, oncolite-peloid packstones and fine-peloid and ooid packstones indicates a moderately wave-agitated shelf setting. In the buildup from Walker Creek Field, cross-bedded oolite grainstones overlying the peloidal packstones formed in highly wave-agitated shoal conditions. The red algal-rich rubble zone in the upper part of the buildup in Haynesville Field suggests, perhaps, that more normal marine conditions existed in a seaward direction from Walker Creek Field, where water depth or wave energy could also have been greater. The thicker peloidal packstones overlying the buildup in Haynesville Field suggest greater distances to the crestal ooid shoals, though crossbedded sand and crestal or flanking gravels indicate high wave (storm generated or normal) energies.

In even higher energy, wave-dominated environments, such as promontories exposed to ocean or deep-shelf wave swells, coral-bearing patch reefs are nearly completely reworked to form extensive and often coalescing piles of bioclastic debris (Fig. 20; type 2c in Fig. 21), in which little *in situ* framework is preserved. This type of buildup appears to be representative of the subsurface Smackover example from Hico Knowles Field, and the reef core diminution displayed by the Bajocian patch reefs of Morocco and the Oxfordian coral-stromatoporoid patch reefs from Austria (Steiger and Wurm, 1980).

Stromatoporoid-Coral Buildups (Type 3).- These buildups dominated the wave-swept platform margins facing open oceans. Reef talus of bioclastic detritus and allochthonous blocks were deposited in basins containing micrites with normal marine biota. Turnsek *et al.* (1981) suggested this association as evidence for a shelf-margin location of the buildups and paleorelief at the margin. A seismic line across the reef complex of the Knowles Limestone in East Texas (Finneran *et al.*,1982) shows a morphologic differentiation into platform and gently dipping slope. The description of carbonate facies and paleocommunities by Finneran *et al.* (1982) suggests closer affinities to the stromatoporoid-coral

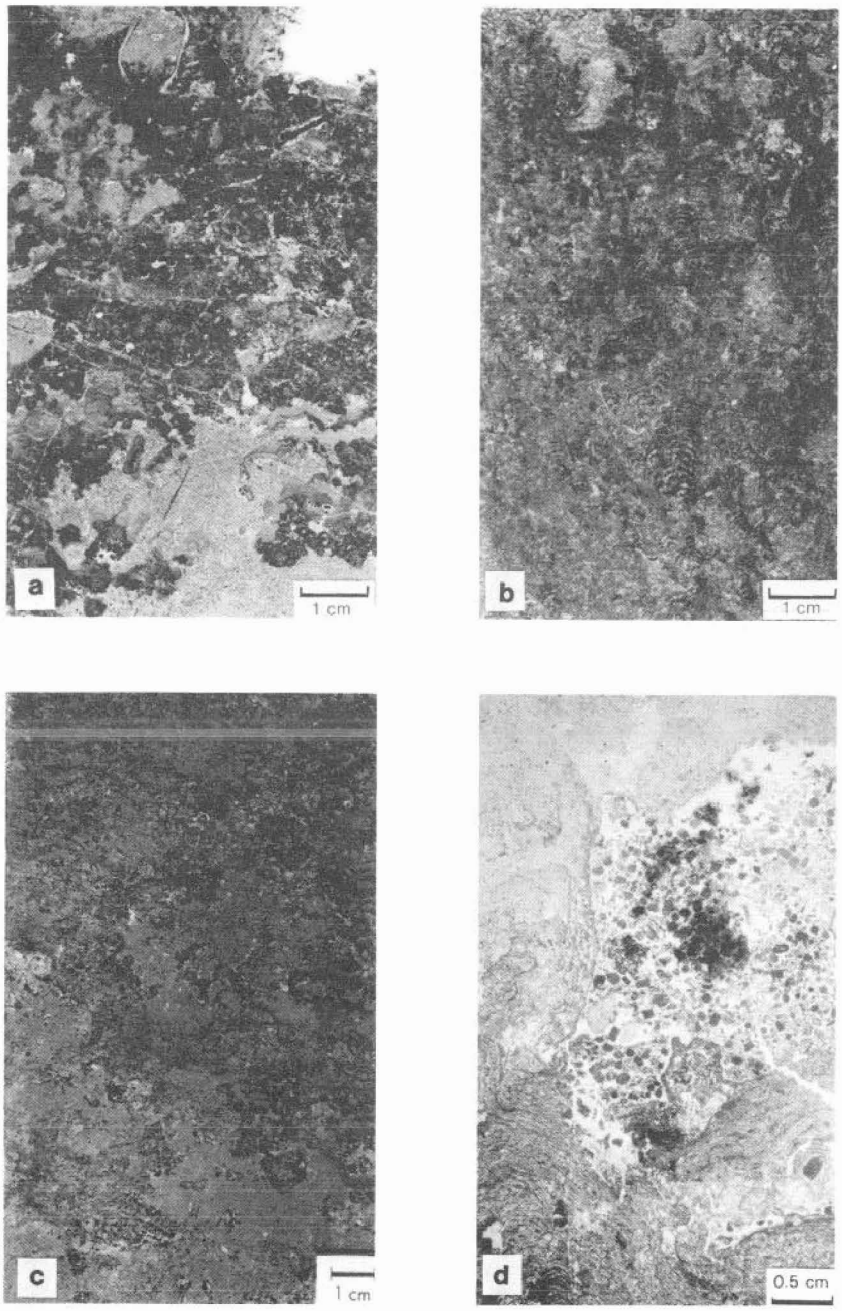


Figure 19

reefs of Turnsek *et al.*(1981) and Steiger and Wurm (1980) than to the types of carbonate reefal buildups recognized in the Smackover Formation. Eliuk (1978) and Jansa *et al.* (1982) also document a Kimmeridgian-Tithonian stromatoporoid-coral dominated shelf margin occurring in the subsurface along the eastern North American margin offshore from Nova Scotia. Seismic profiling revealed a relatively steep carbonate margin with several hundreds of meters of depositional relief facing the Jurassic Atlantic Ocean. Eliuk (1978) and Jansa *et al.* (1982) also recognized that algal-stromatolite buildups (type 1) and calcisponge buildups had occupied deeper water environments along this margin.

Stromatolitic Algal-Mounds (Type 4).- Development of this type of mound has only been reported from the subsurface Smackover wave-agitated platform (Figs. 20 and 21). These buildups may be a variation of the sponge-coral-algal mounds, where the sponges and corals were not very prolific, possibly because of elevated salinities (Baria *et al.* 1982); however, other normal marine, stenohaline organisms, particularly red algae and echinoids, are present. Such mounds have not been reported from studies of Jurassic outcrops, although similarities exist with deepwater mounds.

The development of a subtidal stromatolitic sequence in Paup Spur Field north of the skeletal-rich and biotically diverse buildups of Walker Creek, Hico Knowles, and Haynesville fields was not recognized by Baria *et al.* (1982). Its occurrence north of the skeletal-rich belt, in a more shelfward position, suggests that stromatolite buildups occur some distance up on the shelf, whereas the skeletal-rich buildups are restricted to the margin of the gently sloping platform. This distribution may explain why stromatolite mounds are more common in the eastern part of the Smackover trend where the broader shelf in this region would be less conducive to the development of biotically diverse mounds.

The association of ooid shoals and stromatolitic algal mounds in the Smackover Formation may have a modern counterpart in the Bahamas. Dravis (1983) speculated that the development of columnar stromatolite heads in water depths of 1 to 5 meters is promoted by high physical stress caused by migrating ooid bars, which restricted the activities of grazing organisms. Another modern example of stromatolite development was reported by James and Ginsburg (1979; their Figs. 16-17a and b) from the Belize barrier reef. Here, columnar-, domal-, and digitate-laminated mudstones lithified by aragonite marine cements occur in the reefs. Both of these examples are important modern analogues from which to infer similar associations for thrombolitic or stromatolitic structures found in ancient buildups.

Buildup Geometries and Trends

Subsurface studies of the buildups in the Smackover Formation indicate that they attain thicknesses of 3 to 40 meters. Out-

Figure 19. Polished core slabs and photographs of thin sections illustrating stromatolite mound boundstones to framestones.

a. Thrombolite boundstone (dark color) illustrating boundstone to framestone fabric. Oyster *Lopha* sp. (upper center) and anhydrite-filled coral (upper right); dolomitized and fractured.

b. Stromatolite boundstone illustrating strongly laminated and bifurcating fabric.

c. Dolomitized and oil-stained thrombolite boundstone. a, b, and c are polished core slabs from depths between 15,500 and 16,200 feet (4,724-4,938 m), Baldwin County, Alabama.

d. Photograph of thin section of algal stromatolite illustrating layered columnar and sheet-growth fabric with marine-cemented *Favreina* pellet-peloid grainstone filling constructional reef cavity. Tesoro No. 1 Land Brothers well, Melvin Field, Alabama. 11,252 feet (3,429.6 m).

Table 2. Geometries and Trends of Some Jurassic Buildups

BUILDUP CLASSIFICATION*	THICKNESS (m) individual (stacked)	WIDTH (individual)	TREND (width x length)
Tethyan Buildups			
Sponge-Algal Mounds (1,2) (type 1)	2-100 m (250 m)		
Coral-Dominated Patch Reefs (3,4,5,6) (type 2b)	2-40 m (100 m)	105 m-1 km	10 km x 50 km
Coral-Stromatoporoid (7,8) Patch Reefs (type 3)	2-20 m	0.1-0.3 km	1-5 km x 60-140 km
Stromatoporoid-Coral (7,8) Buildup Margin (type 3)	5-30 m (200-600 m)	0.2-1.5 km	6-10 km x 60-140 km
*U. S. Gulf Coast Subsurface***			
Sponge-Coral-Algal Mounds (9) (type 2a)	3-10 m	0.3-1.5 km	1-2 km x 5 x 10 km
Bioclastic Piles (9) (type 2c)	7-21 m		
Stromatolite Mounds (9,10) (type 4)	4-27 m	0.3-1.5 km	1.6-5 km
Coral-Stromatoporoid Patch Reefs (11) (type 3)	3-25 m		
Stromatoporoid-Coral Margin (12) (type 3)	16 (150 m)		5-11 km x 35 km

* Numbers in parentheses refer to sources as follows: (1) Flugel and Steiger (1981); (2) Gwinner (1976); (3) Barthel (1977); (4) Bollinger and Burri (1970); (5) Giner and Barnolas (1979); (6) Wilson and Exton (1979); (7) Steiger and Wurm (1980); (8) Turnsek *et al.* (1981); (9) Baria *et al.* (1982); (10) McGraw (1982); (11) Cregg and Ahr (1982); (12) Finneran *et al.* (1982).

**Widths and trends of subsurface buildups are based on borehole log correlations and may not represent individual buildups.

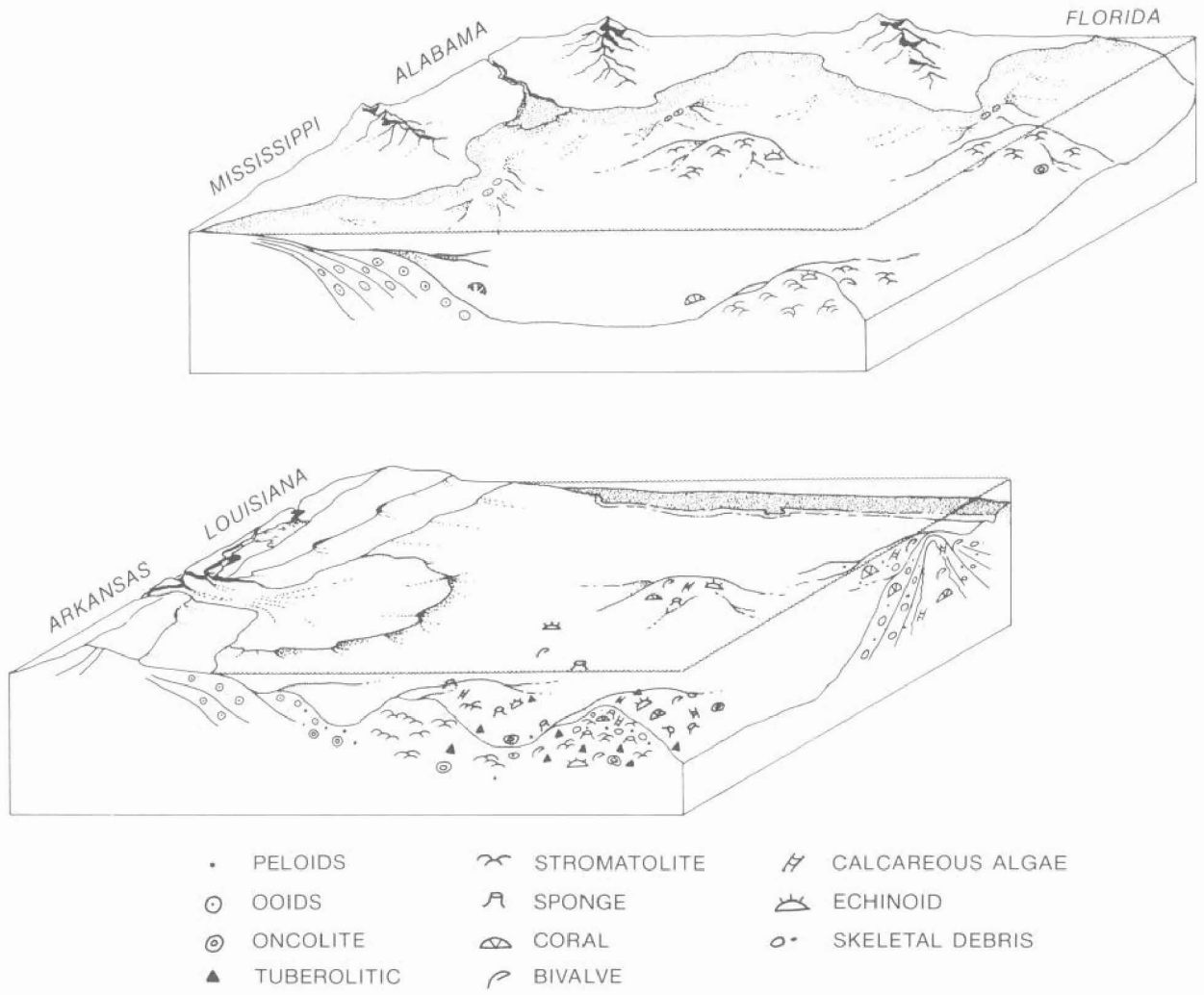


Figure 20. An idealized diagram illustrating the position of buildups developed across the Oxfordian Smackover platform from Arkansas to Florida. Stromatolite mounds occur over the board platform from Mississippi to Florida and up on the Arkansas segment of the platform. Skeletal-rich sponge-coral-algal buildups and bioclastic piles developed on the platform in open-ocean conditions from southern Arkansas to northern Louisiana.

crop studies show similar thicknesses for buildups (Table 2), with those which are 5 to 30 meters thick being the most common. Outcrop studies also show that the areal and lateral extent of individual buildups are generally limited: reef cores range in size from commonly less than 100 meters to, rarely, 1000 meters in diameter.

Complexes made up of mound-rich intervals commonly developed during coalescing mound growth. Coral limestones of the early Kimmeridgian of the Swiss Jura Mountains developed a trend 10 kilometers wide and over 50 kilometers long. Wilson (1975) suggested that the widespread patch-reef trend in the Jura Mountains was developed in several stages during a regressive phase and does not represent simultaneous reef development over the entire area.

The stromatoporoid-coral reef margins range from small developments with dimensions of only 300 meters by 1.5 kilometers (Steiger

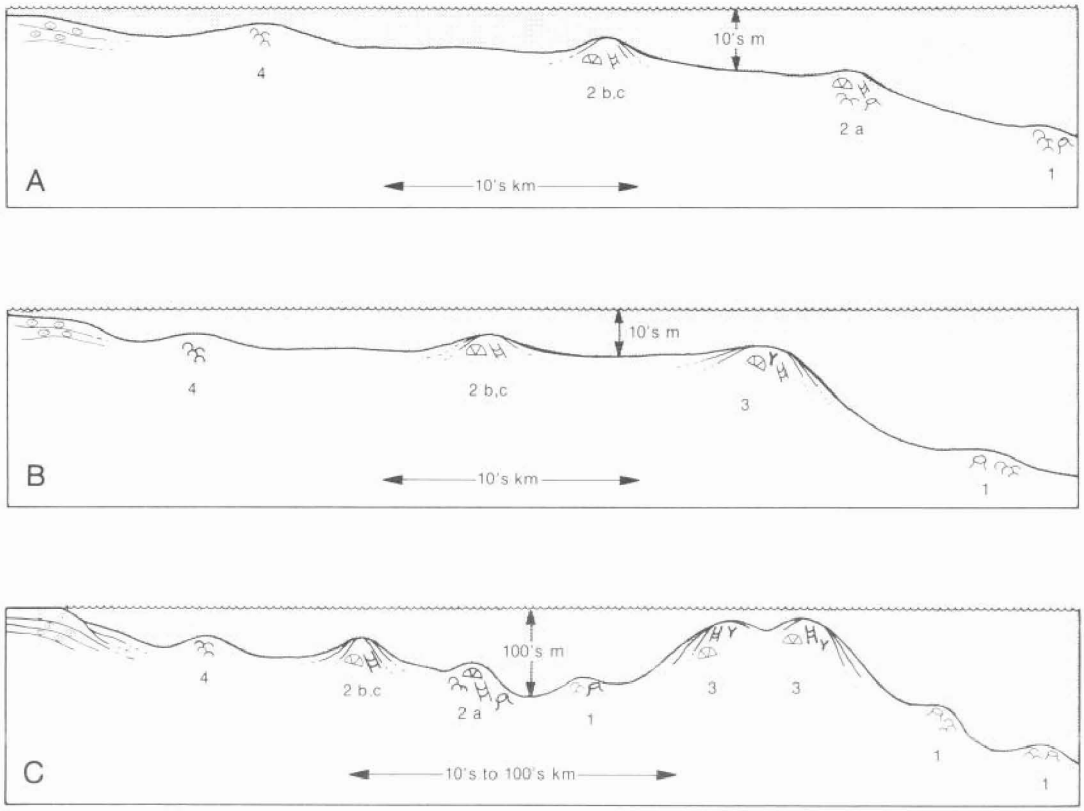


Figure 21. Idealized cross sections illustrating the location of Jurassic carbonate reefal buildups across a gently sloping platform (A), a steepened platform margin (B), and a steepened or rimmed platform margin facing an open ocean with an intrashelf basin or deep-water lagoon (C). Distribution of major reef framebuilders appears to be related to physical energy (wave related) and local environmental stresses (temperature, salinity, nutrients, or turbidity). (type 1) sponge and sponge-algal mounds, (type 2a) sponge-coral-algal buildups, (type 2b and c) coral-dominated patch reefs and bioclastic piles, (type 3) stromatoporoid-coral platformmargin buildups and near back-reef coral-stromatoporoid patch reefs, and (type 4) stromatolite buildups.

and Wurm, 1980) to linear trends several tens to hundreds of kilometers in length (Dinaric Platform; Turnsek *et al.*, 1981). Using borehole logs and seismic data, Finneran *et al.* (1982) estimated that a stromatoporoid-coral boundstone reef complex in the subsurface Knowles Limestone of Texas to be 5 to 11 kilometers wide and to extend a distance of nearly 35 kilometers along trend. This reef complex is similar to the outcropping stromatoporoid-coral platform margins in that the complex consists of interbedded boundstone core facies and bioclastic sediments. Total thickness of the Knowles Limestone complex is about 150 meters.

From well-log correlations, Baria *et al.* (1982) estimated that the Smackover buildups extend for 1 to 2 kilometers along paleotopographic highs and more than one kilometer bankward. Outcrop studies of the sizes, trends, and biotic assemblages of these buildups suggest that the well-log correlations represent entire mound-rich intervals, as commonly observed in outcrop, rather than individual buildups. Preliminary well- log correlations in the Walker Creek Field sug-

gest that the mound-rich interval extends over an area of 50 square kilometers and may be present throughout the entire field (Baria *et al.*, 1982; Harris and Crevello, 1983).

CONCLUSIONS

Modern carbonate reef-building organisms occur in a variety of associations that reflect organism adaptation to specific physical, chemical, and biological conditions. Similarly, Jurassic reef-building paleocommunities adapted to specific depositional settings. Generally, the dominant biotic association enables one to distinguish between deep-water mounds, wave-agitated platforms, and platform-margin reef complexes. Outcrop studies of Jurassic mound geometries, biotic assemblages, and related facies confirm that their counterparts in the Smackover Formation formed on a wave-agitated platform. In addition, these studies suggest that subsurface well-log correlations of Smackover buildups may actually represent mound-rich horizons rather than an individual continuous mound or reef trend. As more buildups are recognized in the subsurface and are mapped seismically, a better understanding of reef-building communities of the Jurassic of the United States Gulf Coast will undoubtedly evolve.

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Appendix A. Photograph of continuous core from the ARCO No. 1 McFadden well, Walker Creek Field, Columbia County, Arkansas. 3-inch-diameter core.

10,945-10,957 ft. (3,336-3,339.6m)
Coarse ooid grainstone, cross laminated.

10,957-10,964 ft. (3,339.6-3,341.8m)
Peloid packstone with oncolites, intraclasts of reef framework (tuberoids or micropeloid clasts), corals, brachiopods, echinoderms, and pelecypods; coarser toward base.

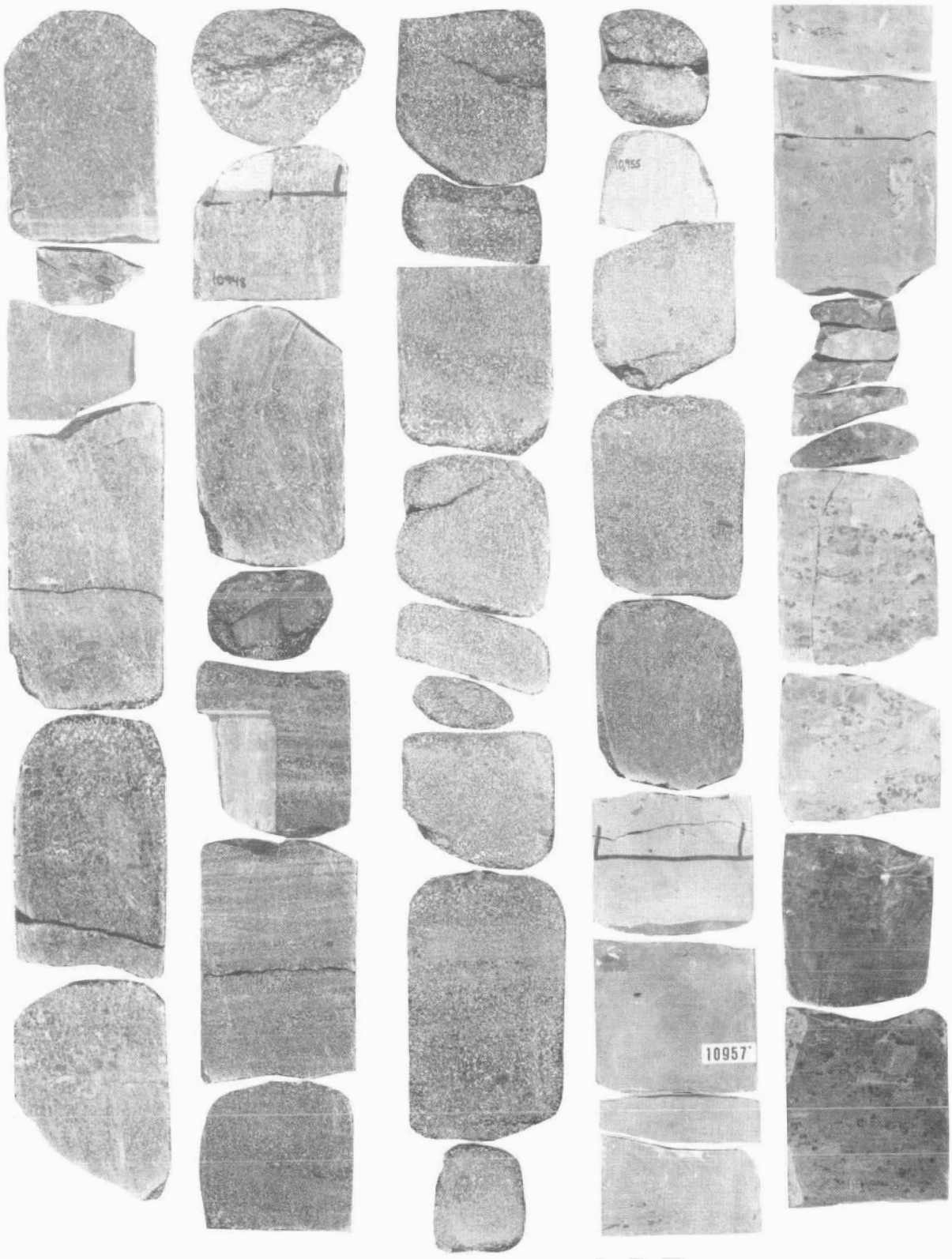
10,964-10,976 ft. (3,341.8-3,345.5m)
Numerous large corals of *Actinastrea* sp. in a reef frame work with digitate stromatolites and thrombolites (very gray), various encrusters, and pelecypods; internal reef sediment (light gray) is fine bioclastic packstone to mudstone. Fractures developed between corals through the reef framework are the result of compaction-fracturing of coral molds and reef matrix.

10,976-10,988 ft. (3,345.5-3,349.1m)
Reef framework as above with fewer large corals but numerous finger-like corals, encrusters, siliceous sponges, echinoids, and pelecypods.

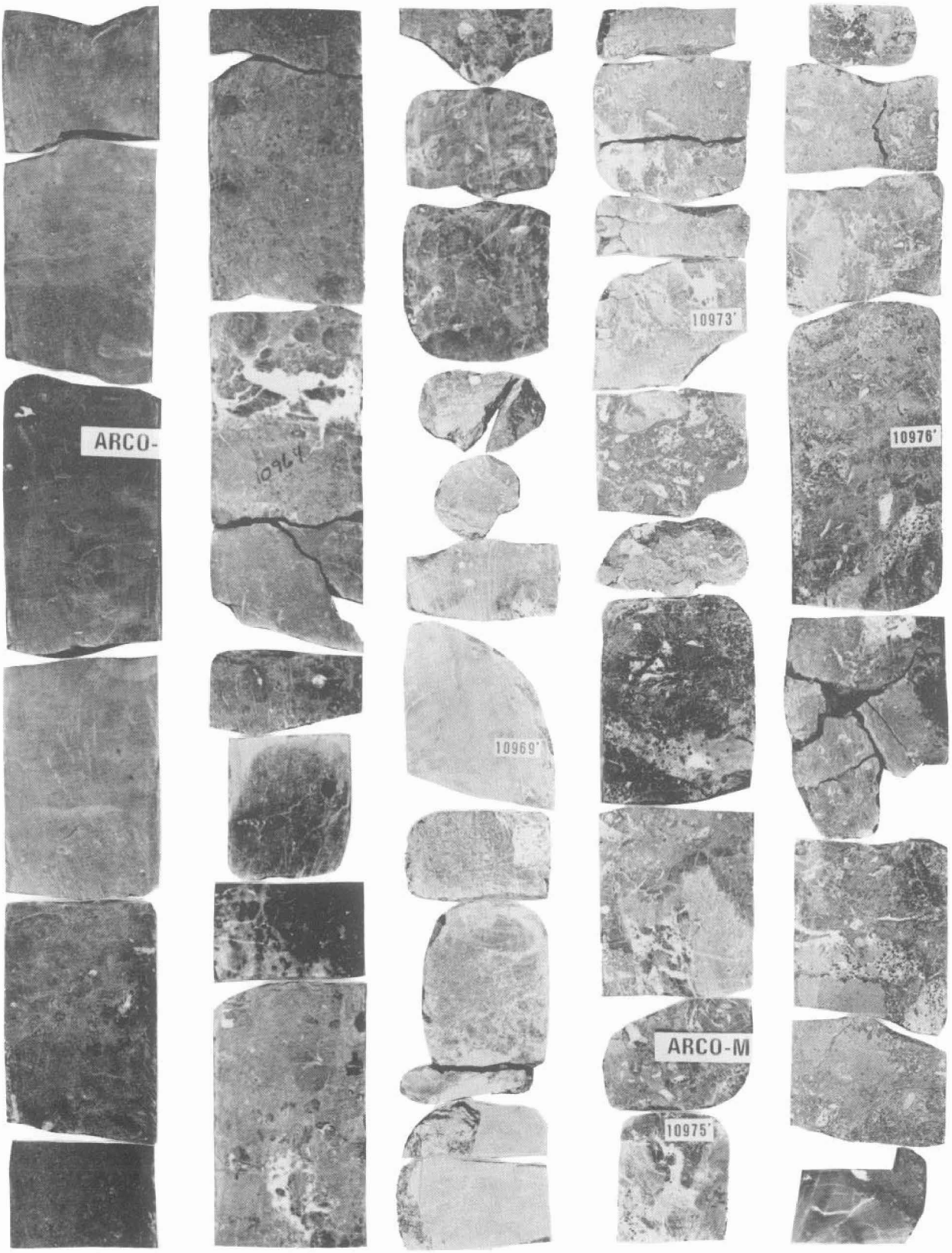
10,988-10,992 ft. (3,349.1-3,350.4m)
Biointraclastic packstone and patches of framework with oysters, bivalves, calcisponges, echinoids, stick-like corals, and intraclasts of micropeloid packstones to wackestones.

10,992-10,998 ft. (3,350.4-3,352.2m)
Poorly sorted biointraclastic and peloid packstones and oncolite rudstones; many oncolites have a digitate growth fabric.

10,998-11,003 ft. (3,352.2-3,353.7m)
Quartz sandstone and poorly-sorted ooid grainstone.

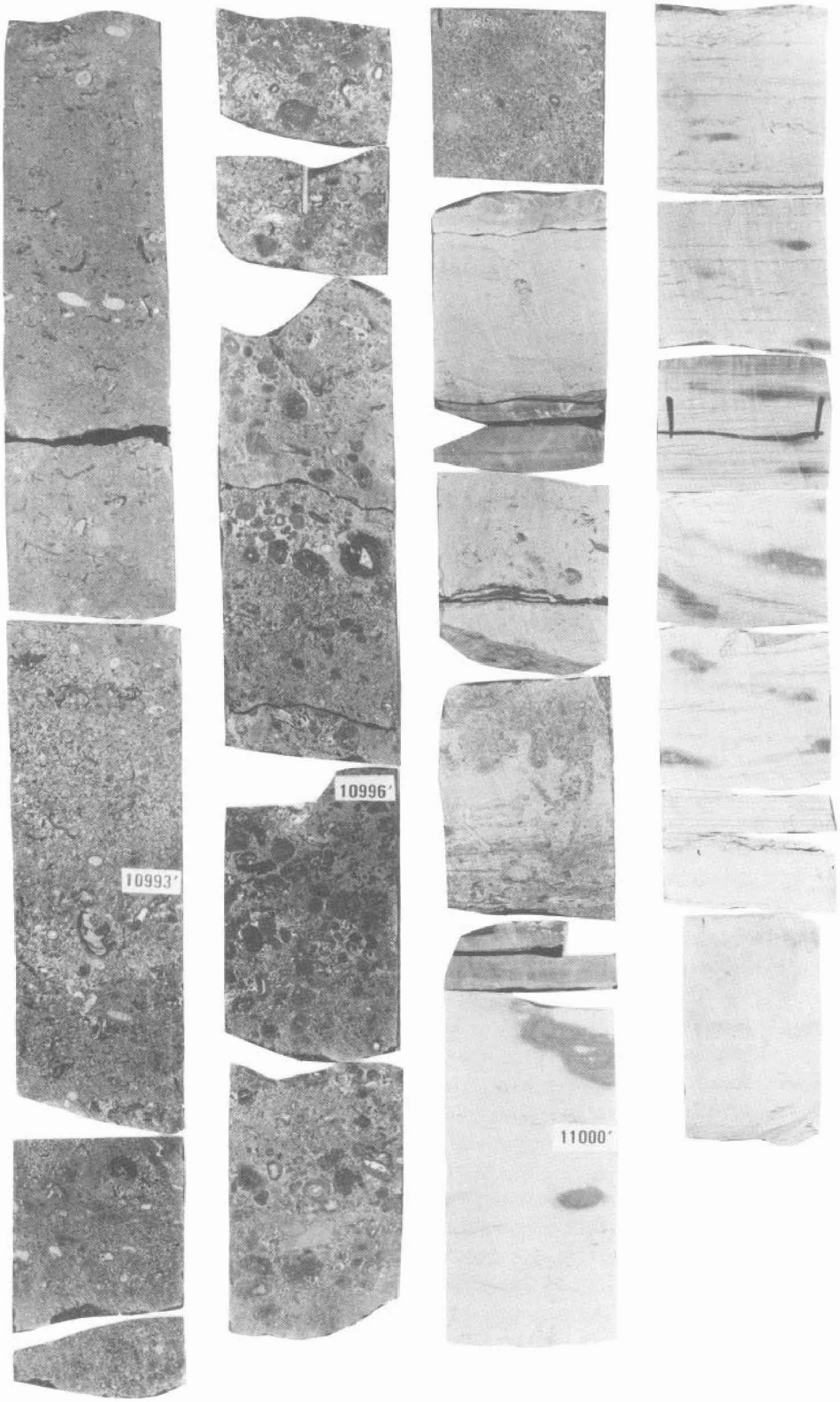


Appendix A - Plate 1



Appendix A - Plate 2

Appendix A - Plate 3



Appendix A – Plate 4

Appendix B. Photograph of continuous core from the Tenneco No. 1 Seegers-Waller well, North Haynesville Field, Claiborne Parish, Louisiana. 3-inch-diameter core.

10,051-10,066 ft. (3,063.5-3,068.1m)
Fine-grained peloid packstone to grainstone with echinoids, thin-walled pelecypods and brachiopod, scattered oncolites and oolites.

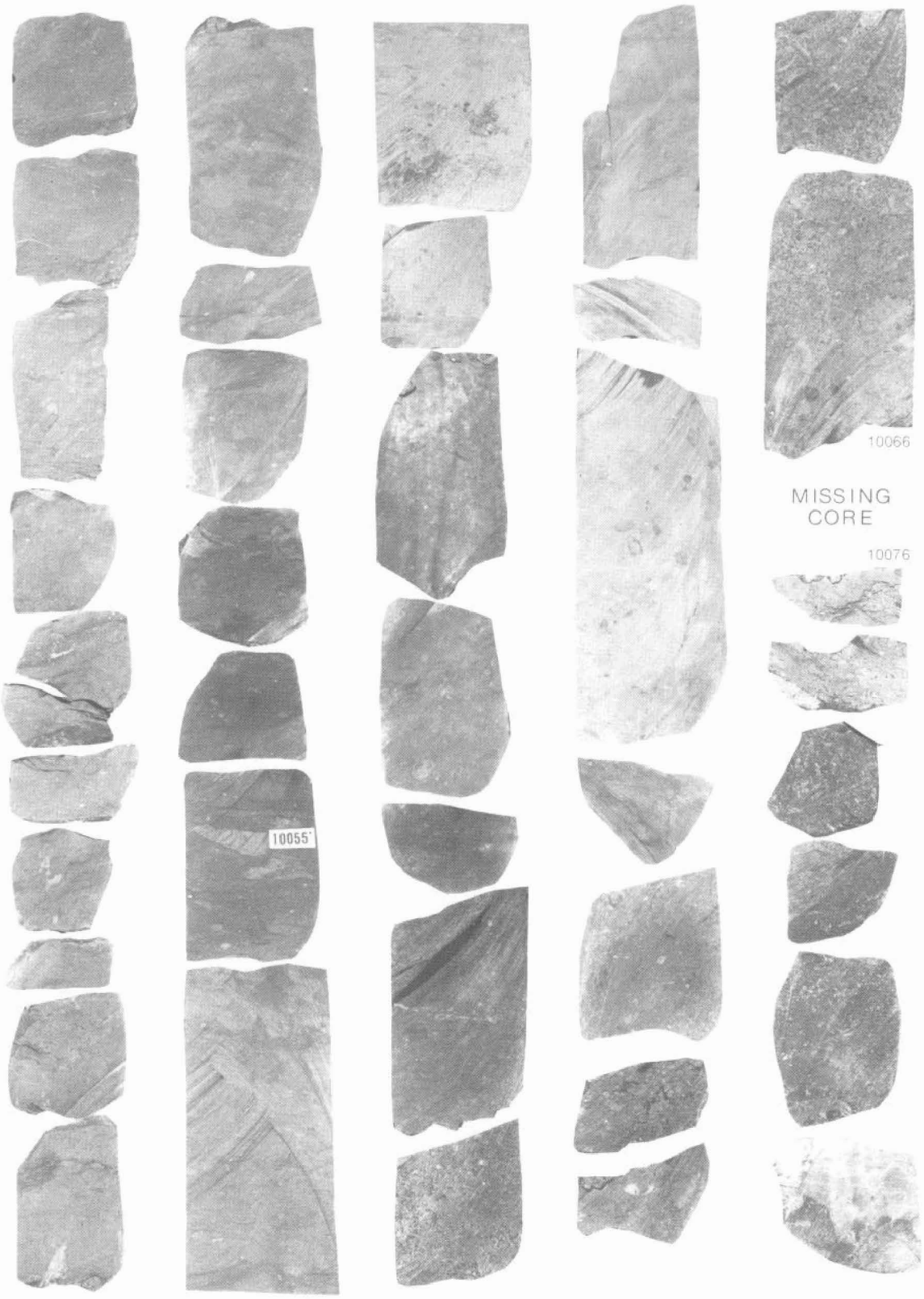
10,066-10,076 ft. (3.068.1-3,071.1m)
Missing Core.

10,076-10,090 ft. (3,071.1-3,075.4m)
Biointraclastic rubble to packstone locally cross-stratified, and bioclastic wackestone interbedded with digitate stromatolite/thrombolite sponge-coral-algal boundstone containing red algae and various encrusting organisms, pelecypods, and echinoids; numerous stylolites and microfractures; corals filled with anhydrite.

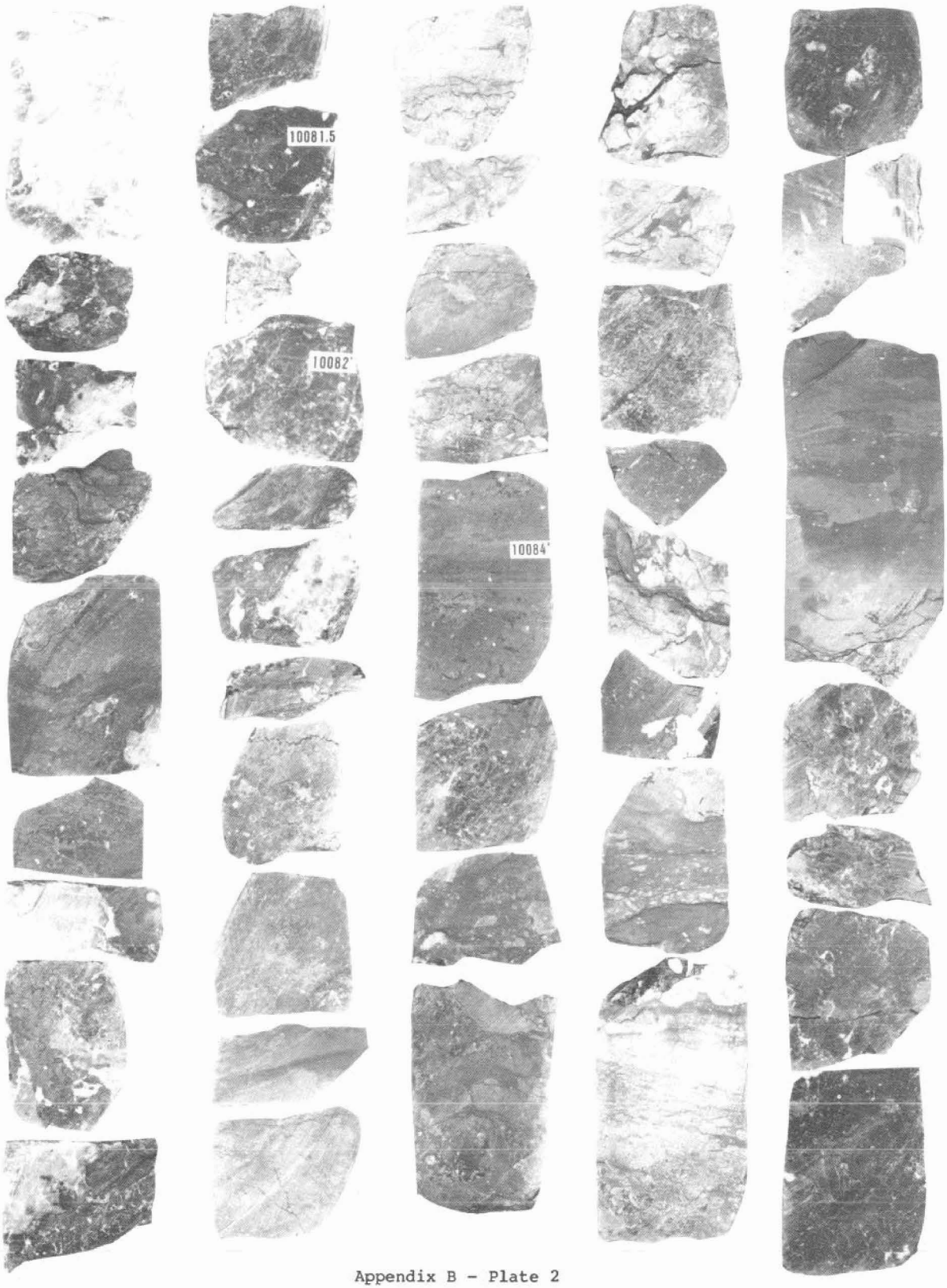
10,090-10,106 ft. (3,075.4-3,080.3m)
Sponge-coral-algal boundstone as above.

10,106-10,109 ft. (3,080.3-3,081.2m)
Biointraclastic and oncolite rudstones to packstones with pelecypods (oysters), echinoids, and intraclasts of micropeloid (tuberoid) packstones to wackestone.

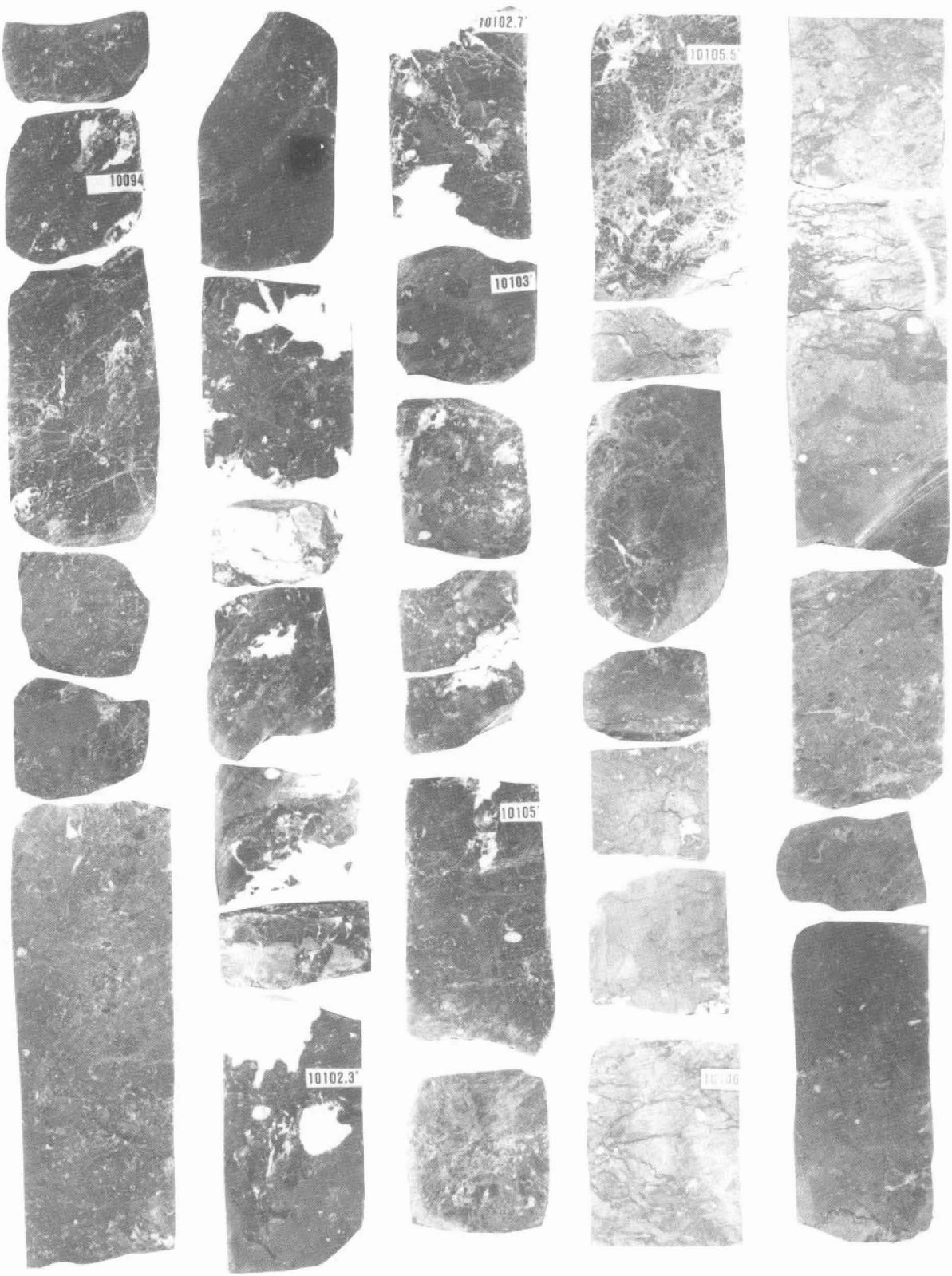
10,109-10,116 ft. (3,081.2-3,083.4m)
Very fine peloidal packstone and wackestone with oncolites, echinoid debris, and brachiopods.



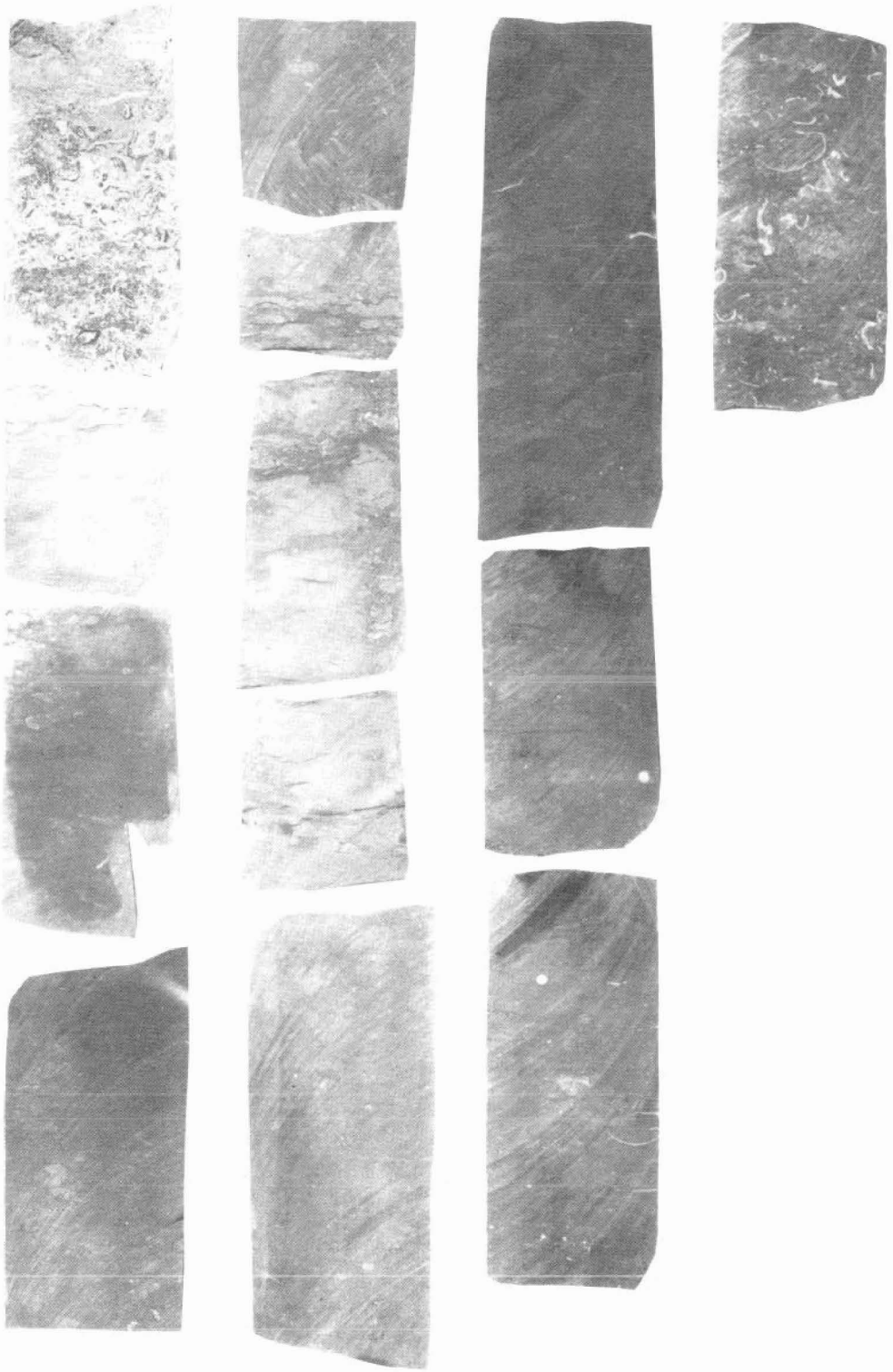
Appendix B - Plate 1



Appendix B - Plate 2



Appendix B - Plate 3

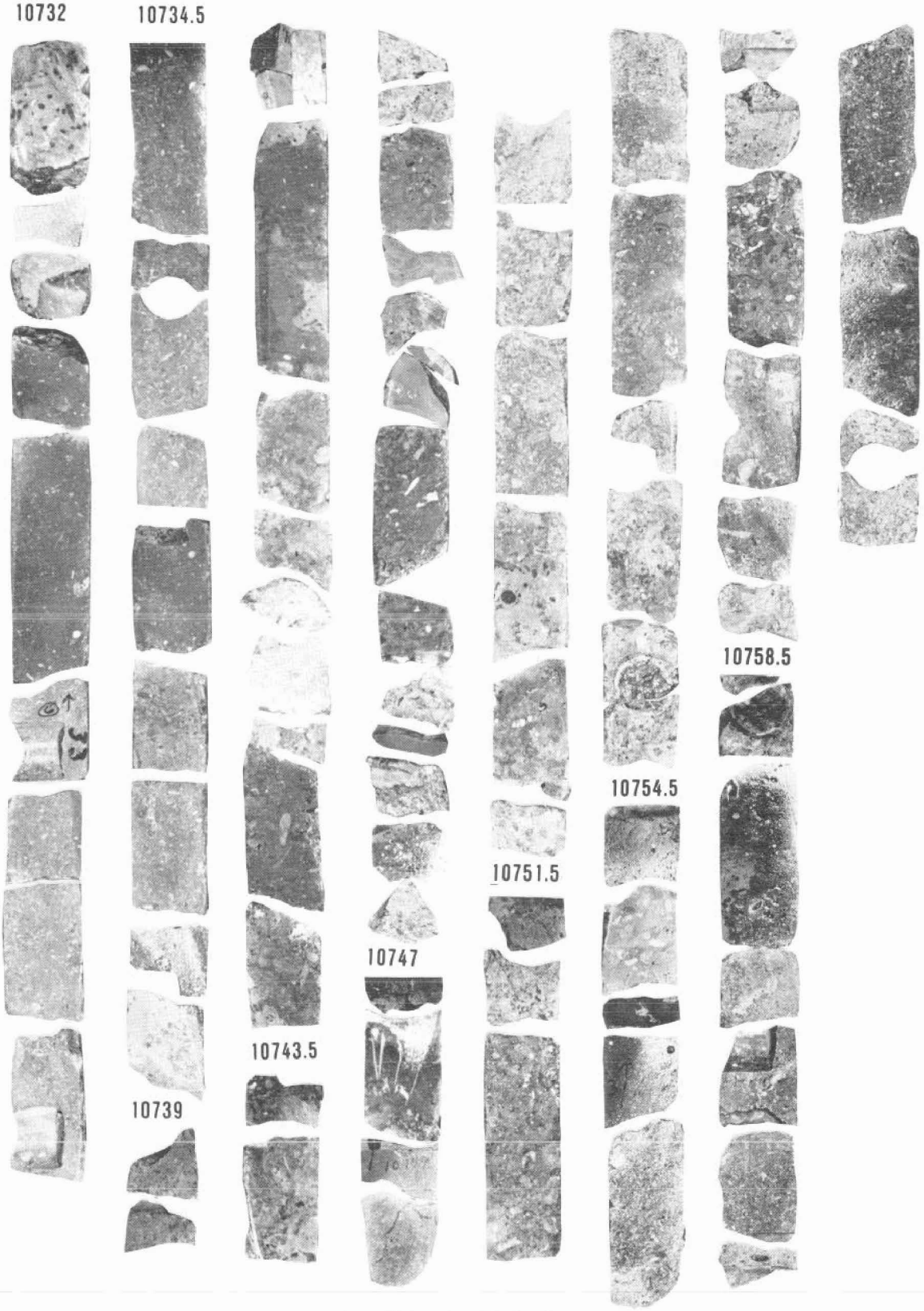


Appendix B - Plate 4

Appendix C. Photograph of continuous core from the Bass #1-A Smith well, Hico Knowles Field, Lincoln Parish, Louisiana. 2-inch-diameter core.

10,732-10,738 ft. (3,271.1-3,272.9m)
Skeletal peloid packstone to grainstone with coral debris, molluscs, and echinoids.

10,738-10,763 ft. (3,272.9-3,280.6m)
Interbedded and crudely layered, possibly graded, sequences of bioclastic rudstones, grainstones, and packstones of corals, calcareous algae, calcisponges, echinoids, molluscs, and chaetitids; punctuated by siltstone at 10,745 ft.(3,275.1m) and 10,747 ft. (3,275.7m), and by silty mudstone at 10,756 ft.(3,278.4m).



Appendix C – Plate 1