Facies Heterogeneity in a Modern Ooid Sand Shoal - An Analog for Hydrocarbon Reservoirs*

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Abstract

The ooid-sand shoals of the Joulters Cays area of Great Bahama Bank were chosen for detailed sedimentologic study to investigate patterns of internal heterogeneity within a modern carbonate sand deposit and to develop criteria for producing the lateral extent of porous and permeable carbonate grainstone facies in hydrocarbon reservoirs. Using aerial photographs, surface observations and shallow coring, we documented three sedimentary facies in a 2.7 km2 (1 mi2) study area dominated by mobile ooid sands. Cores were collected at the spacing characterisitc of wells in mature hydrocarbon reservoirs.

The shoal crest at the locality had aggrading and northward prograding (parallel to depositional strike) washover bars composed of crossbedded, well sorted ooid sands. Burrowed, poorly sorted ooid sands were present seaward of the washover bars, and poorly sorted ooid sand and mud occupied a stabilized area bankward of the actively migrating shoal and local areas between washover bars on the crest of the shoal intraclast-rich zones and mud layers were also present. The shoal was crosscut by tidal channels, and older washover bars were in the process of being dissected by tidal currents.

We anticipate that upon burial and compaction, the poorly sorted ooid sand and mud facies will most likely retain negligible porosity and permeability, whereas both the well sorted ooid sand and poorly sorted ooid sand facies will maintain their high initial porosity and permeability. However, in many ancient subsurface reservoirs, rocks with depositional textures similar to the well sorted ooid sand facies have undergone considerable cementation and have resultant low porosity and permeability. Thus, in many settings, the poorly sorted ooid sand facies could retain the highest porosity and permeability. Additional cementation of intraclast-rich zones will most likely result in thin, low-porosity barriers within a reservoir.

Hurricane Andrew, a category 4 hurricane with wind velocities of approximately 240 km/hr (150 m/h) passed over Joulters Cays in a westerly direction in August 1992,

subsequent to our coring program. The hurricane profoundly changed surface features in the study area by eroding washover bars on the crest of the shoal and by transporting ooid sand seaward leaving a nearly flat shoal crest overlain by a laterally continuous, decimeters-thick (foot-thick) lens of well sorted ooids that thins seaward and bankward. Post-hurricane tidal currents deposited a centimeters-thick (inches-thick) discontinuous layer of carbonate mud over this lens of well sorted ooids. This mud, although more likely to be preserved in tidal channels than on the shoal crest, has the potential to form low-permeability layers that will define reservoir compartment boundaries.

Modern sediment analog studies are an important addition to subsurface reservoir and outcrop analog characterization. Knowledge of the internal geometry of a sand shoal is critical for geologically targeted deployment of production technology and for predicting the efficiency of waterflood and other enhanced-oil recovery operations.

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Facies Heterogeneity in a Modern Ooid Sand Shoal— An Analog for Hydrocarbon Reservoirs

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1996

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ABSTRACT

The ooid-sand shoals of the Joulters Cays area of Great Bahama Bank were chosen for detailed sedimentologic study to investigate patterns of internal heterogeneity within a modern carbonate sand deposit and to develop criteria for predicting the lateral extent of porous and permeable carbonate grainstone facies in hydrocarbon reservoirs. Using aerial photographs, surface observations, and shallow coring, we documented three sedimentary facies in a 2.7-km^2 (1-mi^2) study area dominated by mobile ooid sands. Cores were collected at the spacing characteristic of wells in mature hydrocarbon reservoirs.

The shoal crest at this locality had aggrading and northward-prograding (parallel to depositional strike) washover bars composed of crossbedded, well-sorted ooid sands. Burrowed, poorly sorted ooid sands were present seaward of the washover bars, and poorly sorted ooid sand and mud occupied a stabilized area bankward of the actively migrating shoal and local areas between washover bars on the crest of the shoal. Intraclast-rich zones and mud layers were also present. The shoal was crosscut by tidal channels, and older washover bars were in the process of being dissected by tidal currents.

We anticipate that, upon burial and compaction, the poorly sorted ooid sand and mud facies will most likely retain negligible porosity and permeability, whereas both the well-sorted ooid sand and poorly sorted ooid sand facies will maintain their high initial porosity and permeability. However, in many ancient subsurface reservoirs, rocks with depositional textures similar to the well-sorted ooid sand facies have undergone considerable cementation and have resultant low porosity and permeability. Thus, in many settings, the poorly sorted ooid sand facies could retain the highest porosity and permeability. Additional cementation of intraclast-rich zones will most likely result in thin, low-porosity barriers within a reservoir.

Hurricane Andrew, a category 4 hurricane with wind velocities of approximately 240 km/h (150 mi/h), passed over Joulters Cays in a westerly direction in August 1992, subsequent to our coring program. The hurricane profoundly changed surface features in the study area by eroding washover bars on the crest of the shoal and by transporting ooid sand seaward, leaving a nearly flat shoal crest overlain by a laterally continuous, decimeters-thick (foot-thick) lens of well-sorted ooids that thins seaward and bankward. Posthurricane tidal currents deposited a centimeters-thick (inches-thick) discontinuous layer of carbonate mud over this lens of well-sorted ooids. This mud, although more likely to be preserved in tidal channels than on the shoal crest, has the potential to form low-permeability layers that will define reservoir compartment boundaries.

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Keywords: Bahama Islands, hurricane, modern carbonate sediment, ooid shoal, reservoir analog

INTRODUCTION

Concepts derived from studying modern analogs of ancient grainstone facies are important to hydrocarbon reservoir development because (1) the style of internal geometry of a reservoir should be understood in order to deploy production technology efficiently, (2) the levels of description and quantification required to redesign recovery strategies for low-efficiency reservoirs can be realized, and (3) the potential for extending trends from known reservoirs can be better determined.

Recently the need for more detailed information on hydrocarbon reservoirs has been escalating as operators seek to increase recovery from mature fields. A detailed geologic framework must serve as a template during the geologic and engineering evaluation of hydrocarbon reservoirs in platform carbonates so that porosity and permeability distribution and delineation of fluid-flow units can be reasonably well understood. An appreciation of the nature of such facies variability is needed in reservoir studies to guide correlations of depositional cycles and flow units between wells and to constrain the input parameters for reservoir models.

The Bureau of Economic Geology, The University of Texas at Austin, began carbonate reservoir studies in 1984. These studies were funded by The University of Texas System and were designed to define oil-producing subplays on University Lands, describe reservoirs from each subplay, and propose strategies for additional recovery (Tyler and others, 1991). During this project, problems encountered in predicting permeability continuity within reservoirs prompted the Bureau to establish the industry-funded Reservoir Characterization Research Laboratory, through which the Bureau investigates heterogeneity within carbonate reservoirs and their analogs exposed on laterally continuous outcrops (Kerans and Nance, 1991; Lucia and others, 1992; Kerans and others, 1995; Kerans and Fitchen, 1995). Both reservoir and outcrop studies demand a better understanding of the three-dimensional internal variations in textures and structures of grainstone bodies. Grainstones are significant components in ongoing Bureau studies of the San Andres and Grayburg Formations in the Permian Basin as well as the Cretaceous of Southwest Texas.

Interpreting depositional environments in subsurface ancient carbonate rocks depends largely on comparing them with modern carbonate depositional environments by emphasizing depositional textures, sedimentary structures, stratigraphic successions, and diagenetic overprint. Accordingly, in 1989 we initiated an additional aspect of the Bureau's carbonate reservoir characterization research program, to investigate modern sediments that are analogs of ancient reservoirs.

Modern sediments on carbonate platforms of the Bahama Islands contain several ooid shoal complexes previously examined using coring and seismic profiling (Ball, 1967; Hine, 1977; Harris, 1979, 1983; Hine and others, 1981), and these sediments have served as valuable modern analogs for hydrocarbon reservoirs. However, these previous studies have been based on samples collected at an exploration scale with a core spacing of two to tens of kilometers (one to several miles). In contrast, our study was designed to sample at a development scale of only 330 m (1,000 ft) between cores, which is comparable to well spacing in many oil fields. Of the several ooid shoal complexes in the Bahamas, the Joulters Cays ooid shoals on Great Bahama Bank (fig. 1) were chosen as the location for our detailed, development-scale study because (1) the regional, exploration-scale facies distribution and depositional setting are well known (Halley and Harris, 1979; Harris, 1979, 1983, 1984a; Halley and others, 1983), (2) facies variability in the Joulters Cays area has previously served as an analog for guiding interpretations of numerous subsurface examples of ancient carbonate sand deposits (Ottmann and others, 1973; Bebout and Schatzinger, 1978; Harris, 1984b; Smosna, 1984; Smosna and Koehler, 1993; Harris and others, 1994), and (3) coring operations are relatively simple in such a predominately shallow-water setting (Harris, 1979; Lanesky and others, 1979).

Our choice of Joulters Cays for a modern reservoir analog study provided an unanticipated additional opportunity when Hurricane Andrew passed over this area on August 23, 1992. This major storm postdated our detailed coring program and allowed us to evaluate the effects of this infrequent (on a human time scale) event on sediment types and patterns and their effects on reservoir heterogeneity. By using old aerial photographs taken as early as 1947, we were able to use information collected from cores to track the recent development of the Joulters Cays ooid shoal caused by prevailing tides and wind and to interpret the short-term depositional and erosional effects of a major storm.

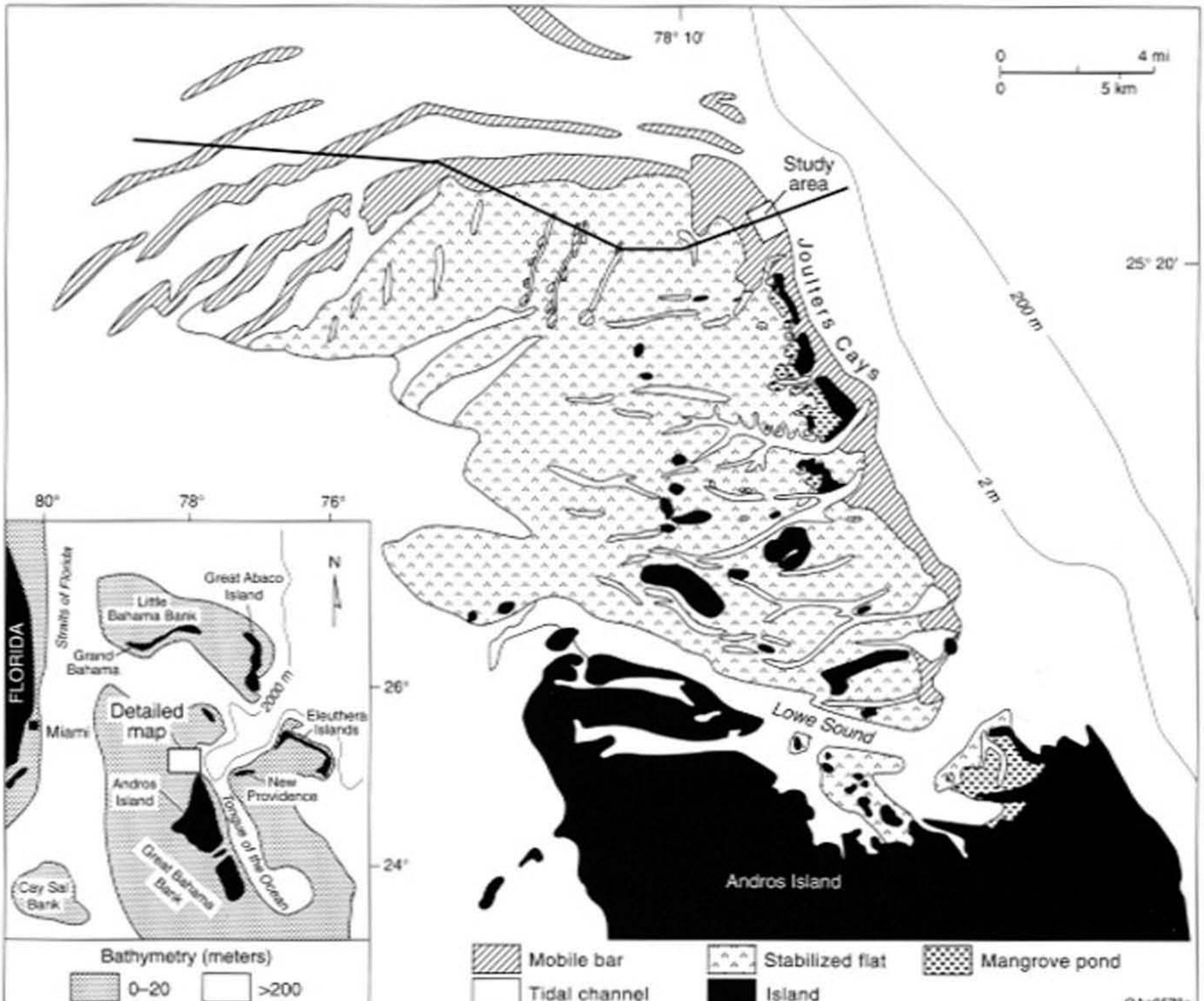


Figure 1. Location map (inset) of the Joulters Cays ooid shoal. The sedimentary facies map illustrates the regional, exploration-scale interpretation of Harris (1979) and the area of the present development-scale study. The indicated cross section is illustrated in figure 2.

Geologic Setting

The Joulters Cays area, immediately north of Andros Island on Great Bahama Bank (fig. 1), displays a variety of environments in which ooid sands can accumulate. The Joulters Cays shoal is a 400-km^2 (155-mi^2) sand flat, partly cut by numerous tidal channels and fringed on the ocean-facing borders by mobile sands (Harris, 1979, 1983). This active border of ooid sands, 0.5 to 2 km (0.3 to 1.2 mi) wide across depositional dip, extends the length of the shoal for 25 km (15.5 mi) along its windward side and terminates abruptly to the east (seaward) onto the shelf margin (figs. 1 and 2). To the west (platformward), mobile sands grade into the sea-grass- and algae-stabilized sand-flat part of the shoal and eventually into the deeper water platform interior. Joulters Cays are three islands that lie within the active area of the shoal. The area of detailed study described herein is approximately 2.7 km^2 (1 mi^2) of mobile ooid sands lying just north of the northernmost of the Joulters Cays (fig. 1).

Regional Facies Relationships

Harris (1979, 1984a) used an extensive coring program to document facies relationships in the Joulters Cays area. Sixty cores were taken at an average spacing of 1.5 km (0.9 mi). This regional, exploration-scale study provides valuable information on facies variability across distances of tens of kilometers.

The relief of the Joulters Cays shoal above the surrounding sea floor results primarily from ooid sands accumulating in one of three facies: mobile fringe, sand flat, or platform interior (Harris, 1979, 1983) (fig. 2). The mobile fringe is a narrow belt along the active ocean-facing shoal margin where ooid accumulation coincides with ooid formation (fig. 1). Ooid and muddy fine-grained peloid sands, the more widespread sediment types exposed on the sand flat and platform interior, result from ooids mixing with other grain types and with carbonate mud. Collectively, these modern sands, more than 3 m (>10 ft) thick, extend 22 km (13.7 mi) across depositional dip in a 260-km^2 (100-mi^2), irregularly shaped part of the shoal. The ooids exceed 7 m (23 ft) in thickness in the area of Joulters Cays.

The basic facies pattern as revealed by regional coring within the shoal (Harris, 1979, 1983) is a fringe of ooid sand bordering opposing wedges of muddy ooid sand underlain by muddy, fine-grained peloid sand (fig. 2). Ooid sand directly overlies Pleistocene limestone bedrock along the seaward margin of the shoal and interfingers with muddier sediments bankward. Throughout most of the sand flat, the vertical succession consists of lithoclast sand and/or pellet mud at the base, muddy, fine-grained peloid sand in the middle, and muddy ooid sand at the top. This succession shows distinct upward trends of increasing grain size, sorting, ooid content, stratification, and grain-supported fabric. Regionally, the succession thins to the south as the underlying Pleistocene bedrock surface rises.

Facies distribution within the Joulters Cays shoal reflects both changes in depositional patterns during shoal development and present-day depositional environments. These changes occurred primarily because of rising sea level and a corre-

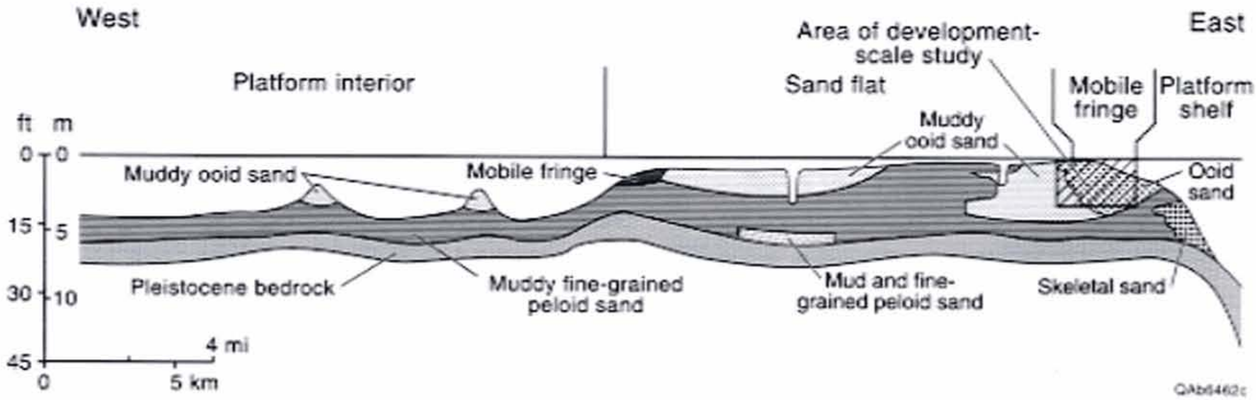


Figure 2. West–east facies cross section of the north part of Joulters Cays shoal (from Harris, 1979). Area of development-scale studies shown; location of section shown in figure 1. Note that the area of our detailed, development-scale study is composed of a single facies within the exploration-scale facies framework.

sponding increase in platform accommodation, and rapid sedimentation and building of syndepositional topography (Harris, 1979; Harris and others, 1994). Holocene deposition in the Joulters Cays area occurred in three stages: bank flooding, shoal formation, and shoal (tidal-sand-bar and barrier) development (Harris, 1979, 1983). During shoal development, production and bankward dispersal of ooid sands through tidal-sand-bar and barrier environments established the present size and physiography of the shoal and changed the composition of sediments throughout the area from muddy peloidal sand to ooid sand.

Exploration-Scale Heterogeneity

Heterogeneity of the Joulters Cays shoal is inferred on the basis of the distribution of depositional facies shown in figure 2. Clean ooid sand along the active margin of the shoal occurs as subtidal-bar, channel-fill, beach, and island facies. In cross section, it occurs in an irregularly shaped area 2 km (1.2 mi) wide and 2 to 3 m (6.6 to 9.8 ft) thick. High initial porosity was measured in similar clean sand by Halley and Harris (1979) and Enos and Sawatsky (1981), and it is confirmed here by thin-section estimation. Immediately bankward of the clean ooid sand are widespread, somewhat irregularly shaped layers containing mixtures of carbonate mud and sand that will most likely result in vastly different reservoir properties. An upper layer of muddy ooid sand, some 20 km (12.4 mi) wide and from 4 to less than 1 m (13 to less than 3.2 ft) thick, thins bankward and overlies a more widespread lower layer of muddy, fine-grained peloid sand more than 30 km (>18.6 mi) wide and ranging from 5 to 2 m (16 to 6.6 ft) in thickness. These layers will most likely have initial porosities lower than those of the more seaward, clean ooid sand, judging from measured values of similar sands by Enos and Sawatsky (1981) and from thin-section estimations. In addition, the upper layer will most likely have better reservoir quality than the lower layer because of larger grain size and lower mud content.

Comparing figures 2 and 3 provides insight into the exploration-scale heterogeneity pattern to

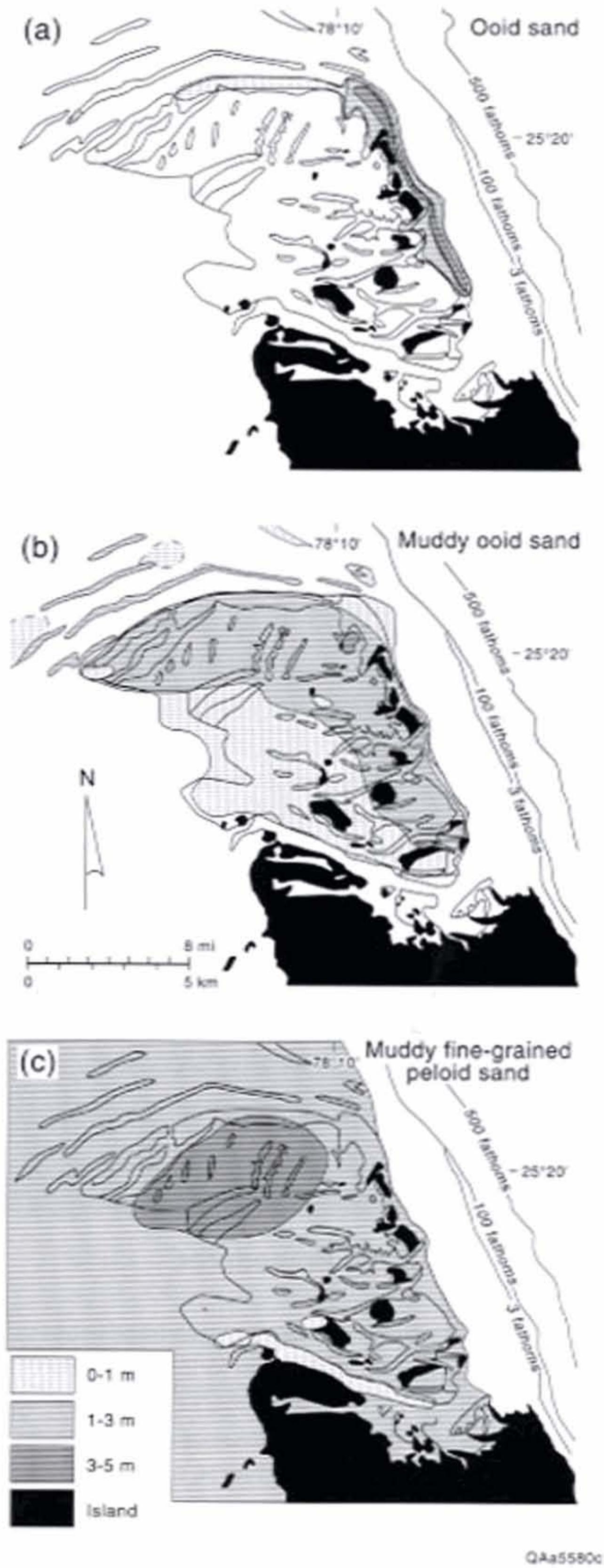


Figure 3. Isopach maps of the (a) ooid sand, (b) muddy ooid sand, and (c) muddy fine-grained peloid sand facies identified by Harris (1979). Patterns indicate thickness; lines illustrate the geometry of washover bars and tidal channels. Because of the exploration-scale sample density used to construct these maps, some development-scale features are not represented.

be expected in a grainstone body such as the Joulters Cays shoal. Harris (1979) presents isopach maps of these three Holocene facies that are based on sediment core data as well as extensive sediment probe data. These isopach maps, modified and reproduced here as figure 3, approximate the three-dimensional geometry of the heterogeneity inferred in the Joulters Cays shoal. Because small-scale facies patterns related to subenvironments of the shoal (such as tidal channels and associated facies and islands) are not portrayed on the isopach maps, significant local variability in the facies distribution is not apparent.

The following sections describe the inferred heterogeneity of one part of the regional facies patterns of the shoal—the clean ooid sand coinciding with the active margin of the shoal. Heterogeneity produced by subtle textural and diagenetic variation within this regionally defined lithology occurs at a development scale, which is necessary for correlating properties between wells in analogous reservoirs.

METHODS

Sampling Grid

The goals of this Joulters Cays study are to (1) establish an area for detailed investigation in this modern shoal that is approximately equal in size (2.7 km^2 [1 mi^2]) to a square-mile section of an oil field in the United States and (2) obtain subsurface information within that area at a development scale with a spacing similar to common well spacing in a reservoir. Thirty-nine sediment core locations were established at 330-m (1,000-ft) spacing along east-west transects also 330 m apart (fig. 4). Locations were marked so that they could be reoccupied when necessary and measured relative to an average sea-level position to establish a datum. Cores were collected at each site; in addition, probes of sediment thickness (using a steel rod pushed vertically into the sediment by hand) were taken at locations 33 m (100 ft) apart on every other line.

Coring Procedures

A portable vibracore drilling rig was used to obtain the cores (fig. 5). This rig, similar to that described in Harris (1979) and Lanesky and others (1979), consists of a 7.6-cm-diameter (3-inch) aluminum core barrel, handles that clamp to the core barrel, a vibrating head connected by a cable to a gasoline motor, a clamp for attaching the vibrating head to the core barrel, a 5.5-m (18-ft) tripod, and a winch. A core catcher was not used because we were unable to design one that did not disrupt the sediment during coring. Penetration by the core barrel went smoothly in areas of loose sediment but posed problems where firmgrounds, hardgrounds, or intraclast-rich layers were encountered. Before the sediment-filled core barrel was pulled from the hole, a cap was placed on top of the barrel, creating suction to help hold the sediment in the barrel. Generally some core (less than 30 cm [1 ft]) was lost from the lower part of the core barrel, but the upper part remained relatively intact.

After core withdrawal the sediment-filled core barrel was stored vertically in a specially designed core rack while draining to ensure that sedimentary structures and textural variations were preserved. After excess water had drained from the barrel, the core, still in a vertical position and capped, was transported to the nearby research vessel. There, some of the cores were impregnated by fast-hardening epoxy resin that was forced through the sediment using pressure and vacuum. The cores then became stable enough to be transported back to the laboratory for sawing and describing.

The remaining, unimpregnated cores were split in half by sawing the aluminum core barrel lengthwise and drawing a thin metal sheet through the sediment. Resin was poured on the partly scooped-out surface of the two halves and allowed to flow gravitationally partly into but not through the sediment. After setting for approximately 24 h, the partly impregnated cores were inverted, and the uncemented sediment was removed by flushing with running water. Because the epoxy resin penetrated farther into the more permeable parts of the core, subtle differences in permeability were well displayed in the resulting core topography. This latter technique proved to be the more useful of the two methods for identifying bed

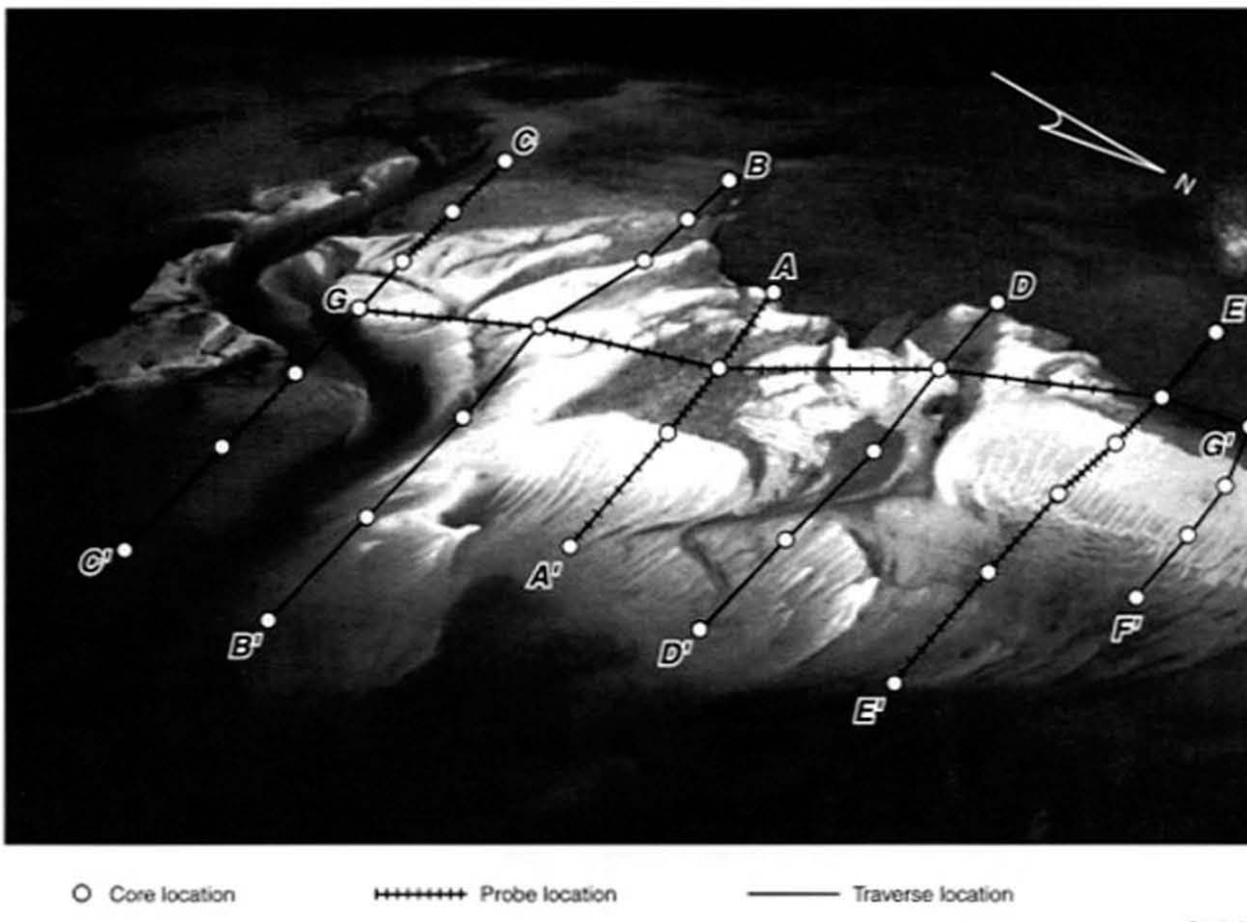


Figure 4. Low-altitude oblique aerial photograph of active part of shoal that constitutes detailed study area. Photograph was taken in 1989. Light areas are large washover bars that extend 0.3 to 0.6 m (1 to 2 ft) above sea level at low tide and are flooded by several centimeters of water at high tide. The study area and core spacing are approximately equivalent to well spacing in a square-mile section of an oil field. Darker areas are muddier sediment stabilized by *Thalassia* and filamentous algae. Also shown are core locations (circles), probe locations (hachures), and lines of cross section. Cross sections A–A', D–D', and E–E' shown in figure 6. There is no bar scale in this figure because this is an oblique photograph; compare cross-section traces shown here with figure 6 for scale.

forms, sedimentary structures, and other depositional features.

Core Description

The impregnated cores were described in the manner of rock cores, generally according to the description format of Bebout and Loucks (1984). Photoreductions of these graphic core descriptions were used for constructing detailed facies cross sections (fig. 6).

Aerial Photographs

Vertical and oblique aerial photographs, taken at approximately 20-yr intervals (1947, 1967, and 1989), were interpreted on the basis of surface observations and core descriptions and were used to map the surface distribution of sediment facies and to interpret the recent development of the shoal. In 1993, following passage of Hurricane Andrew in August 1992, we made additional surface observations and took oblique aerial photographs to interpret the effects of the hurricane.

Figure 5. Vibracore rig used to obtain cores of the ooid shoal. Portable gasoline motor in boat is connected by a flexible cable to a vibrating head that is clamped to the core barrel. The tripod and handles on the core barrel are used to steady the barrel and assist in taking cores.

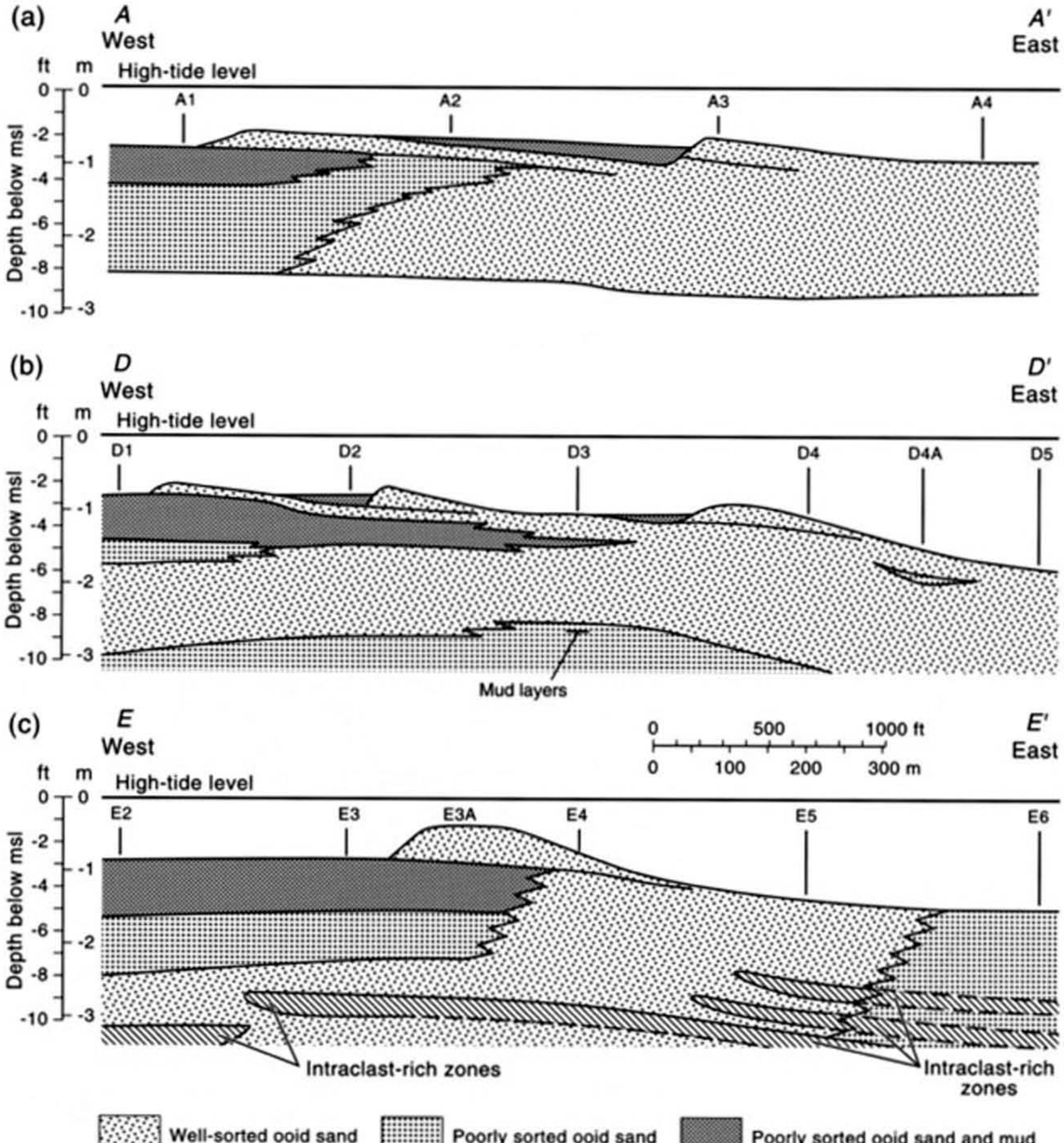


Figure 6. West-east (parallel to depositional dip) cross sections based on cores collected before passage of Hurricane Andrew. Core depths were calibrated to a sea-level datum. Location of sections shown in figure 4. (a) Cross section A–A′ extends from the area dominated by poorly sorted ooid sand and mud–*Thalassia* to the shoal crest, but not as far seaward as the area dominated by poorly sorted ooid sand. (b) Cross section D–D′ crosses a similar set of facies as A–A′ and includes buried mud layers interbedded with poorly sorted ooid sand in core D3. Because these mud layers were not encountered in adjacent cores, the lateral extent of these features is unknown. (c) Cross section E–E′ reaches seaward to an area dominated by poorly sorted ooid sand. Intraclast zones dipping seaward are encountered in cores of this cross section.

FACIES ARCHITECTURE

Depositional Facies

Three depositional subfacies predominate within the ooid sand facies of Harris (1979, 1983) discussed earlier. Well-sorted ooid sand occurs on the active, high-energy shoal crest. The surface of the shoal crest is characterized by washover bars having curved axes convex in a bankward direction. The stoss sides of these bars slope seaward at 10 to 20 degrees; the lee sides slope platformward at approximately 20 to 30 degrees. These features are composed entirely of the well-sorted ooid sand facies. The geometry of washover bars and movement of ooids during the semidiurnal tidal cycle suggest that these features are largely built by incoming tides. Poorly sorted ooid sand is present on the seaward margin of the shoal and in the bankward, shallow subsurface part of the shoal. The poorly sorted ooid sand and mud facies accumulated in lower energy areas between washover bars on the crest of the shoal, where it is stabilized by filamentous algae, and in an area bankward of the active shoal, where it is stabilized by the sea grass *Thalassia*. The distribution of these facies within the detailed study area of figure 4 is shown on cross sections in figure 6. Differences in grain size, grain sorting, and sedimentary structures among these three facies will potentially lead to heterogeneity.

It should be emphasized that these sediments are unconsolidated. Were these sediments to be lithified, it is anticipated that well-sorted ooid sand and poorly sorted ooid sand would become grainstones and poorly sorted ooid sand and mud would become a packstone (terminology of Dunham, 1962). As will be discussed in more detail in a following section, these subtle changes in depositional facies (as well as diagenetic overprint) would, upon burial, respond to compaction and cementation differently and probably result in significant permeability variability within a single grainstone depositional cycle or reservoir flow unit.

Well-Sorted Ooid Sand

The well-sorted ooid sand facies consists of 80 to 90 percent ooids (dominantly 0.4 to 0.5 mm in diameter), 5 to 20 percent coated pellets and unidentified grains (generally less than 0.2 mm in diameter), and 5 percent skeletal fragments (fig. 7). Scattered, poorly cemented intraclasts consist of broken burrow linings and hardground crusts. The sparse, somewhat rounded skeletal material includes fragments of pelecypods, gastropods, green alga *Halimeda*, peneroplid foraminifers, and red alga *Goniolithon*. Structures include crossbedding, horizontal burrows, tracks, and trails; vertically lined burrows; and horizontal and inclined laminations.

The well-sorted ooid sand facies coincides with the intertidal, most highly agitated central and seaward parts of the active shoal. This facies occurs at the surface in a broad band that is approximately 1.8 km (1 mi) wide in the south part of the study area but that narrows to only 1 km (0.6 mi) toward the north (fig. 4). This facies, which is nearly 3 m (10 ft) thick in some locations, is most widespread in the lower, older part of the shoal, generally narrowing and shifting seaward stratigraphically upward. In washover bars (discussed below), however, this facies is consistently wider at the surface because these bars shift bankward over the less agitated surface environments (fig. 6).

Poorly Sorted Ooid Sand

The poorly sorted ooid sand facies contains 60 to 80 percent ooids (0.4 to 0.5 mm in diameter), 20 to 40 percent coated pellets and unidentified grains (0.1 to 0.2 mm in diameter), and 5 percent skeletal fragments (fig. 8). The skeletal fragments (primarily in the upper few centimeters of the shoal) are from pelecypods, gastropods, *Halimeda*, peneroplid foraminifers, and *Goniolithon*. Burrows are common, and there are no laminations.

The poorly sorted ooid sand facies accumulated in a less agitated environment than the well-sorted ooid sand facies and occurs seaward of it at the surface and both seaward and bankward of it in the shallow subsurface (figs. 4 and 6). This facies is as much as 1.3 m (4 ft) thick and occurs in water depths of approximately 0.5 m (1.5 ft) at low tide; it is found in greater thicknesses where exposed at the surface on the seaward side of the shoal than elsewhere on the shoal.

Poorly Sorted Ooid Sand and Mud

This facies contains a trace to 20 percent carbonate mud, 30 to 70 percent ooids, 20 to 40 percent coated pellets and unidentified grains, and 5 to 20 percent skeletal fragments (fig. 9). Burrows, the common structure in the cores, are expressed at the surface as mounds and depressions. Roots from the sea grass *Thalassia* are also common; living *Thalassia* and *Goniolithon* occur on the surface. Sparse, small bushes of *Halimeda* are present, particularly in the transition zone between this facies and the well-sorted ooid sand facies. Peneroplid foraminifers and pelecypod fragments are prevalent.

The poorly sorted ooid sand and mud facies occurs within the upper 1 m (3 ft) of the stratigraphic section and is present at the surface on the very shallow water (several centimeters deep at low tide), bankward side of the shoal and in low areas between washover bars composed of well-sorted ooid sand (fig. 4). This facies grades downward and in some locations seaward into the poorly sorted ooid sand facies (fig. 6). It is stabilized by filamentous algae in low areas on the crest of the shoal and by *Thalassia* on the bankward side of the shoal. Coatings of algae and *Thalassia* give the surface a darker color on aerial photographs (fig. 4).

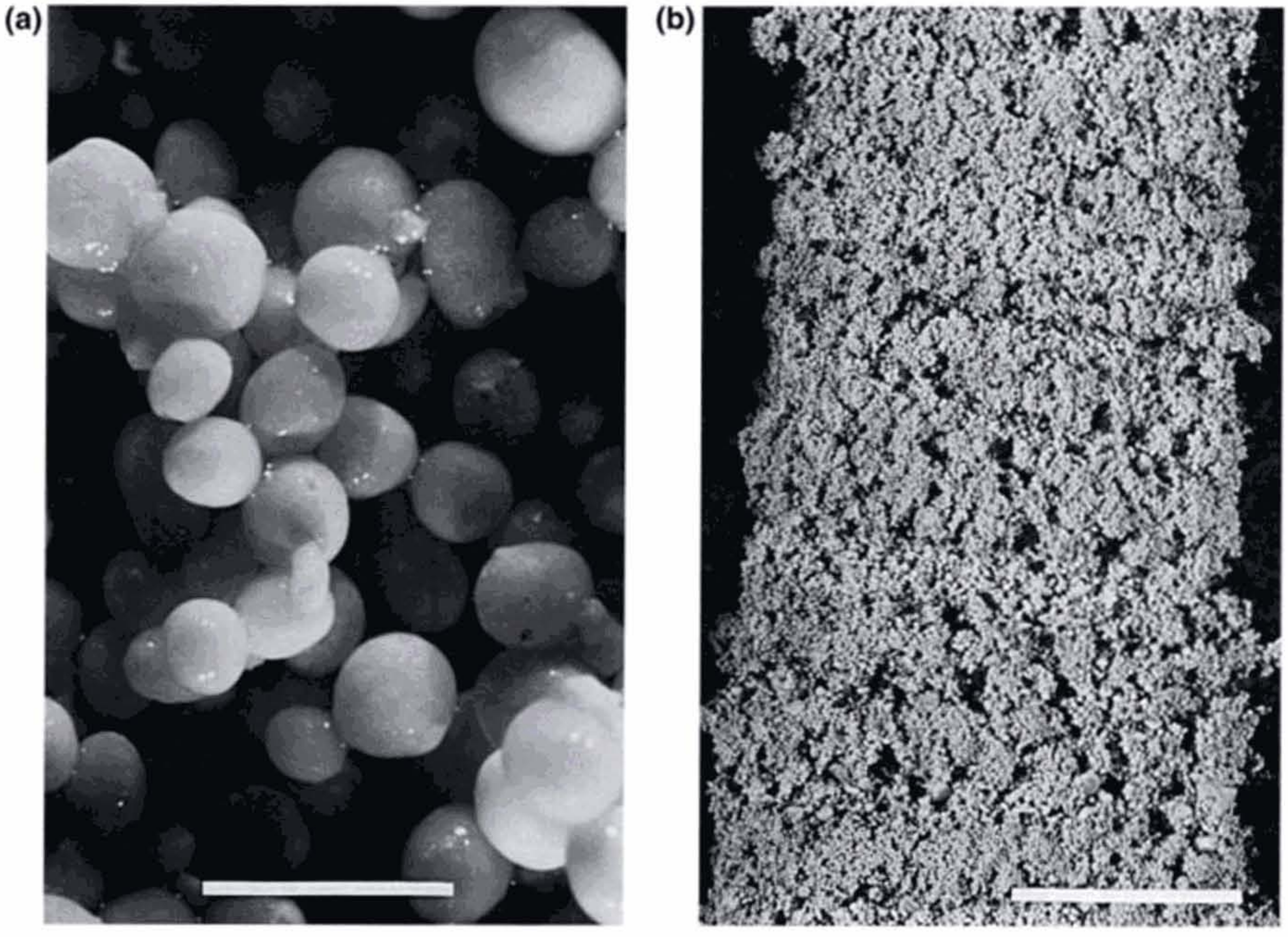


Figure 7. Well-sorted ooid sand facies from top of core A3. (a) Close-up view (scale bar = 1 mm). (b) Slab photograph (scale bar = 2 cm). Core location shown in figures 4 and 6.

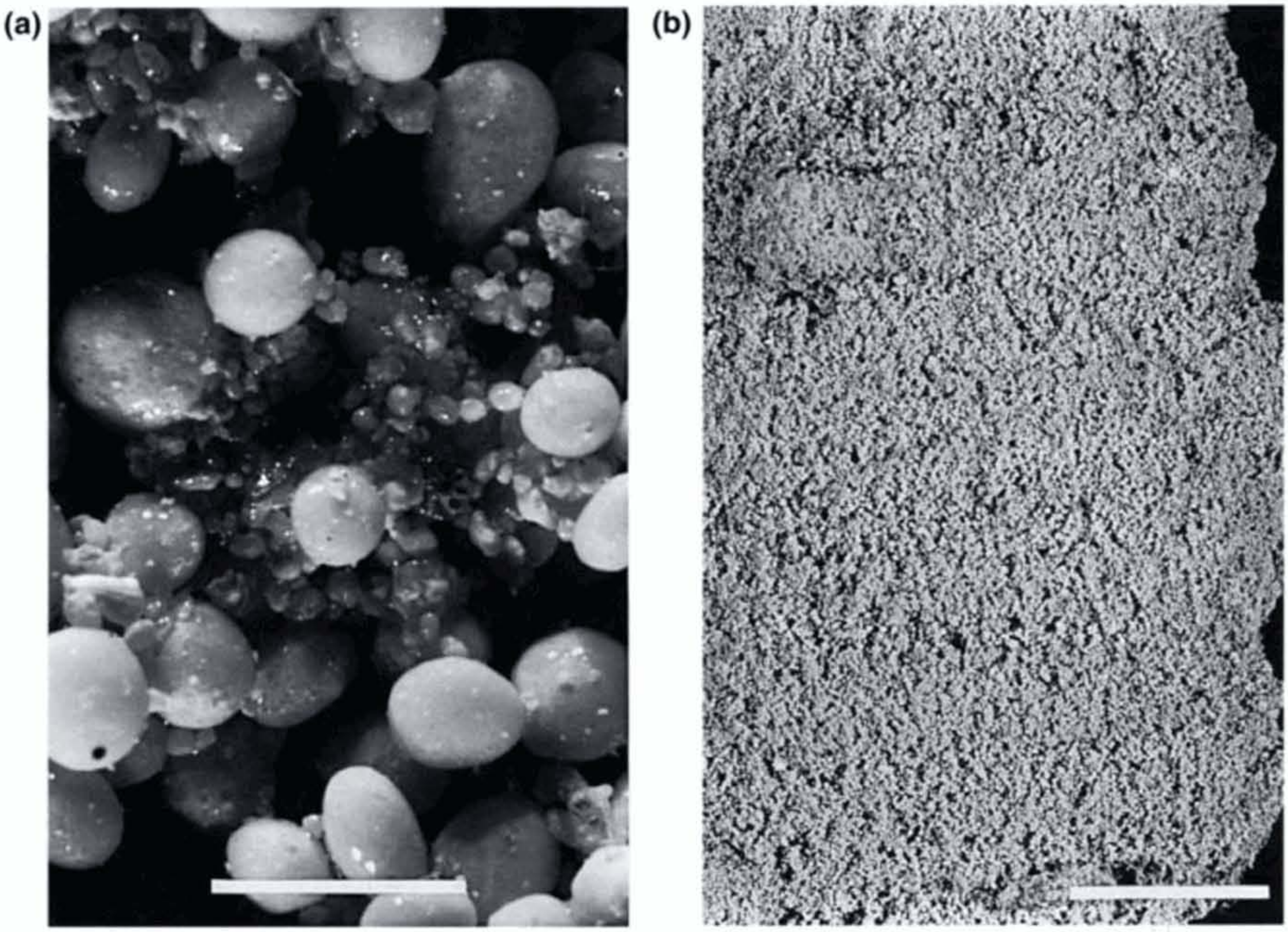


Figure 8. Poorly sorted ooid sand facies from near top of core A2. (a) Close-up view (scale bar = 1 mm). (b) Slab photograph (scale bar = 2 cm). Core location shown in figures 4 and 6.

Sedimentary Features

Intraclast-Rich Zones

Sparsely cemented intraclasts, including fragments of burrow linings and broken hardgrounds that have been cemented by various amounts of aragonite cement (fig. 10), are concentrated in thin zones less than 0.5 m (1.5 ft) thick in many of the cores. In these zones, as many as 30 percent of the sediments are intraclasts or large shell fragments, 40 to 80 percent are ooids, and as many as 70 percent are hardened pellets. Similar deposits are accumulating in troughs on the present-day surface.

The intraclast-rich zones are most common in the lower part of the well-sorted ooid sand facies in the north part of the study area. In cores, these zones are best represented on the seaward side of the cross section in figure 6c, where they occur in an offlapping pattern that reflects the progradation of the shoal complex. These zones were correlated laterally as far as 600 m (1,970 ft) during sediment probing and were traced even farther by Harris (1979) in that regional study. Although the zones are partly lithified, porosity and permeability have not been greatly reduced in the intraclasts, as estimated by thin-section observations, but these zones could potentially form barriers to fluid flow should they subsequently serve as preferential nucleation sites for additional cementation.

Mud Layers

Two discrete mud layers, the upper layer 2 cm (0.8 in) thick and the lower layer 4 cm (1.6 in) thick, separated by 4 cm of poorly sorted ooid sand (fig. 11) occur at the top of the burrowed, poorly sorted ooid sand facies in core D3 (fig. 6b). Because these mud layers were not recovered in any other core, the layers are presumably local in distribution (which is corroborated by posthurricane field observations of discontinuous mud layers on the surface of the shoal, reported below) and of only minor importance from a reservoir heterogeneity perspective. Other occurrences of mud layers associated with ooid sands in the Bahamas were reported in tidal channels by Boardman and Carney (1991) and Shinn and others (1993). Because of some variability in the localized settings where mud can be deposited and preserved in direct association with ooid sands, some mud layers probably will have greater lateral extent and greater importance as potential low-permeability layers and fluid-flow barriers.

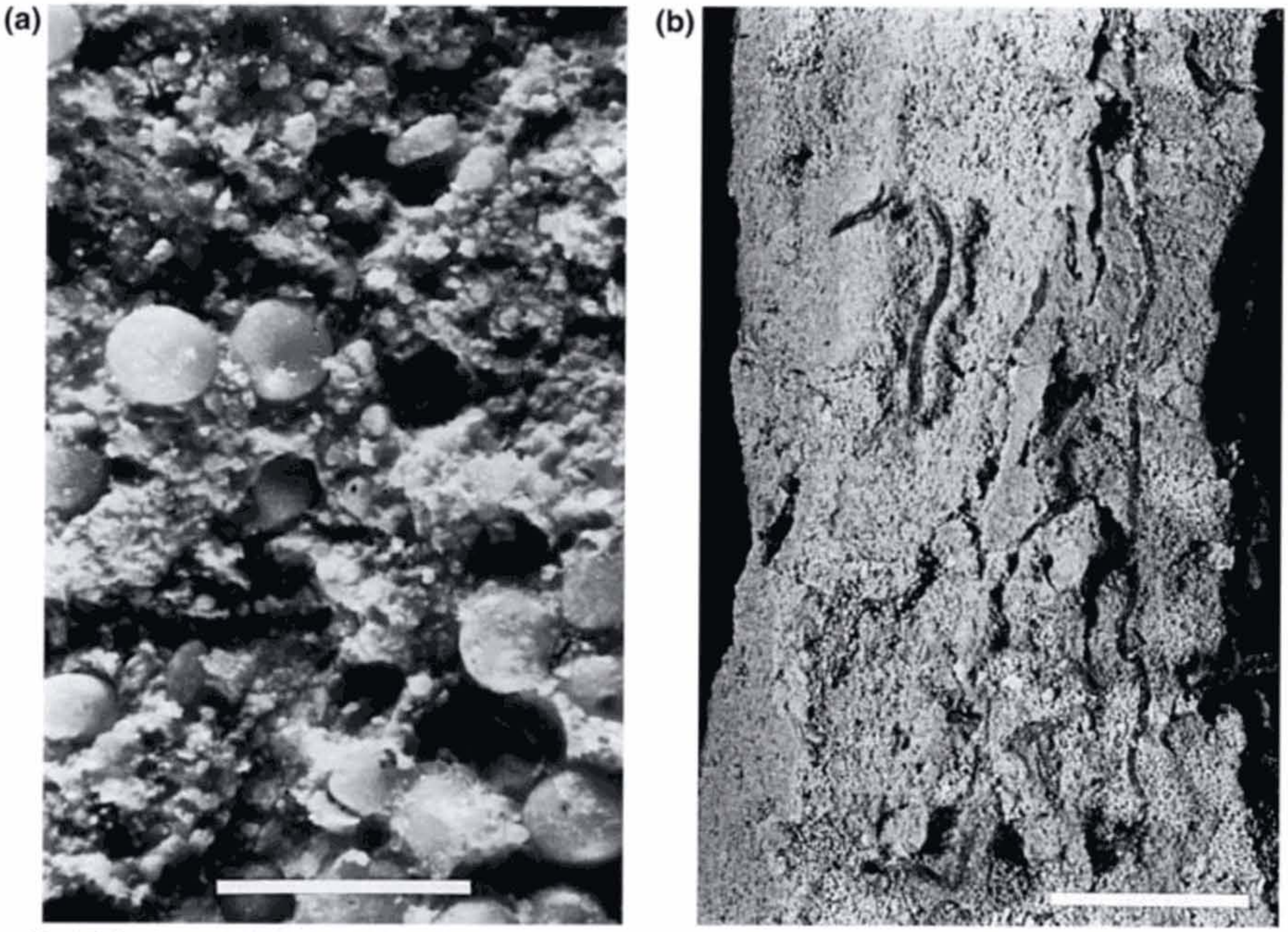


Figure 9. Poorly sorted ooid sand and mud facies, from a depth of 0.3 m in core C1. (a) Close-up view (scale bar = 1 mm). (b) Slab photograph (scale bar = 2 cm), including blades of *Thalassia* in this example. Core location shown in figure 4.

Figure 10. Intraclasts in a cemented layer recovered from core B3 at a depth of 2.4 m (7.9 ft) (scale bar = 2 cm). This intraclast zone occurs at the base of the well-sorted ooid sand facies just above the poorly sorted ooid sand facies. Core location shown in figure 4.

Figure 11. Mud layers recovered from near the top of a buried interval of poorly sorted ooid sand facies in core D3 at a depth of 1.5 m (4.9 ft) (scale bar = 2 cm). Core location shown in figures 4 and 6.

Development-Scale Heterogeneity

Local-scale patterns of heterogeneity within the active part of the Joulters Cays shoal are inferred from the facies distribution (figs. 4 and 6). The well-sorted ooid sand facies occurs in the center of the shoal complex where the entire area (305 to 607 m [1,000 to 2,000 ft] wide and 1.8 to 2.4 m [6 to 8 ft] thick) is exposed at low tide. The poorly sorted ooid sand facies occurs both bankward and seaward of the well-sorted ooid sand facies. Although the limits of the poorly sorted ooid sand facies were not encountered in this study, the regional study of Harris (1979) indicates that it forms a very narrow band seaward of the shoal and occurs over a very broad area several kilometers wide on the platformward side; the poorly sorted ooid sand facies and associated poorly sorted ooid sand and mud facies are 0.6 to 1.5 m (2 to 5 ft) thick at the shoal and thin platformward.

Heterogeneity is inferred because of mud content, burrowing, and grain type variations. These subtle variations occur on a scale of hundreds of meters (approximately 1,000 ft), which is consistent with well spacing in mature hydrocarbon reservoirs like those of the Permian Basin in the southwestern United States. The scale of variation illustrated here should thus be considered when correlating at the common development interwell scale. In addition, the heterogeneity portrayed here occurs within a single facies (ooid sands) as identified within the more regional, exploration-scale core study of Harris (1979). By analogy, similar subtle textural variations can be expected to produce local heterogeneity within ooid grainstone reservoirs.

Recent Depositional History

To better understand and calibrate the stratigraphy and facies patterns observed in cores (fig. 6), we analyzed the recent (approximately 40 yr) geological development of the study area with the aid of sequential aerial photographs. Using surface observations and the 1989 aerial photograph taken at the time of our first field excursion, we divided the poorly sorted ooid sand and mud facies into two facies on the basis of whether they are stabilized by *Thalassia* or filamentous algae. Thus, the low-energy, bankward part of the shoal, which remained remarkably unchanged from 1947 until 1989, is occupied by the poorly sorted ooid sand and mud–*Thalassia* facies, and the low-energy areas on the crest of the shoal are occupied by the poorly sorted ooid sand and mud–filamentous algae facies. Although some *Thalassia* was observed in cores, the filamentous algae were not recognized in cores; therefore, our cross sections do not distinguish these two facies.

In 1947 (figs. 12a and 13a), the well-sorted ooid sand facies was spread across nearly the entire north Joulters Cays study area. The poorly sorted ooid sand and mud–*Thalassia* facies on the bankward (west) side of the bar virtually matches the present-day position of this facies. The poorly sorted ooid sand and mud–filamentous algae facies occurred on the north end of the bar, where northward-prograding washover bars of well-sorted ooid sand had not yet migrated. A relatively small area of poorly sorted ooid sand occurred on the seaward margin in approximately the center of the study area. Note that the major washover bars in the south part of the study area were not dissected by tidal channels, presumably because the bars had sufficiently low topography that receding tides were able to drain uniformly across the bars without causing significant erosion.

By 1967 (figs. 12b and 13b), the washover bars of well-sorted ooid sand had migrated to the north

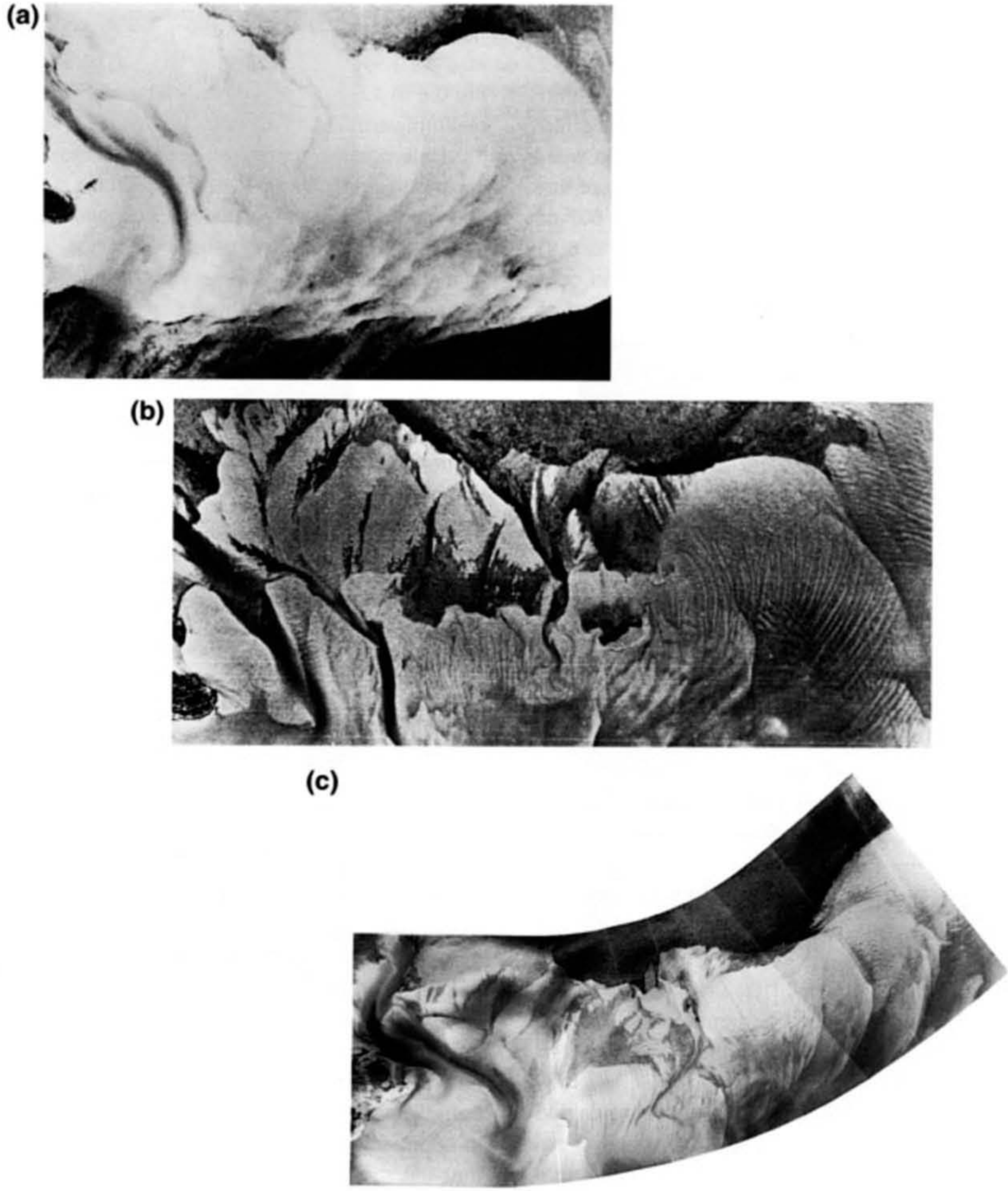


Figure 12. Vertical aerial photographs of the Joulters Cays ooid shoal taken in (a) 1947 and (b) 1967. (c) Oblique aerial photograph taken in 1989. These photographs were taken before Hurricane Andrew passed over the study area.

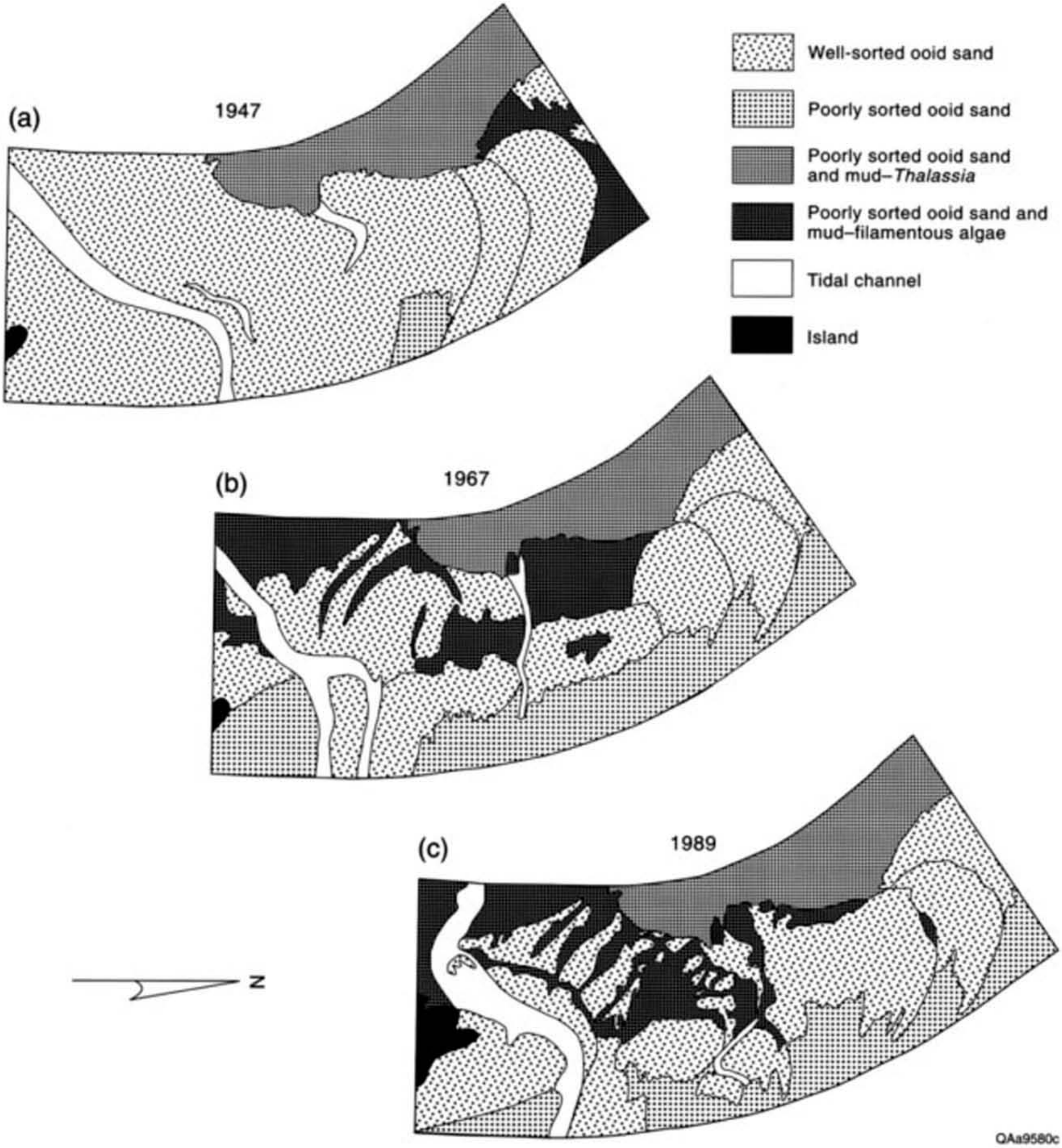


Figure 13. Surface facies-distribution maps of the Joulters Cays ooid shoal in (a) 1947, (b) 1967, and (c) 1989. Maps are based on photograph interpretation (fig. 12) and cross sections constructed from cores (fig. 6). Perspectives of 1947 and 1967 maps have been adjusted to oblique view of 1989. A horizontal scale is omitted because of the oblique perspective; compare figures 4 and 6 for horizontal scale. The poorly sorted ooid sand and mud facies has been divided into two facies on the basis of presence of stabilizing organisms—whether *Thalassia* or filamentous algae. This distinction was not possible in cores; therefore, these facies are not distinguished in the cross sections in figure 6. These facies-distribution maps reflect patterns established before Hurricane Andrew passed over the study area.

end of the study area. In the south part of the study area, washover bars had aggraded to a sufficient height that receding tidal currents were beginning to erode bar crests. The areas between washover bar highs contained poorly sorted ooid sand and mud–filamentous algae. Note that the washover bar in approximately the middle of the study area was partly dissected and that the crest of the bar was then approximately midway between the seaward and bankward margins of the study area.

In 1989 (figs. 12c and 13c), when cores used to construct the cross sections in figure 6 were collected, the washover bars in the south part of the study area were severely dissected by tidal currents, and large areas contained poorly sorted ooid sand and mud–filamentous algae. The washover bar in approximately the center of the study area had migrated bankward and nearly reached the margin of the poorly sorted ooid sand and mud–*Thalassia* facies, which has remained remarkably stable for at least 40 yr.

The pattern illustrated by these changes that were recorded by aerial photographs suggests aggradation of washover bars and progradation northward by longshore drift. As the washover bars both aggrade and prograde, they form a barrier to seaward drainage of tide waters. In the south part of the study area, washover bars have thus been dissected by tidal currents. We anticipate that if this pattern continues without interruption, with further progradation northward and aggradation in the center of the study area, the central tidal channel will deepen and widen and the central washover bars will be dissected.

EFFECTS OF HURRICANE ANDREW

Hurricane Andrew, a category 4 hurricane with wind velocities of approximately 240 km/h (150 mi/h), passed over Joulters Cays in a westerly direction on August 23, 1992. Before the passing of Hurricane Andrew, the study area (figs. 12c and 13c) displayed distinctive surface features dominated by tidal current washover bars (light areas) that extended 30 to 60 cm (1 to 2 ft) above sea level at low tide and were flooded by only a few centimeters (1 to 3 inches) of water at high tide. The bar crests typically were embellished by variously oriented symmetrical ripples. These topographically high features provided nominal protection for sparsely grass-stabilized areas (dark areas on the bankward side of the shoal), in which grains were less well sorted and some carbonate mud accumulated, and also provided some protection for filamentous-algae-stabilized areas between washover bars on the crest of the shoal, where slightly muddy sediment also accumulated.

Hurricane Andrew passed from east to west over the study area, and the center of the storm was just north of the Joulters Cays ooid shoal (fig. 14). Winds blew over the shoal generally from west to east because of the counterclockwise rotation of the storm cell. Consequently, sediment was transported seaward off the shoal. The boundary between the active, high-energy part of the shoal and the grass-stabilized area to the west remained relatively unchanged after the passing of the storm (fig. 15). In contrast, the surface of the active part of the shoal changed considerably. Low areas, which were previously the sites of deposition of poorly sorted ooid sand and mud–filamentous algae (fig. 13c), are now covered by a layer of well-sorted ooids several centimeters thick. The posthurricane relief across the active part of the shoal is reduced, and the surface is now relatively featureless. Ooids not trapped in low areas on the shoal were transported seaward.

Very thin (a few millimeters to 1 cm thick), laterally discontinuous layers of carbonate mud, generally no more than a few square meters in area, were observed on the surface of the shoal crest at low tide (fig. 16). Tide floodwaters observed a few weeks after Hurricane Andrew contained large amounts of suspended carbonate mud, suggesting that mud on the shoal crest was delivered to this depositional site by tide waters.

The changes in surface features of the Joulters Cays ooid shoals caused by Hurricane Andrew were profound, but they will probably be only partly preserved. Prevailing winds and currents that caused formation of the aggrading and northward-prograding washover bars illustrated in figures 12 and 13 will, in all likelihood, reestablish the pattern of well-sorted ooid sand washover bars flanked seaward by poorly sorted ooid sand and flanked bankward and in low areas on the crest by poorly sorted ooid sand and mud. Although the storm layer of well-sorted ooid sand may be preserved in some low areas on the crest of the shoal, we have not found recognizable ooid storm beds from previous storms in the prehurricane cores we collected on the shoal crest.

Those ooids swept seaward by easterly (counterclockwise) storm currents will most likely be preserved in areas normally having less agitated conditions, where fine-grained sediments are normally deposited. Indeed, Harris (1979) reported ooid grains, many of them micritized, in cores collected a few kilometers seaward of our study area. Because prevailing tidal currents transport ooids bankward rather than seaward, those ooids in seaward locations may be the result of earlier storms.

The thin, discontinuous mud layers deposited on the crest of the shoal (fig. 16) probably have relatively low preservation potential. Several months after Hurricane Andrew passed over the study area, we observed diurnal tides resuspending these muds. (Shinn and others [1993] reported a similar observation on ooid shoals at Cat Cay, Bahamas.) Moreover, the very

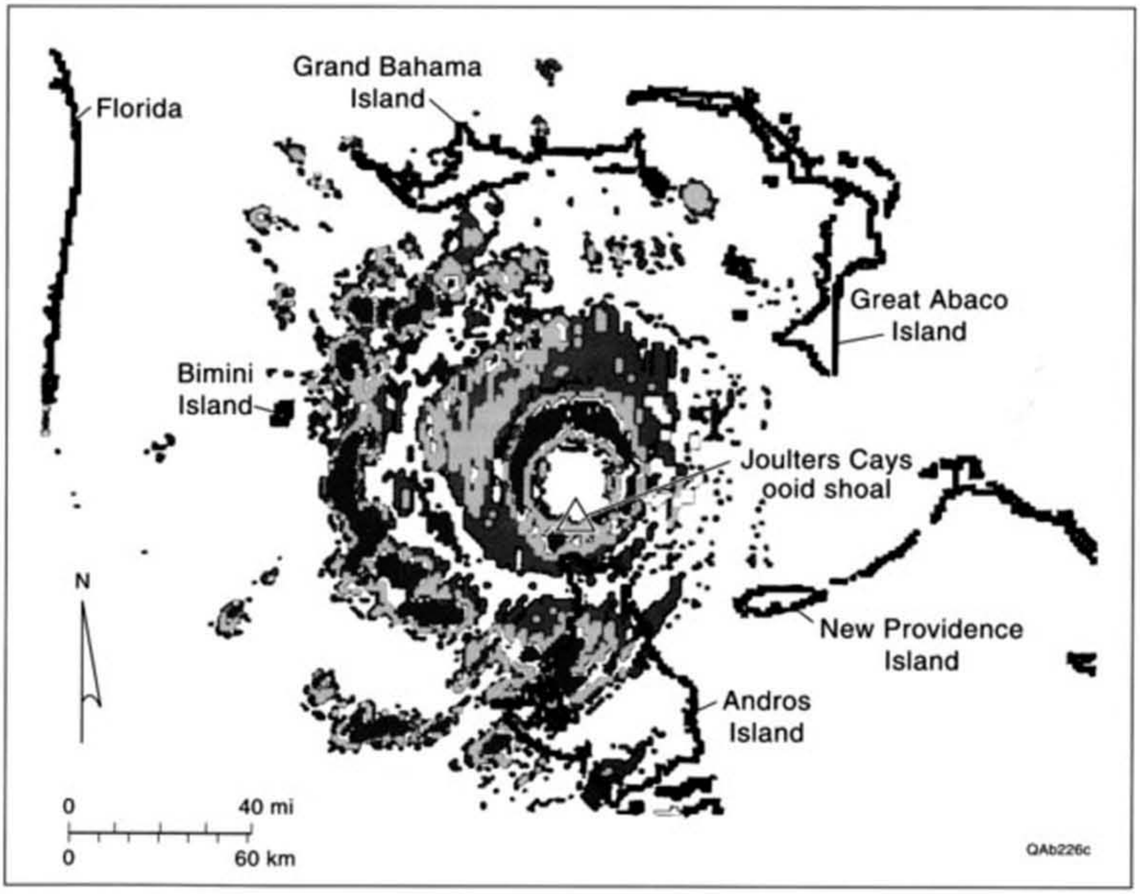
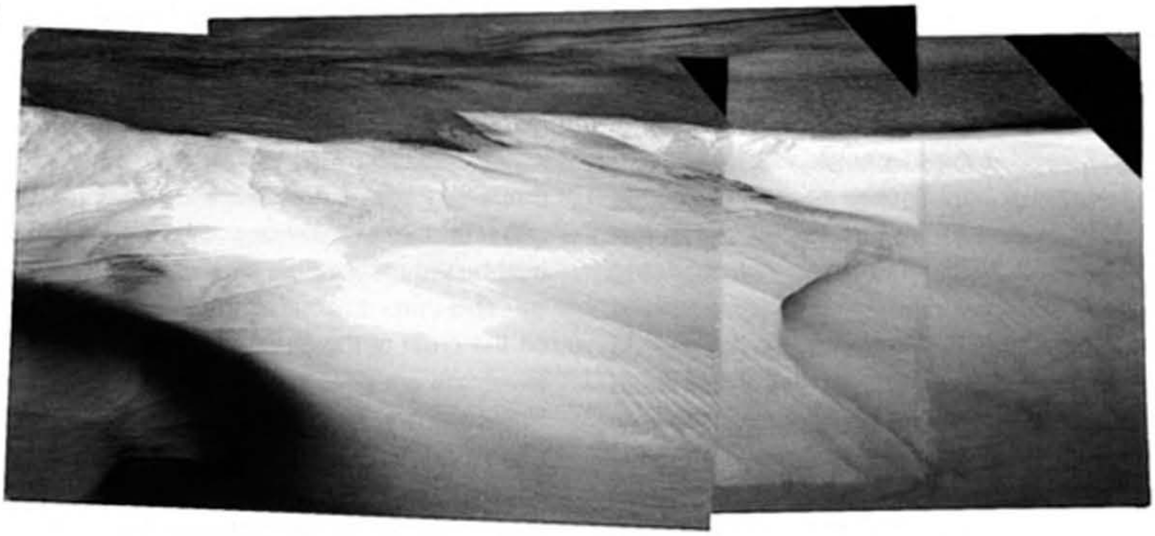


Figure 14. Radar image of track of Hurricane Andrew recorded by the National Weather Service. The center of the hurricane passed just north of the study area. Because of the counterclockwise rotation of the storm, the direction of storm surge in the study area was seaward.

(a)



(b)

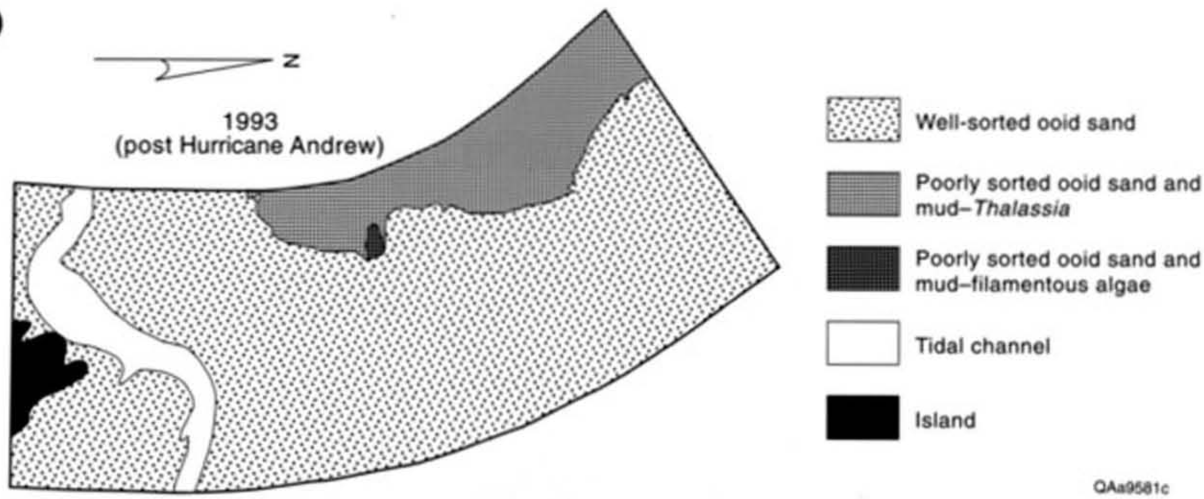


Figure 15. (a) Low-altitude oblique aerial photograph taken in 1993, seven months after passing of Hurricane Andrew, of active part of ooid shoal at north end of Joulters Cays area. (b) Surface facies-distribution map of same area at the same time. The perspective of the map has been adjusted to the same oblique view used in figure 13.

discontinuous nature of these deposits suggests that they had at one time been much larger. However, if prevailing tidal currents reestablish washover bars before the mud deposits are completely removed, some of the deposits may be preserved beneath washover bars. There they will provide local permeability barriers when these sediments are buried and lithified. Indeed, shallow subsurface mud layers on the shoal crest, such as the pre-Andrew layer observed in core D3 (fig. 6b), probably formed by this process during an earlier storm.

Although the preservation potential of this mud layer is low on the shoal crest, preservation in adjacent tidal channels is almost a certainty. After Hurricane Andrew passed over Joulters Cays, Shinn and others (1993) reported thin beds (as much as

Figure 16. Very thin, laterally discontinuous layers of carbonate mud deposited on well-sorted ooids at the crest of the shoal following Hurricane Andrew. Although this feature may be preserved (see older example in core D3, fig. 6b), much of this mud will probably be removed by tides and not become part of the rock record.

5 cm [2 inches] thick) of laminated carbonate mud in troughs of ooid dunes and ripples in high-energy subtidal channels of Joulters Cays. They proposed that a slurrylike mixture of carbonate mud, which resulted from the passing of Hurricane Andrew, moved through the channels. As the storm winds and currents waned, mud settled to the channel floor and was preserved in ripple troughs. Shinn and others (1993) proposed that an older, more compacted mud layer stratigraphically below the Hurricane Andrew mud layer is also a storm deposit. Boardman and Carney (1991), whose investigation predated Hurricane Andrew, attributed the older mud layer in these tidal channels to direct precipitation from seawater at a time when the tidal channel was separated from the open sea by migrating ooid sand bars. The mud layers deposited in tidal channels will be important, albeit local, permeability barriers when these sands have been buried and lithified. Note in figure 1 that although the tidal channels are local phenomena, their linear extent is as much as three-quarters of the width of the shoal.

Because the center of Hurricane Andrew passed a short distance north of the study area and, thus, the prevailing direction of storm surge was seaward, the major features that will be preserved in the stratigraphic record are seaward of our study area. Had the center of the hurricane passed a short distance south of the study area, the prevailing storm surge would have been platformward. Under these circumstances it is likely that transport of well-sorted ooid sand would have been platformward and would have been overlain by a relatively thick layer of carbonate mud on the entire shoal crest. This thick mud layer would have a much higher preservation potential. Thus, a more southerly storm track would most likely result in a major horizontal permeability barrier when these sediments were buried and lithified, and this would result in a major reservoir compartment boundary.

Ancient Analogs

Carbonate grainstones analogous to the sediments investigated at Joulters Cays are hydrocarbon reservoirs of various geologic ages (Peryt, 1983; Harris, 1984b; Roehl and Choquette, 1985; Keith and Zuppann, 1993). Hydrocarbons are produced from Mississippian ooid grainstone reservoirs in the Illinois, Anadarko, Appalachian, and Williston Basins and the Hugoton Embayment (Keith and Zuppann, 1993). The most prolific area of production from Mississippian ooid grainstones is the Illinois Basin, where the Ste. Genevieve Limestone accounts for 743 million barrels (MMbbl) of oil, or 18 percent of the cumulative production from the basin (Keith and Zuppann, 1993). In the Hugoton Embayment of southwestern Kansas, Damme field has produced 13 MMbbl of oil from Mississippian ooid grainstone shoal facies (Handford, 1988; Parham and Sutterlin, 1993). Grainstones, although not exclusively ooid grainstones, are a principal reservoir facies in the San Andres and Grayburg Formations of the Permian Basin in West Texas and New Mexico, which have a combined cumulative production of 7.7 billion barrels, or 46 percent of the oil produced from the entire basin (Bebout and Harris, 1990). Grainstones of Jurassic Arab-C and Arab-D reservoirs of the Middle East, many of which are ooid grainstones, are prolific reservoirs; indeed, the giant Qatif field of Saudi Arabia alone has an estimated ultimate recovery of 9 billion barrels of oil (Halbouty and others, 1970; Wilson, 1985). Jurassic ooid grainstone reservoirs also occur in northern Louisiana and eastern Texas (Ventress and others, 1984) and the Paris Basin, France (Cussey and Friedman, 1977; Purser, 1978). Cretaceous ooid grainstones are oil and gas reservoirs in the Gulf Coast of Texas (Bebout and Loucks, 1977; Fitchen and others, in press), and in the Middle East (Longacre and Ginger, 1988).

Depositional facies variability and early diagenetic alteration both contribute to reservoir-scale heterogeneities in the carbonate sand deposits of the Joulters Cays area and potentially in ancient analogs. For example, interwell-scale heterogeneities in hydrocarbon reservoirs of the San Andres and Grayburg Formations of the Permian Basin have been documented on a scale of hundreds of meters or less (Bebout and others, 1987; Ruppel and Cander, 1988; Bebout and Harris, 1990; Harris and Walker, 1990a, b; Longacre, 1990; Major and others, 1990). The details of this level of variability have been shown in outcrop analogs for these same reservoirs in the Guadalupe Mountains (Kerans and Nance, 1991; Grant and others, 1994; Harris and others, 1994; Barnaby and Ward, 1995; Kerans and others, 1995; Kerans and Fitchen, 1995).

Thin-section examination demonstrates that both the well-sorted ooid sand facies and poorly sorted ooid sand facies of the Joulters Cays area were mud free and had high initial porosity at the time of deposition (Halley and Harris, 1979). In some ancient subsurface settings, however, similar well-sorted ooid grainstones are cemented by calcite or anhydrite cement and have low resultant porosity (Bebout and others, 1987; Harris and Walker, 1990a, b; Longacre, 1990). In these ancient settings, the more poorly sorted ooid or peloid grainstones and packstones commonly retain primary porosity and thus become the better reservoir facies.

At Joulters Cays, the poorly sorted ooid sand facies occurs on the seaward and landward sides of the well-sorted ooid sand facies and also underlies the poorly sorted ooid sand and mud facies. If the early-cemented intraclasts that we encountered as layers in the Joulters Cays shoal were to act as nucleating sites of later cements, layers of tightly cemented ooids could form impermeable barriers as much as 0.6 m (2 ft) thick within the otherwise permeable facies, causing a reservoir to become vertically partitioned.

Alabama Ferry Field

Oil and gas from a Lower Cretaceous reservoir in Alabama Ferry field, along the Texas Gulf Coast in Leon County, are produced from a grainstone that

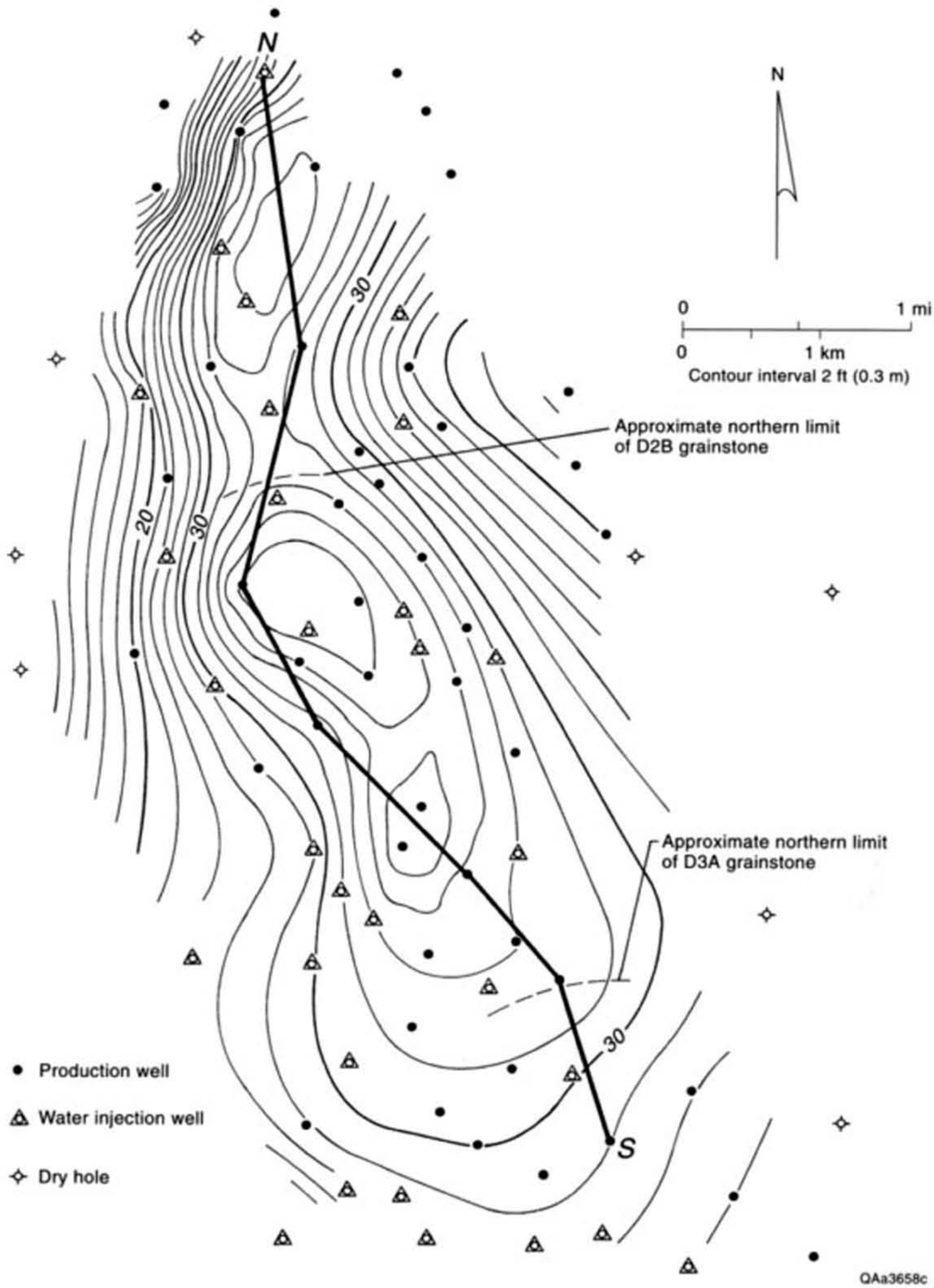


Figure 17. Upper Glen Rose "D" (Lower Cretaceous) thickness map of Alabama Ferry field, Leon County, Texas (after Fitchen and others, in press). This map includes three grainstone units that are each analogous in composition, size, and geometry to the Joulters Cays ooid shoal. Cross section shown in figure 18.

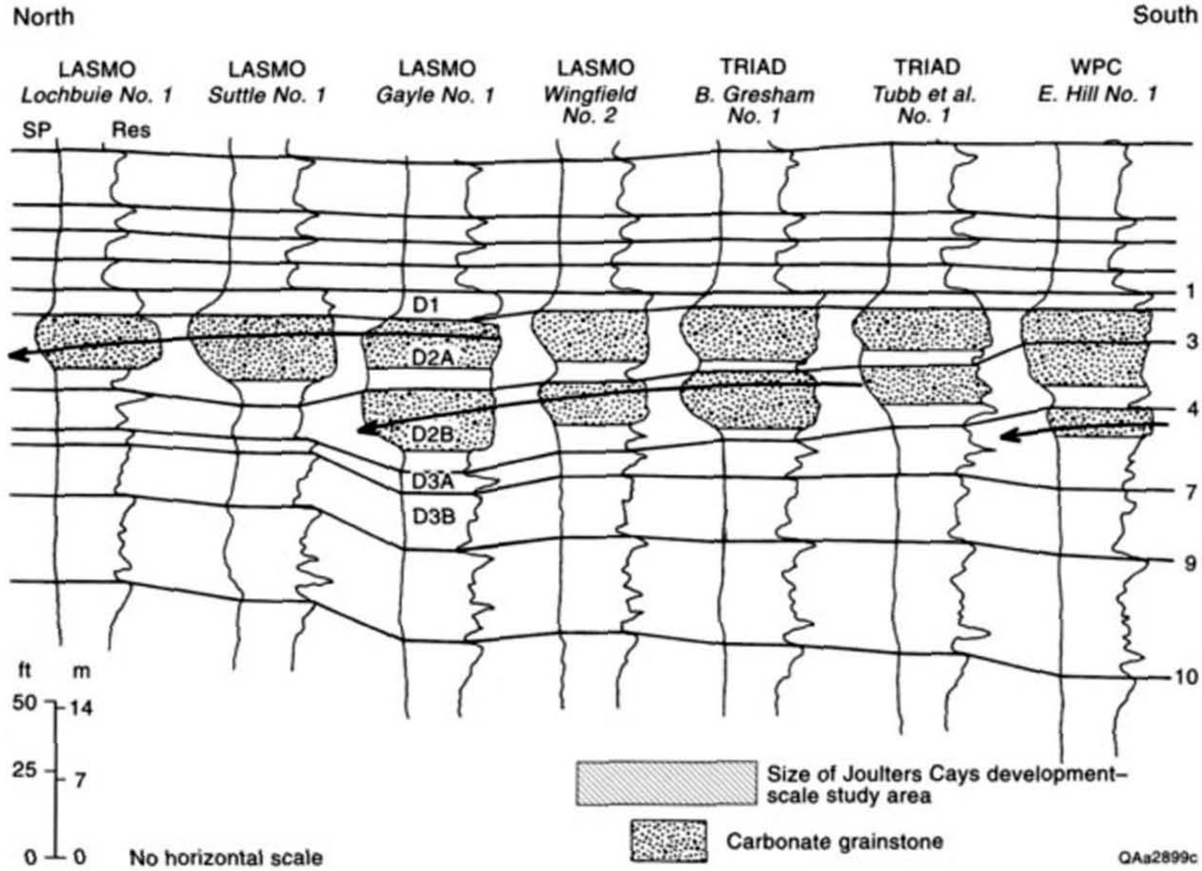


Figure 18. North-south stratigraphic electric log cross section of Alabama Ferry field (from Fitchen and others, in press). Offlap of three ooid and skeletal grainstone units from southeast to northwest indicated by arrows. Trace of cross section shown in figure 17.

is analogous to that of the Joulters Cays area (Lomando and others, 1987; Pollard, 1989; Bruno and others, 1991; Fitchen and others, in press). Correlations across this Lower Cretaceous reservoir indicate the presence of several north-offlapping grainstone units separated by thin shales (Fitchen and others, in press) (figs. 17 and 18). This offlapping pattern resembles that inferred to exist at Joulters Cays, where bars migrated from southeast to northwest, parallel to the edge of the shelf. Importantly, the grainstone unit at Alabama Ferry field is, in terms of lithology and thickness, approximately equivalent to the ooid sand facies of Harris (1979, 1983) (fig. 2). Thus, our development-scale investigation of Joulters Cays provides insight that may suggest criteria to divide these grainstone units into finer divisions that would be pertinent to subsurface fluid flow.

Porosity at Alabama Ferry field is highest (as much as 20 percent) in the upper part of each grainstone unit and lowest at the base. At Joulters Cays, we conclude that the rate of deposition is probably less in the lower part of the prograding shoal complex than in the upper part, as evidenced by the presence of well-developed intraclast-rich zones, that is, hardgrounds and gravel zones (figs. 6c and 10). At Alabama Ferry field, Fitchen and others (in press) also interpreted

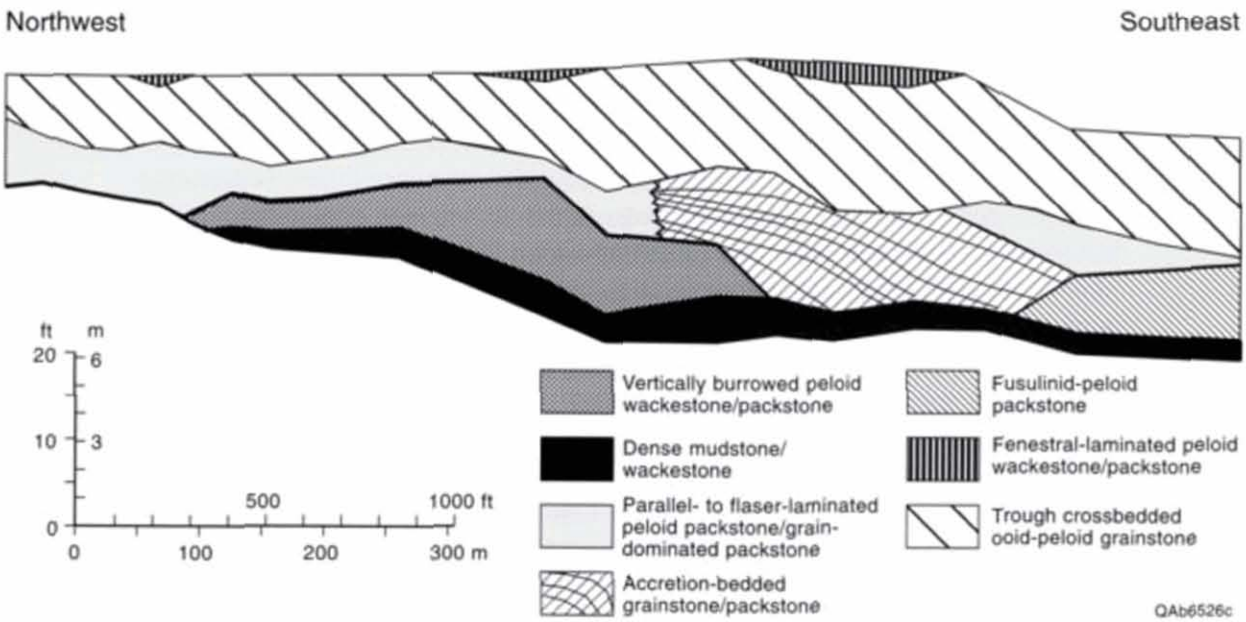


Figure 19. Outcrop interpretation of cycle 7 of the San Andres Formation exposed in Lawyer Canyon, Algerita Escarpment. The ooid grainstone part of this transgressive-regressive cycle is comparable in composition and size to the area of Joulters Cays shown in figures 2 and 4 (figure modified from Kerans and Fitchen, 1995).

a low rate of deposition in the lower parts of the grainstone units because the lower parts of these grainstones contain more isopachous, fibrous marine cement than the upper parts and, thus, have lower porosities. The offlapping pattern of ooid bars at Joulters Cays, demonstrated by the shift in position of bar crests and the offlapping pattern of intraclast-rich zones as seen in cross section, is also expressed at Alabama Ferry field by the northward shift in position of the grainstone units.

San Andres Formation Outcrop

An outcrop analog for subsurface carbonate grainstone reservoirs in the Permian San Andres Formation of the Guadalupe Mountains of West Texas and New Mexico is also similar in composition, size, and geometry to the ooid sand facies of Harris (1979, 1983). Kerans and Fitchen (1995) interpreted an ooid grainstone in their cycle 7 (Lawyer Canyon area of Algerita Escarpment) to have formed as part of a transgressive-regressive depositional cycle (fig. 19). This ooid grainstone, although subdivided on the basis of postdepositional meteoric-diagenetic alteration (Hovorka and others, 1993), is described as a single depositional facies. By analogy with our subdivision of the ooid sand facies of Harris (1979) at Joulters Cays, this ooid grainstone may also be divisible into development-scale depositional subfacies that would affect fluid flow in similarly deposited subsurface reservoirs.

Conclusions

During geologic and engineering evaluation of hydrocarbon reservoirs in platform carbonates, a detailed geologic framework must serve as a template for understanding porosity and permeability distribution and delineation of fluid-flow units. Modern deposition at Joulters Cays began with a mud-dominated subtidal section that grades upward into grain-dominated facies. Laterally, the extent of burrowing, amount of mud, and types of grains increase away from active parts of the shoal. Results presented herein emphasize local variations of depositional texture and diagenesis within an overall active setting that can cause local heterogeneity. The modern analog discussed here illustrates the lateral extent and complexity of facies relationships using cores collected at a well spacing appropriate to identify development-scale heterogeneity.

Certainly such complexity cannot be fully addressed in normal subsurface situations using downhole log and limited core information, especially when some of the relationships occur at distances of less than normal well spacing even in extensively developed fields. An appreciation of the nature of such facies variability is nonetheless useful in reservoir studies to help correlate depositional cycles and flow units between wells and to constrain input into reservoir models. An understanding of facies variability at this scale is particularly critical for reservoir modeling when creating areal variograms, designing templates for attribute distribution, and establishing directional bins for interpolation. Thus, study of modern sediment analogs such as the Joulters Cays shoal is an important addition to studies of hydrocarbon reservoirs and outcrop reservoir analogs.

Coring and surface-sediment mapping in the Joulters Cays ooid shoal of Great Bahama Bank reveal the three-dimensional complexity of an upward-coarsening and upward-shallowing cycle. This modern example reveals difficulties in interpreting and correlating grainstone zones in subsurface studies of platform carbonate reservoirs. Shoal growth, largely in response to a relative sea-level rise, records rapid expansion of ooid sands, island formation and associated meteoric diagenesis, local shoal stabilization and reworking by burrowing, and generation of hardground layers. All of these relationships have geometries that are significant at a development scale.

Sand generation and topography varied greatly in the Joulters Cays area as the platform flooded and the shoal developed. Such variation should be expected in ancient examples. Within the upper grain-dominated facies at Joulters Cays that have been emphasized herein, textural variation and early diagenetic alteration contribute to potential fine-scale heterogeneities equivalent to documented development-scale hydrocarbon reservoir heterogeneities. Facies patterns are produced by migrating sand bars within the active parts of the shoal and are impacted by short-term storm events.

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