Internal Geometry of a Modern Carbonate Grainstone Shoal—an Analog for Hydrocarbon Reservoir Heterogeneity

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ABSTRACT

We chose the ooid sand shoals of the Joulters Cays area of Great Bahama Bank for detailed sedimentological study to investigate the patterns of internal heterogeneity within a modern carbonate sand belt and to develop criteria for predicting the lateral extent of carbonate sand facies. Major facies identified from cores were (1) crossbedded, well-sorted ooids, (2) burrowed, poorly sorted ooids, and (3) poorly sorted ooids and mud containing *Thalassia*. Clast-rich zones and mud layers were also encountered. We propose that upon burial and compaction, the poorly sorted ooids and mud containing *Thalassia* will likely retain negligible porosity and permeability, whereas both the crossbedded, well-sorted ooids and burrowed poorly sorted ooids will likely maintain their high initial porosity and permeability. However, study of many ancient subsurface reservoirs indicates that the crossbedded, well-sorted ooids can undergo considerable cementation and have low resultant porosity and permeability. Thus, in many settings, the burrowed, poorly sorted ooids could retain the highest porosity and permeability. Additional cementation within the clast-rich zones, which occur in both the crossbedded, well-sorted ooids and burrowed, poorly sorted ooids, will result in thin, low-porosity barriers within a reservoir.

Locally the surface configuration of the modern shoal complex at Joulters Cays was altered significantly by the passing of Hurricane Andrew in August 1992. Prominent washover bars were planed off, and well-sorted ooids were deposited in low areas of the shoal where poorly sorted and mud-rich deposits of ooids had previously accumulated. The post-hurricane configuration of the shoal demonstrates how a single short-term depositional event contributed significantly to the internal heterogeneity of the shoal complex.

INTRODUCTION

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

Recently the need for more detailed information on hydrocarbon reservoirs has been escalating as operators seek to increase recovery from existing reservoirs. 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 understood. An appreciation of the nature of such facies variability is needed in reservoir studies to guide correlations of cycles and flow units between wells and to constrain the input into reservoir models or forward-looking geologic models.

In concert with establishing better constrained geologic frameworks in hydrocarbon reservoir studies, The University of Texas at Austin, Bureau of Economic Geology, began carbonate-reservoir studies in 1984, which were funded by The University of Texas System 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 led to the Bureau's establishing of the industry-funded Reservoir Characterization Research Laboratory through which the Bureau investigates heterogeneity within carbonate reservoirs and their analogs exposed on continuous outcrop (Kerans and others, 1994; Lucia and others, 1992).

Both reservoir and outcrop studies demanded a better understanding of the three-dimensional internal variations in textures and structures of grainstone bodies. Interpreting depositional environments in subsurface ancient carbonates depends largely on comparing because similar facies relationships have commonly been identified in ancient carbonate sand bodies (see papers in Peryt, 1983; Harris, 1984a; Bebout and Harris, 1990; Keith and Zuppann, 1993). The Joulters 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) in a dip direction, extends the length of the shoal for 25 km (15.5 mi) along its windward side and terminates abruptly to the east onto the platform-margin shelf (figs. 4 and 5). To the west, the active sands grade into the sea-grass- and algae-stabilized sand-flat part of the shoal and eventually the deeper water platform interior. The Joulters Cays are three islands that lie within the active area of the shoal. The area of detailed study described herein is approximately 2.6 km^2 (1 mi^2) of mobile ooid sands lying just north of the northernmost of the Joulters Cays (figs. 1 and 2).

Regional Facies Relations

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

The relief of the Joulters Cays shoal above the surrounding sea floor primarily results from ooid sands accumulating in one of three facies: mobile fringe, sand flat, or platform interior (Harris, 1979, 1983). The ooid fringe is a narrow belt along the active ocean-facing borders of the shoal, where ooid accumulation coincides with ooid formation (fig. 5). Ooid and fine-grained peloid muddy sands, the more widespread sediment types exposed on the sand flat and platform interior west of the mobile fringe, respectively, result from ooids mixing with other grain types and carbonate mud. Collectively these modern sands, more than 3 m (>10 ft) thick, extend 22 km (13.7 mi) in a dip direction in a 260-km^2 (100-mi^2), irregularly shaped part of the

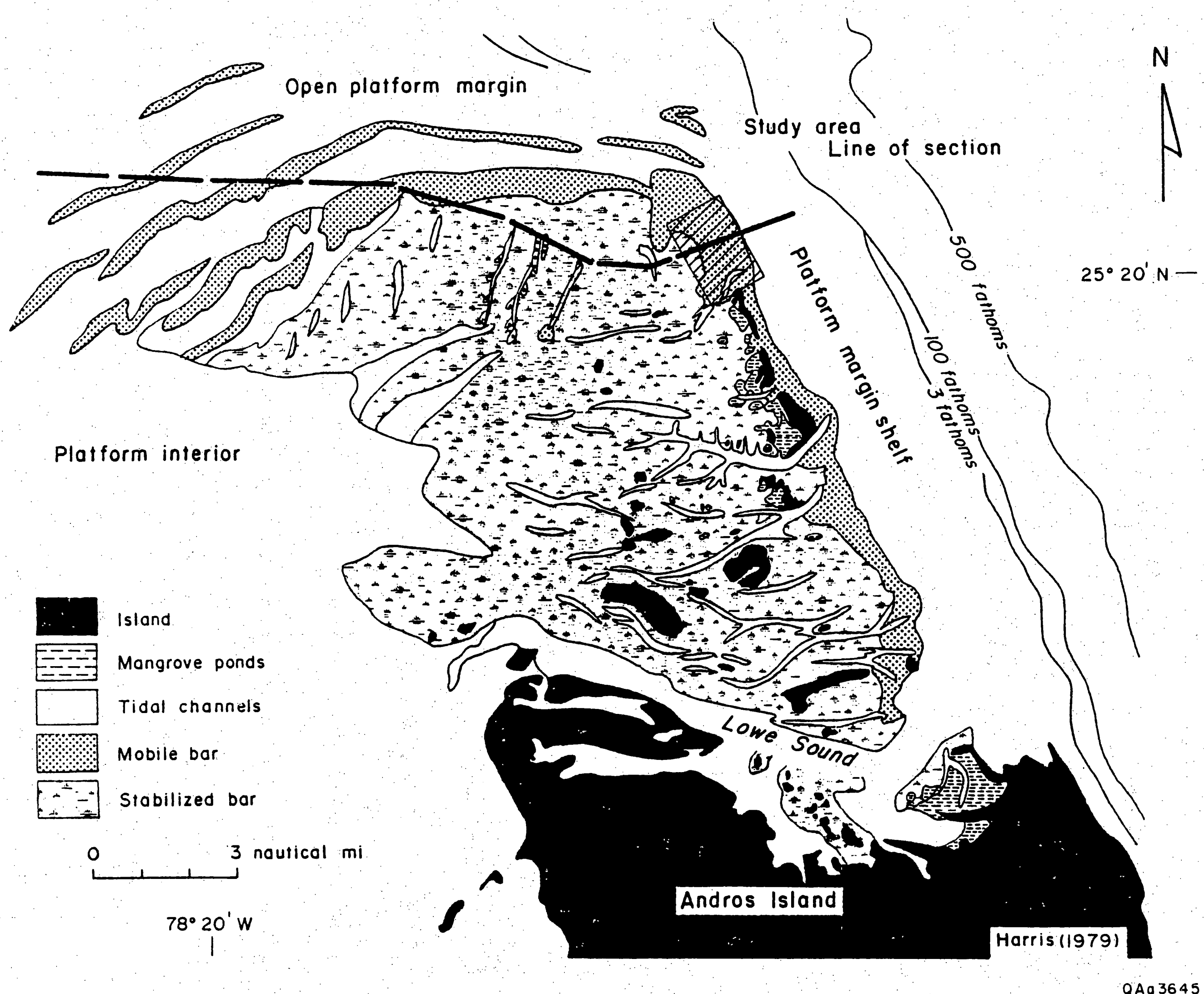

Figure 4. Map of depositional environments of Joulters shoal (from Harris, 1979); compare with figure 1. Also shown are line of section of figure 5 and area of investigation.

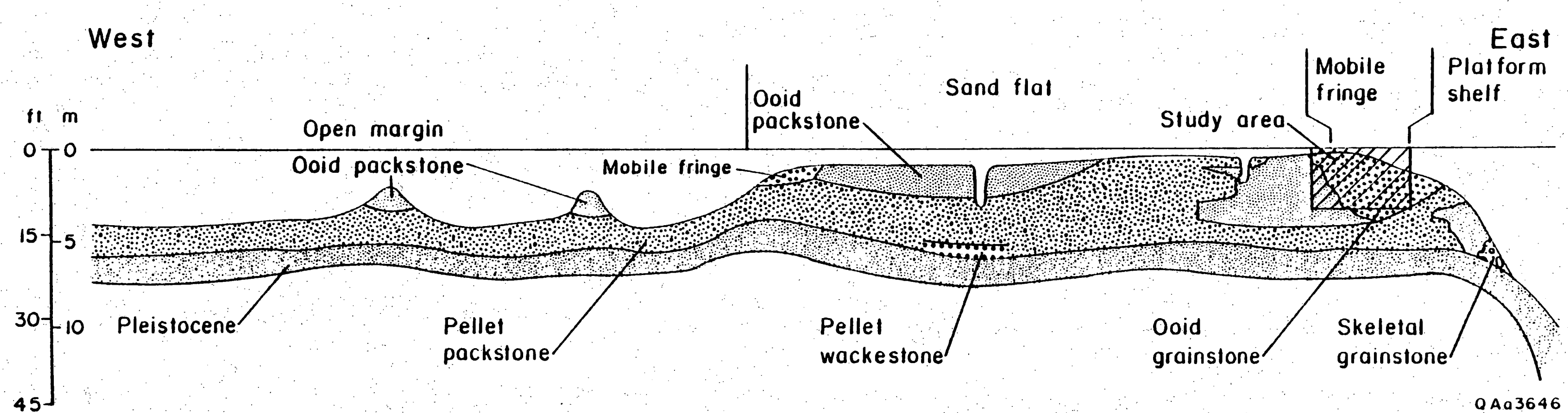

Figure 5. West-east facies cross section of north part of Joulters shoal (from Harris, 1979). Area of reservoir-scale studies shown; location of section shown in figure 4.

shoal. The ooids exceed 7 m (23 ft) in thickness in an area coinciding with the Joulters Cays islands.

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. 5). Ooid sand directly overlies Pleistocene limestone along the seaward margin of the shoal and interfingers with muddier sediments bankward. Throughout most of the sandflat, the vertical succession is of lithoclast sand and/or pellet mud at the base, muddy fine-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 limestone surface rises.

Facies distribution within the Joulters Cays shoal is a product both of changes in depositional patterns during development of the shoal and today's depositional environments. The changes occurred primarily because of rising sea level, a corresponding increase of platform accommodation, and rapid sedimentation (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, the 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 nature of sediments throughout the area from muddy peloidal to ooid sands.

Large-Scale Heterogeneity Patterns

Heterogeneity of the Joulters shoal is inferred on the basis of the distribution of depositional facies shown in figure 5. Clean ooid sands (grainstones) along the active margin of the shoal occur as subtidal bar, channel fill, beach and island facies. In cross section they occur 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 such clean sands by Halley and Harris (1979) and Enos and Sawatsky (1981), and it is confirmed here in thin-section estimations. Immediately bankward of the clean ooid sands are widespread, somewhat irregularly shaped layers containing mixtures of carbonate mud and sand that will likely result in vastly different reservoir properties. An upper layer of muddy ooid sands, some 20 km (12.4 mi) wide and from 4 to less than 1 m (13 to <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 varying from 5 to 2 m (16 to 6.6 ft) in thickness. These layers will likely have initial porosities lower than the more seaward clean ooid sands, judging from measured values of similar sands by Enos and Sawatsky (1981) and thin-section estimations. In addition, the upper layer will likely have better reservoir quality than the lower layer because of coarser grain size and less mud content.

Comparing figures 5 and 6 provides insight into the large-scale heterogeneity pattern to be expected in a grainstone body such as the Joulters shoal. The cross sections are somewhat simplified, however, because of the spacing of the regional coring grid. Harris (1979) presented isopach maps of these three Holocene facies that had been based on sediment core data as well as extensive sediment probe data. These isopach maps, modified and reproduced here as figure 6, approximate the three-dimensional geometry of the heterogeneity inferred in the Joulters 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 absent.

The sections following investigate the inferred heterogeneity of one part of the regional facies patterns presented for the shoal, that is, the clean ooid sand coinciding with the active margin of the shoal. Heterogeneity produced by subtle textural and diagenetic variation within this "uniform" lithology occurs at a scale that is critical for correlating properties between wells in analogous reservoirs.

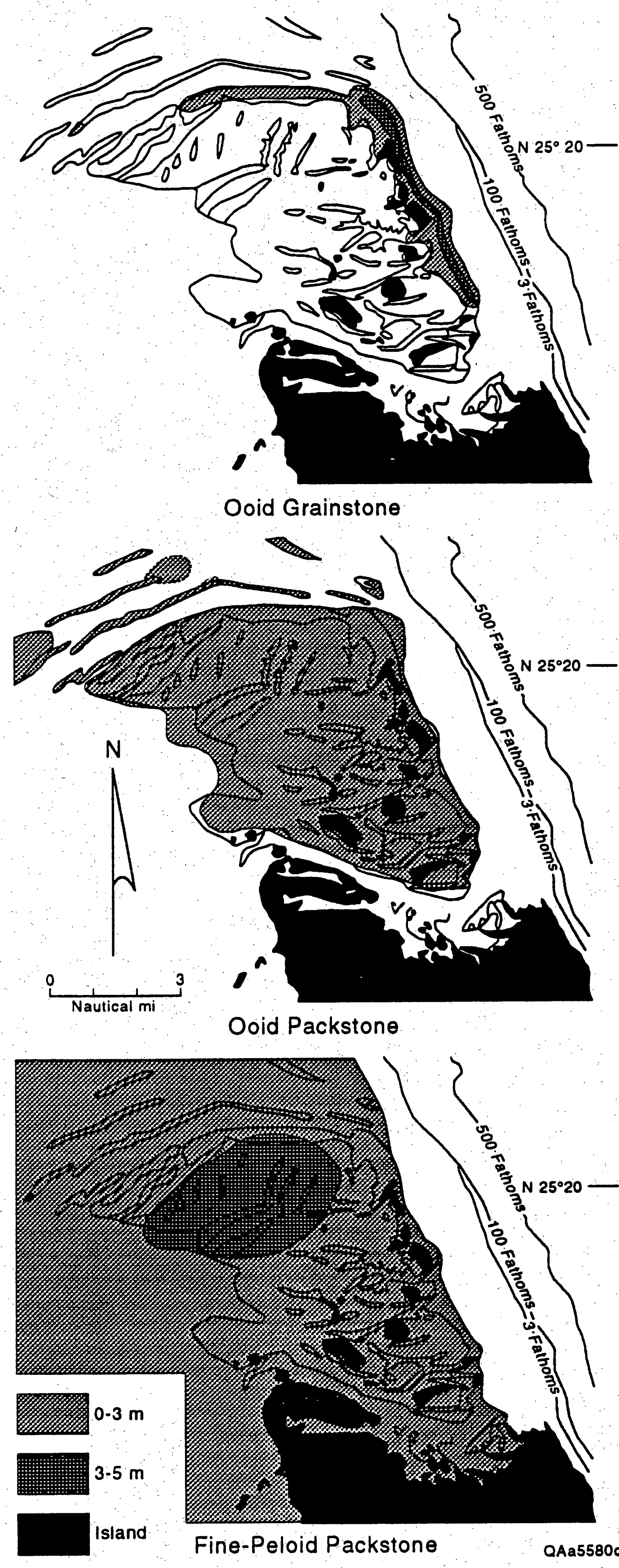

Figure 6. Isopach maps of (a) the ooid grainstone, (b) ooid packstone, and (c) fine peloid packstone facies identified by Harris (1979).

RESERVOIR-SCALE FACIES VARIABILITY AND SMALL-SCALE HETEROGENEITY PATTERNS

Depositional facies variability and early diagenetic alteration both contribute to fine-scale heterogeneities in the grain-rich upper parts of the succession of the Joulters Cays area, which appear to be at a scale equivalent to that of reservoir heterogeneities. For example, interwell-scale heterogeneities in hydrocarbon reservoirs of the San Andres/Grayburg Formation 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 and b; Longacre, 1990; Major and others, 1990; Grant and others, 1994; Harris and others, 1994). To collect more information from the modern analog at the reservoir scale, we built upon the regional framework in the Joulters Cays area discussed in the preceding section by coring a subarea of the active part of the shoal (fig. 2). These results, presented in preliminary form in Bebout and others (1991), are herein described in detail.

Three depositional subfacies predominate within the ooid sand facies of Harris (1979, 1983, 1984b) discussed earlier. Crossbedded, well-sorted ooid sand occurs on the active, high-energy bar crests in the subarea of the shoal investigated in detail. Burrowed, poorly sorted ooid sand accumulated along the landward and seaward edges of the subarea. Poorly sorted ooid sand and mud, which became stabilized by sea grass and algae, occur just bankward of the bar crest and represent a transition into the adjacent sand-flat environment. The distribution of these facies within the detailed study area of figure 2 is shown on cross sections A–A′ (fig. 7), D–D′ (fig. 8), and E–E′ (fig. 9). Differences in grain size, grain sorting, and sedimentary structures among the three facies will potentially lead to heterogeneity. As will be discussed in more detail in a following section, these subtle changes in depositional facies (as well as early diagenetic overprint) would, upon burial, respond to compaction and cementation differently and likely result in significant permeability variability within a single grainstone depositional cycle or flow unit.

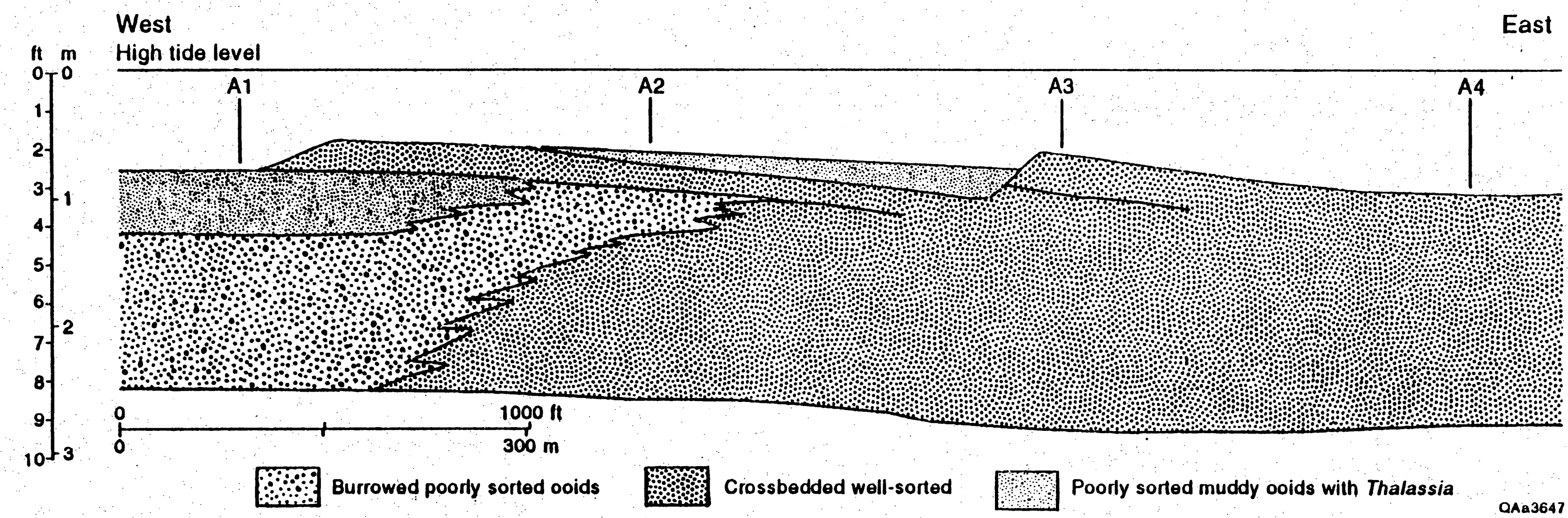

Figure 7. West-east cross section A–A′ before passage of Hurricane Andrew. Location of section shown in figure 2. Core locations were leveled to a sea-level datum. At this location main part of ooid bar is 1.5 to 1.8 m (5 to 6 ft) thick and at least 760 m (2,500 ft) wide. Surface features result from two storm-washover bars, which have formed between them a low area in which some mud accumulated. Transition from crossbedded, well-sorted ooids into burrowed, poorly sorted ooids occurs on bankward side between A1 and A2. Position of seaward transition from crossbedded, well-sorted ooids into burrowed, poorly sorted ooids was not reached by this transect.

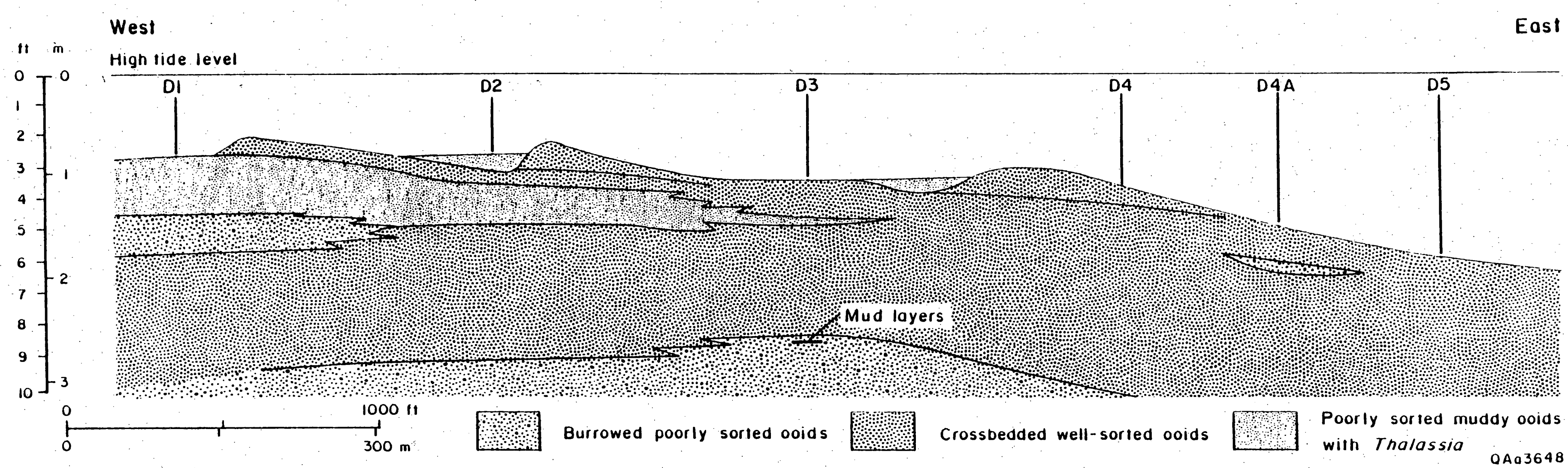

Figure 8. West-east cross section D–D′ before passage of Hurricane Andrew. Location of section shown in figure 2. Ooid bar at this location is at least 1,220 m (4,000 ft) wide, and transition into burrowed, poorly sorted ooids was not reached on bankward or seaward side. Three storm-washover bars dominate the surface topography and form lows between that have served as sites of accumulation of carbonate mud along with the ooids. Mud layers shown in figure 13 lie at top of lower burrowed, poorly sorted ooids zone in D3.

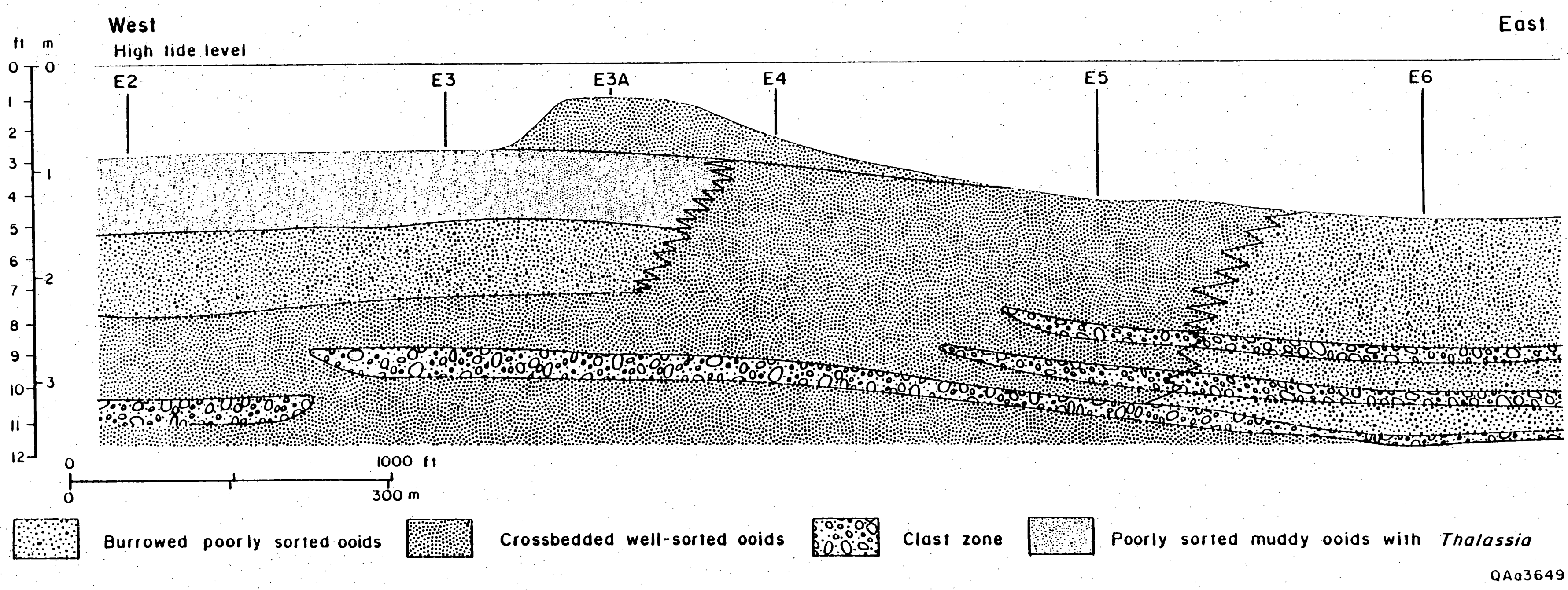

Figure 9. West-east cross section E–E′ before passage of Hurricane Andrew. Location of section shown in figure 2. Ooid bar less than 610 m (2,000 ft) wide at this location. Transition from crossbedded, well-sorted ooids into burrowed, poorly sorted ooids occurs on bankward side between E3 and E4 and on seaward side between E5 and E6. Single large bar crest was deposited as a storm washover and consists of less than 0.6 m (2 ft) of crossbedded, well-sorted ooids that overlie poorly sorted muddy ooids containing *Thalassia*. Thick clast zones, shown in offlapping occurrence at base of section, are best represented on this cross section.

seaward side of the E–E′ and F–F′ cross sections (fig. 9), where they occur in an offlapping pattern that reflects the northward migration of the shoal complex. The zones were correlated laterally as far as 600 m (~2,000 ft) during sediment probing and were traced even farther by Harris (1978, 1979) in his regional study. Porosity and permeability have not been greatly reduced in the clasts 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.

Oil and gas from a Lower Cretaceous reservoir in Alabama Ferry field, along the Texas Gulf Coast in Leon County, also produce from a grainstone (Lomando and others, 1987; Pollard, 1989; Bruno and others, 1991). Correlations across this Lower Cretaceous reservoir indicate the presence of several north-offlapping grainstone units separated by thin shales (fig. 14). This offlapping pattern resembles that observed at Joulters Cays, where bar migration occurs from southeast to northwest, parallel to the edge of the shelf. Porosity at Alabama Ferry is highest (as much as 20 percent) in the upper part and low at the base of each grainstone. At Joulters, we concluded that the rate of deposition was probably less in the lower part of the Joulters prograding shoal complex than in the upper, as evidenced by the presence of well-developed clast-rich zones, that is, hardgrounds and gravel zones (figs. 9 and 13). At Alabama Ferry, a similar low rate of deposition is also probable in the lower parts of the grainstone units, as indicated by isopachous fibrous cement, thought to be of marine origin, being more common. The offlapping pattern of ooid bars at Joulters, demonstrated by the shift in position of bar crests and the offlapping pattern of clast-rich zones as seen in cross section, is also expressed at Alabama Ferry by the northward shift in position of the grainstone units.

Mud Layers

Two discrete mud layers, the upper one 2 cm (3/4 inch) thick and the lower one 4 cm (1.5 inches) thick, separated by 4 cm (1.5 inches) of poorly sorted ooids (fig. 15) occur at the

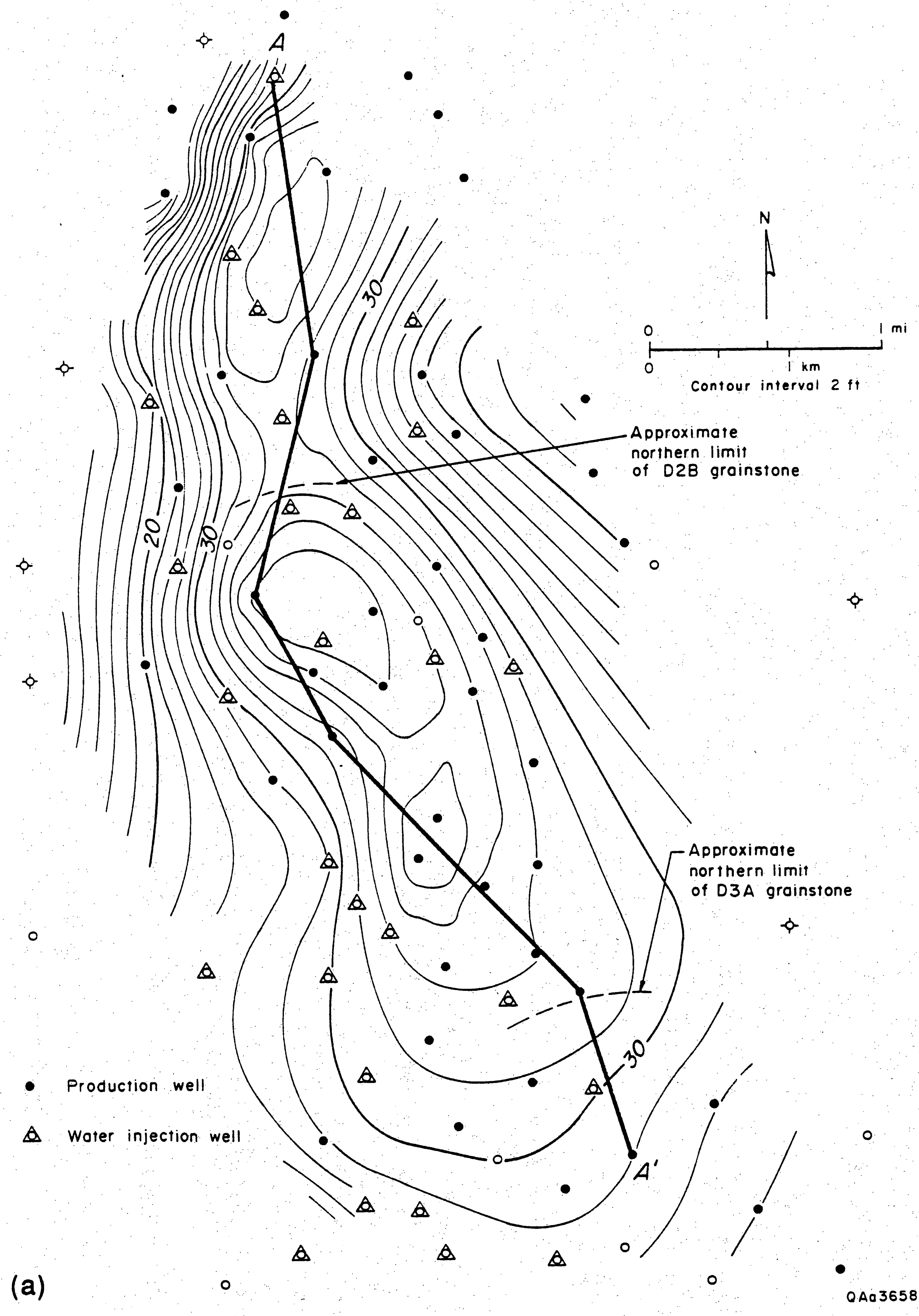

Figure 14. (a) Upper Glen Rose "D" (Lower Cretaceous) thickness and (b) north-south stratigraphic electric log cross section of Alabama Ferry field, Leon County, Texas. Offlap of three ooid and skeletal grainstone units from southeast to northwest indicated by arrows. Thickness map of Glen Rose includes all three grainstone units.

top of the burrowed, poorly sorted ooid facies in one core (core D3 of figure 8). Because these mud layers were not recovered in any other core, we think the layers are only local in distribution 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 streaks and fluid-flow barriers.

After the passing of Hurricane Andrew, Shinn and others (1993) also observed the occurrence of thin beds (as much as 5 cm [1.7 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 a major storm (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. Boardman and Carney (1991) attributed this accumulation of mud in the channels as resulting from ooid-sand barriers restricting channels.

Shinn and others (1993) presented an example of an approximately 1-cm-thick mudstone bed deposited within a crossbedded ooid grainstone in the Pleistocene Miami Limestone of south Florida, clearly demonstrating that these storm-related depositional features can be preserved in ancient rocks. Other ancient examples, from Upper Cambrian limestone and dolomite of western Newfoundland, Canada, were reported by Cowan and James (1992). The Upper Cambrian mudstone beds that occur interbedded with ooid grainstones of subtidal marine origin are somewhat thicker, including some as much as 4 cm (1.6 inches) thick.

Small-Scale Heterogeneity Patterns

Small-scale patterns of heterogeneity within the active part of the Joulters shoal (fig. 6a) are inferred from the facies distribution (figs. 8 and 9). The crossbedded, well-sorted ooids facies occurs in the center of the shoal complex and the entire area exposed at low tide, an area 305 to 607 m (1,000 to 2,000 ft) in width and 1.8 to 2.4 m (6 to 8 ft) in thickness. The burrowed, poorly sorted ooids facies occurs both bankward and seaward of the crossbedded, well-sorted ooids facies. Although the limits of the burrowed, poorly sorted ooids 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 bankward side; the burrowed, poorly sorted ooids and associated poorly sorted ooids with *Thalassia* and *Goniolithon* facies are 0.6 to 1.5 m (2 to 5 ft) thick at the shoal and thin bankward.

Heterogeneity is inferred because of mud content, burrowing, and grain type variations. These subtle variations occur on a scale of hundreds of meters, which is consistent with well spacing in mature hydrocarbon reservoirs like those of the Permian Basin. The scale of variation illustrated here should thus be considered in 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 core study. By analogy, similar subtle textural variations can be expected to produce local heterogeneity within ooid-grainstone reservoirs. Small-scale heterogeneity was well documented in ancient settings by Harris (1984a), Bebout and Harris (1990), and Keith and Zuppann (1993).

As discussed earlier, the proposed internal heterogeneities within ooid sands of the Joulters shoal are controlled by depositional and diagenetic processes. Thin sections show that both the crossbedded, well-sorted ooid and burrowed, poorly sorted ooid facies were mud free and had high initial porosity at the time of deposition (Halley and Harris, 1979). In some ancient subsurface settings, however, well-sorted ooid grainstones are cemented by calcite or anhydrite cement and have low resultant porosity (Bebout and others, 1987; Harris and Walker,

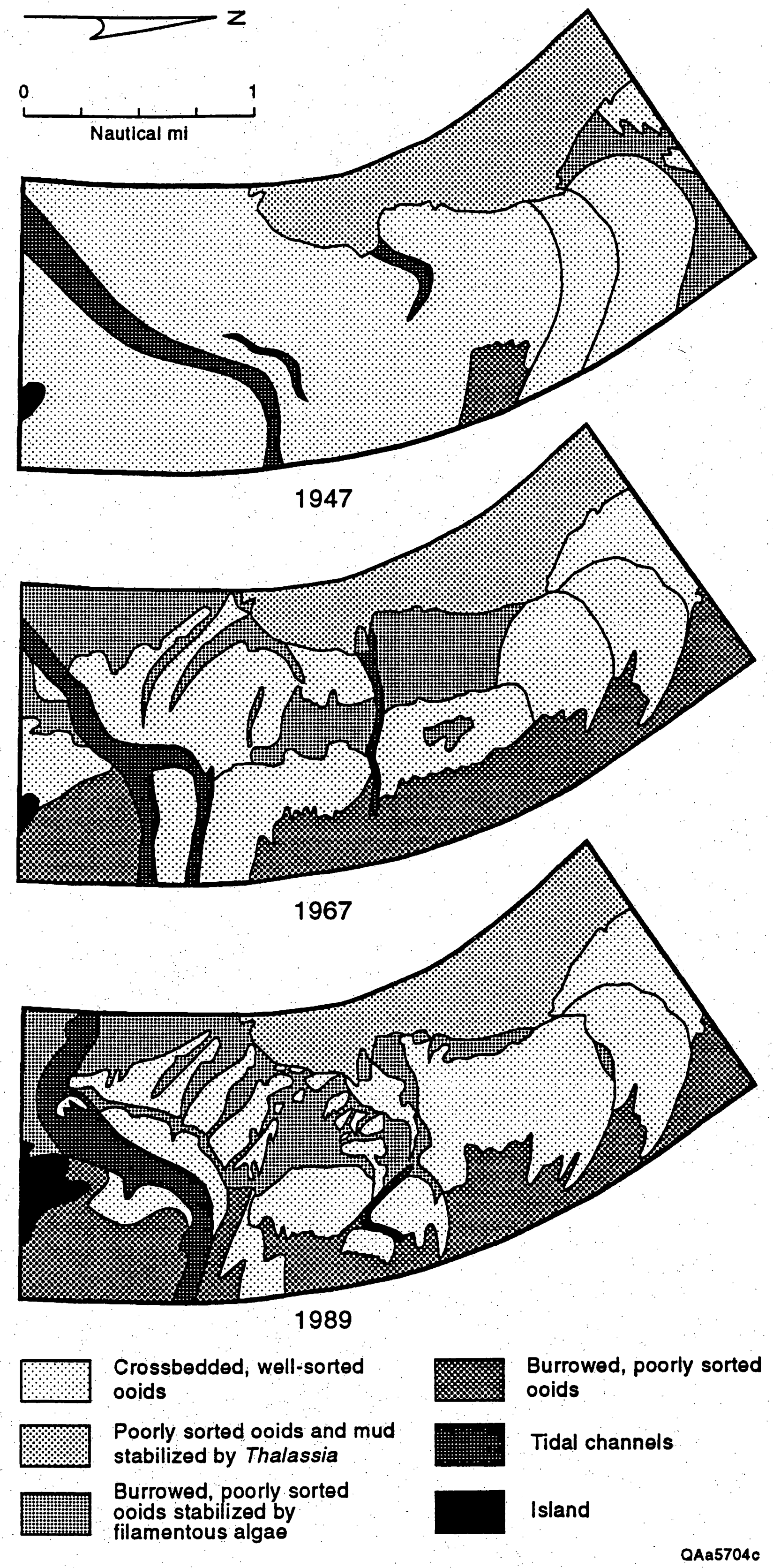

Figure 17. Surface sediment-distribution maps of the Joulters ooid shoal in (a) 1947, (b) 1967, and (c) 1989. Maps derived from aerial photographs (fig. 16) and cross sections (figs. 7, 8, and 9). Perspectives of 1947 and 1967 maps have been adjusted to oblique view of 1989.

By 1967 (figs. 16b and 17b) the washover bars of crossbedded, well-sorted ooids had migrated to the north end of the study area. In the south part of the study area washover bars had aggraded to a height sufficient that receding tidal currents were beginning to erode bar crests. The areas between washover bar highs contain burrowed, poorly sorted ooids partly stabilized by a surface coating of 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. 16c and 17c), the date the cores used in this study were collected, the washover bars in the south part of the study area were severely dissected by tidal currents, and large areas contained burrowed, poorly sorted ooids stabilized by 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 ooids and mud facies, which has remained remarkably stable for at least 40 yr.

The pattern illustrated by these changes that were recorded by aerial photographs suggests a general pattern of 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, were this pattern to continue without interruption, further progradation northward and aggradation in the center of the study area would result in the central tidal channel deepening and widening and the central washover bars becoming dissected.

SHORT-TERM MODIFICATION OF SURFACE MORPHOLOGY, FACIES PATTERNS, AND HETEROGENEITY

Before the passing of Hurricane Andrew on August 23, 1992, the study area (fig. 2) displayed distinctive surface features dominated by large wave- and tide-modified storm-

This pioneering study of a modern shoal complex at the hydrocarbon-reservoir scale met with both successes and failures. Coring and recovering undisturbed sediment from ooid sands has historically been difficult. Some of the cores taken from the Joulters shoal preserve original textures and structures, but many highly disturbed samples yielded few original features. In spite of this problem, we were able to reconstruct the depositional history of the ooid-shoal complex and derive information applicable to ancient hydrocarbon reservoirs. Future studies should be preceded by improving methods of coring unconsolidated grain bars.

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