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High-Resolution Multibeam Bathymetry of East and West Flower Gardens and Stetson Banks, Gulf of Mexico

JAMES V. GARDNER, LARRY A. MAYER, JOHN E. HUGHES CLARKE, AND ART KLEINER

The 1990s have seen rapid advances in seafloor mapping technology. Multibeam sonars are now capable of mapping a wide range of water depths with beams as narrow as 1°, and provide up to a 150° swath. When these multibeam sonars are coupled with an extremely accurate vehicle motion sensor and very precise navigation, they are capable of producing unprecedented images of the seafloor. This technology was used in December 1997 to map the East and West Flower Gardens and Stetson Banks, Gulf of Mexico. The results from this survey provide the most accurate maps of these areas yet produced and reveal features at submeter resolution never mapped in these areas before. The digital data provide a database that should become the fundamental base maps for all subsequent work in this recently established National Marine Sanctuary.

The East and West Flower Gardens and Stetson Banks are coralgal-encrusted piercement salt and shale diapirs on the edge of the U.S. Gulf Coast continental shelf (Fig. 1) that have attracted the attention of marine geologists since the 1930s (Shepard, 1937; Rezak et al., 1985 and references therein). The first bathymetric map of the area was produced by the U.S. Coast and Geodetic Survey in 1937 using leadlines. Because the banks are such unusual bathymetric highs on an otherwise smooth outer shelf, marine geologists over the years have constructed ever more detailed bathymetric maps of the banks using the latest echo-sounding equipment of the day. During December 1997, the U.S. Geological Survey (USGS), the Ocean Mapping Group at the University of New Brunswick (OMG), and C&C Technologies, Lafayette, LA, conducted sea trials in the Gulf of Mexico using a Kongsberg Simrad EM300 multibeam swath-mapping system, the latest generation of high-resolution multibeam systems. The EM300 was designed for water depths of 20–4,000 m, although we initially suspected it might perform best in depths greater than 100 m. To test the system, we searched for a small area with depths that range between 20 and 150 m. Stetson Bank and the Flower Gardens Banks fit our criteria, so we conducted our shallow-water trials in these areas.

Although the surveys were intended only for sea trials, the data quality is high enough to warrant publication. In fact, these new maps are vastly superior to any published bathymetry of these areas. This report consists of brief descriptions of the EM300 multibeam mapping system and the geomorphology of the East and West Flower Gardens and Stetson Banks, with

various maps and oblique views of the immediate areas. The images can be accessed on the World Wide Web at <http://walrus.wr.usgs.gov/pacmaps/> (click on Gulf of Mexico).

KONGSBERG SIMRAD EM300 MULTIBEAM SYSTEM

The theory behind high-resolution multibeam systems is discussed by Hughes Clarke et al. (1996). The EM300 system is one of a family of high-resolution multibeam mapping systems now available. We used an EM300 system owned and operated by C&C Technologies, Inc., and permanently installed on the RV *Ocean Alert*. The EM300 system consists of hull-mounted sonar arrays, a highly accurate vehicle motion sensor, and a dual-differential global positioning navigation system (DGPS).

The EM300 operates at 30 kHz, transmitting a swath of sound up to 150° athwartship and receiving from 135 electronically separated beams (Fig. 2). Achievable swath widths vary, depending on the water depth, ping rate, and pulse length, but were typically about 400 m in the shallow waters of these banks. The pulse length was less than 2 msec and the ping rate was typically 0.25 sec. Sound-velocity profiles (SVP) were routinely measured so that ray tracing techniques could be used to correct beam paths for the effects of acoustic refraction through the water column. Accurate ray tracing allows the precise location of each beam's footprint on the seafloor. SeaBird CTD stations (measures conductivity and temperature vs depth) were used to get a reference SVP, and Sippican T-5 expendable bathythermographs were periodically used throughout the duration of the survey to confirm or adjust the sound speed profile. Two additional sound ve-

Fig. 1. Index map of a portion of the northern Gulf of Mexico. Filled circles mark general location of the East and West Garden and Stetson Banks. The isobaths (50, 100, 150, and 200) are in meters.

locity sensors were installed at the transducer arrays to determine the speed of sound in water directly at the transducer. All the SVP data were fed into the Kongsberg Simrad EM300 processor for real-time ray tracing of each beam during each recording cycle.

Depth values for each beam were calculated from both amplitude and phase calculations. The EM300 system's quality control criteria determined the most reliable depth value, resulting in a measurement accuracy of $< 0.45\%$ (rms) of water depth. The amplitude of the signals returned from the seafloor from within the ensonified footprint are measured over the duration of the receive cycle and are recorded as a time series of received signal strength calibrated to the receive array. The backscatter signal strengths were used to generate a coregistered backscatter image, similar in appearance to a sidescan sonar record. One major difference is that the angular resolution of each beam of a multibeam is precisely known so that the backscatter pixel can be properly georeferenced and coregistered to the bathymetry. Another major difference between the multibeam backscatter image and a typical si-

descan sonar record is that the multibeam backscatter signal strength is calibrated to the outgoing signal strength and the receive array so that the backscatter values are in decibels, not an arbitrary signal strength distributed within an 8-bit range. However, because of manuscript length considerations, we do not discuss backscatter data in this report, although they can be found on the web site cited above.

The ship's pitch, roll, yaw, and heave motions were measured to $\pm 0.1^\circ$ or better at a 100-Hz sampling rate with an GPS-aided inertial-navigator vehicle motion sensor. Positions were determined by a DGPS system using a commercial satellite differential station. All of these measurements of ship attitude were used to compensate the soundings for ship motions. Although the multibeam system is capable of collecting hydrographic-quality data at speeds exceeding 15 knots, the Gulf of Mexico surveys were run at speeds that range from 9 to 14 knots.

Acoustic mapping systems measure the response from an ensonified footprint on the seafloor. The size and azimuth of this foot-

Fig. 2. Diagram depicting a multibeam system mapping a swath of seafloor. The fan-shaped feature beneath the ship depicts the 135 beams of the EM300 system.

print, in part, determine the resolution of the data. The pulse length and sampling rate become critical factors as the azimuth increases. The variation in footprint size is important to determine the gridding cell size for generating a digital map.

Data processing utilizes software developed by the OMG to process, analyze, and visualize the multibeam data sets (Hughes Clarke et al., 1996; Mayer et al., 1997; Paton, et al., 1997). Data processing (Fig. 3) consisted of (1) editing the navigation data to flag bad fixes; (2) editing each ping to flag outliers, bad data, etc.; (3) merging the depth and backscatter data with the cleaned navigation; (4) reducing all depth values to mean lower low water based on measured tides; (5) performing any additional refraction corrections; (6) separating out the amplitude measurements for conversion to backscatter; (7) gridding depth and backscatter data at the highest resolution possible for a given water depth; (8) regridding individual subareas of bathymetry and backscatter into final map sheets; (9) gridding and contouring the bathymetry; and (10) producing the final maps and 3D visualizations.

First-order derivative maps produced for each area consist of contour, shaded-relief, and backscatter maps, as well as oblique views. Bathymetric contour maps are familiar representations of the seafloor; however, because the seafloor has been so thoroughly covered with soundings by the multibeam system, a contour map would represent less than 10% of the multibeam soundings. Therefore, we used a shaded-relief map to show 100% of the bathymetric data. A shaded-relief map is a pseudo-sun illumination of a topographic surface, treating the seafloor as a Lambertian surface (Eq. 1),

$$B = I(\cos \Phi), \quad (1)$$

where B is the pseudo-sun brightness, I is the maximum brightness, and Φ is the angle between the pseudo-sun and a normal to the bathymetric surface.

SETTING

Stetson Bank and the Flower Garden Banks are located about 200 km south of the Texas-Louisiana border on the outer continental

Fig. 3. Flow diagram outlining the major processing steps used for the Stetson and Flower Garden Banks data.

shelf (Fig. 1). The banks occur within a zone of outer-shelf diapirs (Shepard, 1937; Curray, 1960). The surface sediments of the shelf are composed of reworked late Quaternary and Holocene bioclastic and terrigenous sands and silty clays that have been reworked by repeated sea level fluctuations. The geology of the East and West Flower Gardens and Stetson Banks has been detailed by Rezak et al. (1985). The banks are surface expressions of salt or shale piercement diapirs (Shepard, 1937; Rezak et al., 1985) that are capped with corallgal reefs to form the northernmost coral reefs in North America (Rezak et al., 1990). In 1992, the East and West Flower Garden Banks were designated as the Flower Garden Banks National Marine Sanctuary; Stetson Bank was added to the sanctuary in 1996.

STETSON BANK

Stetson Bank is located about 50 km north of the continental shelf break (Fig. 1). Published literature on Stetson Bank is rather sparse. Shepard (1937) discusses surface expressions of salt domes of the Gulf of Mexico

and included the area of Stetson Bank. Lankford and Curray (1957) sampled Stetson Bank and reported middle Miocene sandstones and claystones dredged from its surface, but they did not mention any samples of salt. Their sample descriptions include the mention of slickensides, suggesting faulting. Lankford and Curray (1957) used the middle Miocene age to suggest Stetson Bank had been uplifted many thousands of feet by a salt dome intrusion.

Stetson Bank (Fig. 4) was the first area surveyed during the sea trials; consequently, the data contain some artifacts that were corrected later during the trials. Even though some of the artifacts are obvious in the images, the data quality is still good enough to provide an excellent view of the area and to construct accurate maps. Artifacts are manifested as track-parallel nadir stripes and noise that resembles random, small-scale, relief on the flat portions of the seafloor; however, this noise has a depth amplitude of less than 100 cm. The causes of most of the artifacts were eliminated by the end of the sea trials.

The multibeam bathymetry shows Stetson Bank is 800 m long, 300 m wide, and abruptly rises 36 m above the 53-m depth of the local seafloor at its highest point (17 m water depth). The northwest side has a slope of 18°, the southeast side has a slope of 20°, the slope of the southwest nose is 29°, and the slope of the northeast nose is 18°. However, short sections of the flanks have much steeper slopes. The south side of the block is suspiciously straight, suggesting fault control. The block rises within a 2,500-m diameter circular arc with a maximum of 2.5 m of relief on the northeast (Fig. 5b) and about 1 m of relief on the rest of the perimeter. The arc around Stetson Bank resembles the outline of a salt dome, lending support to earlier interpretations of the Stetson Bank feature (Shepard, 1937). A few depressions, generally less than 2 m deep, are found within the rim on the west and northwest sides (Fig. 5b). A trawl mark incises the seafloor just northwest of the Stetson block (Fig. 5a). The trawl mark is about 50 cm deep and tracks for more than 1,500 m.

Oblique views of Stetson Bank (Fig. 5a,c,d) are not particularly dramatic, but they do demonstrate the relatively flat summit and uncomplicated flanks of the feature. Small-scale relief (~ 1 m) is found on the top of the bank, and there is some hint of northwest-trending structure near the northeast nose (Fig. 5d).

Fig. 4. North-looking oblique view of color-coded shaded-relief bathymetry of Stetson Bank. Vertical exaggeration 5 $\times$. See Figure 5b for scale.

WEST FLOWER GARDEN BANK

West Flower Garden Bank (WFG; Fig. 6) is located about 70 km southeast of Stetson Bank (Fig. 1) along the outer edge of the continental shelf in about 120 m of water. WFG has been described as a “much older” salt dome (Rezak et al., 1985). A consensus opinion is that there has been a large amount of salt removal at the WFG site, causing significant movement along associated faults. WFG is thought to rest directly on a northeast-southwest trending crestral graben (Rezak et al., 1985). A reasonably good bathymetric map that captures the general large-scale morphology of WFG was produced by Edwards (1971) using a wide-angle single-beam depth recorder and Loran, Omega, and satellite navigation.

The multibeam bathymetry show West Flower Garden Bank to be roughly rectangular in shape with sides of 6.5 by 8.9 km, rotated about 35° from north (Fig. 7). The bank is composed of a broad region with three distinctive summit plateaus. The most prominent and highest plateau is about 3,000 by 1,800 m in size and occupies an area between the 40- and 50-m isobaths. This feature rests on a gently inclined regional seafloor that deepens from the 110-m isobath at the northwest corner of the survey

to the 170-m isobath at the southeast corner. Rezak and Bryant (1973) describe observing a drowned reef at 128 m depth, which suggests the edges of the plateau are composed of reef material. The west and south sides of the plateau are linear (Fig. 8) and are most likely fault scarps previously mapped by Trippet (1980) and described by Rezak et al. (1985). A relatively flat, footprint-shaped, summit area about 1,000 by 200 m in size rises 20 m above the plateau and is roughly oriented east-west. This summit area is the region described by Rezak (1985) and Rezak et al. (1985, 1990) as supporting a living coral reef. The shoalest depth of the summit area is 18 m water depth. The summit area has steep northeast (22°) and northwest (15°) sides but gentler southwest (6°) and southeast (11°) sides.

The second, irregularly shaped plateau is located about 3 km west of the prominent plateau (Figs. 7, 8a), separated by a shallow 1,000-m wide depression. Like the major plateau, this one also is in water depths between 40 and 50 m. However, this plateau has no shallow summit area. The shoalest point on this plateau rises only to 48 m water depth. The third plateau is teardrop shaped and about 2.2 km north of the major plateau (Fig. 7) and sepa-

Fig. 5. (a) Oblique view of grayscale shaded-relief bathymetry of area southwest of Stetson Bank, looking north. Arrowheads point out systematic artifacts. (b) Plan view of shaded-relief bathymetry of Stetson Bank with illumination azimuth of 045° (c) Oblique view of Stetson Bank looking south. (d) Oblique view of Stetson Bank looking southwest. Vertical exaggeration 6× on all images.

rated from it by a 800-m wide depression. This third plateau is the smallest of the three in size and rises only to 64 m water depth.

A 1,500-m wide and 10-m deep moat exists on the west side of WFG (described by Trippet, 1985), but there is also a gentle swale on the southeast side that is 200 m wide at its north end and broadens to 1,200 m wide on its south end. This swale varies in relief from 5 to 25 m, becoming deeper toward the southwest. It is difficult from the geomorphology to speculate whether either of these depressions are the result of current scour, as suggested by Trippet (1985), or whether they represent subsidence related to salt dome tectonics.

The remaining region mapped in the West Flower Garden Bank area is composed of a variety of small-scale features (Figs. 7, 8). Numerous pinnacles are scattered along the edges

of the plateaus but rise less than 5 m above the regional seafloor. Several linear troughs (grabens?) traverse the area that correlate with faults mapped by Trippet (1980). The most prominent trough occurs southwest of the main plateau and is 25 m deep and 700 m wide, trending northwest to southeast for at least 4,000 m across the mapped region. A second trough, previously unmapped, trends north away from the major plateau and borders the teardrop-shaped plateau on its east side. This trough is up to 1,700 m wide and about 15 m deep and has several apparent fault scarps running through it. A third, previously unmapped, trough is located to the southeast of the major plateau that trends south-southwest. This trough is a gentle swale that descends from the 130-m isobath to the 155-m isobath over 4.7 km. The trough varies

Fig. 6. North-looking oblique view of color-coded shaded-relief bathymetry of West Flower Garden Bank. Vertical exaggeration 5 $\times$; illumination azimuth of 045°. See Figure 7 for scale.

from 300 to 1,400 m wide and opens to the south. A gentle swale with less than 2° gradients borders the northwest side of the rectangular bank. This swale appears to be a moat similar to those that commonly accompany intrusive salt domes.

Numerous linear offsets with less than 2 m of relief trend west–southwest across the broad region of West Flower Garden Bank. These generally correlate to faults, many of which were mapped by Trippet (1980). The only slumping identified in the multibeam data occurs on the southwest corner of the plateau along the prominent fault scarp (Fig. 7) with a debris pile that extends about 1,000 m to the southwest out onto the seafloor.

EAST FLOWER GARDEN BANK

East Flower Garden Bank (EFG; Fig. 9) is located approximately 22 km east–northeast from WFG (Fig. 1) along the outer edge of the continental shelf. The seafloor surrounding EFG gently dips from water depths of 100 m in the north of the survey to 140 m in the south. The pear-shaped EFG bank (Fig. 10) has a long north–south axis of 8.7 km and a shorter east–west axis of 5.2 km. The bank has north and west flanks that gradually rise above the regional seafloor, but the eastern flank has slopes in excess of 8° and the southern flank has slopes of 22° (Fig. 11). The bank appears to be composed of three steps (Fig. 11c); the

lower step rises about 10 m above the regional seafloor, then there is a 350-m wide bench at the 75-m isobath. The second step rises 20 m above the first step to the 55-m isobath and varies in width from 200 to 2,300 m. The third step rises 10 to 13 m to the 45-m isobath and is up to 250 m wide. The steps are best developed on the southwest side (Fig. 10), but it is difficult to determine from the geomorphology whether these benches are wave-cut or constructional features. The summit platform of EFG is actually two platforms, separated by 380 m. The southern summit platform has the shoalest point of 19 m water depth. This platform has been described by Rezak et al. (1985, 1990) as supporting living coral reef. The northern platform is similar in size and shape to the southern one. The northern platform rises only to 30 m water depth and is separated from the main platform by a 730-m-wide trough. The northern platform has previously been mapped as a continuation of the main platform.

There is a persistent 300° trend to lineations that are presumably faults related to the active diapir. Rezak et al. (1985) suggest most of the faulting is concentric, following the map of Trippet (1980). However, if the lineations are traces of faults, then the pattern is more radial than concentric. A relatively large depression, roughly square in shape, occurs on the southeast corner of the bank (Figs. 10, 11d). The depression appears to be outlined by a conju-

Fig. 7. Plan view of grayscale shaded-relief bathymetry of West Flower Garden Bank. Dashed line outlines slumped material. Illumination azimuth is 045°.

gate set of faults that trend 350° and 054°. Most of the fault lineations radiate out toward the northwest; the exceptions are the steep eastern and southern sides of the platform.

Smaller scale features mapped within EFG include pinnacles that are concentrated on the southwestern and north-central sides of the survey that rise up to 5 m above the seafloor (Fig. 11b). Pock marks, presumably gas escape features, are found in three zones on the east, west, and south sides of the platform (Fig. 10). Individual pocks are up to 25 m across and 1–2 m deep. A small field of bedforms (Figs. 10, 11b) with wavelengths of about 25 m and wave

heights of ~ 50 cm occurs on the western flank of the platform.

A major feature of scientific interest has been the a small brine pool and outflow canyon at the southeastern corner of EFG (Figs. 10, 11d). This feature has been studied (Brooks et al., 1979; Bright et al., 1980a,b; Rezak and Bright, 1981), especially for the geochemistry of the brine and the biotic assemblages contained within and surrounding the feature. There are three small depressions on the outer southeastern edge of EFG, all within a much large basin. The basin is 2,000 by 1,280 m in size and is 5–12 m deeper than the sur-

Fig. 8. (a) Oblique view of West Flower Garden Bank looking northwest. (b) Oblique view of West Flower Garden looking south. (c) Oblique view of West Flower Garden looking west. (d) Oblique view looking south. Vertical exaggeration 5 $\times$ on all images. See Figure 7 for scale.

Fig. 9. North-looking oblique view of color-coded shaded-relief bathymetry of East Flower Garden Bank. Three small depressions are indicated; the northern depression has a known brine pool. Vertical exaggeration 5X. See Figure 10 for scale.

rounding bank top. The center of the floor of the basin is at 51–52 m water depth, but two low-relief channels ring the central portion—one at the 57-m and the other at the 56-m isobath—and are separated by a sill on the western side that rises to 50 m water depth. The northern depression, which contains the known brine pool, is 110 by 80 m in size and about 8 m deeper than the upper surface. There is an outflow canyon on the depression's southern side. The outflow canyon descends from 69.2 to 75 m in a distance of 72 m before it disappears on the flank of the bank. A second shallow outflow leads from the northern depression to the middle depression, although it is only 2 m deep. The middle depression is 110 by 120 m in size and is 4 m deeper than the bank surface. This depression has no outflow. The southern depression is only 25 by 25 m in size and is 6 m deeper (63.7 m water depth) than the bank surface. This depression has an outflow channel that courses from the southern side of the depression. However, there is a 5-m sill immediately down-channel from the depression, then the channel drops to the 59.4-m isobath. The southern depression also may contain a brine

pool, although it has not previously been mapped (Steve Gittings, pers. comm.).

CONCLUSIONS

The high-resolution digital maps and images of the Stetson and Flower Garden Banks provided by current seafloor mapping technology offers opportunities for interpretation of geological processes and features not heretofore available. The possibility of disseminating digital data via the World Wide Web is another indication of the evolving methods of making vast quantities of data available to the interested researcher. The data created by this mapping effort, and the derivative maps, should become the fundamental base maps for the next generation of multidisciplinary researchers and managers of the Stetson and Flower Garden Banks.

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Fig. 10. Plan view of grayscale shaded-relief bathymetry of East Flower Garden Bank. Dashed lines outline areas of pock marks; solid lines outline bedform fields. Illumination azimuth is 045°.

Fig. 11. (a) Oblique overview of bedform field (foreground) on west-central flank of East Flower Garden Bank looking southeast. (b) Close-up view of bedforms looking north. (c) Oblique overview of East Flower Garden looking north. (d) Close-up oblique view of East Flower Garden brine pool depression. (e) Oblique view of East Flower Garden looking south. Vertical exaggeration 5× on all images. See Figure 10 for scale.

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