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Sedimentary Environments of East and West Flower Garden Banks Area

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SHORT PAPERS AND NOTES

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SEDIMENTARY ENVIRONMENTS OF EAST AND WEST FLOWER GARDEN BANKS AREA.—The Flower Garden Banks lie in the northwestern Gulf of Mexico on the outer continental shelf, about 170 km due south of the Texas–Louisiana border (Fig. 1) and comprise the northernmost tropical coral reefs in the United States. Although fishermen have appreciated the productivity of the "Flower Gardens" for more than 100 yr, it was not until the 1970s that the general public began to urge that these fragile ecosystems be afforded protection. Between 1992 and 1996, three small areas were set aside as a National Marine Sanctuary (Gardner et al., 1998). The East Flower Garden Bank (EFGB) and West Flower Garden Bank (WFGB) lie at the shelf edge in regional water depths of 100–150 m and encompass about 66 and 77 km^2, respectively. Stetson Bank lies about 55 km northwest of WFGB in about 60 m of water and is less than 4 km^2 in area. The tops of the reefs in these three areas rise dramatically above the surrounding seafloor, in places to within 20 m of the water surface. A fortuitous combination of biological, geological, and oceanographic factors (including uplift of rock strata by upward flowing salt, the formation of submarine brine pools, and currents that deliver larvae from Caribbean reef organisms) allowed the formation of these isolated reefs, making them a fascinating and important natural laboratory for interdisciplinary studies (e.g., Rezak et al., 1985; Gittings and Hickerson, 1998).

To effectively manage or protect (or both) this unique marine ecosystem, it is necessary to know the extent and character of the seafloor substrate that supports it. For this reason, we constructed reconnaissance-scale maps of the distribution of seafloor sedimentary environments, using texture and carbonate-content data from 107 seafloor sediment samples collected within and near the EFGB and WFGB areas. Previously collected multibeam bathymetry and backscatter data (Dartnell and Gardner, 1999) and biologic zonation maps (Rezak et al., 1985) were used to supplement the new analytical data. The resulting maps of seafloor types are intended for resource managers and can be used, with additional data, as a basis for future habitat mapping.

Previous work.—Scientists from government agencies, the oil industry, and academic institutions have carried out numerous studies of these unusual coral reef and brine pool ecosystems both before and after the designation of the banks as a National Marine Sanctuary in 1992. These studies, by expanding our knowledge about and our understanding of the region, contribute to effective management of the Sanctuary. Most of the studies, however, have concentrated on biological and ecological aspects of the area; geologic studies have been less numerous, and very few sedimentologic studies have been done. Curray (1960) established the regional sedimentary framework for the northwestern Gulf of Mexico, but this scale is not sufficient for management needs. Edwards (1971) first described sedimentary facies of WFGB. Rezak et al. (1985) subsequently expanded Edwards' work to EFGB and the surrounding area. These studies subdivided the carbonate sediments into four facies on the basis of their major components and classified the terrigenous sediments on the basis of texture. This excellent body of work suffers only from relatively sparse sampling and the less-accurate navigation of the time period. The U.S. Geological Survey (USGS) published preliminary maps of the topography, geologic structures, and sediment thickness of EFGB and WFGB (Trippet, 1980), but these were based on seismic reflection data and did not include sediment sampling. Studies by scientists and students at Louisiana State University, Texas A&M University, other academic institutions, and in NOAA's (National Oceanic and Atmospheric Administration) National Marine Sanctuary Program have addressed some aspects of geology and physical habitat of the banks. Much of this work is summarized in Rezak et al. (1985) and Roberts et al. (1999). Recently, multibeam bathymetry and acoustic backscatter coverage of all three parts of the Flower Garden Banks National Marine Sanctuary were collected by the USGS (Dartnell and Gardner, 1999). The area that lies between the banks is not part of the Sanctuary and was not included in the multibeam survey (Figs. 3, 4). In 2004, additional multibeam bathymetry and acoustic backscatter data were collected from the Flower Garden Banks and the surrounding area by NOAA (Hickerson and Schmahl, this issue), but they were not available for use in this study.

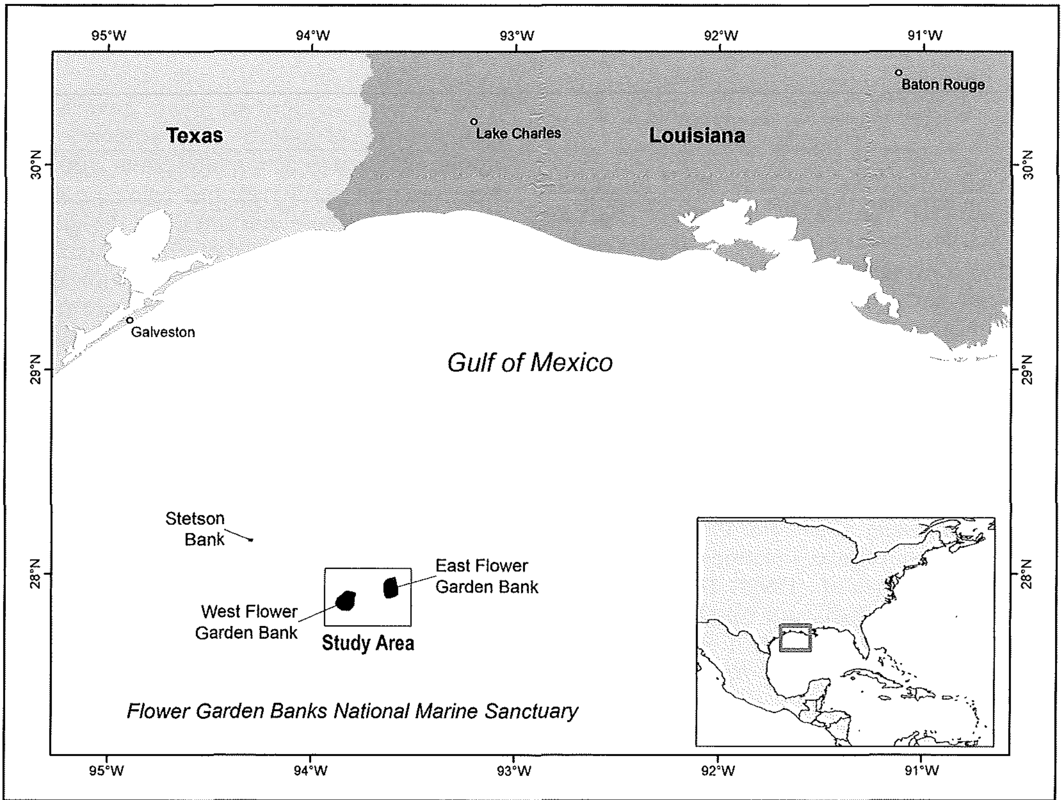

Fig. 1. Location map, showing the study area and the boundaries of the Flower Garden Banks National Marine Sanctuary in the northwestern Gulf of Mexico.

Methods.—A total of 107 sediment samples were collected and analyzed for sediment grain size and $CaCO_3$ content in this study. Approximately equal numbers of samples were collected from EFGB, WFGB, and the surrounding shelf. No samples were taken on or near Stetson Bank. All samples were collected during USGS cruise FERL01052 on the NOAA ship *FERREL* between 27 May 2001 and 02 June 2001, using a modified Van Veen sediment grab sampler (Fig. 2). This sediment grab takes a relatively undisturbed sample about 32 by 32 cm in area and about 15 cm deep. The samples for grain size and calcium carbonate analysis were taken from the upper 2 cm of the sediment in the grab. Grain size analyses were done in the USGS Sediment Lab in Woods Hole, MA, according to procedures detailed in Poppe and Polloni (2000). Fifty grams of sediment from each grab sample was analyzed, unless the sample contained gravel, then the entire sample collected was used. The samples were weighed before and after desiccation, and the dry weight was adjusted for salt content of the seawater. The samples were disaggregated and then wet sieved through a number 230, 62-μ (4ø) sieve to separate the coarse and fine fractions. The coarse fraction was dry sieved through a number 10, 2.0-mm (-1ø) sieve to separate the sand and gravel. The sand fraction was dry sieved at whole phi intervals, using a Ro-Tap shaker. The size distribution within the gravel fraction was determined by sieving. The fine fraction was analyzed by Coulter Counter. Calibration for this study allowed determination of the distribution down to 0.7μ or about two thirds of the 11ø fraction. Because clay particles finer than this diameter and the entire colloidal fraction were not determined, a slight decrease in the 11ø (and finer) fraction is present in the size distributions. For the purposes of this report, we used the sediment classification scheme of Folk (1974) to describe sediment types.

Carbonate analyses were also carried out in the USGS Sediment Lab in Woods Hole, MA. The percentage of calcium carbonate material was determined by weight loss of 15 g of bulk material after digestion with 10% HCl.

A summary of the sediment analyses, indi-

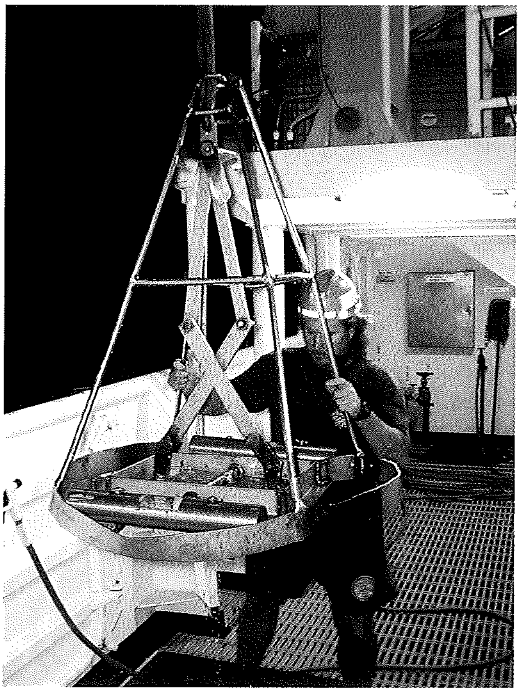

Fig. 2. Modified vanVeen sediment grab sampler shown being recovered with the jaws shut.

cating weight percentages of gravel, sand, silt, and clay size particles and $CaCO_3$ content, is given in Table 1. The complete analytical data are available as downloadable Excel files and in an ArcView project on a CD-ROM (Scanlon et al., 2003) or can be downloaded without charge from a USGS publications web site (http://pubs.usgs.gov/of/2003/of03-002). The complete analytical data consist of 70 fields, including weight percentages of size classes for phi units from 0 to 11, means, modes, skewness, kurtosis, and other statistical data.

Discussion of data.—Interpretation of sediment texture data from an area such as the Flower Garden Banks, where clastic terrigenous sediments are found in association with biogenic carbonate sediments, is not straightforward. For example, in a clastic depositional environment, it can be assumed that the largest grains are related to the maximum current speed present during deposition. In a biogenic depositional environment, the largest grains may be pieces of shell that are present because the animal lived and died there and have no bearing on the dynamics of sediment deposition. For this reason, we analyzed the $CaCO_3$ content of each sediment sample, in addition to the texture. Samples that have a high percentage of $CaCO_3$ (>60%) are assumed to be mainly biogenic in origin, whereas those low in $CaCO_3$ (<40%) are assumed to be made up predominantly of clastic terrigenous sediments.

For the map of seafloor types (Figs. 3, 4), we have relied on the works of Trippet (1980), Rezak et al. (1985), Gardner et al. (1998), and Dartnell and Gardner (1999) in addition to the new sedimentologic data to help define mappable units. We identified four major types of seafloor: high-relief hardbottom, low-relief hardbottom, coarse-grained biogenic sediment, and fine-grained terrigenous sediment. To delineate the contacts between high-relief hardbottom and low-relief hardbottom, we relied on the multibeam bathymetry and acoustic backscatter data, which are located within the Sanctuary boundaries. No sediment samples were taken in those areas because they are close to living reefs. The coarse-grained biogenic sediment and fine-grained terrigenous sediment were defined by sediment texture (Fig. 3) and carbonate content (Fig. 4), and contacts between them were delineated with the help of the multibeam bathymetry and backscatter data. Outside the Sanctuary boundaries, nearly all the samples are fine-grained terrigenous sediment. We did not attempt to draw contacts between sediment types outside of the Sanctuary boundaries, where no multibeam data were available.

Any sediment texture classification creates artificial boundaries between sediments of different types. In the real world, changes in sediment textures can be abrupt, but more often, are gradational. The difference between samples classed as sandy mud and muddy sand, for example, may be less than a percentage point in sand content. Within each of the seafloor types described here, there is a great deal of consistency in the texture and carbonate content of the sediment samples, although some variability exists because of the inherent "patchiness" of continental shelf sedimentary environments. In places, a sediment sample with texture or carbonate content differing from others nearby may be included within a larger, more dominant, seafloor type.

Sedimentary environments.—Four units, defined on the basis of a combination of the seafloor topography, the roughness of the seafloor, the presence or absence of sediment, and the texture and carbonate content of the sediment, represent the major sedimentary environments in the Flower Garden Banks area (Figs. 3, 4).

TABLE 1. Summary of sediment texture analyses and carbonate analyses. Depth refers to water depth in meters. % Gravel is the weight percentage of particles −1 phi or larger. % Sand, % silt and % clay are the weight percentages of particles from 0 to 4 phi, 5 to 8 phi, and 9 phi and smaller, respectively. The complete analytical data can be found in Scanlon et al. (2003).

Sample ID	Depth (m)	Latitude	Longitude	% $CaCO_3$	% Gravel	% Sand	% Silt	% Clay	Folk (1974) classification
FGB01-1A	105	27.92167	−93.88500	19.35	0.77	47.57	20.88	30.78	Slightly gravelly sandy mud
FGB01-2	118	27.90167	−93.88330	25.82	0.07	13.10	49.89	36.94	Slightly gravelly sandy mud
FGB01-3	125	27.88083	−93.88370	38.31	0.71	24.89	40.59	33.80	Slightly gravelly sandy mud
FGB01-4	116	27.86017	−93.88400	63.01	0.18	56.77	18.14	24.90	Slightly gravelly muddy sand
FGB01-5	120	27.83950	−93.88420	62.11	0.06	56.29	21.70	21.95	Slightly gravelly muddy sand
FGB01-6	150	27.81900	−93.88450	35.24	0.08	12.98	38.92	48.02	Slightly gravelly sandy mud
FGB01-7	110	27.92250	−93.86350	20.07	0.00	58.25	21.47	20.28	Muddy sand
FGB01-8	174	27.90200	−93.86330	26.42	0.00	8.12	49.01	42.87	Mud
FGB01-9	89	27.88067	−93.86280	75.01	9.12	61.31	12.32	17.25	Gravelly muddy sand
FGB01-10	76	27.86017	−93.86300	96.88	2.46	96.51	0.35	0.68	Slightly gravelly sand
FGB01-11A	110	27.83950	−93.86270	66.17	32.19	39.65	13.49	14.68	Muddy sandy gravel
FGB01-12A	145	27.81833	−93.86330	27.53	0.00	3.47	40.00	56.53	Mud
FGB01-13	109	27.92267	−93.84220	25.38	0.07	44.43	35.71	19.79	Slightly gravelly sandy mud
FGB01-14	112	27.90217	−93.84300	48.09	0.00	45.66	32.74	21.60	Sandy mud
FGB01-15	79	27.88083	−93.84230	94.13	18.30	76.84	1.78	3.08	Gravelly mud
FGB01-16	89	27.86000	−93.84380	83.37	1.10	77.68	8.52	12.70	Slightly gravelly muddy sand
FGB01-16RED	87	27.79200	−93.88630	30.45	0.04	8.40	39.79	51.77	Slightly gravelly mud
FGB01-17B	87	27.84000	−93.84320	95.76	3.43	95.36	0.49	0.73	Slightly gravelly sand
FGB01-17RED	179	27.79183	−93.84630	27.86	0.00	1.34	38.56	60.10	Mud
FGB01-18	137	27.82050	−93.84500	28.81	0.01	2.64	47.92	49.43	Slightly gravelly mud
FGB01-18RED	208	27.79200	−93.80200	28.19	0.00	1.54	31.16	67.30	Clay
FGB01-24	117	27.92283	−93.82230	34.78	2.23	39.98	28.35	29.44	Slightly gravelly sandy mud
FGB01-25	102	27.92033	−93.78420	29.08	0.00	49.90	28.72	21.38	Sandy mud
FGB01-26	79	27.90150	−93.80100	91.17	12.34	80.82	2.96	3.88	Gravelly sand
FGB01-27	85	27.88217	−93.80020	85.18	7.27	75.52	6.29	10.92	Gravelly muddy sand
FGB01-28	105	27.83967	−93.82130	63.65	3.90	51.03	15.78	29.29	Slightly gravelly muddy sand
FGB01-29	140	27.81883	−93.82230	28.21	0.21	3.22	45.08	51.49	Slightly gravelly mud
FGB01-30B	150	27.81900	−93.80250	27.80	0.00	12.58	33.87	53.55	Sandy mud
FGB01-31B	120	27.83917	−93.80170	34.68	0.02	12.89	45.13	41.95	Slightly gravelly sandy mud
FGB01-31RED	154	27.82133	−93.91650	28.77	0.00	4.51	35.19	60.31	Mud
FGB01-32	97	27.85983	−93.80130	80.22	10.23	68.00	10.80	10.98	Gravelly muddy sand
FGB01-32RED	123	27.86067	−93.91700	27.48	0.06	4.96	39.99	54.98	Slightly gravelly mud
FGB01-33A	150	27.81867	−93.77880	28.01	0.00	1.75	41.26	56.99	Mud
FGB01-34	130	27.84017	−93.77970	27.25	0.00	3.44	47.61	48.96	Mud

TABLE 1. Continued.

Sample ID	Depth (m)	Latitude	Longitude	% $CaCO_3$	% Gravel	% Sand	% Silt	% Clay	Folk (1974) classification
FGB01-35	125	27.86033	−93.78000	31.02	0.58	11.64	38.24	49.54	Slightly gravelly sandy mud
FGB01-36	110	27.88033	−93.78150	29.66	0.00	9.12	54.33	36.55	Mud
FGB01-37	105	27.90167	−93.78100	33.67	0.00	32.03	34.89	33.08	Sandy mud
FGB01-38	103	27.92283	−93.78080	27.94	0.01	38.48	40.30	21.21	Slightly gravelly sandy mud
FGB01-39	111	27.90133	−93.93380	22.18	0.00	25.66	42.60	31.74	Sandy mud
FGB01-40	89	27.96350	−93.88420	12.92	0.00	76.69	16.23	7.08	Silty sand
FGB01-41	76	28.00200	−93.88600	11.35	0.27	89.46	4.52	5.75	Slightly gravelly muddy sand
FGB01-42	90	28.00183	−93.84530	17.58	0.01	59.60	21.73	18.66	Slightly gravelly muddy sand
FGB01-43	92	27.96333	−93.84570	16.44	0.00	61.71	23.65	14.63	Muddy sand
FGB01-44	98	27.96367	−93.80020	19.01	0.00	41.90	32.17	25.93	Sandy mud
FGB01-45	82	28.00200	−93.79970	22.66	0.10	79.18	11.36	9.36	Slightly gravelly muddy sand
FGB01-46	90	28.00283	−93.75230	19.76	0.04	31.52	41.05	27.40	Slightly gravelly sandy mud
FGB01-46BOTTOM	90	28.00283	−93.75230	20.65	0.01	43.36	33.31	23.33	Slightly gravelly sandy mud
FGB01-47	98	27.96317	−93.75220	22.07	17.80	16.10	30.39	35.71	Gravelly mud
FGB01-48	105	27.89983	−93.75250	29.55	0.00	21.60	45.31	33.09	Sandy mud
FGB01-49A	139	27.83967	−93.76930	26.89	0.06	4.13	42.33	53.48	Slightly gravelly mud
FGB01-50	193	27.79017	−93.75230	26.70	0.00	1.42	28.58	70.00	Clay
FGB01-51	160	27.79033	−93.71400	33.59	0.08	13.24	30.78	55.90	Slightly gravelly sandy mud
FGB01-52	133	27.83883	−93.71450	35.61	0.02	38.97	23.98	37.04	Slightly gravelly sandy mud
FGB01-53	103	27.90100	−93.71370	36.11	0.04	27.79	55.48	16.69	Slightly gravelly sandy mud
FGB01-54	96	27.96233	−93.71430	24.51	0.23	34.65	38.89	26.23	Slightly gravelly sandy mud
FGB01-55	97	28.00117	−93.71330	20.44	0.59	47.23	29.26	22.92	Slightly gravelly sandy mud
FGB01-56	97	28.00167	−93.67250	26.15	0.11	62.03	27.44	10.42	Slightly gravelly muddy sand
FGB01-57	97	27.95500	−93.68070	33.07	0.05	36.15	43.03	20.77	Slightly gravelly sandy mud
FGB01-58	103	28.90017	−93.67180	46.76	0.08	33.97	32.45	33.50	Slightly gravelly sandy mud
FGB01-59	124	27.83900	−93.67250	47.99	0.74	57.02	22.15	20.09	Slightly gravelly muddy sand
FGB01-60	139	27.79083	−93.67250	15.77	1.20	89.86	3.58	5.36	Slightly gravelly sand
FGB01-61	155	27.79017	−93.63680	31.63	0.01	9.44	30.66	59.89	Slightly gravelly mud
FGB01-62	136	27.83900	−93.63500	37.77	0.94	23.93	36.87	38.26	Slightly gravelly sandy mud
FGB01-63	107	27.87850	−93.65170	39.39	0.48	21.84	32.66	45.02	Slightly gravelly sandy mud
FGB01-64	100	28.89933	−93.65180	78.02	0.40	85.58	8.55	5.48	Slightly gravelly muddy sand
FGB01-65A	101	27.91900	−93.65180	55.53	0.03	32.77	41.01	26.18	Slightly gravelly sandy mud
FGB01-66	99	27.93983	−93.65150	52.09	0.00	40.55	36.01	23.44	Sandy mud
FGB01-67	97	27.96167	−93.65130	56.82	0.00	77.39	14.44	8.17	Muddy sand
FGB01-68	97	27.98233	−93.65180	25.77	0.03	17.05	37.30	45.62	Slightly gravelly sandy mud
FGB01-69	93	28.00200	−93.63500	26.47	0.00	29.40	40.09	30.50	Sandy mud
FGB01-70A	99	27.98200	−93.63530	31.22	0.03	28.97	39.87	31.13	Slightly gravelly sandy mud

TABLE 1. Continued.

Sample ID	Depth (m)	Latitude	Longitude	% $CaCO_3$	% Gravel	% Sand	% Silt	% Clay	Folk (1974) classification
FGB01-71	98	27.96100	−93.63470	77.67	0.14	80.86	7.42	11.58	Slightly gravelly muddy sand
FGB01-72	100	27.94017	−93.63530	82.18	0.00	77.10	11.63	11.27	Muddy sand
FGB01-73	91	27.91983	−93.63530	88.11	0.00	84.32	9.61	6.07	Muddy sand
FGB01-74	93	28.89833	−93.63580	67.96	8.51	50.94	16.24	24.31	Gravelly muddy sand
FGB01-75	107	27.87833	−93.63630	36.08	0.00	14.52	41.90	43.58	Sandy mud
FGB01-76	179	27.79083	−93.60580	39.66	0.56	20.49	30.43	48.52	Slightly gravelly sandy mud
FGB01-77	133	27.83867	−93.60550	29.50	0.45	6.57	35.49	57.49	Slightly gravelly mud
FGB01-78	100	27.87817	−93.61950	71.89	17.04	51.90	12.06	19.00	Gravelly muddy sand
FGB01-79	91	28.89817	−93.61980	89.63	79.94	6.30	5.88	7.88	Muddy gravel
FGB01-80	78	27.93967	−93.61900	94.71	16.12	77.93	1.89	4.06	Gravelly sand
FGB01-81	98	27.96100	−93.61970	83.90	4.17	77.77	6.24	11.83	Slightly gravelly muddy sand
FGB01-82	101	27.98167	−93.61900	43.02	0.01	79.37	10.17	10.44	Slightly gravelly muddy sand
FGB01-83	95	28.00117	−93.60380	31.83	0.15	45.41	27.35	27.09	Slightly gravelly sandy mud
FGB01-84	100	27.98133	−93.60330	32.24	0.42	31.01	37.29	31.28	Slightly gravelly sandy mud
FGB01-85	78	27.96067	−93.60300	85.68	8.76	76.06	5.36	9.82	Gravelly muddy sand
FGB01-86	85	28.00200	−93.57170	33.12	0.16	93.16	3.39	3.29	Slightly gravelly sand
FGB01-87	93	27.98167	−93.58670	57.90	19.30	33.32	25.38	22.01	Gravelly mud
FGB01-88	102	27.96150	−93.58720	37.16	0.16	24.17	39.58	36.10	Slightly gravelly sandy mud
FGB01-89	103	27.93917	−93.58670	35.77	0.06	13.30	45.72	40.92	Slightly gravelly sandy mud
FGB01-90	91	28.89833	−93.58650	80.77	23.01	55.56	8.33	13.10	Gravelly muddy sand
FGB01-91	116	27.87867	−93.60370	27.75	0.00	4.11	48.90	46.99	Mud
FGB01-92	123	27.87883	−93.58750	25.69	0.00	0.74	41.22	58.04	Mud
FGB01-93A	165	27.83867	−93.57200	26.43	0.00	2.27	40.35	57.37	Mud
FGB01-94	208	27.78950	−93.57300	29.81	0.00	1.35	41.98	56.67	Mud
FGB01-95	151	27.87967	−93.53420	26.46	0.00	0.56	34.46	64.99	Mud
FGB01-96	131	27.87867	−93.57170	24.97	0.42	1.00	39.43	59.15	Slightly gravelly mud
FGB01-97	127	27.89867	−93.56170	24.90	0.02	0.77	43.04	56.18	Slightly gravelly mud
FGB01-98	125	27.91917	−93.40450	25.33	0.45	1.84	39.52	58.19	Slightly gravelly mud
FGB01-99	127	27.92000	−93.53400	25.04	0.00	1.46	46.53	52.01	Mud
FGB01-100	104	27.96083	−93.53450	23.72	0.14	4.74	44.35	50.76	Slightly gravelly mud
FGB01-101	107	27.93967	−93.57120	25.64	0.00	1.13	51.48	47.39	Mud
FGB01-102	102	27.96133	−93.57220	25.47	0.00	1.67	44.19	54.14	Mud
FGB01-103	96	27.98117	−93.57170	26.57	0.82	29.10	37.64	32.44	Slightly gravelly sandy mud
FGB01-104	100	27.93000	−93.69320	38.94	1.20	32.36	43.75	22.69	Slightly gravelly sandy mud
FGB01-105	108	27.87000	−93.69270	53.07	4.15	42.19	34.17	19.49	Slightly gravelly sandy mud
FGB01-106	120	27.86983	−93.73250	35.96	0.51	12.83	47.77	38.89	Slightly gravelly sandy mud
FGB01-107	101	27.93167	−93.73420	28.59	0.08	30.66	48.64	20.62	Slightly gravelly sandy mud

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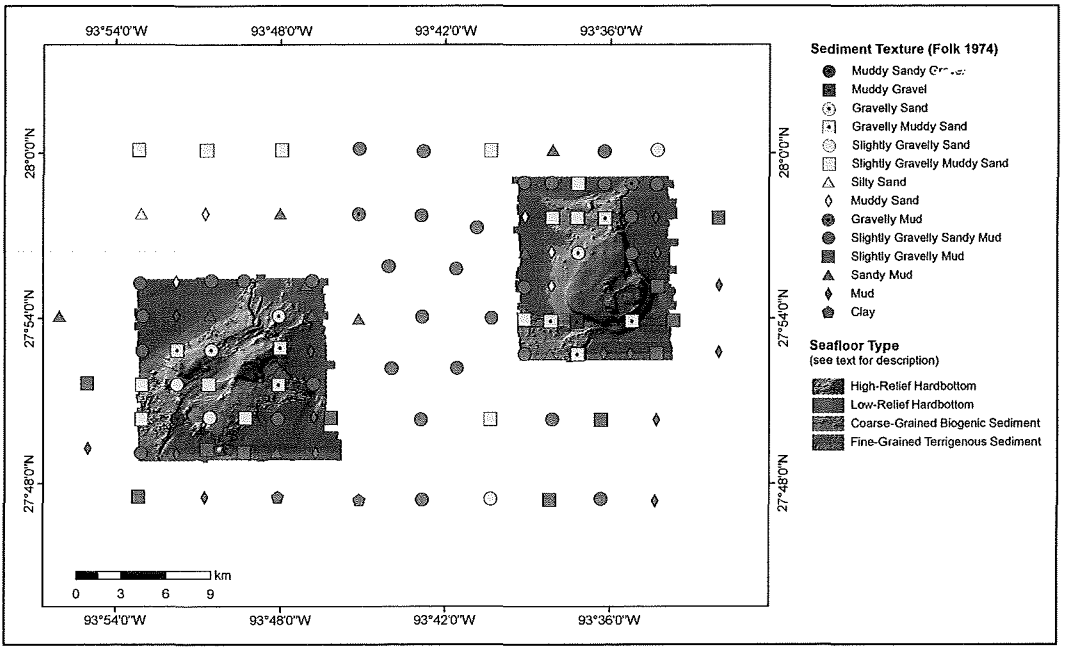

Fig. 3. Map of East and West Flower Garden Banks showing seafloor type with sediment texture superimposed. Shaded relief was created using data from Dartnell and Gardner (1999).

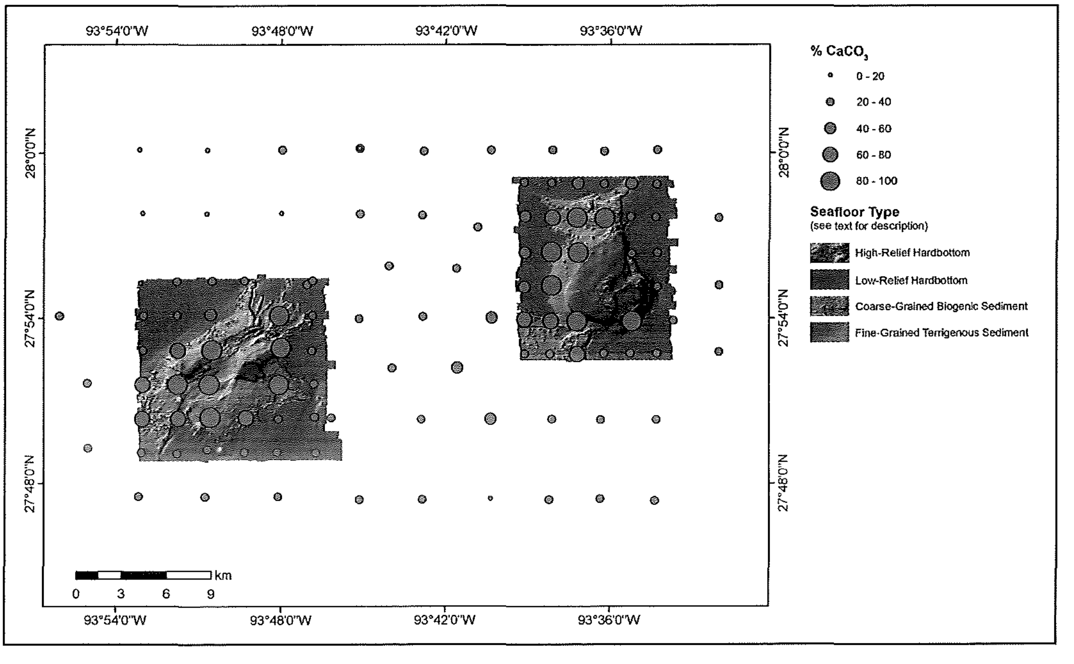

Fig. 4. Map of East and West Flower Garden Banks showing seafloor type with percentage of calcium carbonate content superimposed. Shaded relief was created using data from Dartnell and Gardner (1999).

Two of the units are predominantly hardbottom. We chose that term to describe those units because it does not imply anything about the genesis of the substrate, a discussion of which is beyond the scope of this article. Hardbottom can include outcrops of rocky strata, authigenically cemented sediments, isolated boulders, cobble fields, and living or dead reefs. An area covered by any material that provides a hard substrate to which sessile organisms could attach could be considered hardbottom. At Flower Garden Banks, the hardbottom areas are predominantly living and dead reefs and coral rubble associated with those reefs, but there is also evidence of outcrops of sedimentary strata that have been upturned and faulted by rising salt diapirs.

High-relief hardbottom: These areas exhibit high acoustic backscatter, and their topography is rough on a scale of a few meters. Because these areas are readily accessible to SCUBA divers, we know they are living coral reef habitat (e.g., Rezak et al., 1985). We did not attempt to take sediment samples in this area because of the very high risk of damaging living corals and the associated biologic community. However, Rezak et al. (1985) described coarse biogenic sand in pockets between coral heads. These are the shallowest parts of the study area, extending from about 40 m water depth upward to within less than 20 m of the sea surface. There are three such areas, two in EFGB and one in WFGB. Each is less than 1 km^2 in area and rises abruptly several meters above the surrounding terrain.

Low-relief hardbottom: These areas exhibit high acoustic backscatter, suggesting that they are hardbottom or coarse sand or gravel substrate. The multibeam bathymetry shows only small-scale relief. Rezak et al. (1985) described from diver and submersible observations a diverse bottom community of crustose corals and algae underlain by coarse carbonate sand or flat hardbottom. We did not attempt to sample sediments from this area. This type of seafloor surrounds each of the living reef areas and is found in an additional area on WFGB that has no living reef associated with it. The seabed slopes gradually away from the living reefs between 40 and 50 m water depth, but steepens between 50 and 70 m.

Coarse-grained biogenic sediment: Acoustic backscatter is moderately high and patchy in nature in these areas. Our analyses show the texture of these sediments to be predominantly sand, but ranges from muddy sand to gravelly sand to muddy sandy gravel. The seafloor morphology in these areas is complex. The bathymetry slopes gently away from the hardbottom areas but shows roughness that may be relict topography from buried or partially buried reefs. Carbonate contents are high, generally greater than 60%. This, together with qualitative visual inspections of the coarse fractions of the analyzed sediment samples, suggests that the sediment is mainly of biogenic origin, derived directly or indirectly from the nearby reefs and hardbottoms. The areas closest to the high-relief hardbottom (i.e., living reefs) are covered by coarser biogenic sediments than those areas farther away. This bottom type surrounds the low-relief hardbottom, forming a very narrow band next to it in some places and extends up to 5 km away from it in other places.

Fine-grained terrigenous sediment: Acoustic backscatter in these areas is low. The carbonate contents of the samples are all below 60% and most are below 40%. The texture, based on our analyses, is mainly mud with varying amounts of sand and small amounts of gravel in some samples. The gravel fraction is made up of shells and shell fragments, whereas the finer grains appear to be predominantly clastic sediments of terrigenous origin. Circular pockmarks, probably created by the release of gas through the sediments, are evident in the multibeam bathymetry of this bottom type, particularly on the seaward sides of both EFGB and WFGB, but also to a lesser extent, west of the banks (Gardner et al., 1998; Scanlon et al., 2005). The seafloor is otherwise smooth and slopes very gently seaward. In general, the sediments throughout the entire study area are either biogenic sand or terrigenous mud. However, one area of relatively coarse-grained terrigenous sediment (mainly muddy sand) is evident in the northwest corner of the study area, north of WFGB. Unlike other sediment samples classed as "sand" in unit 3 ("coarse-grained biogenic sediment") closer to the elevated reef areas, all the samples from the northwest corner are low in carbonate content (between 11% and 23%), indicating that they are mainly of terrigenous origin. The presence of coarse terrigenous sediment in this setting suggests that either strong currents carried the larger grains far from the present coast or the deposit is a relict from an earlier time when sea level was lower, terrigenous sources closer, and the environmental energy higher.

Conclusions.—Texture and carbonate content of the sediments on and around EFGB and WFGB show a clear pattern of variability related to proximity to the hardbottom and high-relief reef areas. Samples that were taken closest to the reefs (water depths between 70 and 120 m) have the highest carbonate content (generally >60%) and the coarsest texture (generally >50% sand or gravel). Those taken farther from the reefs (water depths greater than 120 m) have less than 60% carbonate content and are finer grained. This is expected because the coarse fraction is predominantly biogenic material derived from the reefs, whereas finer terrigenous material dominates away from the reefs. In addition, winnowing of fine sediments from the reef areas by currents focused by the rough topography may contribute to the grain size difference. Further examination of the coarse fractions from the carbonate sediments could identify the organisms that created the biogenic material and provide information about habitat zones in the study area. Similarly, identification of the composition of the constituent grains and their condition could provide a key to understanding the age and origin of the terrigenous sediments. This information, together with additional biological, geological, physical, and chemical data, will provide a basis for constructing habitat maps of the Sanctuary.

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Literature Cited

Curray, J. R. 1960. Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, p. 221–266. *In:* Recent Sediments, Northwest Gulf of Mexico. F. P. Shepard, F. B. Phleger, and T. H. Van Andel, (eds.). AAPG, Tulsa, Oklahoma.

Dartnell P., and J. V. Gardner. 1999. Sea-floor images and data from multibeam surveys in San Francisco Bay, Southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada. USGS Digital Data Series DDS-55, CD-ROM. U. S. Geological Survey, Reston, VA.

Edwards, G. S. 1971. Geology of the West Flower Garden Bank. Texas A&M Sea Grant Publication, TAMU-SG-71-215. College Station, TX

Folk, R. L. 1974. Petrology of sedimentary rocks. Hemphill Publishing Co., Austin, TX.

Gardner, J. V., L. A. Mayer, J. E. Hughes Clarke, and A. Kleiner. 1998. High-resolution multibeam bathymetry of East and West Flower Gardens and Stetson Banks, Gulf of Mexico. Gulf Mex. Sci. 16(2):131–143.

Gittings, S. R., and E. L. Hickerson, eds. 1998. Flower Garden Banks National Marine Sanctuary, Gulf Mex. Sci. 16(2):127–237.

Poppe, L. J., and C. F. Polloni. 2000. USGS east-coast sediment analysis: procedures, database, and georeferenced displays. U.S. Geological Survey Open-file Report 00-358, CD-ROM. U. S. Geological Survey, Reston, VA.

Rezak, R., T. J. Bright, and D. W. McGrail. 1985. Reefs and banks of the Northwestern Gulf of Mexico. John Wiley and Sons Inc. New York, NY.

Roberts, H. H., R. A. McBride, and J. M. Coleman. 1999. Outer shelf and slope geology of the Gulf of Mexico: an overview. *In:* The Gulf of Mexico large marine ecosystem. H. Kumpf, K. Steidinger, and K. Sherman, (eds.). Blackwell Science. Malden, MA.

Scanlon, K. M., S. D. Ackerman, and J. E. Rozycki. 2003. Texture, carbonate content, and preliminary maps of surficial sediments of the flower garden banks area, Northwest Gulf of Mexico Outer Shelf. U.S. Geological Survey Open-File Report 03-002, CD-ROM. (http://pubs.usgs.gov/of/2003/of03-002). U. S. Geological Survey, Reston, VA.

———, F. C. Coleman, and C. C. Koenig. 2005. Pockmarks on the outer shelf in the northern Gulf of Mexico: gas-release features or habitat modifications by fish? Pages 301–312 in P. W. Barnes and J. P. Thomas, (eds). Benthic habitats and the effects of fishing. American Fisheries Society, Symposium 41, Bethesda, Maryland.

Trippet, A. 1980. Maps showing geology of East and West flower garden banks, Northwest Gulf of Mexico. USGS Miscellaneous Field Studies Map MF-1232, 1 sheet. U. S. Geological Survey, Reston, VA.

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