Autonomous underwater vehicle (AUV) mapping reveals coral mound distribution, morphology, and oceanography in deep water of the Straits of Florida

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[1] To make progress in understanding the distribution and genesis of coral mounds in cold and dark water, maps of morphology and oceanographic conditions resolving features at the 1–10 m scale are needed. An autonomous underwater vehicle (AUV) cruising 40 m above the seafloor surveyed a 48 km^2 coral mound field in 600–800 m water depth at the base of slope of Great Bahama Bank. The AUV acquired 1–3 meter resolution acoustic backscatter and bathymetry together with current vectors, salinity, and temperature. The multibeam bathymetry resolved more than 200 coral mounds reaching up to 90 m height. Mound morphology is surprisingly diverse and mound distribution follows E-W oriented off-bank ridges. Bottom currents reverse every 6 hours indicating tidal flow decoupled from the north flowing surface current. The AUV data fill the gap between low-resolution surface-based mapping and visual observations on the seafloor, revealing the dynamic environment and spatial relationships of an entire coral mound field. **Citation:** Grasmueck, M., G. P. Eberli, D. A. Viggiano, T. Correa, G. Rathwell, and J. Luo (2006), Autonomous underwater vehicle (AUV) mapping reveals coral mound distribution, morphology, and oceanography in deep water of the Straits of Florida, *Geophys. Res. Lett.*, *33*, L23616, doi:10.1029/2006GL027734.

1. Introduction

[2] Cold-water corals and associated fauna require no sunlight and occur in oceanic waters of all latitudes at 4°–12°C [*Freiwald et al.*, 2004; *Roberts et al.*, 2006]. Coral mounds in the Atlantic have attracted most research activity [e.g. *De Mol et al.*, 2002; *Ferdelman et al.*, 2006]. In the Straits of Florida, dredge sampling [*Pourtales*, 1868; *Cairns*, 1979, 2000] and manned submersible dives [*Neumann and Ball*, 1970; *Ballard and Uchupi*, 1971; *Mullins et al.*, 1981; *Messing et al.*, 1990; *Paull et al.*, 2000; *Reed et al.*, 2006] document an abundance of mound-forming deep-water corals *Lophelia pertusa, Enallopsammia profunda* and *Madrepora oculata* in 400–800 m water depth (Figure 1). However this vast database is a collection of observations scattered both in location and time: The existing bathymetric charts do not resolve coral mounds preventing the linkage of sampling points and visual observations with mound morphology, distribution and extent of coral mound fields. Similarly the oceanographic time series are too short to assess diurnal changes.

[3] This paper demonstrates how modern multibeam mapping, backscatter classification and sensor deployment from an autonomous underwater vehicle (AUV) open a window of opportunity to fill in the scale gap of basic information on deep-water ecosystems. We used a surface deployed multibeam system to detect mound features larger than 20m demarcating a field of mounds. The AUV then acoustically mapped the entire field of 48 km^2 at high resolution in one dive over a period of 45 hrs and continuously recorded bottom currents, temperature and salinity. The AUV technology reveals the oceanographic environment, the morphology of the mounds and their spatial distribution in unprecedented detail. Most importantly, these new data question some of the existing paradigms for the evolution of deep water coral reefs.

2. Surface Multibeam Bathymetry and Backscatter Classification for Site Selection

[4] Several mounds were discovered at the base of slope on the western margin of Great Bahama Bank (Figure 1) during the site survey for Ocean Drilling Program (ODP) Leg 166 [*Anselmetti et al.*, 2000]. As the grid of seismic lines spaced by 2–5 km detected only a small subset of mounds, we acquired surface-based multibeam data just before the AUV deployment. Figure 2a depicts the seafloor topography at a water depth of 590–750 m mapped with a 95 kHz Kongsberg™ EM1002 system. The map has 20 m grid resolution revealing a field of mounds in the northern part of the survey area. To further differentiate the seabed character we applied backscatter classification processing utilizing QTC MULTIVIEW™ [*Preston et al.*, 2004]. Variations in the amplitudes and texture of the multibeam backscatter (Figure S1 in the auxiliary material[1]) are a result of change in seabed character. Beam grazing angle and range are compensated with a patented process. Principal component analysis and clustering divide the backscatter into three classes (Figure 2b). The "blue" class dominating the southern area is likely to represent a soft seabed. Cores from ODP Site 1007 recovered soft, muddy sediments [*Eberli et al.*, 1997]. This interpretation is confirmed by AUV subbottom and sidescan data showing fine horizontal stratification and a smooth surface (Figure S2). The north is

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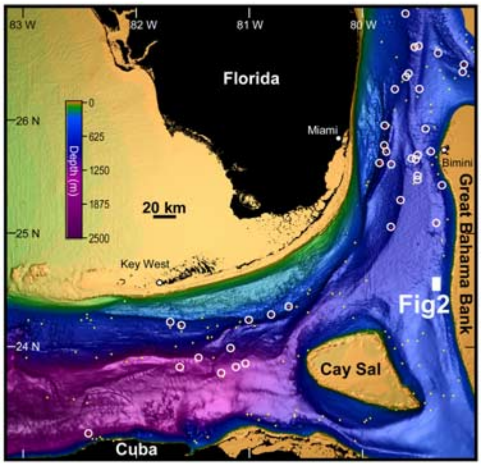

Figure 1. Seafloor morphology of the Straits of Florida based on National Ocean Service Hydrographic Survey Data. This major seaway connects the Gulf of Mexico with the Atlantic. It is bordered by the Florida peninsula in the NW, Cuba in the south, and the Bahamas in the east. The Florida Current, a warm surface current, flows through the Straits of Florida into the North Atlantic where it converges with the smaller Antilles Current to form the Gulf Stream. The Florida Current has produced stream line shaped drift deposits. Superimposed on the map are the locations of scientific dredge sampling in the 1960s and 70s at water depths deeper than 400 m [*Cairns*, 1979, 2000]. The dredge locations highlighted with red dots and white circles retrieved mound-forming deep-water corals *Lophelia pertusa*, *Enallopsammia profunda* and *Madrepora oculata*. The coral mound field mapped with the AUV is located at the base of slope of the western margin of Great Bahama Bank.

characterized by strong surface reflections and drop camera pictures (see below) indicate coarse sands. Besides this ''tan'' class, the ''green'' class is characterized by abundant superficial scattering and mostly occurs on the north side of mounds. We interpret this as increased surface roughness caused by coral rubble and standing thickets of alive or dead coral. Together with the bathymetry, the backscatter classification confirms the northern part of the survey area to be most interesting for high-resolution AUV data acquisition.

3. AUV Data Acquisition, Processing, and Ground-Truthing Methodology

[5] The AUV survey was conducted in December 2005 by the C-Surveyor II™ AUV (Figure S3a) deployed from the RV Northern Resolution. The 48 km^2 were covered with thirty-six 6.8 km long N-S running primary lines spaced by 200 m and by two 7.1 km long E-W running tie lines. The AUV is rated to 3000 m water depth and is powered by an aluminum oxygen fuel cell providing a mission endurance of more than 55 hours. The AUV cruises 40 m above the seafloor at a speed of 1.8 m/s. Positioning and navigation accuracy of the AUV at 800 m depth is better than 3 m [*Jalving et al.*, 2003]. A Kalman filter combines the inputs from the AUV fiber optic gyro compass, acoustic Doppler profiler and high precision pressure (depth) sensor. Positioning drift is minimized with fixes from an ultra short baseline (USBL) acoustic and differential global positioning system installed on the mother vessel [*Chance and Northcutt*, 2001]. Communications between mother vessel and AUV by acoustic modem allow quality control on decimated data in real-time during the mission.

[6] The high-resolution bathymetry data are acquired using a 200 kHz Kongsberg EM2000 multibeam system installed on the AUV. At a cruising altitude of 40 m the swath width is 300 m providing 100 m overlap between adjacent lines. Precision accelerometers on board the AUV correct the multibeam data for heave, pitch and roll. C&C Technologies proprietary HydroMap™ software [*Lee and George*, 2004] is used to process the data and produce bathymetric maps with 3 m resolution within a couple hours after the AUV resurfaces.

[7] Besides the multibeam mapping system, the AUV carries a number of complementary sensors continuously recording data during the entire mission. An Edgetech™ 120 kHz sidescan sonar reveals the acoustic surface texture of the seafloor at 1 m resolution over a swath width of 400 m. The subbottom profiles are generated by an Edgetech 2–8 kHz chirp sounder (Figure S2). Bottom current velocity and direction, salinity, and water temperature are recorded at 1 s intervals. The currents are based on a back calculation using measurements from a 300 kHz Workhorse Navigator™ Doppler Velocity Log sensor (across-track and along-track) and headings from the gyro compass. Two

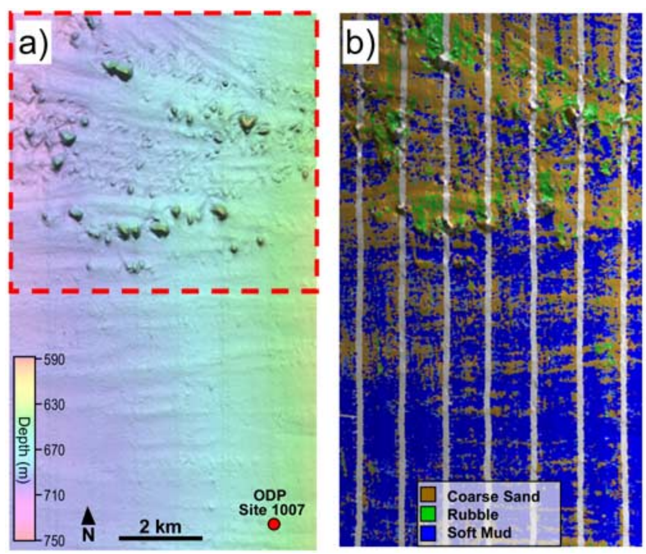

Figure 2. (a) Reconnaissance bathymetric map acquired with a hull-mounted 95 kHz multibeam system. The 20 m resolution map images numerous mound features associated with low relief ridges extending in a slightly divergent pattern in E-W direction. (b) Backscatter classification differentiates the bottom types of the reconnaissance survey into three acoustically distinct classes. The N-S running thin grey stripes are gaps in the seabed classification at points vertically below the ship track. Mud retrieved at ODP Leg 166 Site 1007 calibrates the blue class as soft sediment. Sidescan, subbottom and drop camera data were used to interpret the tan and green classes as coarse sand and coral rubble respectively. The red box outlines the area of the high-resolution AUV survey.

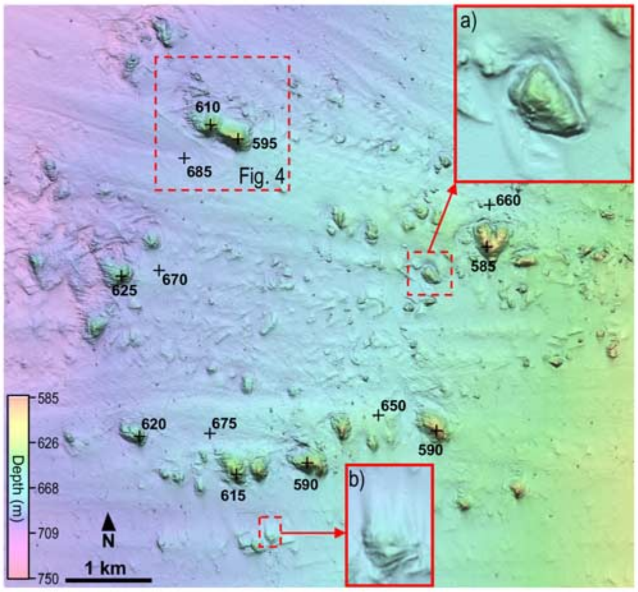

Figure 3. High-resolution bathymetry based on 200 kHz multibeam data acquired with the AUV at a cruising altitude of 40 m above the seafloor. The map images more than 200 mounds within an area of 48 km^2 (for higher resolution image see Figure S4). The shapes of the mounds are diverse, including single conical, pyramid or wedge shaped peaks, twin peaks, random shaped mounds and even an almost perfect heart shape. Black crosses with numbers refer to point depth in meters below mean sea level. Stippled red rectangles outline enlarged map areas illustrating: moat surrounding mound (inset a), sediment wedge thinning towards the north (inset b), and curved ridges at the base of mounds are shown in Figure 4a.

FastCAT™ Conductivity-Temperature-Salinity sensors measured the properties of the seawater passing by the AUV.

[8] The 40 m cruising altitude of the AUV was too high to illuminate the seafloor for photographs or video to verify the presence of corals on the mounds. To fill this gap we developed a low cost drop camera for deployment just after the AUV survey was completed. The "Crystal Ball" drop camera consisted of a compact digital camera within a 15 cm diameter evacuated glass sphere rated to 6700 m depth taking pictures every 1.5 seconds for 70 minutes (Figure S3b). The drop camera was attached to a deep-sea fishing-line and kept neutrally buoyant 1–2 meters above the seafloor by the variable weight of a loose steel chain. LED lights illuminated the seafloor. An acoustic pinger together with the USBL system enabled tracking the camera position with ±50 m precision. The pinger was attached with 40 kg of lead ballast 50 m above the camera to reduce the risk of loosing the pinger in case the camera would entangle on the ground. We used the AUV bathymetric map to select an off-mound camera landing site and to monitor the camera trajectory across the tallest mound. Currents and the vessel pulling on the line moved the camera at an approximate speed of 0.5 m/s. The pinger altitude was adjusted with a winch to follow the seabed topography at a height of 50 m above ground. In order to save valuable AUV time and as the drop camera can also be deployed from small fishing boats we only deployed the drop camera once during the AUV cruise.

4. AUV Mapped Coral Mound Morphology

[9] The 3 m grid resolution AUV bathymetry map shows 37 mounds, which are at least 25 m high, and numerous smaller ones (Figure 3; for higher resolution see Figure S4). The tallest mound reaches a height of 90 m and has a minimum base width of 350 m. The map also images more than 180 smaller mounds. The distribution of mounds is

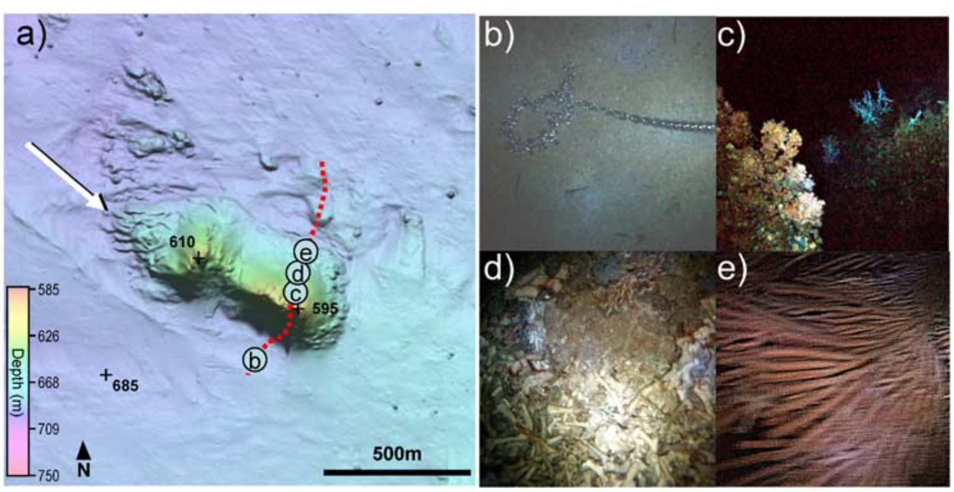

Figure 4. (a) Enlarged view of tallest mound with a height of 90 m. White arrow points at a field of 2–4 m tall ridges spaced by 15–25 m which occur at the base of most large mounds. Red stippled line indicates the drop camera trajectory and the location of pictures. (b) The landing site on the south side of the mound shows coarse skeletal sand and linear fragments of *Thalassia* sea grass. The 1.5 cm thick chain attached to the camera helps to keep neutral buoyancy 1–2 m above the seafloor. (c) Living cold-water corals near the mound peak. (d) Dead coral rubble and living glass sponges and brittle stars on the north slope. (e) Gorgonian fans on the lower slope.

non-random and follows low relief ridges (500–1500 m wide and 5 m high) extending in a slightly divergent pattern in an E-W direction. The same ridges appear as a distinct class in the backscatter classification of the EM1002 reconnaissance survey (tan colored class in Figure 2). The shapes of the mounds are diverse, including single conical, pyramid or wedge shaped peaks, twin peaks, and even an almost perfect heart shape. The mound shapes do not resemble the ''tear drop'' morphology expected from exposure to a steady current [*Neumann et al.*, 1977; *Messing et al.*, 1990]. Fields of 2–4 m tall ridges spaced by 15–25 m occur at the base of most large mounds (Figure 4a). Some mounds are completely or partly surrounded by 5–10 m deep and 25–50 m wide moats (Figure 3, inset a). Smaller mounds generally lack the moat but have a sediment wedge attached that thins towards the north (Figure 3, inset b).

[10] Drop Camera pictures recorded on the south side of the tallest mound show coarse skeletal sand and fragments of *Thalassia* sea grass growing in shallow water less than 10 m deep (Figure 4). This might be an indication for off-bank transport of sediments to depths deeper than 600 m over a distance of more than 10 km. The images from near the mound peak show living corals, while the slope facing north is covered with dead coral rubble as well as living glass sponges and brittle stars. Further down the slope large gorgonian fans appear. This successful drop camera deployment is also a proof of concept for future inexpensive ground truth missions before or after AUV surveys.

5. Tidal Control of Currents in the Mound Field

[11] The complementary oceanographic data acquired by the AUV provide a valuable resource for integrated analysis of the deep-water coral mound environment. The bottom currents within the 40 m water column between AUV and seafloor show a remarkable variation in strength and direction (Figure 5). Current strength never exceeded 0.5 m/s with sustained peak strengths of 0.2 m/s in north or south direction. The primary N-S lines acquired in a lawnmower pattern progressing from east to west show how the currents were changing direction between north- and southward flow seven times over 45 hours. The average time interval between changes is approximately 6 hrs. At first sight the E-W tie line measurements seem not to match the currents recorded on the primary N-S lines. However, the data were acquired in a sequence starting with the outline of the survey area and then proceeding with the remaining primary lines. Thus, these first lines show how at the beginning of the survey the flow was mostly southward before changing to a northward direction. These changes in current direction correlate with the first derivative of the modeled tide level curve for North Bimini (D. Pentcheff, WWW Tide and Current Predictor, http://tbone.biol.sc.edu/tide, 10 May 2006). Such bottom current behavior is rather surprising as the surface currents in the study area generally flow north [*Richardson et al.*, 1969; *Leaman et al.*, 1995, *Wang and Mooers*, 1997] but short seasonal flow reversals are reported along the western side of the Santaren Channel [*Lee et al.*, 1995]. Also, the Florida Current is a warm surface current that produces a vertical temperature and transport partitioning within the Straits of Florida with

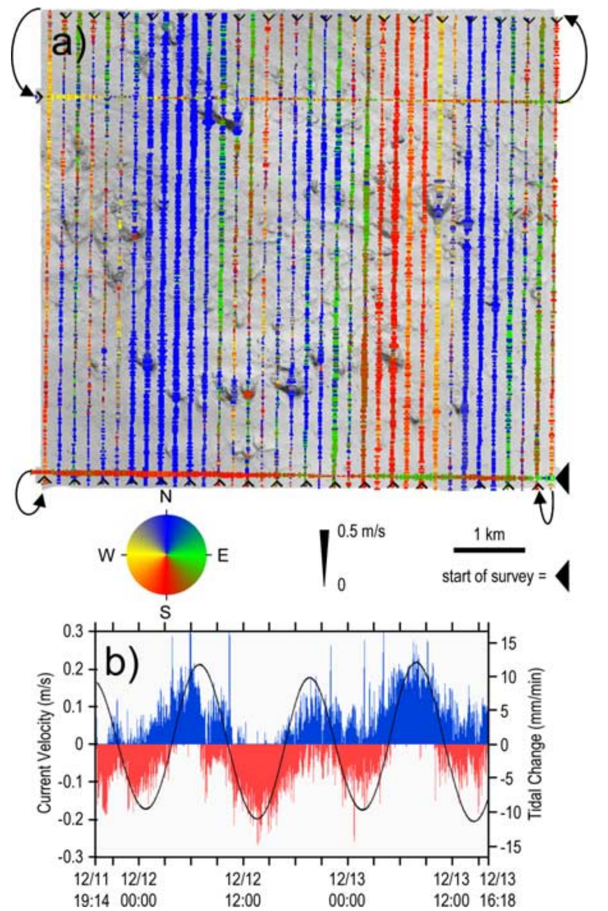

Figure 5. The bottom currents within the 40 m water column between AUV and seafloor show a remarkable variation in strength and direction. (a) The primary N-S lines acquired in a lawnmower pattern progressing from east to west show how the currents were changing direction between north- and southward flow seven times over 45 hours. Current direction and speed are represented by color and width of the AUV tracks. Some mounds locally accelerate the currents. Black arrows show acquisition direction and sequence of survey lines. (b) Superposition of north-south current component with the first derivative of the tide level curve modeled for North Bimini indicates tidal control of the currents at the base of slope of Great Bahama Bank in 600–800 m water depth.

minimum currents at the bottom of the Straits [*Schmitz and Richardson*, 1991]. At the study site, 40 m above seafloor the transport velocity of the Florida Current is minimal and consequently our data is interpreted to display mostly tidal current velocities. The interference of internal tidal motions on the Florida Current is complex but is estimated to account for approximately 5 SV in total transport of the Florida Current (32–33 SV) [*Mayer et al.*, 1984]. In our AUV data, the north-flowing currents appear to be slightly stronger, which could be the contribution of the Florida Current. This is in agreement with the consistent northward orientation of the sediment wedges associated with small mounds. The strongest bottom current directions are perpendicular to the E-W trend in the mound distribution aligned with the low relief ridges formed by off-bank transported sediment. The current data together with the temperature and salinity data (Figures S5–S7) show how the organisms on the mounds are subject to a dynamic oceanographic environment. This may be the cause for the diversity in mound morphology.

6. Conclusions and Implications

[12] The C-Surveyor II AUV proved to be an extremely efficient multi-sensor platform. In just 45 hrs a 48 km^2 field of coral mounds was covered with dense grids of bathymetric, acoustic and oceanographic measurements. This synoptic high-resolution dataset offers for the first time spatially extensive observations of current velocities and directions, salinity, and temperature associated with cold-water coral mounds and their benthos at depths of 600–800 m in total darkness and 8–12°C cold water. The AUV data reveal an unexpected E-W alignment and diversity of mound morphologies subject to a N-S current regime reversing on average every 6 hours. Previous conceptual models for coral mound development in the Straits of Florida and elsewhere hinged on nutrient supply from steady currents for the initiation and maintenance of the cold-water coral mounds [*Neumann et al.*, 1977; *Messing et al.*, 1990]. As the currents across the mound field at the base of slope of Great Bahama Bank follow a tidal cycle, water-borne nutrient supply is probably less steady and abundant than originally anticipated. Water column nutrients should be measured and alternative energy sources such as seepage of hydrocarbon bearing fluids considered. The high-resolution AUV maps and oceanographic data will help guide future sampling and monitoring to critical locations in the coral mound field.

[13] This AUV survey covers only a minuscule portion of the Straits of Florida, which contain extensive cold-water coral ecosystems as indicated by dredging and submersible dives. Time and cost are prohibitive for mapping the entire Straits with an AUV. As an outcome from this first application of AUV technology to mapping of deep-water coral mounds we propose the following survey strategy, which is also applicable to deep-water environments elsewhere: 1) Regional surface bathymetric mapping and backscatter classification for identification of mound areas. 2) Drop camera deployment from small boats on selected mounds to determine presence of live or dead coral cover. 3) High-resolution AUV surveying of key areas 4) Based on the AUV maps perform further drop camera deployments for more detailed ground truth. 5) Use of submersibles and ROV for sample collection and deployment of permanent monitoring equipment. This staged approach including modern oceanographic mapping tools enables a new level of interdisciplinary deep-water research, unifying local observations with their regional environments. The results will provide increased understanding of these remarkable benthic communities. In addition, maps of cold-water coral mounds are essential for making inventories of mound resources and designing management plans.

[14] **Acknowledgments.** We received ship time for the AUV survey from the NOAA Ocean Explorer program. Justin Manley (OE program manager), Heather Langill (C&C Geophysical Operations & Bid Coordinator) and Chas Honea (C&C AUV Field Project Manager) were instrumental for facilitating this project. We express our gratitude to the officers and crew of the RV Northern Resolution and the scientific and technical staff of C&C Technologies. Their efficiency and competence enabled data acquisition and processing in a very short time. We especially appreciated how they accommodated all our special requests in their workflow. Pre- and post-cruise research was made possible by the Industrial Associates of the Comparative Sedimentology Laboratory. IVS 3D Fledermaus™ software was used for visualization of the bathymetric maps. Advice and support from Gerald Abich (Nautilus Marine Service GmbH) and Mark Graham (RSMAS) were instrumental for the rapid development of the "Crystal Ball" drop camera.

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