High-Resolution Multibeam and Subbottom Surveys of Submarine Canyons, Deep-Sea Fan Channels, and Gas Seeps Using the MBARI Mapping AUV

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***Abstract* - The Monterey Bay Aquarium Research Institute (MBARI) has developed an autonomous seafloor mapping capability for high resolution mapping of the deep ocean seafloor. The MBARI Mapping AUV is a 21" diameter, *Dorado* class autonomous underwater vehicle (AUV) equipped with a 200 kHz multibeam sonar, 110 kHz and 410 kHz sidescan sonars, and a 2-16 kHz subbottom profiler. All components of the vehicle are rated to 6000 m depth. Using precise navigation and attitude data from an laser-ring-gyro-based inertial navigation system (INS) integrated with a Doppler velocity log sonar (DVL), the Mapping AUV can image the deep-ocean seafloor and shallow subsurface structure with much greater resolution than is possible with hull-mounted sonars. The system can also be operated in an ROV-mounted configuration, allowing near-bottom surveys in very restricted terrain. The Mapping AUV has conducted several autonomous surveys of Monterey Canyon and Smooth Ridge in Monterey Bay, and ROV-mounted surveys of five sites along the Monterey Canyon axis during 2005 and 2006. During June 2006, the Mapping AUV surveyed mounds and channel deposits in the Santa Monica Basin. The bathymetric surveys have achieved a vertical precision of 0.3 m; surveys from a 20 m altitude achieve sub-meter lateral resolution and surveys from 50-100 m altitudes achieve lateral resolutions less than 2 m. The subbottom profile data provides resolution of ~0.1 m with penetrations up to 50 m in soft sediments. The combination of high-resolution bathymetry with closely spaced subbottom profiles allow us to Additional Mapping AUV expeditions are planned for 2006, including surveys of Barclay submarine canyon and the summits of Davidson and Axial seamounts.**

I. INTRODUCTION

Acoustic mapping of seafloor bathymetry, character, and subbottom structure is a fundamental activity in oceanography. In general, the resolution of seafloor mapping data improves as sonars are operated closer to the seafloor and as shorter acoustic wavelengths are used. Consequently, high-resolution seafloor mapping in the deep ocean is best accomplished by operating high frequency sonars near the seafloor on depth-capable platforms. Recent mapping work from both autonomous and remote operated vehicles (e.g. [1-3]) has demonstrated the feasibility and utility of these vehicles as mapping platforms.

The Monterey Bay Aquarium Research Institute (MBARI) has developed a Dorado class Autonomous Underwater Vehicle (AUV) to map the deep-ocean seafloor efficiently in high-resolution. The MBARI Mapping AUV (Fig. 1) combines mapping sonars (multibeam, sidescan, and and subbottom profiler), a high performance inertial navigation system, and efficient propulsion in a vehicle that can be easily operated from a variety of vessels. The mapping and navigation components can also be mounted on MBARI's ROV Ventana (Fig. 2), allowing near-bottom surveys in areas of extreme bathymetry such as the depths of submarine canyons.

The development and testing of the MBARI Mapping AUV has been previously described [4][5]. In this paper we summarize the current vehicle capabilities and present some results from the first year of full survey operation.

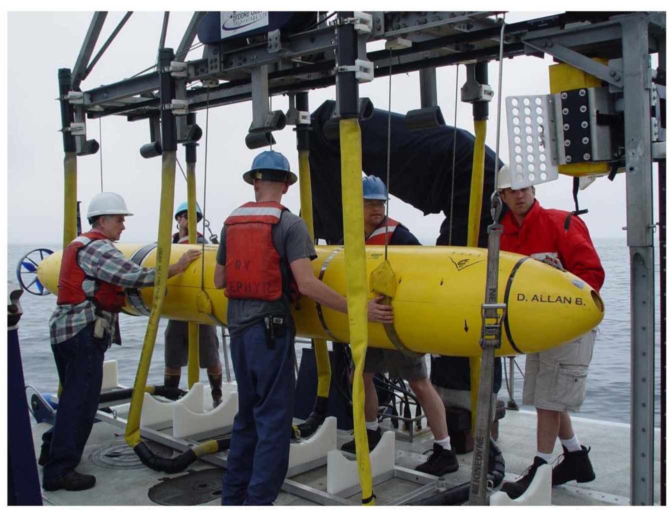

Fig. 1. The MBARI Mapping AUV being prepared for deployment from the R/V Zephyr. This 21" diameter, 17.2' long vehicle includes a 200 kHz multibeam, 110 kHz and 410 kHz chirp sidescans, and 2-16 kHz subbottom profiler.

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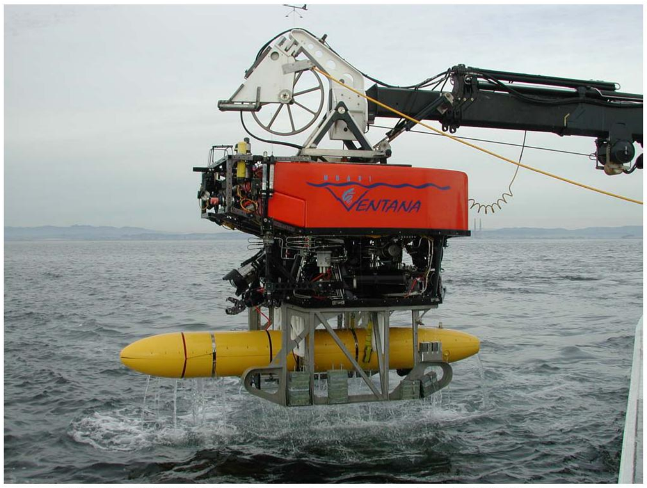

Fig. 2. MBARI Mapping system mounted on ROV Ventana.

II. System Design and Capabilities

A. Dorado Class AUV Characteristics

Dorado class AUVs [6-8] are 21" diameter variable length vehicles that have been developed and operated at MBARI. *Dorado* vehicles are constructed from multiple modular sections (Fig. 3). A nose section and tail section are required at a minimum to provide the power and propulsion. This modular approach allows many different custom payloads to be inserted and deployed from the same core vehicle. A single articulated propeller inside a circular duct provides propulsion; this duct serves as the vehicle's only control surface. The overall torpedo shape produces very little drag.

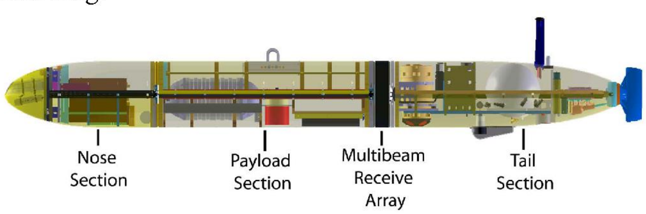

Fig. 3. Mapping AUV modular layout.

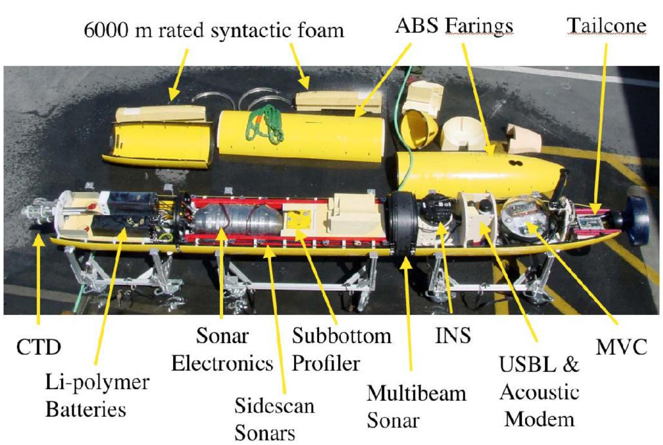

Fig. 4. The interior of the MBARI Mapping AUV

The main hull sections of a *Dorado* vehicle are acrylonitrile butadiene styrene (ABS) plastic. The plastic skin acts as the main structural strength member of the vehicle and carries the vehicle loads in air as well as in water. ABS is also acoustically transparent at the frequencies used by communications and mapping sonars, allowing most sonar transducer arrays to be located within the vehicle body. Buoyancy is provided by blocks of syntactic foam.

B. Modular Construction

The Mapping AUV is constructed from three sections: a nose containing batteries and conductivity, temperature, and pressure depth (CTD) sensors, a midbody containing the mapping sonar payload, and a tail section including navigation, communications, main vehicle control, and propulsion (Fig. 3 and 4). In its autonomous configuration, the Mapping AUV weighs about 1500 lbs in air. The modular design also allows the mapping AUV to be quickly reconfigured into a remotely operated vehicle (ROV) payload (Fig. 2). The ROV operational mode allows interactive low altitude survey operations in dangerous or restricted terrain (e.g. around scarps, canyon walls, wrecks, or other hazards). All vehicle components are rated to a depth of at least 6000 m.

C. Main Vehicle Computer Housing

The main vehicle computer (MVC), GPS receiver, Iridium satellite receiver, radio modem, and ultra-short baseline (USBL) positioning electronics are housed in a 17" glass sphere located in the tail section, just forward of the tailcone. An object-oriented framework, running with the QNX operating system on a PC-104 stack, provides the foundation for all the vehicle software, including guidance and control functions, data logging, and interfaces to any payload devices.

D. Mapping Payload

The primary mapping sensor is a Reson 7125 200 kHz multibeam sonar that provides swath bathymetry and acoustic backscatter intensity. The multibeam provides 256 1°x1° resolution beams spread over a 150° swath. The Edgetech FSDW chirp sonar package includes dual 110 kHz and 410 kHz sidescans that image the seafloor character with greater fidelity than the multibeam backscatter, augmenting the bathymetry. The FSDW also includes a 2-16 kHz sweep chirp subbottom profiler that images subsurface structure. All of the sonar electronics are contained in a single, cylindrical titanium housing. A payload controller computer logs all of the mapping sonar data as well as navigation and attitude data derived from the navigation system.

Additional acoustic devices include a Doppler velocimeter log (part of the navigation system), ultra-short baseline (USBL) positioning, and an acoustic modem. All of the acoustic systems other than the USBL beacon and the acoustic modem are externally triggered to avoid interference between sonars. The triggering is designed so that the sonars all end their ping cycles simultaneously, and thus no sonars are in a receive cycle as another sonar pings.

E. Navigation

The central component of the vehicle navigation system is an inertial navigation system (INS) incorporating a ring laser gyro and accelerometers. The INS is integrated to the DVL in a commercially available package from Kearfott called SeaDevil. The real-time navigation error is 0.05% of distance traveled, assuming the DVL has continuous bottom tracking (typically bottom lock is maintained for altitudes less than 130 m). At the surface, the INS is aided by GPS fixes. During descent and ascent, the vehicle must navigate without the aid of the bottom tracking DVL. When possible, the vehicle is launched in water less than 130 m deep so that GPS and DVL bottom lock are simultaneously achieved at the start of the mission. When the vehicle is launched in deep water, the INS navigation is aided during descent and ascent by USBL fixes communicated to the vehicle over the acoustic modem.

F. Power

The Mapping AUV can be operated with two types of rechargeable battery packs. Initial testing was conducted using up to three 2 kWhr pressure tolerant Li-polymer batteries (Fig 4). Recent operations have used a 5 kWhr package of Li-ion cells housed in a 17" glass sphere. The latter configuration allows for an 8.5-hour survey mission duration running at 1.5 m/s speed.

G. Vehicle Safety

Vehicle safety is a major concern. Typically the vehicle is ballasted to be approximately 8 lbs buoyant. The tail section includes a 22 lb emergency drop weight that can be triggered by acoustic command or will be dropped automatically after 15 minutes if the vehicle is submerged and its mission has ended or aborted. Vehicle status can be requested by acoustic modem at any time, though during survey operations communication is limited to avoid acoustically interfering with the mapping sonars. Once the vehicle surfaces, it communicates its position over both radio modem (line of sight range) and Iridium satellite modem (unlimited range).

H. Data Processing

The seafloor mapping data are processed using an open source software package called MB-System [9,10] that is developed collaboratively by MBARI and the Lamont-Doherty Earth Observatory. One MB-System [9,10] tool called MBnavadjust is particularly important for the Mapping AUV; this tool adjusts navigation by solving for an optimal navigation model so that features observed in crossing bathymetry swathes match. The resulting navigational precision approaches the lateral resolution of the multibeam bathymetry.

I. Mission Planning and Execution

AUV mission scripts are downloaded and executed over radio modem while the vehicle is on the surface. Each mission script includes both a series of behaviors to be executed sequentially and overriding behaviors setting safety parameters such as maximum depth and minimum altitude. Violation of the safety parameters causes mission abort. Sequential behaviors include such capabilities as descending to a specified depth, ascending to the surface, navigating to a waypoint following a specified depth profile or altitude, and modifying mapping sonar parameters. In practice, an interactive MB-System [9,10] visualization application called MBgrdviz is used to lay out survey lines and generate the survey mission scripts.

III. Recent Mapping AUV Surveys

A. Repeat Surveys in Monterey Canyon

Vigorous sediment transport events are known to occur in upper Monterey Canyon (Fig. 5) with a recurrence interval of considerably less than a year [11-13]. In order to observe bathymetric changes associated with these sediment transport events within the canyon's axis, MBARI has begun repeated near-bottom ROV-mounted multibeam surveys. Five sites along the upper Monterey Canyon axis at depths of 100 m, 300 m, 520 m, 1000 m, and 1400 m (Fig. 5) will be surveyed thrice yearly for the foreseeable future. Each ROV-mounted survey is conducted with a 20 m altitude and 30 m line spacing.

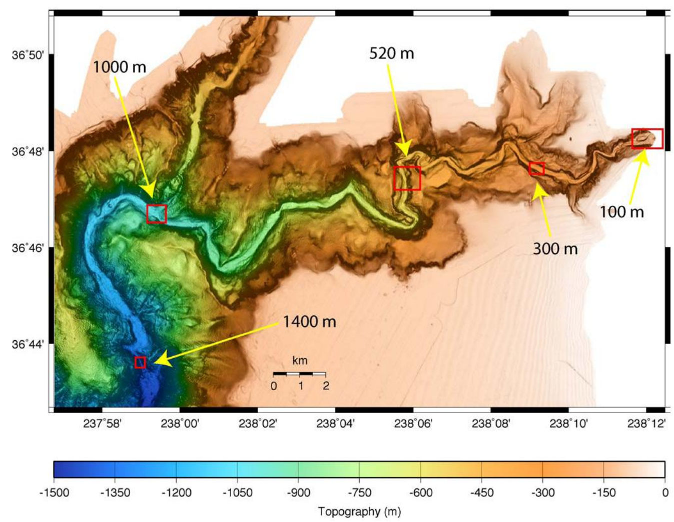

Fig 5. Location of repeat mapping sites in upper Monterey Canyon. Each site is surveyed using the ROV-mounted configuration at 20 m altitude and 30 m line spacing.

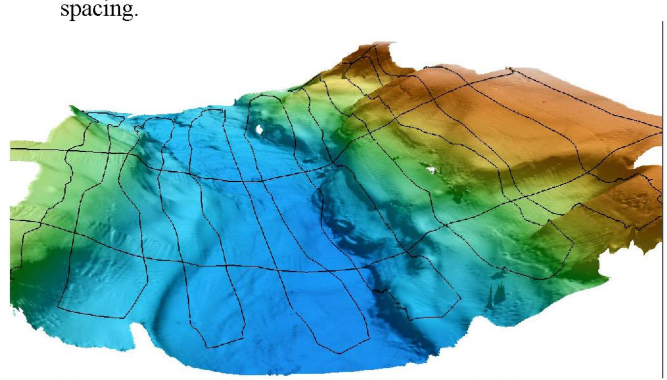

Fig 6. Perspective view of multibeam of 520 m repeat mapping site overlain with vehicle tracks. This 0.5 m resolution grid derives from the February 2006 survey.

The initial surveys commenced during sea trials in late 2004; the data collected during 2005 and 2006 have improved considerably as problems with the multibeam and the vehicle system integration were solved. Figure 6 presents the bathymetric survey of the 520 m site collected in February 2006. The mapping system now achieves a 0.5 m lateral resolution and a 0.3 m vertical precision. These results demonstrate the capability to generate a long-term time series of surveys documenting changes in canyon axis morphology due to sediment transport.

B. MARS Cable Route Survey

The Monterey Accelerated Research System (MARS) will be a cabled observatory testbed connecting seafloor instruments to shore via a 51 km long power and fiber-optic communications cable (Fig. 7). To augment the surveys associated with the most problematic portion of the cable route the Mapping AUV conducted a bathymetric survey in November 2005. This 7-hour autonomous mission collected multibeam data from a 50 m altitude using 150 m line spacing, covering a 1 km by 5 km area with a 1 m lateral resolution (Fig. 8-9). These data revealed the existence of 5-10 m high scarps where the cable route crosses the San Gregorio Fault, and resulted in important modifications to the cable route.

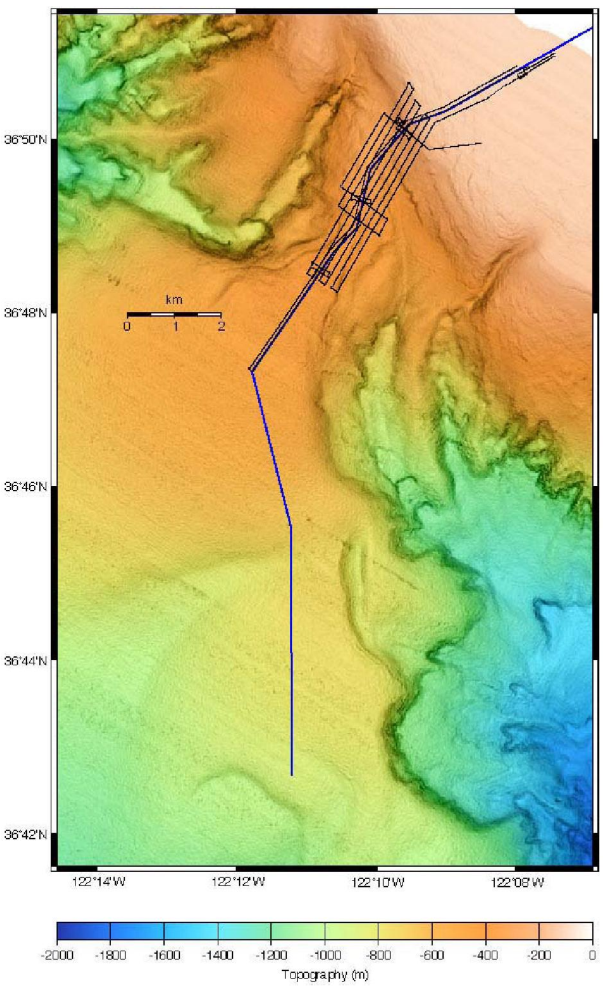

Fig. 7. Location of Mapping AUV MARS cable route survey tracks (black) in Monterey Bay. The cable route is shown in blue.

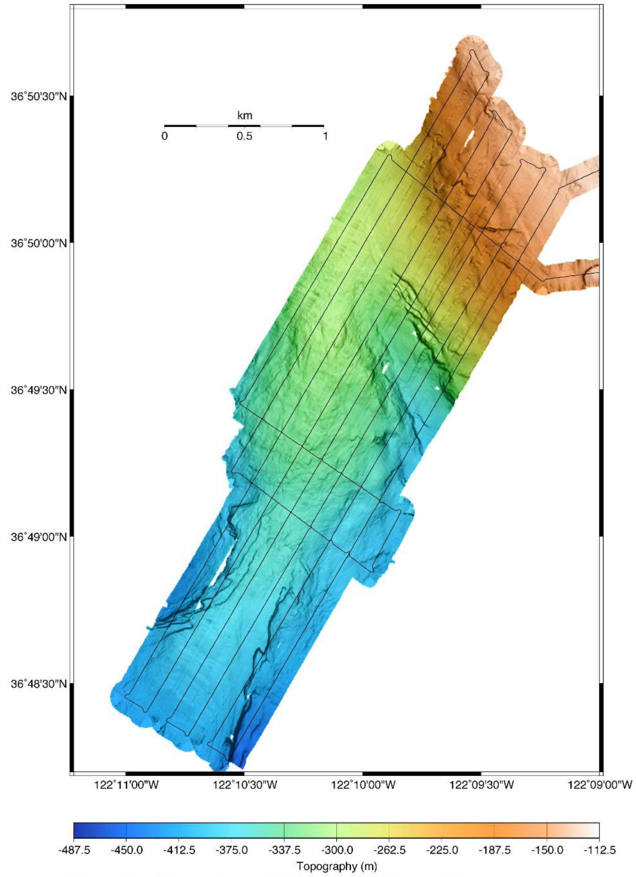

Fig. 8. Mapping AUV MARS cable route survey bathymetry and vehicle tracks (50 m altitude, 150 m line track spacing). The cable route is shown in blue.

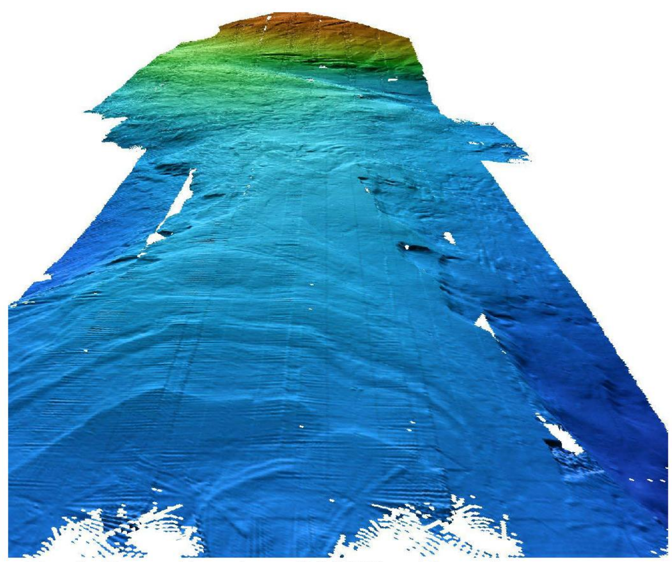

Fig. 9. Perspective view of MARS cable route survey bathymetry. Note subtle (<1 m) expression of sediment layer outcrops in the foreground.

C. Santa Monica Basin Surveys

The first expeditionary use of the mapping AUV occurred in June 2006, with five consecutive days of operation in Santa Monica Basin. The primary goal was to image surface and subsurface structure of mounds known to be associated with gas hydrates and gas venting [14]. The bathymetry data show that the mounds are circular, about 150 m across and 10-15 m high (Fig. 9). The subbottom profiles reveal shallow faults that offset and deform near surface sediments (Fig. 10). The vehicle also surveyed a section of the channel that extends from the mount of Redondo Canyon onto the adjacent fan. Scour-like features had been inferred from a hull-mounted multibeam survey; the Mapping AUV data imaged the fan channel morphology with much higher resolution, demonstrating that these features exist at a variety of scales (Fig. 11).

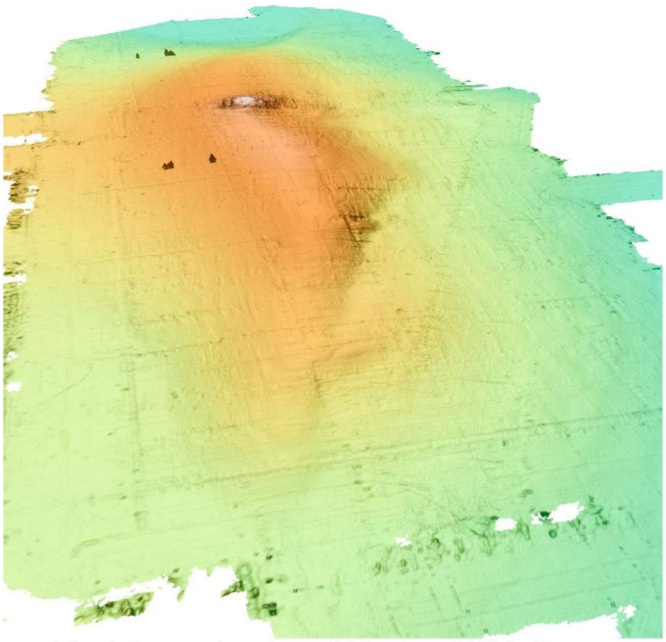

Fig. 9. Perspective view of Mapping AUV bathymetry imaging a gas hydrate mound at the summit of a larger, fault controlled bulge in the Santa Monica Basin. The area shown is approximately 1 km across with 50 m vertical relief. Surveyed with a vehicle altitude of 60-80 m. The grid resolution is 2 m.

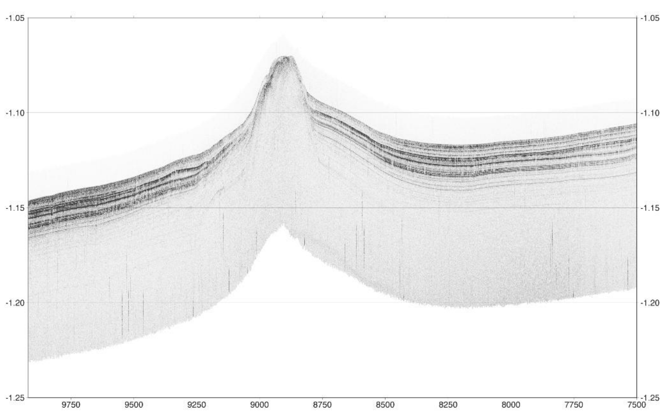

Fig. 10. Subbottom profile across the mound shown in Fig. 9 revealing sediment deformation across the hydrate deposit. Sediment layer structure is resolved to 0.1 m. The vertical relief of the seafloor shown here is 50 m.

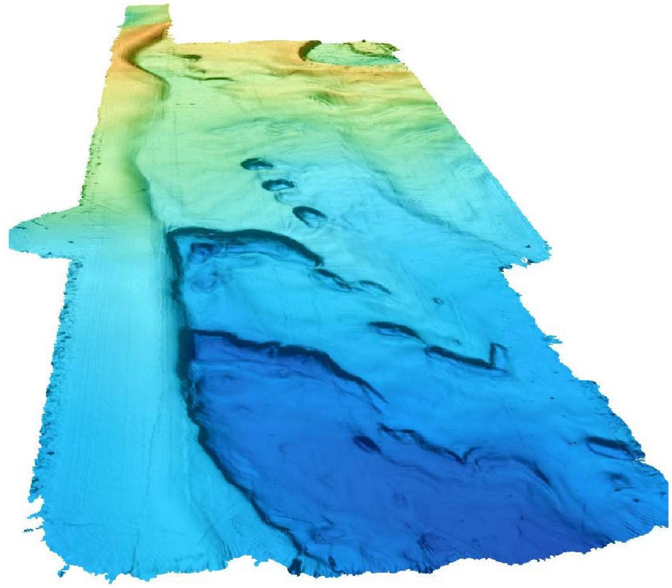

Fig. 11. Perspective view of Mapping AUV bathymetry survey of the Redondo Fan, showing scour-like features. The area shown is 1 km across and was surveyed in a single dive using a vehicle altitude of 60 m. The grid resolution is 2 m.

IV. Future Plans

A. Scheduled Surveys

Several additional Mapping AUV expeditions are planned during the remainder of 2006. During August the vehicle will survey Barcley Canyon, offshore British Columbia, and also perform cable route surveys near Barcley Canyon in support of the cabled seafloor observatory effort of Neptune Canada. Immediately afterward, the Mapping AUV will be used to survey the summit caldera of Axial Seamount on the Juan de Fuca Ridge. In October, the summit of Davidson Seamount offshore California will be surveyed. Finally, an additional set of Monterey Canyon repeat mapping surveys will be conducted in November.

B. Improvements

We continue to augment and improve the Mapping AUV. By 2007, the existing Reson 7125 multibeam, which includes a flat receive array, will be replaced by a Reson 7100 multibeam including a circular receive array that is conformal to the vehicle's hull. The new multibeam will achieve improved performance and outer-swath resolution due to the circular array geometry. A second 5 kWhr battery package will be integrated during 2007, allowing 17 hour survey missions. Also, a forward-looking obstacle avoidance sonar capability is under development; this will ultimately improve the vehicle's ability to operate near-bottom in regions of extreme bathymetry.

V. CONCLUSIONS

MBARI's Mapping AUV is now fully operational and has been demonstrated to efficiently collect high-resolution bathymetry, sidescan, and subbottom data in the deep ocean. This new capability effectively makes possible a new class of seafloor observations that is improving existing projects and enabling new avenues of research at MBARI.

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