

High-Resolution Multibeam, Sidescan, and Subbottom Surveys Using the MBARI AUV *D. Allan B.*

David W. Caress, Hans Thomas, William J. Kirkwood, Rob McEwen,
Richard Henthorn, David A. Clague, Charles K. Paull, and Jenny Paduan
Monterey Bay Aquarium Research Institute, Moss Landing, California

Katherine L. Maier
Stanford University, Department of Earth and Environmental Sciences, Stanford, California

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 *D. Allan B.* is a 0.53 m diameter, Dorado class autonomous underwater vehicle 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 6,000 m depth. Using precise navigation and attitude data from a laser-ring-gyro-based inertial navigation system integrated with a Doppler velocity log sonar, the *D. Allan B.* can image the deep-ocean seafloor and shallow subsurface structure with much greater resolution than is possible with sonars operated from surface vessels. Typical survey operations use a vehicle speed of 1.5 m per second (3 knots) and an altitude of 40 m to 100 m. The *D. Allan B.* has now been operated in a variety of settings, including submarine canyons (Monterey Canyon, Barkley Canyon), submarine fan systems (Redondo Channel, Lucia Chica, San Clemente), seamounts (Axial Seamount), methane hydrate outcrops and gas seeps (Santa Monica Basin, Barkley Canyon), and cable route surveys across continental margin slopes (Monterey Bay). The bathymetry surveys achieve a vertical precision of 0.1 m; surveys from a 50 m altitude achieve 1 m lateral resolution and surveys from up to 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. These survey data are sufficient in quality and resolution to use in conjunction with visual observations and sampling for mapping benthic habitats in the deep ocean.

Introduction

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 *D. Allan B.* (Figs. 1-3) combines mapping sonars (multibeam, sidescan, 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. Some aspects of the devel-

opment and testing of the MBARI mapping AUV have been previously described (Kirkwood et al. 2004, 2005; Kirkwood 2007). In this paper we discuss the current vehicle capabilities, present results from surveys in a variety of deep ocean settings, and comment on the utility of AUV survey data for benthic habitat classification.

The use of acoustic sensors to map the bathymetry, character, and subbottom structure of the seafloor is one of the most fundamental activities in oceanography, with applications in every aspect of marine science and technology that involves the seafloor. In the deep ocean (>500 m), achieving lateral resolution of a few meters or better requires mounting high frequency sonars on platforms that can be operated near the seafloor, such as tethered remotely operated vehicles (ROVs) (e.g., Yoerger et al. 1999b, Chadwick et al. 2001) or untethered AUVs (e.g., Eddy Lee et al. 2004; Yoerger et al. 1999a, 2007; Deschamps et al. 2007). AUVs tend to be better mapping sonar platforms than ROVs because AUVs move at higher, more consistent speeds and because AUV propulsion systems tend to be acoustically quieter than ROVs.

One emerging application of seafloor mapping is benthic habitat classification in support of ecological studies and fisheries management. Considerable effort has been made over the past two decades to develop both operational and interpretational techniques for classifying seafloor habitat through a combination of acoustic remote sensing, sampling, and photographic or video imaging (e.g., Greene et al. 1999, Kenny et al. 2003). In most cases, benthic habitat interpretation requires morphologic, textural, and lithological information with resolutions of a few meters, or better. The various habitats are characterized in a few places through direct observations by ROV or submersible and sampling. This information is then extended over a large area through interpretation of the seafloor mapping data. To date, the majority of habitat-mapping projects have involved relatively shallow water habitats (<200 m) for which hull-mounted sonars operated from vessels provide adequate resolution. Near-bottom surveys, such as those conducted using the *D. Allan B.*, provide a means to extend the habitat classification methodology into the deep ocean. Although none of the surveys presented here were performed for the purpose of



Figure 1. The MBARI AUV *D. Allan B.* being prepared for deployment from the R/V *Zephyr*. The *Zephyr* is equipped with a specialized J-frame crane for AUV launch and recovery over the stern.

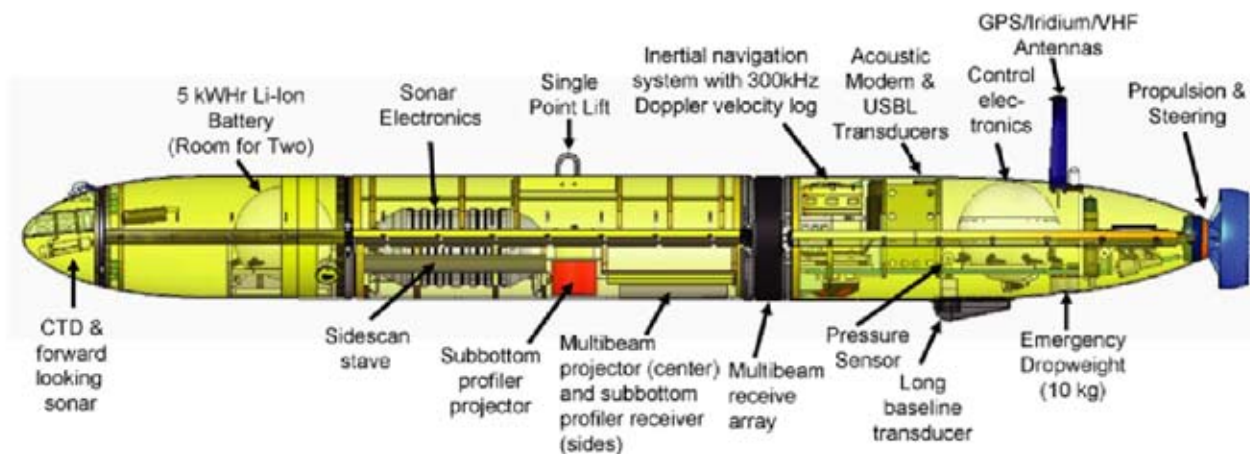


Figure 2. Design of the MBARI mapping AUV *D. Allan B.* This 0.53 m diameter, 5.2 m long Dorado class vehicle includes a 200 kHz multibeam, 110 kHz and 410 kHz chirp sidescans, and 2-16 kHz subbottom profiler.

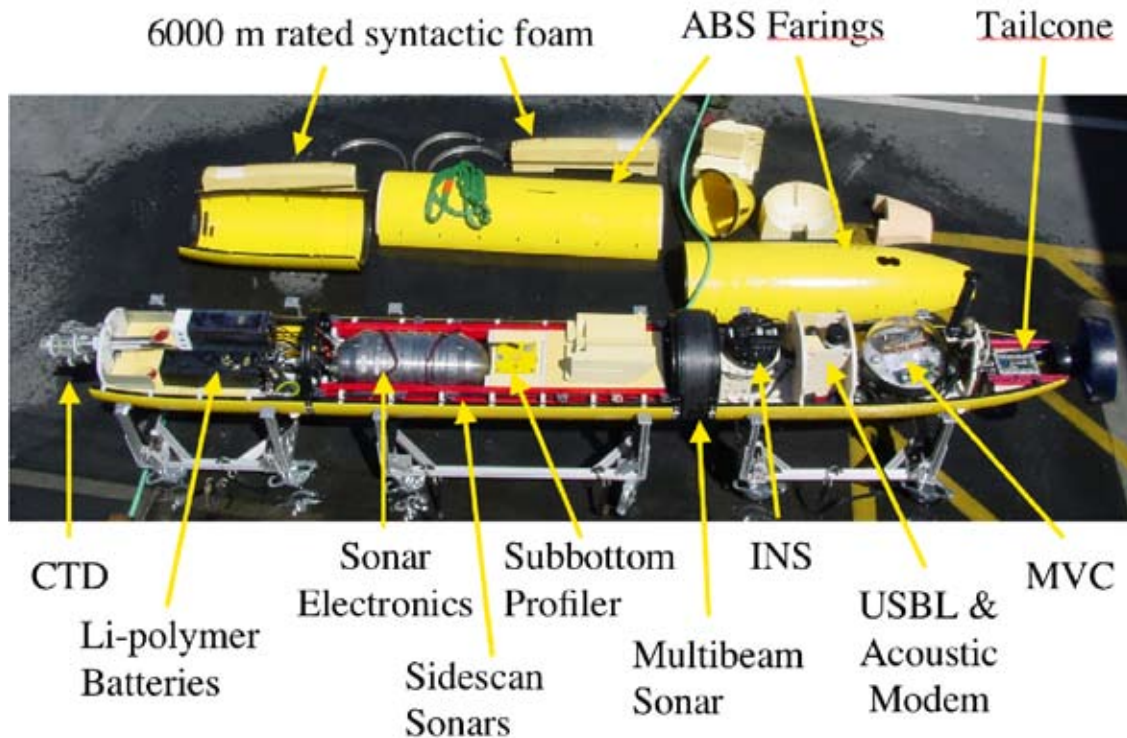


Figure 3. The interior of the *D. Allan B.* This photograph shows the original pressure tolerant Li-polymer batteries that have since been replaced by Li-ion batteries in a glass sphere housing.

habitat classification, where possible we note aspects of the data that have clear implications for benthic habitat.

Mapping AUV design and capabilities

Dorado class AUVs

Dorado class AUVs (Bellingham et al. 2000; O'Reilly 2000; Kirkwood et al. 2001, 2004, 2005; Kirkwood 2007) are 0.53 m (21 inch) diameter, variable length autonomous vehicles that have been developed and operated at MBARI since 2000. The first Dorado vehicle was designed to operate under ice in the Arctic ocean (Bellingham et al. 2000, Kirkwood et al. 2001). Three Dorados have been subsequently built; one is used to collect a variety of data and samples from the water column, a second serves as an engineering test platform, and the third, the *D. Allan B.*, is used for seafloor mapping. Although these vehicles differ in purpose and instrument payloads, they share many common features, particularly the frame and fairing construction, the propulsion system, and the vehicle control software.

Dorado vehicles are constructed from multiple sections (Figs. 2 and 3). A nose section and tail section are required at a minimum to provide vehicle control, communications, navigation, 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; the only protuberance is an antenna extending up from the tail section.

The main hull sections of a Dorado vehicle consist of upper and lower hulls made of 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. Blocks of syntactic foam fitted between and around the various housings provide buoyancy.

The heart of every Dorado vehicle is a main vehicle computer (MVC) housed in a 17 inch glass sphere located in the tail section, just forward of the tailcone. An object-oriented software framework, running with the QNX operating system on a PC-104 computer, provides the foundation for all the vehicle software, including guidance and control functions, data logging, and interfaces to any payload devices. Communications and navigation electronics are typically also located in the MVC sphere, though the specific systems vary amongst the vehicles.

Mapping AUV construction

The *D. Allan B.* is constructed from three sections: a nose containing batteries and conductivity, temperature, and



Figure 4. AUV pick using an articulated crane on R/V Thompson.

pressure depth (CTD) sensors; a midbody containing the mapping sonar payload; and a tail section including navigation, communications, main vehicle control, and propulsion (Figs. 2 and 3). All vehicle components are rated to a depth of at least 6,000 m. The *D. Allan B.* weighs about 1,500 pounds in air; a single lifting bale is located over the center of mass in the midbody. The MBARI vessel R/V *Zephyr* is equipped with a specialized J-frame crane for AUV launch and recovery. On other vessels, articulated cranes are typically used for over-the-side deployments (Fig. 4).

Communications and tracking

An FM radio modem provides 57 kbps line of sight communications to and from the vehicle when it is at the sea surface. This modem is utilized to connect the vehicle to a shipboard computer network, allowing operators to log on to vehicle computers, download missions, upload data, and start or terminate missions. An iridium satellite modem allows one-way communication from the vehicle; the vehicle uses this capability to email its location following each mission. An 8–15 kHz acoustic modem provides roughly 300 bps two-way communication when the vehicle is underwater. This modem is used to request and receive status reports from the vehicle, to update the vehicle position based on shipboard tracking, and to abort missions.

The vehicle can be tracked from surface vessels using ultra-short baseline (USBL) sonars. When operating from MBARI vessels, the *D. Allan B.* uses a Sonardyne MF USBL

(19 kHz interrogation, 27 kHz return); other USBL systems are used as required on non-MBARI vessels. Coded USBL interrogation pulses can be used to abort missions. The vehicle is also capable of operating within a long-baseline (LBL) transponder net.

Mapping payload

The primary mapping sensor is a Reson 7125 200 kHz multibeam sonar that provides swath bathymetry and acoustic backscatter intensity (Fig. 5). The multibeam provides soundings from 256 $1^\circ \times 1^\circ$ beams spread over a 150° swath from each ping. The $1^\circ \times 1^\circ$ beam widths translate to 0.75 m nadir beam footprints at a 50 m altitude (0.38 m at 25 m altitude, and 1.5 m at 100 m altitude). Because the beam footprints get larger toward the edge of the swath, the multibeam bathymetry has an overall resolution of 1 m when operated at a 50 m altitude. 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.

Additional acoustic devices include a 300 kHz Doppler velocity log (DVL) (part of the navigation system shown in Fig. 6), a USBL transponder, and an acoustic modem. All of the acoustic systems other than the USBL beacon and the acoustic modem are externally triggered to avoid interfer-

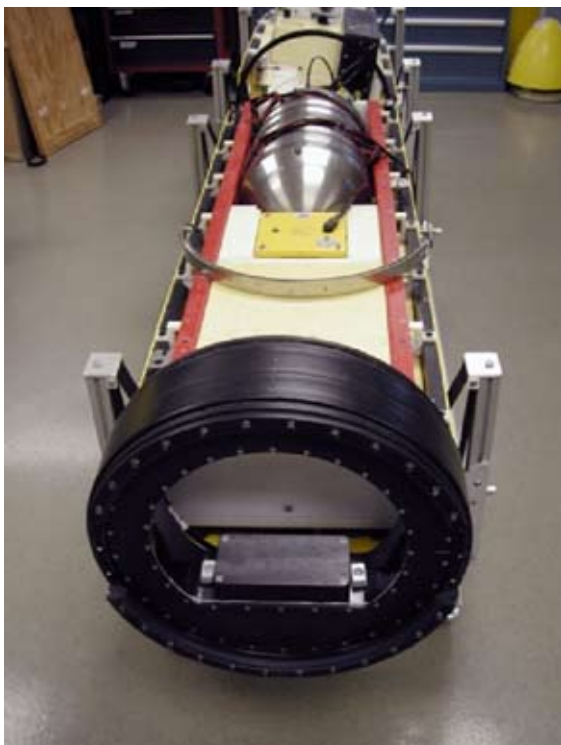


Figure 5. Interior of the mapping payload section. The flat multibeam receive array is embedded in the black ring in the foreground. The multibeam projector, subbottom profiler, and sidescan staves are located along the bottom and sides of the section. The titanium pressure housing holding all of the sonar electronics is seen at the aft end. Missing is a large body of 6,000 m rated syntactic foam and the upper midbody hull.

ence 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.

All mapping sonar commands, including starting and stopping of logging, and power, gain, range, and mode settings, are included in the mission script executed by the MVC. A software package called 6046, supplied by Reson, runs on the primary multibeam computer and serves as the mapping payload controller. The payload controller receives commands from the MVC and passes them on to the respective sonars. The payload controller also receives and logs all data from the multibeam subbottom profiler, and sidescan sonars in a single data stream. Navigation and attitude data from the INS and CTD data (including a calculated water sound speed) are logged in the sonar data stream as asynchronous records. Files are generally limited to 200 Mbytes in size. The sonars ping synchronously at 2 Hz, producing 200 Mbytes of data approximately every 20 minutes. The raw data are stored in the Reson 7 k data format.



Figure 6. Kearfott Seadevil inertial navigation system (INS) lying on its side. The lower end of the housing consists of a 300 kHz RDI Doppler velocity log (DVL). The aluminum housing encloses both the INS and DVL electronics.

Navigation and vehicle attitude

The central component of the vehicle navigation system is a Kearfott Seadevil inertial navigation system (INS) incorporating a ring laser gyro, accelerometers, and the DVL (Fig. 6). When possible, the INS Kalman filter is stabilized by DVL measurements of vehicle velocity relative to the seafloor. 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. The INS is also the source of vehicle attitude (roll, pitch, and heading) data for the multibeam sonar. Roll and pitch data are accurate to $\pm 0.025^\circ$, and heading data to $\pm 0.1^\circ$. Vehicle depth is calculated from pressure observations from a Paroscientific Digiquartz pressure sensor. When operating to depths less than 3,000 m, a pressure sensor with a 0.1 m precision is used. Deeper operations require use of a 6,000 m rated sensor that is precise to 0.3 m.

When the INS is in free inertial (unaided by DVL, GPS, or other sources of position or velocity), position errors can

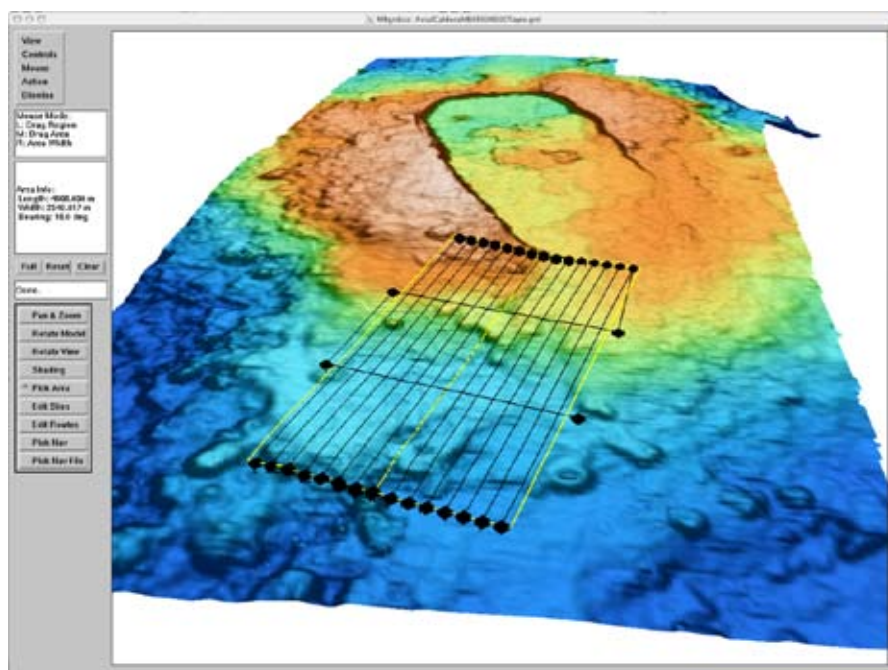


Figure 7. Screen dump of interactive AUV mission planning using MB-System program MBgrdviz. MBgrdviz is a general-purpose bathymetry 2-D/3-D visualization tool that allows users to explore bathymetry grids. Sidescan overlays, slope maps, survey navigation, routes, and sites can also be displayed and manipulated. For this application, users can select an arbitrary region on the seafloor, and automatically lay out a survey with the desired line spacing and number of cross lines. Users can also manually add, delete, or move waypoints as desired. The resulting “route” file is translated to an AUV mission script that can be used to execute the survey.

accumulate at rates of multiple kilometers per hour. 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 tracking fixes communicated to the vehicle over the acoustic modem.

Power

The *D. Allan B.* can be operated with two types of rechargeable battery packs. Initial testing was conducted using up to three 2 kWh, pressure tolerant Li-polymer batteries (Fig. 3). Recent operations have used a 5 kWh package of Li-ion cells housed in a 17 inch glass sphere (Fig. 2). The latter configuration allows for an 8.5 hour survey mission duration running at 1.5 m per second speed.

Vehicle safety

Vehicle safety is always a major concern. Typically the vehicle is ballasted to be approximately 3 kg buoyant, so that in the event of a power failure, the vehicle floats to the surface. The tail section includes a 10 kg emergency drop weight that can be triggered by commands from either the acoustic modem or the USBL. The additional buoyancy is sufficient to overcome flooding of any of the electronics housings, with the exception of the MVC sphere. In the event that a mission

ends or aborts while the vehicle is submerged, the weight will be dropped automatically after 15 minutes. 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 through email via the iridium satellite modem (unlimited range).

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 or 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 (Caress and Chayes 1996, 2008) visualization application, called MBgrdviz, is used to lay out survey lines and generate the survey mission scripts (Fig. 7).

Ongoing development

In conjunction with ongoing operations, MBARI continues to develop and augment the seafloor mapping capabilities of the *D. Allan B.* The battery capacity of the vehicle was doubled during late 2007, allowing 18 hour missions during 2008 operations. A forward-looking obstacle avoidance sonar is being tested; this will ultimately improve the vehicle's ability to operate near-bottom in regions of extreme bathymetry. Finally, during 2008 the existing Reson 7125 multibeam, which utilizes a flat receive array, is expected to 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.

Data processing

MB-System

The *D. Allan B.* multibeam, sidescan, and subbottom profiler data are processed using MB-System (Caress and Chayes 1996, 2008), an open source software package for the processing and display of swath mapping sonar. Among the tasks typically undertaken in processing are multibeam bathymetry editing, application of roll and pitch bias, navigation adjustment, tide correction, and sidescan correction. The processed swath data files are produced in the same data format used for logging. A number of data products are produced from the processed swath data, including bathymetry grids, sidescan mosaics, subbottom sections, maps, and GIS data layers.

Bathymetry editing

Multibeam bathymetry always includes some erroneous soundings, and consequently, editing or filtering of some sort is required to remove these artifacts. MB-System provides two interactive bathymetry editors, MBedit and MBeditviz. MBedit (Fig. 8) allows users to step sequentially through a swath bathymetry file and to flag soundings that are judged to be artifacts. The soundings from each ping are displayed as an across-track profile; multiple pings are shown in a waterfall display. MBeditviz loads and grids bathymetry from multiple files, displaying the bathymetry in a map or 3-D perspective view (Fig. 8). Users can select arbitrary areas of the seafloor, which results in the program identifying all soundings in the target region and then displaying these soundings in a 3-D view that allows interactive editing. This new capability allows users to more rapidly identify and fix bathymetry data problems.

Navigation adjustment

Navigation is critical to seafloor mapping applications in both an absolute sense (accurately placing features on the seafloor) and in a relative sense (matching seafloor features in overlapping bathymetry or sidescan swaths). As discussed above, the *D. Allan B.* achieves excellent navigation through its DVL-aided INS. However, over the course of an 8.5 hour

mission, the INS will still accumulate position errors of up to 20 m. Since the bathymetric resolution is typically on the order of 1 m, the relative navigation error produces quite noticeable artifacts where swaths overlap and cross.

Vertical offsets between overlapping swaths are also frequently quite significant sources of artifacts. Although the pressure depth sensor is precise to 0.1 m (0.3 m when the 6,000 m range sensor is used), absolute accuracy in vehicle depth also depends on correcting for the barometric pressure at the sea surface. Vehicle depth offsets of up to 1 m are found between identical missions. Tides are often a greater source of vertical offsets, and some surveys are performed in locations where tidal models or data are unavailable.

An MB-System tool called MBnavadjust (Fig. 9) has been developed to allow users to obtain navigation models that are as accurate in a relative sense as the lateral and vertical resolution of the bathymetry. This software identifies all places where bathymetry swaths overlap or cross, and then allows users to interactively determine what x, y, and z offsets are required to match bathymetric features in both swaths. MBnavadjust then solves for an optimal navigation model that fits all of the relative offsets while minimizing perturbations to speed and acceleration. The resulting navigation model is applied as part of the data processing. This methodology simultaneously addresses errors from navigation, pressure depth, and tides.

Bathymetry gridding

The processed swath bathymetry data are translated into a uniformly spaced terrain model, or grid, using an MB-System program called MBgrid. The preferred MBgrid algorithm uses the sonar geometry, altitude, and the angular beam widths to calculate the location and size of the seafloor footprint associated with each sounding. A weighting value is calculated for each grid cell that fully or partially lies within the beam footprint; these weighting values represent the fraction of the beam contained within the cell. This approach allows one to sensibly grid data using a resolution greater than that of the raw data. Thus, if one has data with a large altitude variation, or data from multiple sources, one can generate a grid with cell spacing appropriate for the higher resolution data and still get sensible results in regions covered by lower resolution data where the grid cells may be much smaller than the beam footprints.

Sidescan processing

Sidescan data are processed following bathymetry editing and navigation adjustment. The sidescan imagery is first located on the seafloor using the multibeam bathymetry (as opposed to a flat bottom correction). Then the sidescan data are corrected for the variation in amplitude with grazing angle using an average model derived from the raw values. The amplitude-vs.-grazing angle correction may be a smoothly varying function calculated from local data along the vehicle track, or a single global average for an entire survey. Users mosaic the corrected sidescan imagery by specifying priorities for look

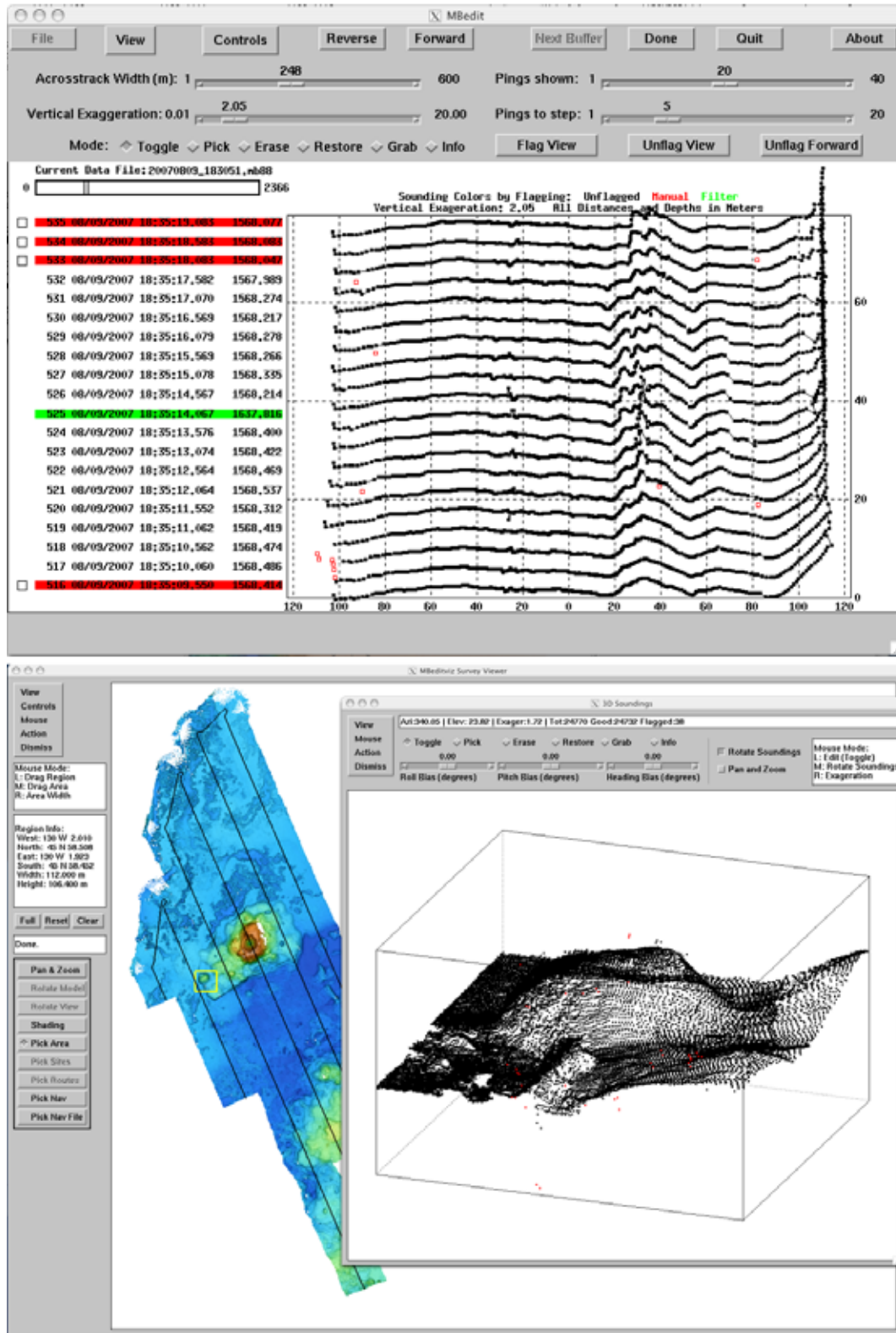


Figure 8. Interactive bathymetry editing in MB-System. Top: Simple waterfall display ping editor MBedit. Users step through a file, flagging and unflagging soundings as required. Bottom: Visualization based bathymetry editor MBeditviz. The user selects one or more swath files, which are gridded and displayed in a 2-D/3-D visualization environment similar to MBgrdviz (Fig. 7). When the user selects an arbitrary area on the map, all of the soundings within that area are displayed in a 3-D volume. The volume can be rotated, exaggerated, or resized, and soundings can be flagged or unflagged as necessary. MBeditviz also functions as a patch test tool, allowing interactive determination of roll and pitch bias.

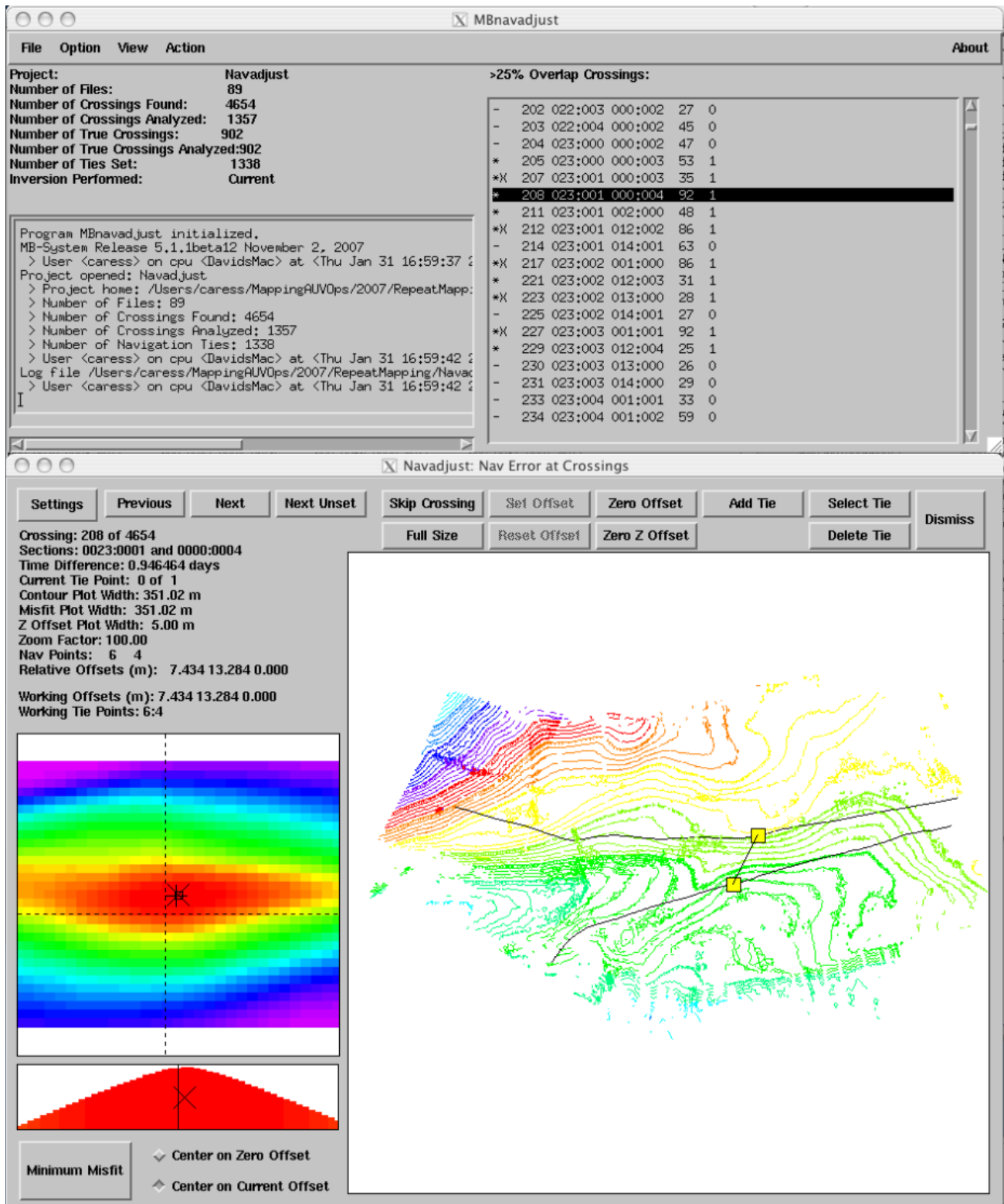


Figure 9. Navigation adjustment in MB-System. The tool MBnavadjust loads bathymetry survey files and identifies all places where swaths overlap or cross. Users then interactively inspect contour maps and 3-D cross-correlations between the swaths at each crossing/overlap point, picking the relative x, y, and z displacements required to match bathymetric features. Once all crossings have been inspected, MBnavadjust solves for an optimal navigation model that eliminates mismatches in overlapping swaths. The resulting navigation is accurate, in a relative sense, to the bathymetric feature resolution (typically ~1 m).

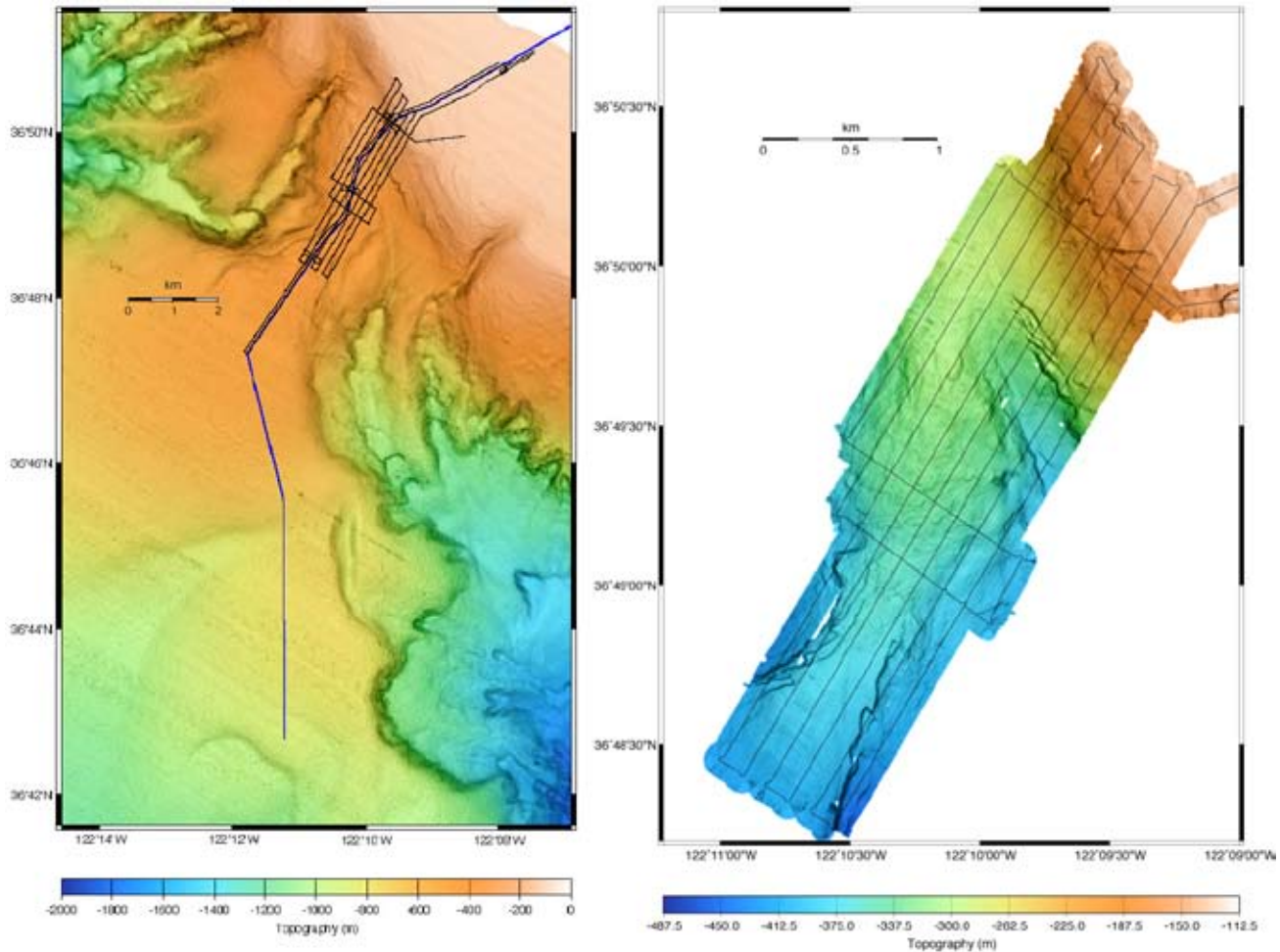


Figure 10. Left: Location of *D. Allan B.* MARS cable route survey tracks (black) in Monterey Bay. The cable route is shown in blue. Right: *D. Allan B.* MARS cable route survey bathymetry and vehicle tracks (50 m altitude, 150 m line track spacing). A set of en echelon scarps on the north side of a gully marks the San Gregorio Fault.

azimuth (e.g., use NE-looking data only) and swath position (e.g., prioritize data from 30° to 60° over data from the nadir region of 0° to 30°).

Subbottom profiler data

The subbottom profiler data are extracted to line files in the SEG-Y seismic data format. Profile sections can be plotted using MB-System or processed and plotted using one of the many software packages available for working with seismic reflection data.

Example *D. Allan B.* surveys

Some results from six *D. Allan B.* surveys are presented here in order to document the resolution and data quality that are now routinely achieved. The 1 m resolution multibeam bathymetry is emphasized, but examples of subbottom profiles and sidescan mosaics are also shown.

MARS cable route

The Monterey Accelerated Research System (MARS) is a cabled observatory testbed in Monterey Bay connecting seafloor instruments to shore via a 51 km long power and fiber-optic communications cable (Fig. 10). The first autonomous bathymetric survey by the *D. Allan B.* was conducted in November 2005 covering the most problematic portion of the cable route. This 7 hour 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 (Figs. 10–11). A similar-resolution ROV-based survey would have taken at least ten times as long, but with inferior data quality due to greater acoustic noise. 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. The high-resolution bathymetry also revealed small (<1 m) outcrops created by differential erosion of sediments. Although the surficial lithology varies little in

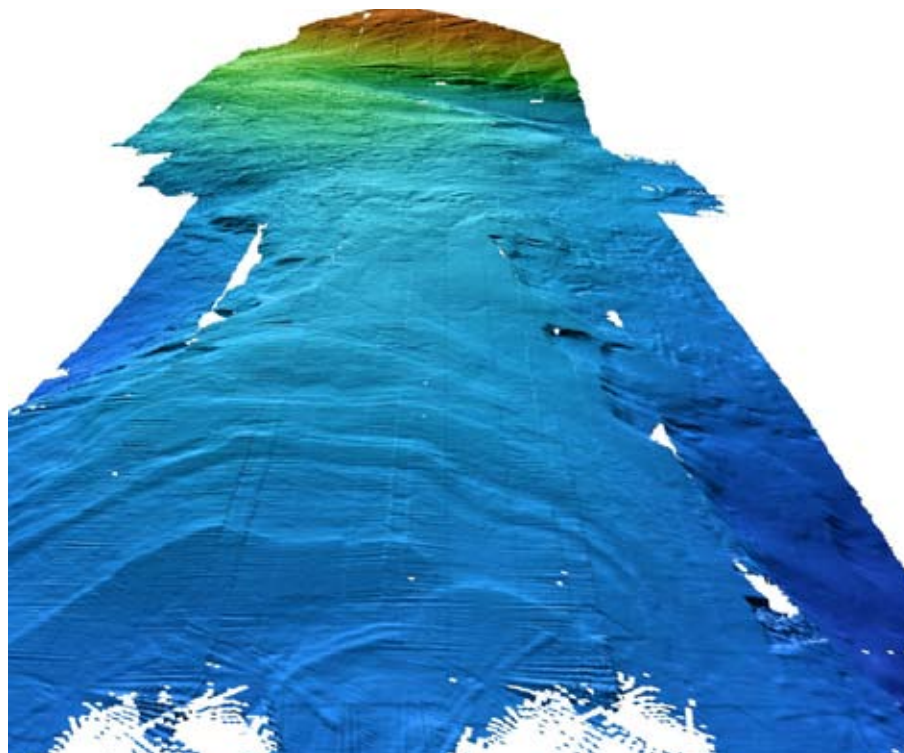


Figure 11. Perspective view of MARS cable route survey bathymetry. Note subtle (<1 m) expression of sediment layer outcrops in the foreground. View is toward the northeast.

this survey, some benthic animals prefer locations with local relief. Thus, it is possible that the communities living along the outcrops imaged by the AUV differ from those on the surrounding flat, muddy seafloor.

Santa Monica Basin surveys

The first expeditionary use of the *D. Allan B.* 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 methane hydrates and methane venting (Paull et al. 2008). The bathymetry data show that the mounds are circular, about 150 m across and 10–15 m high (Fig. 12). The subbottom profiles reveal shallow faults that offset and deform near surface sediments (Fig. 12). Hydrocarbon seeps and hydrate outcrops are known to harbor chemosynthetic communities (e.g., Roberts 2001, Pohlman et al. 2005), so identifying vent sites has direct implications for habitat mapping. The vehicle also surveyed a section of the channel that extends from the mouth of Redondo Canyon onto the adjacent fan. Scour-like features had been inferred from a hull-mounted multibeam survey; the AUV data imaged the fan channel morphology with much higher resolution, demonstrating that these features exist at a variety of scales (Fig. 13) (Normark et al. 2007).

Barkley Canyon gas hydrate outcrops

In 2000, a fishing trawler accidentally discovered gas hydrate outcrops at Barkley Canyon, offshore British Columbia, Canada (Spence et al. 2001). Subsequent ROV dives revealed massive outcrops of gas hydrates at the seafloor exposed in 1–2 m high mounds covered by a thin veneer of sediment (Pohlman et al. 2005, Lu et al. 2006). The Barkley Canyon hydrate outcrops are located at 850 m depth on the northwest canyon wall on a 0.5 km wide, 1 km long plateau perched 150 m above the canyon floor. In 2006, the *D. Allan B.* surveyed a 1.8 km by 1.6 km area encompassing the plateau, the canyon wall above, and the canyon floor below (Fig. 14). The survey was conducted from a 50 m altitude with 150 m line spacing. In addition to mapping the large-scale features of the site, the multibeam bathymetry also imaged the hydrate outcrop mounds explored by ROV and a 10–15 m high fault scarp uphill of the hydrates. The mounds identified in the bathymetry support communities of vesicomyid clams and white bacterial mats (Pohlman et al. 2005) that are absent from the surrounding canyon seafloor.

Axial Seamount

Axial Seamount is an active volcano situated on the Juan de Fuca Ridge, an oceanic spreading center located offshore Washington state and British Columbia. The 1,500 m deep summit features a 3 km wide and 8 km long caldera, and has

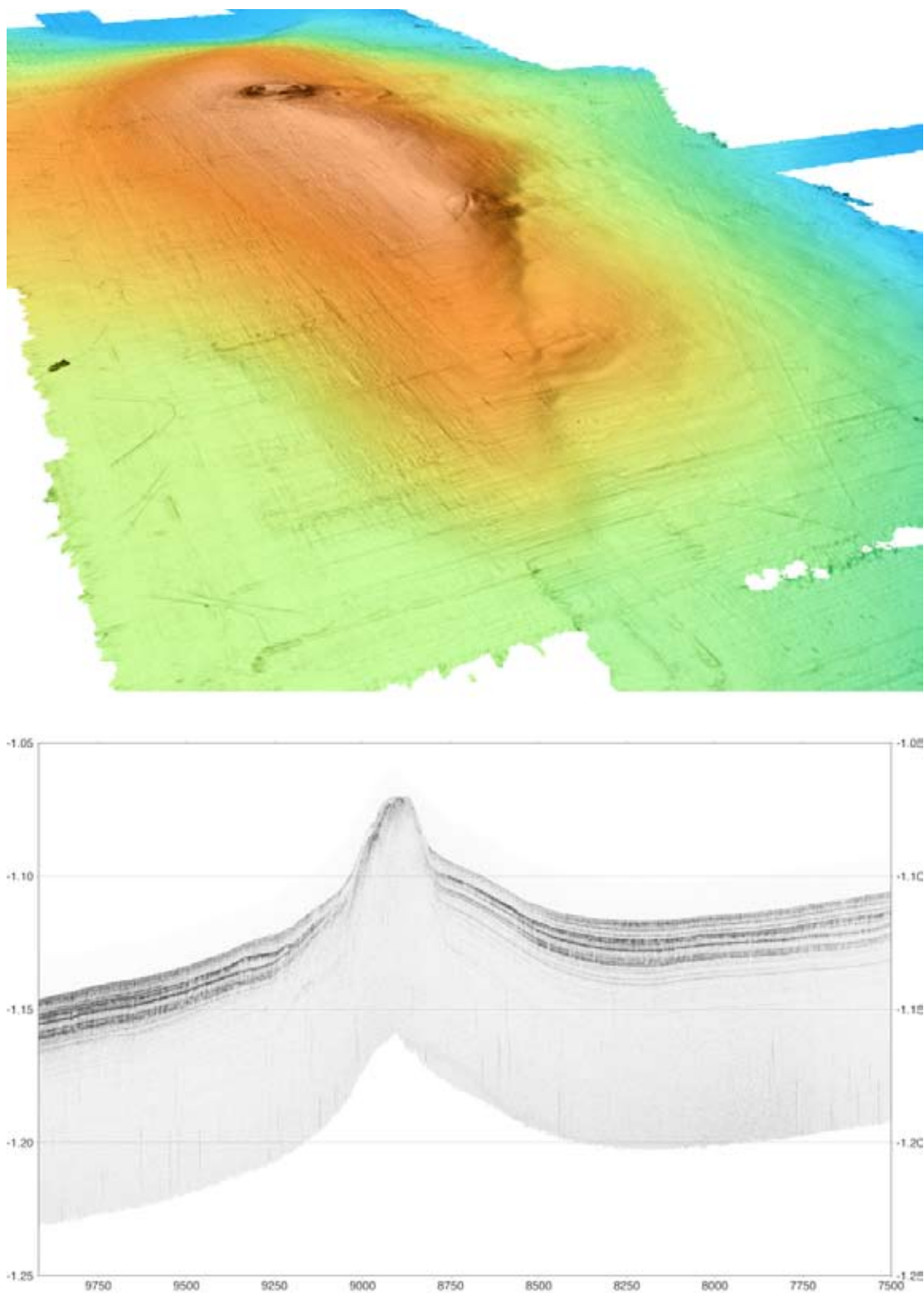


Figure 12. Top: Perspective view of *D. Allan B.* bathymetry imaging a gas hydrate mound at the summit of a larger, fault-controlled bulge in the Santa Monica Basin. The area shown is approximately 1 km across with 50 m vertical relief. Surveyed with a vehicle altitude of 60-80 m. The grid resolution is 1 m. Bottom: Subbottom profile across the mound, 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.

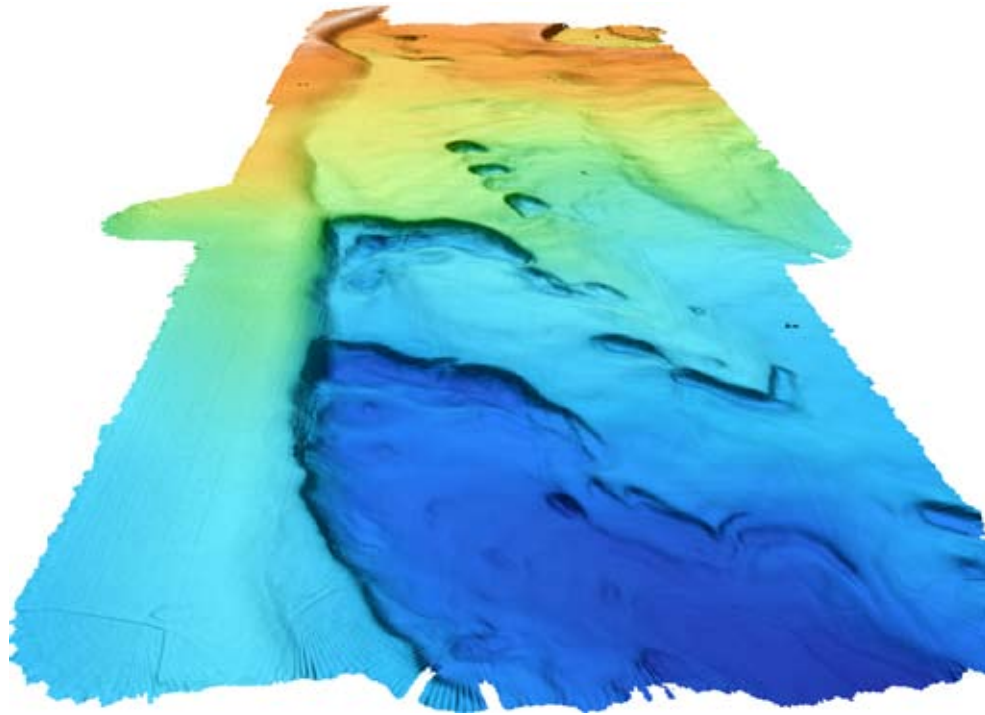


Figure 13. Perspective view of *D. Allan B.* bathymetry survey of the Redondo Fan, showing scour features in an overflow channel. The primary channel and its levee are seen in the upper right. The area shown is 1 km across and was surveyed in a single dive using a vehicle altitude of 60 m. The grid resolution is 1 m.

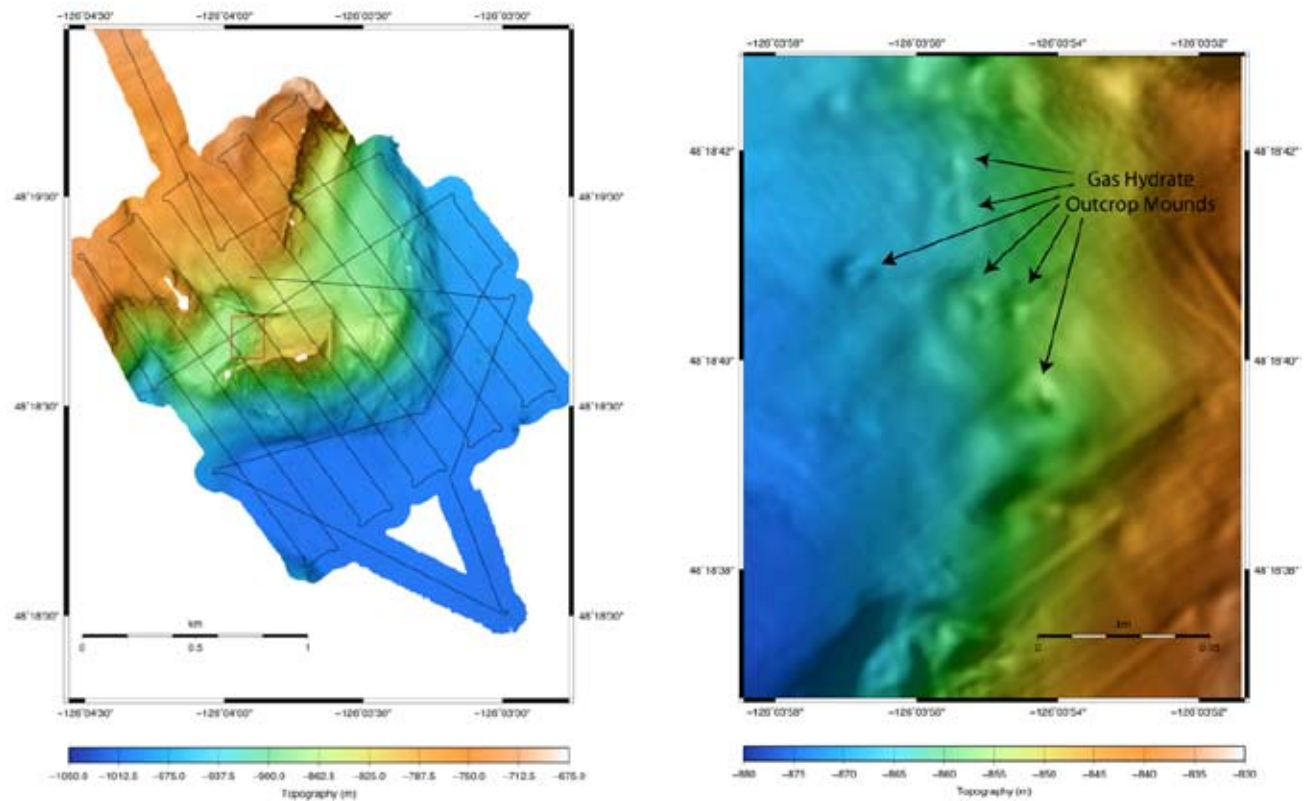


Figure 14. Left: *D. Allan B.* vehicle tracks and multibeam bathymetry of the Barkley Canyon survey. The gas hydrate outcrops occur inside the red box. Right: Detailed bathymetry of gas hydrate outcrop site, with individual 1-2 m high hydrate mounds indicated.

experienced significant eruptions as recently as 1998. The *D. Allan B.* ran seven survey missions (Fig. 15) during 2006 and 2007, covering about two-thirds of the caldera interior and about one-third of the rim with 1 to 1.5 m resolution bathymetry and sidescan (Thomas et al. 2006, Caress et al. 2007, Clague et al. 2007). The efficiency of AUV-based mapping is demonstrated by the bathymetric coverage of an ~40 km² area with 1.5 m resolution or better using only four days of ship time (8 hour missions followed by 6 hours battery charging). As shown in Fig. 16, the combination of the high-resolution bathymetry and sidescan allows for detailed interpretation of the seafloor sediment cover. ROV and submersible dives on Axial Seamount show that recent volcanic flows are only sparsely inhabited; areas of older seafloor with at least some sediment cover harbor communities of sponges and limpets. Thus, the use of sidescan imagery to infer relative lava flow age is also a means to infer density of the young benthic communities. Fig. 17 also shows the utility of high-resolution bathymetry for identifying small features of interest, in this case a previously unknown group of hydrothermal vents. In addition to constructing large sulfide chimney edifices, these newly discovered vents also support robust chemosynthetic communities of tube worms, bacterial mats, and associated animals (Thomas et al. 2006).

Lucia Chica Fan

In order to study the sediment deposition associated with deep sea fans, a 2007 *D. Allan B.* survey focused on a flat mid-slope portion of the Lucia Chica canyon system, offshore Big Sur, California (Maier et al. 2007). The bathymetry (Fig. 18) imaged a complex, anastomosing system of channels, and also revealed a field of pockmarks. Many of the pockmarks are subtle features, less than 5 m across and as little as 0.3 m deep (Figs. 19 and 20). The existence of the larger pockmarks was previously known from surveys conducted using hull-mounted multibeam, but the smaller features can only be resolved using near-bottom surveys.

San Clemente margin

As part of a series of investigations of faulting offshore southern California, conducted during July 2007, the *D. Allan B.* surveyed an 800 m deep, flat, sedimented area west of San Clemente from a 50 m altitude. As shown in Figs. 21–24, seafloor that is flat and uninteresting when surveyed using hull-mounted multibeam can reveal complex, if subtle, morphologies when studied with near-bottom sonar surveys. The bathymetry (Figs. 21–23) is dominated by two 200–400 m wide, 5 m deep troughs or channels surrounded by several distinct basins that are 30–50 m across and 2–3 m deep. A 0.4 m thick, 200 m wide mass wasting flow lobe extends 500 meters into the survey from the north. In addition, much of the seafloor outside the troughs and basins is sprinkled with mounds that are only a few meters across and less than 0.5 m high (Fig. 23). A few of these mounds exist on top of the

mass wasting flow, suggesting that at least some of these features have formed since the mass wasting event occurred. The subbottom profile data (Fig. 24) indicate that a 1–1.5 m thick surficial sediment layer covers the seafloor, though the acoustic character of this layer varies considerably. Any habitat mapping effort at this site should investigate the possible importance of the small mounds, the basins, and the variations in the surface sediment characteristics.

Fig. 23 presents an analysis of the bathymetric resolution and accuracy achieved using the *D. Allan B.* Two overlapping multibeam bathymetry swaths covering a few dozen of the aforementioned small mounds are shown as 1 m grids following the usual processing, including navigation adjustment by co-registration (Fig. 9). All of the mounds are similarly imaged in both swaths, and a difference map reveals that, aside from the noisy swath edges, the two surveys generally differ by less than 0.1 m. We infer that the expected lateral resolution of 1 m is achieved with a vertical precision equal to that of the pressure depth. This assessment is confirmed by a histogram plot of the bathymetry differences, which shows that the one standard deviation difference “noise” is approximately ± 0.1 m.

Upper Monterey Canyon

Vigorous sediment transport events are known to occur in upper Monterey Canyon with a recurrence interval of considerably less than a year (Xu et al. 2004; Paull et al. 2002, 2006). In order to observe bathymetric changes associated with these sediment transport events within the canyon’s axis, MBARI has begun repeatedly surveying the upper Monterey Canyon axis with the *D. Allan B.* (Paull et al. 2007). Fig. 25 shows a portion of the Monterey Canyon axis. The apparent bedforms have wavelengths up to 70 m long and amplitudes of 0.5–2 m. Surveys to date have demonstrated that these features extend from 100 m depth at the canyon head (Smith et al. 2005) to at least 1000 m depth in Monterey Canyon (Caress et al. 2005, Paull et al. 2007), and that these features change over time. Continued repeat surveys will hopefully reveal how the formation and evolution of these bedforms relates to down-canyon sediment transport.

Conclusions

MBARI’s mapping AUV *D. Allan B.* 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 makes possible a new class of seafloor observations that, among other uses, can enable the habitat mapping techniques developed in shallow water to be applied to deep-ocean benthic habitats.

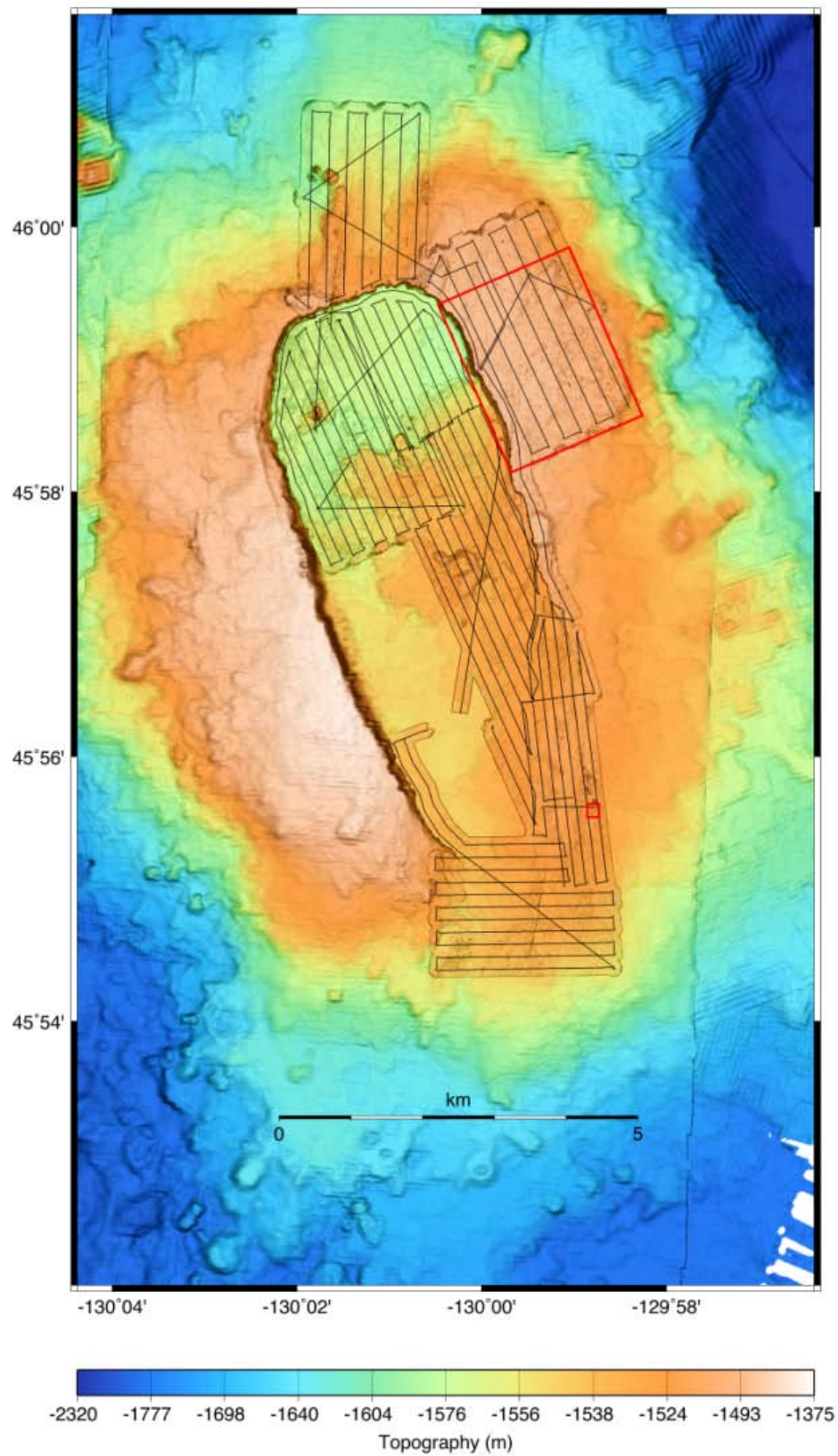


Figure 15. Summit of Axial Seamount showing AUV tracks from seven survey missions (Thomas et al. 2006, Caress et al. 2007, Clague et al. 2007). The vehicle flew at a 50 m altitude inside the caldera and a 90 m altitude on the northern rim, providing 1-1.5 m lateral resolution bathymetry. The red boxes indicate the locations of the data shown in Figs. 16 and 17.

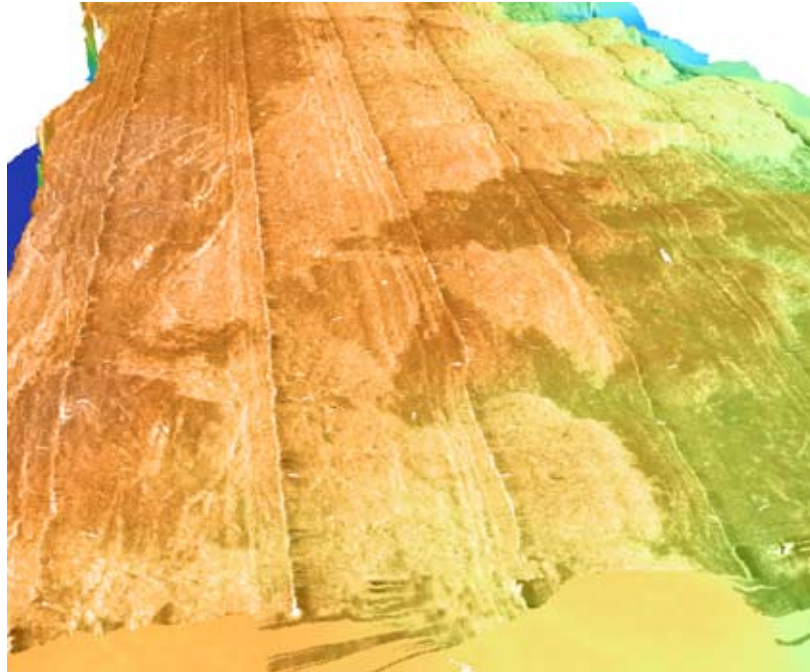


Figure 16. 110 kHz sidescan draped on multibeam bathymetry from the northern rim of the Axial Seamount summit caldera (location shown by large red box in Fig. 15). High amplitude backscatter is shown as light, and low backscatter as dark. The light areas map recent lava flows erupted from fissures on the left, which show as very bright lines. The dark areas are covered by 1-2 m of volcanoclastic sediment.

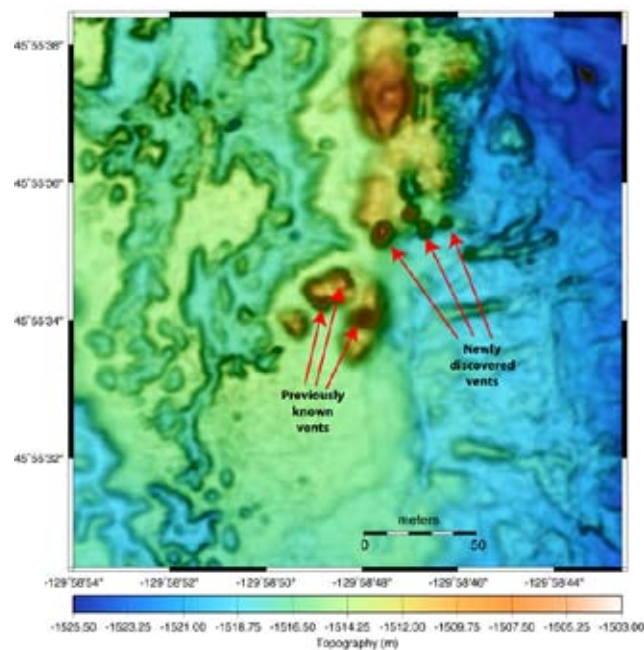


Figure 17. *D. Allan B.* bathymetry of a small region in the south caldera of Axial Seamount (location shown by the small red box in Fig. 16). The 1 m resolution bathymetry reveals collapse features in a recent lava flow, 2-3 m high lava pillars along the collapse margins, and a set of sulfide mounds associated with active high temperature hydrothermal venting. The southeastern vents had been visited frequently by submersibles and ROVs for over ten years. The northeastern group of vents was discovered less than 50 m away in 2006 using the bathymetry from the first *D. Allan B.* survey on Axial Seamount. The newly discovered vents include “El Guapo,” the highest temperature vent discovered so far on this seamount.

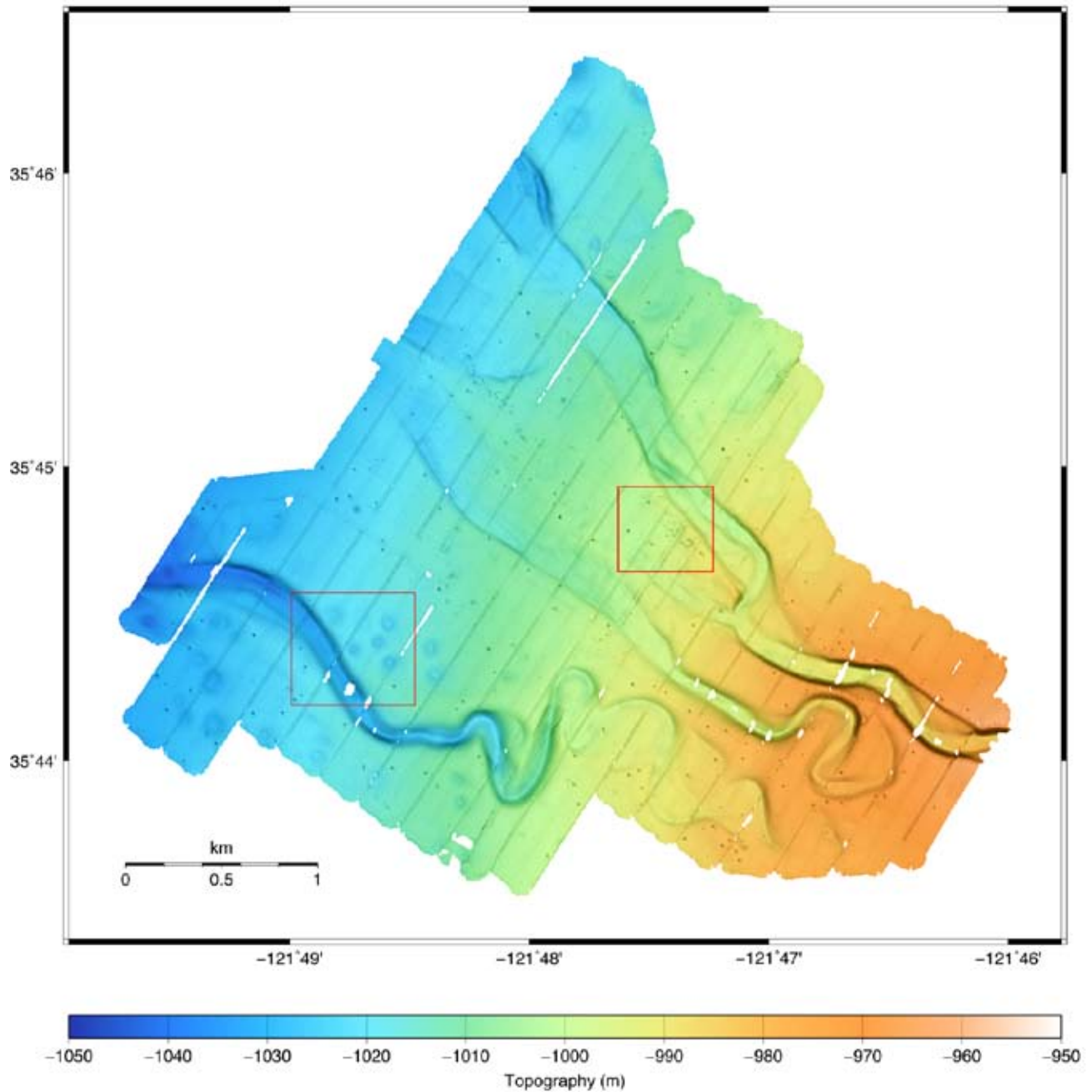


Figure 18. *D. Allan B.* bathymetry survey of the Lucia Chica midslope fan, offshore Big Sur, California. The AUV flew lines spaced 150 m at a 50 m altitude. The artifacts parallel to vehicle tracks are associated with the increased noisiness of the outer swath. This fan exhibits anastomosing and meandering channels. Also note that pockmarks, some as small as 0.3 m deep and 5 m wide, are located throughout the survey area. Figs. 19 and 20 show the detailed bathymetry of the areas enclosed in the right and left red boxes, respectively.

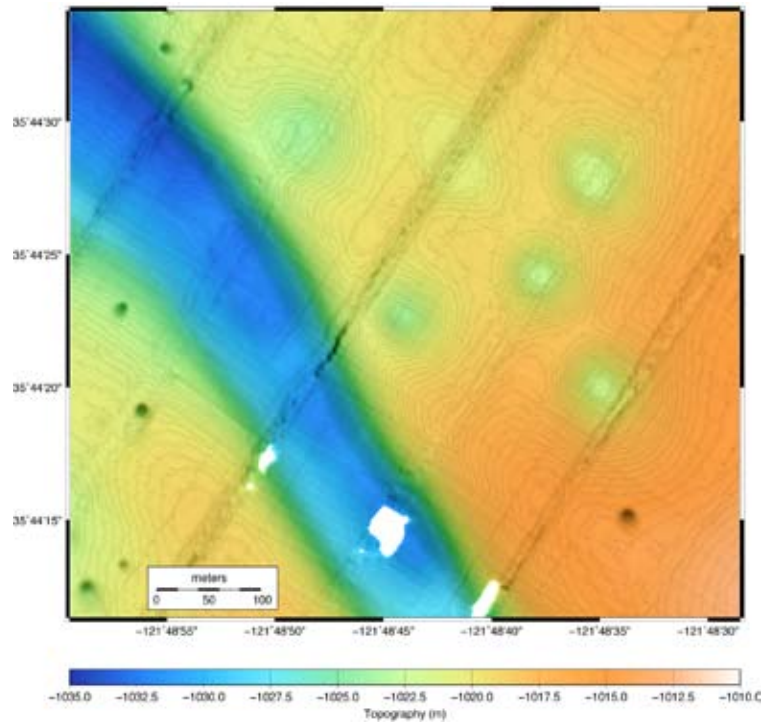


Figure 19. Pockmarks adjacent to a fan channel in the Lucia Chica survey (location shown in Fig. 18). The larger pockmarks are ~100 m in diameter and 3 m deep. The contour interval is 0.25 m.

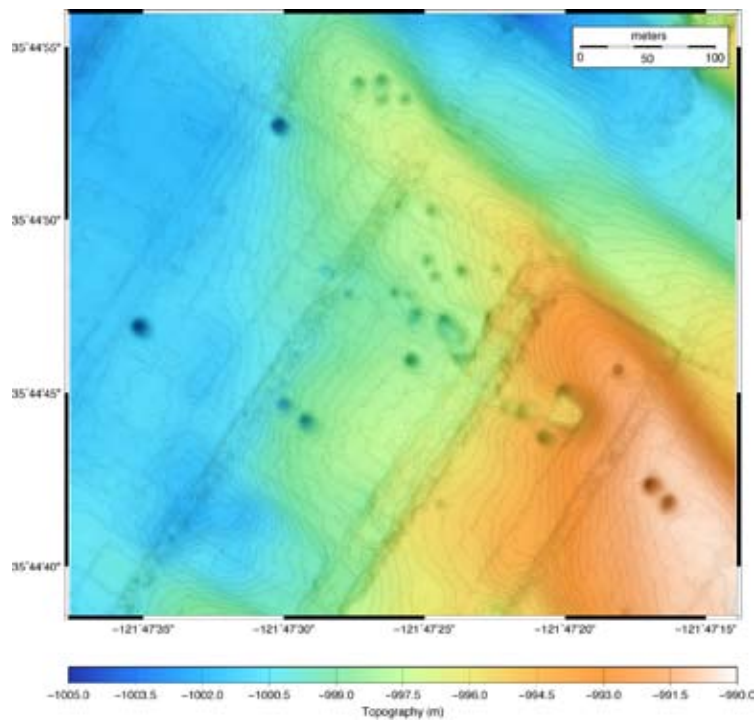


Figure 20. A field of small (3-10 m diameter) pockmarks in the Lucia Chica survey (location shown in Fig. 18). The contour interval is 0.25 m.

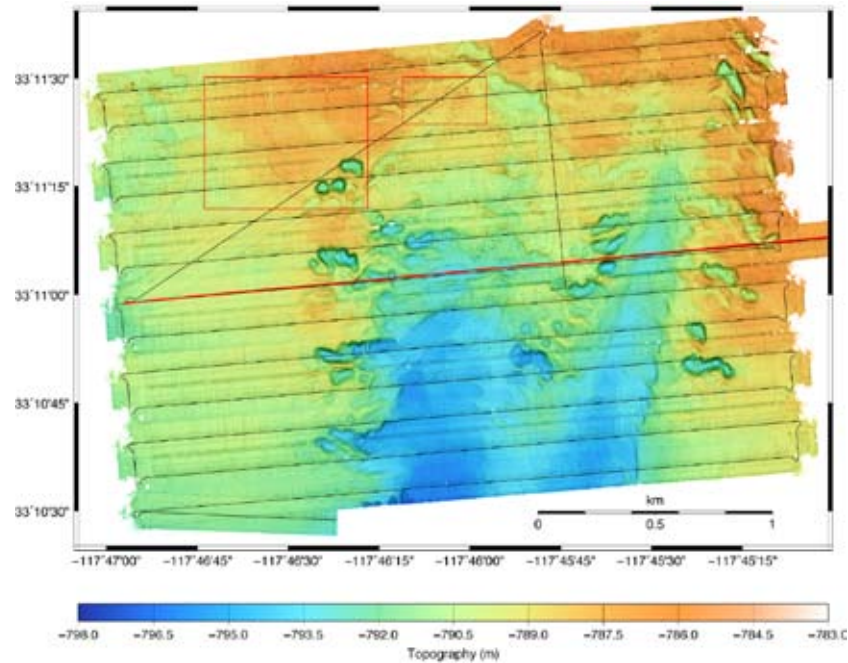


Figure 21. *D. Allan B.* bathymetry survey of a flat, sedimented seafloor offshore San Clemente, California. The total relief of this 8 km² area is only 12 m, but the fine-scale bathymetry reveals a complex morphology including mass wasting (left red box, Fig. 22), nascent channels, shallow basins, and numerous small (<5 m across and <0.5 m high) mounds. One set of mounds (right red box) is displayed in Fig. 23; this region is used to assess the accuracy of the 1 m lateral resolution bathymetry. The bold red line shows the location of a subbottom profile displayed in Fig. 24.

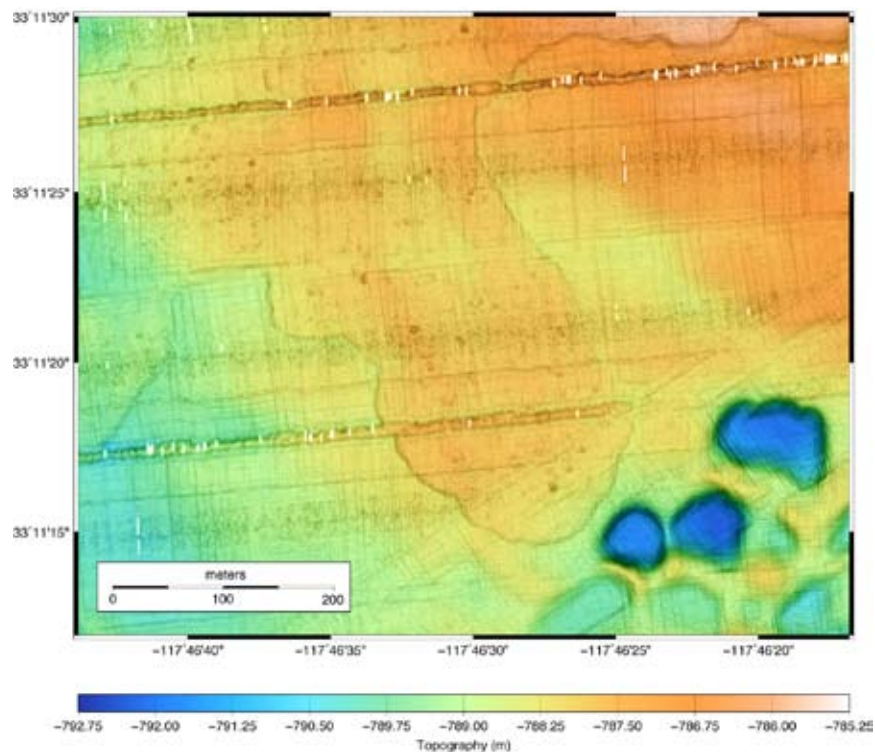


Figure 22. Mass wasting flow front; the flow deposit is ~0.4 m thick. The basins in the lower right are ~2 m deep and 50-100 m across. Location shown in Fig. 21.

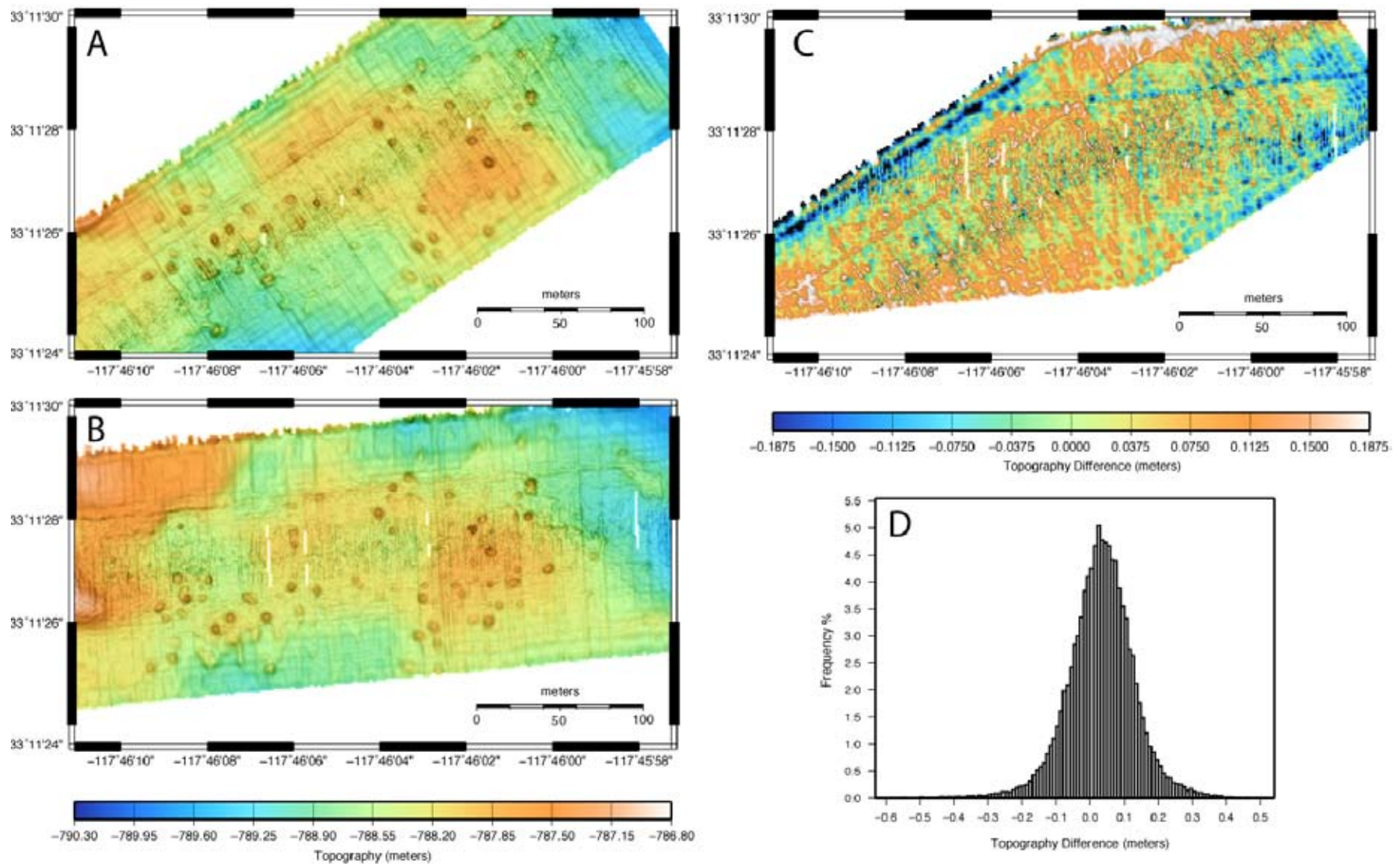


Figure 23. Assessment of bathymetric resolution and precision from multibeam bathymetry collected from MBARI's mapping AUV *D. Allan B.* in July 2007 offshore San Clemente. The location of these maps is shown in Fig. 21. These data from two separate AUV missions have been processed as described in the text, including editing, navigation adjustment, and gridding. (A) Bathymetry collected July 14 shown as slope shaded 1 m resolution grid. (B) Bathymetry collected July 15 crossing the swath from the earlier mission. Note the close correspondence of ~3 m diameter, 0.3 m high mounds between the two surveys. The grid registration and color map in A and B are the same. (C) Topographic difference between the two surveys. The difference is less than 0.1 m except at the swath edges. (D) Frequency histogram of topographic differences between the two grids of A and B. The bathymetric repeatability achieved is ± 0.1 m at the one standard deviation level, with a 0.04 m static offset between the two surveys.

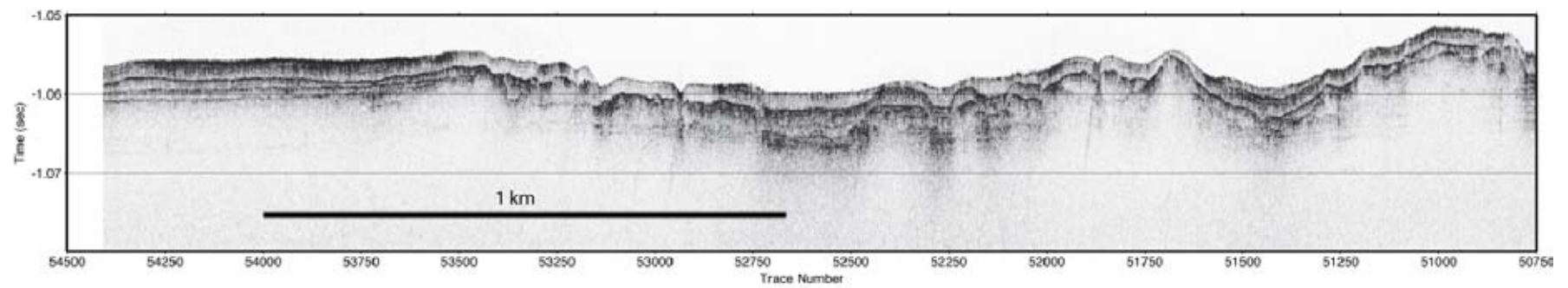


Figure 24. Subbottom profile across the map of Fig. 21. The surficial sediment layer is 1-1.5 m thick.

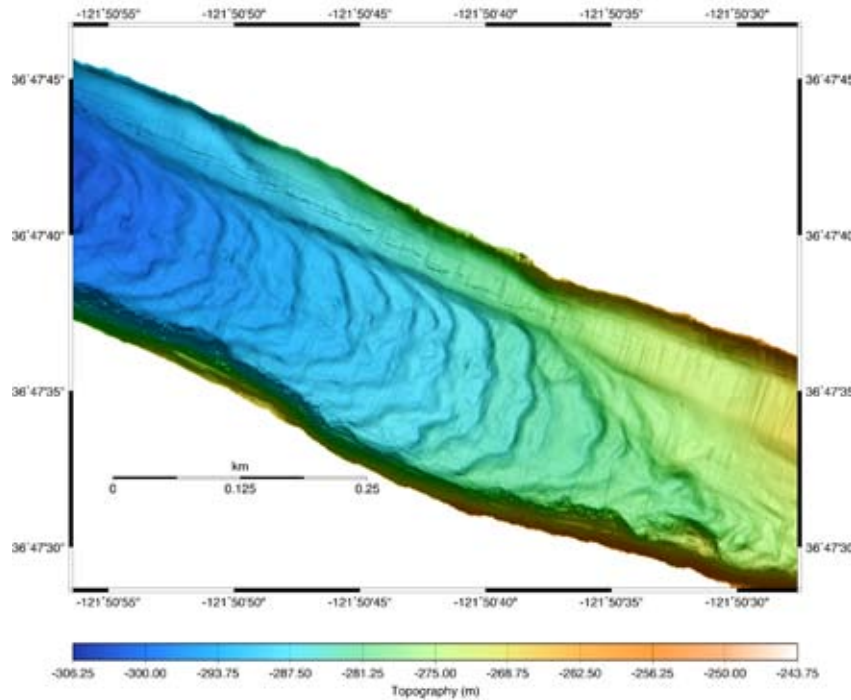


Figure 25. *D. Allan B.* bathymetry of the Monterey Canyon axis at about 275 m depth. The 0.5-m high bedforms imaged here extend along the canyon axis from the canyon head at 100 m depth to at least 1,000 m depth (Caress et al. 2005, Paull et al. 2007).

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