

High-Resolution Mapping of Mass Wasting, Tectonic, and Volcanic Hazards Using the MBARI Mapping AUV

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The Monterey Bay Aquarium Research Institute (MBARI) has developed an autonomous underwater vehicle (AUV) for high resolution seafloor mapping. This vehicle is equipped with a 200 kHz multibeam sonar, 110/410 kHz sidescan sonar, and a 2-16 kHz subbottom profiler. From a 50 m altitude, the AUV achieves 1-meter lateral and 0.1-meter vertical bathymetric resolution and <1-meter resolution sidescan imagery. The subbottom profiler images subsurface structure at 0.1-meter resolution with up to 60-m penetration. Applications to geohazard mapping include mapping of recently active faults, slumps, submarine canyons, and volcanic terrains. Repeated surveys allow detection of morphological changes associated with active processes.

Introduction. The use of acoustic mapping technology to image the morphology, character and subsurface structure of the seafloor is a fundamental activity in oceanography, with applications in every aspect of marine science. Hull-mounted or shallow-towed sonars routinely provide high resolution seafloor maps in shallow water, but can do little better than hint at the presence of subtle seafloor features such as slumps, surficial fault breaks, or lava flows when operated in depths greater than 100 m. Achieving 1-m resolution of the deep seafloor requires mounting high-frequency sonars on platforms that can be operated near the bottom, such as towed systems, submersibles or autonomous vehicles (Caress *et al.*, 2008). Submersibles tend to be expensive, acoustically noisy, and to travel slowly and erratically. Visual observation and sampling dive objectives also compete with mapping data collection. The Monterey Bay Aquarium Research Institute (MBARI) has developed an autonomous underwater vehicle (AUV) to map the deep ocean floor at high resolution, efficiently, and with multiple sonars. It can be operated from a variety of vessels simultaneously with remotely-operated vehicle (ROV) or human-occupied submersible operations or other shipboard activities.

This paper describes the vehicle and explores the emerging applications of this technology to mapping and understanding geologic hazards.

Methods. The MBARI Mapping AUV, *D. Allan B.*, is a 0.53 m diameter, 5.3 m long, Dorado class autonomous underwater vehicle, consisting of three modular sections (Fig. 1; detailed specifications in Caress *et al.*, 2008). The hull is ABS plastic, which provides structural strength

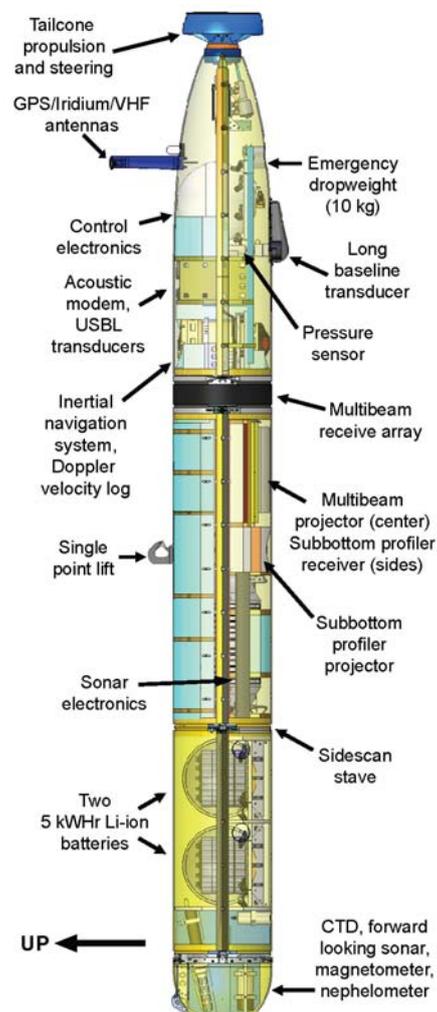


Fig. 1. Design of the MBARI Mapping AUV *D. Allan B.* This 0.53 m diameter, 5.3 m long Dorado class vehicle includes a 200 kHz multibeam, 110 and 410 kHz chirp sidescans, and 2-16 kHz subbottom profiler.

and is acoustically transparent at the relevant frequencies. Blocks of syntactic foam fitted

between various housings provide buoyancy. It weighs about 680 kg in air, is capable of survey durations of 17.5 hours, typically moves 1.5 m/s (5.4 km/hr; 3 knots), and all components are rated to 6000 m depth.

The nose section contains lithium-ion batteries, a conductivity, temperature and depth (CTD) sensor, a 200 kHz forward looking sonar, and a fluorometer. A magnetometer, an EH sensor, and a nephelometer are currently being integrated for 2009 operations.

The tail section contains the main vehicle computer (MVC), a Kearfott inertial navigation system (INS) with Doppler velocity log (DVL), ultra-short baseline (USBL) and acoustic modem for communications, and a single articulated propeller inside a circular duct for propulsion.

The midbody module contains the sonar payload. The primary mapping sensor is a 200 kHz Reson 7125 multibeam sonar that provides swath bathymetry and acoustic backscatter intensity. An Edgetech FSDW system includes dual 110 kHz and 410 kHz chirp sidescans and a 2-16 kHz sweep chirp subbottom profiler that images sub-surface structure. The sonar electronics are contained in a single cylindrical titanium housing. Soundings from 256 1° x 1° beams are spread over a 150° swath from each ping. The beam widths translate to 0.75 m nadir beam footprints when the vehicle is flown at a 50 m altitude (0.38 m at 25 m altitude, 1.5m at 100 m altitude); because the beam footprints are larger toward the edge of the swath, the bathymetry has an overall resolution of 1 m when operated at 50 m. A 17.5-hour mission at 50 m altitude and 150 m line spacing covers about 12 km² of sea floor at 2000 m, with 2 hours of descent and ascent.



Fig. 2. Recovery of the AUV aboard R/V Atlantis in 2008.

The navigation system is a Kearfott SeaDevil INS, incorporating a ring laser gyro, accelerometers, and the DVL (Fig. 1). The INS Kalman filter is stabilized by DVL measurements of vehicle velocity relative to the seafloor at altitudes less than 130 m. The real-time navigation error is 0.05% of distance travelled, assuming the DVL has continuous bottom

tracking. The INS is also the source of vehicle attitude (roll, pitch and heading) data for the multibeam sonar. Vehicle depth is derived from a Paroscientific Digiquartz pressure sensor that is precise to 0.1 m at less than 3000 m or to 0.3 m at 3000-6000 m.

Mission planning employs the interactive application MBgrdviz of the MB-System software package (Caress and Chayes, 2009). Survey lines of desired spacing are laid out over existing lower-resolution bathymetric data, and include crossing lines so that accumulated navigation errors can be removed in post-processing. The lines are converted to a series of waypoints of depth and position to navigate the vehicle through the survey, and incorporated into a mission script.

The vehicle is deployed over the side or stern of the ship (Fig. 2). While it floats at the surface, the mission script is downloaded via acoustic modem, system status is checked, and the vehicle is commanded to dive. When the vehicle is launched in water deeper than 130 m, surface GPS fixes and DVL lock are not simultaneously achieved at the start of the mission, so the INS navigation is aided during descent by USBL tracking fixes communicated by the acoustic modem. The vehicle typically is not tracked or followed once it begins the survey on the seafloor, leaving the ship free for other operations.

After the mission, multibeam, sidescan, and subbottom profiler data are processed using MB-System (Caress and Chayes, 2009). Processing includes editing erroneous soundings from the bathymetry, applying pitch and roll bias and tide correction, and navigation adjustment. The latter is a critically important task, because significant position errors accumulate through the mission in the DVL-aided INS data. The upper bound on navigation error for a 17.5-hour survey is 44 m, and 10 to 20 m errors are typical. Navigation adjustments are made using the MBnavadjust tool of MB-System, by correlating seafloor features in overlapping swaths and solving for an optimal navigation model (details in Caress et al., 2008). If a good tidal model is not available, the navigation adjustment solution can include a vertical tidal component. Sidescan data are processed by locating imagery using the multibeam bathymetry as opposed to a flat bottom, and correcting for the variation in amplitude with grazing angle. Subbottom profiler data is extracted to SEG-Y format and can be processed using MB-System or other seismic reflection profile software. A number of data products are produced from the processed swath data with MB-System, including bathymetry grids, sidescan mosaics, subbottom sections, maps, and GIS data layers.

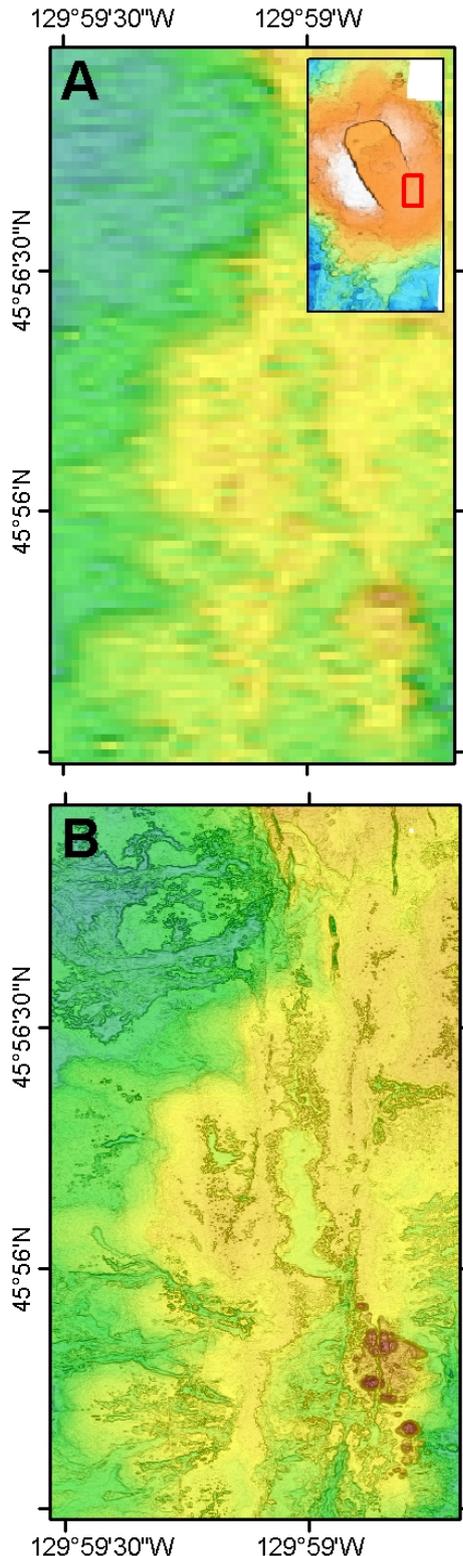


Fig. 3. Comparison of multibeam data for the same region of the 1998 lava flow on Axial Volcano at about 1500 m depth (inset). A) hull-mounted EM-300 sonar (R/V Ocean Alert, collected in 1998), gridded at 20 m resolution. B) AUV-mounted Reson-7125 sonar (MBARI Mapping AUV, 2006), at 1 m resolution. The depth range for each map is 1543 to 1503 m.

Results and Discussion. The 1-m lateral resolution, and navigation and depth integrity of the AUV data are far higher than possible with hull-mounted or even submersible-mounted systems. A comparison of 2 data sets is shown from Axial Volcano in Fig. 3. At 5.4 km/hr, 50 m altitude, and 150 m swath-width, it took about 3.5 hours to cover the 2.85 km² area shown.

The vehicle has been operated off 5 different ships so far. It has been used as part of projects to study canyon formation and sediment transport, gas hydrate location, habitat mapping, and cable route planning, in canyons and basins of the Southern California Bight, canyons off central California including the Monterey Canyon, and Barkley Canyon off Vancouver Island, Canada. It has been deployed to study seamount and mid-ocean ridge volcanism and explosive eruptions at the summit of Davidson Seamount, the caldera and flanks of Axial Volcano and the axis of the Endeavour segment of the Juan de Fuca Ridge. Many of the surveys have produced data relevant to evaluation and understanding of geological hazards. These can be divided into sedimentary (sediment transport and slumps), tectonic, and volcanic hazards.

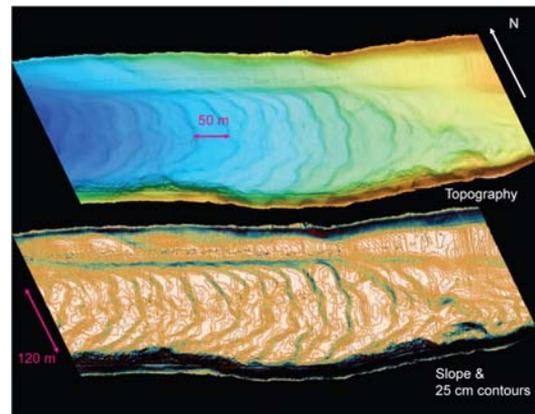


Fig. 4. Bedforms in Monterey Canyon, 273 to 303 m depth. The AUV was flown at 60 m altitude; swath-width is 120 m and beam footprint is 90 cm. The 0.5 to 2 m high bed-forms imaged here extend along the canyon axis from the canyon head to at least 1000 m depth. Top: slope-shaded bathymetry. Bottom: slope grid and 25 cm contours.

Sedimentary features have been examined, discovered, and monitored using the Mapping AUV. Numerous canyons bisect the California continental margin, 9 of which have been mapped with the Mapping AUV. The largest is the Monterey Canyon, and MBARI has begun repeat surveys with the AUV to monitor the axis. Vigorous sediment transport events are known to occur in the upper canyon, with a recurrence interval of considerably less than a year (Paull *et al*, 2007). Surveys have discovered apparent bedforms (Fig. 4) that have wavelengths up to 70 m long and amplitudes of 0.5-2 m, which extend

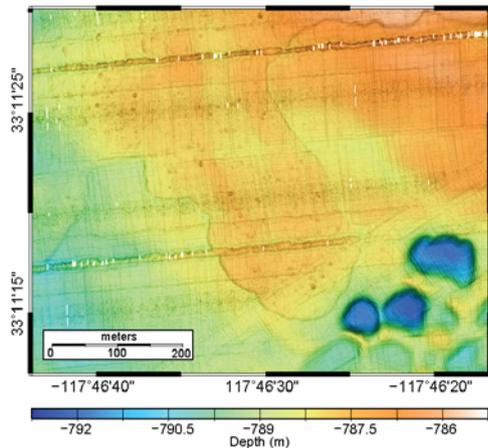


Fig. 5. Mass wasting flow front; the flow deposit is ~0.4 m thick. The basins in the lower right are ~2 m deep and 50-100 m across. The deposit is on flat, sedimented seafloor offshore San Clemente, California.

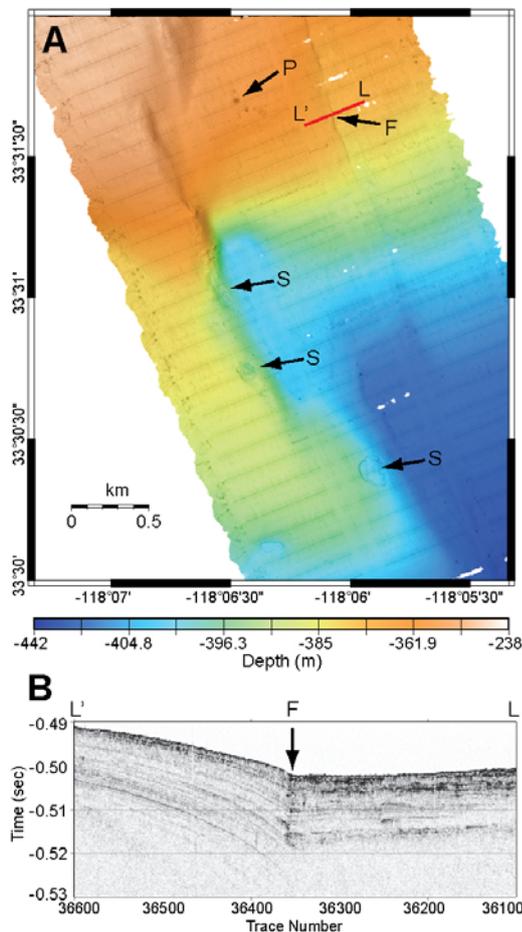


Fig. 6. A) Bathymetric map of northern part of Palos Verde Canyon, off of Los Angeles, California. The red line marks the survey line in B from L to L'. The Palos Verde Fault is marked (F) where it crosses the survey line. Slumps (S) and a cluster of pockmarks (P) are also indicated. B) Subbottom profile of one survey line across the Palos Verde Fault, from L to L'. The arrow marks the fault. Each 0.01 second increment corresponds to 7.5 m in water and somewhat more in the subsurface. Each 100 pings is 75 m laterally. The vertical exaggeration is roughly 4.4:1.

from the canyon head at ~100m to 1000 m depth, and which change location with time. We interpret them as folds in sediment slumps.

A subtle but large mass wasting flow lobe was discovered in San Clemente Basin, near heavily populated Los Angeles, after mapping with the AUV (Fig. 5). It is just 0.4 m thick, 200 m wide and extends 500 m into the survey from the north (Caress *et al.*, 2008). The seafloor as previously mapped was flat and uninteresting based on lower-resolution hull-mounted multibeam data.

As part of a study of sediment deposition in deep sea fans, the AUV surveyed the Lucia Chica Canyon system off central California. Within the complex, anastomosing system of channels, a field of pockmarks that are less than 5 m across and as little as 0.3 m deep was imaged (Caress *et al.*, 2008). These small features can only be resolved using near-bottom surveys.

Faults have been imaged with the multibeam and subbottom profiler sonars of the Mapping AUV. The Palos Verde fault (Fig. 6) off Los Angeles, California, has been resolved.

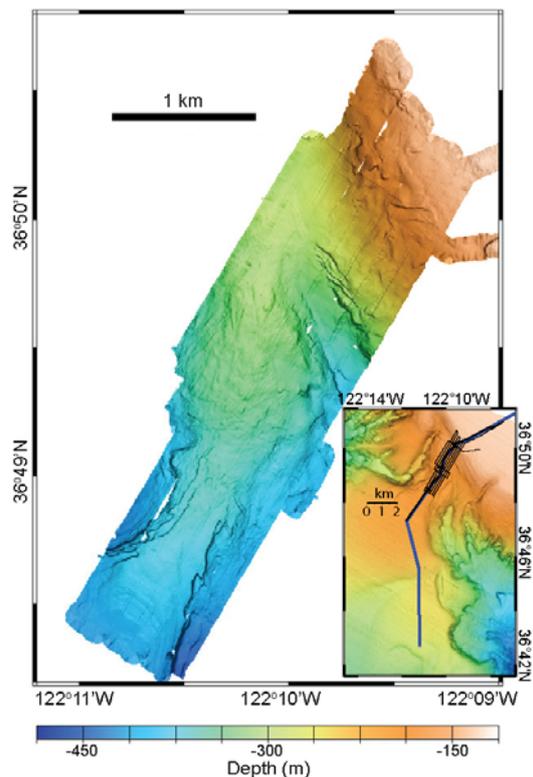


Fig. 7. Survey of the upper section of MBARI's MARS observing system cable route, which stretches from near shore to 1000 m depth on Smooth Ridge, Monterey Bay (blue line in inset). Black lines are the navigation track of the AUV. A set of en echelon scarps on the north side of a gully marks the San Gregorio Fault.

The San Gregorio Fault in Monterey Bay, California (Fig. 7) was imaged with the Mapping AUV as part of cable route planning for the Monterey Accelerated Research System (MARS)

cabled observatory. This AUV mission took just 7 hours. Scarps 5-10 m high where the cable route crosses the fault were revealed (Caress *et al.*, 2008). As a result, the cable route was modified. Repeat mapping following earthquakes on these submarine faults should allow detection of fault offsets.

Gas hydrate mounds 1-2 m high that support communities of vesicomyid clams and bacterial mats and a 10-15 m high fault scarp have been imaged at Barkley Canyon, offshore British Columbia, Canada (Caress *et al.*, 2008).

Volcanic terrain has been imaged at Axial Volcano on expeditions in 2006, 2007, and 2008 at high enough resolution to image individual lava pillars, distinguish between lava flows so their stratigraphy can be determined, and identify eruptive fissures (Fig. 8; Clague *et al.*, 2007).

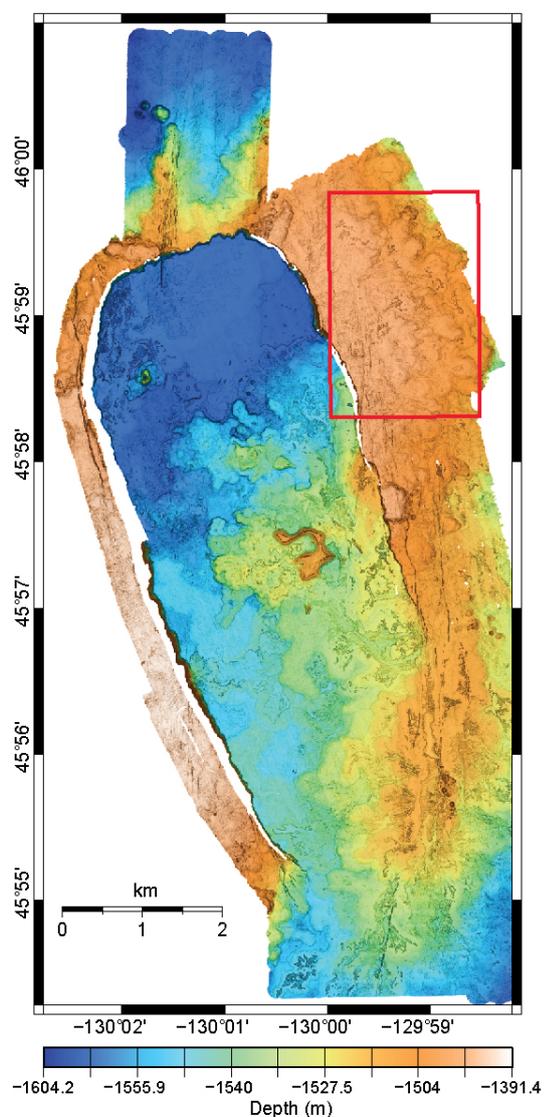


Fig. 8. Axial Volcano on the Juan de Fuca Ridge was surveyed with 9 missions on 3 expeditions. The AUV data shown here is gridded at 1-m resolution. The sharp oval boundary is the caldera wall. The red box is the extent of Fig. 9.

Sidescan data shows the high backscatter of young, lightly sedimented lava flows relative to the thick volcanoclastic deposits upon which they erupted (Fig. 9); these interpretations were confirmed by observations and sampling with the ROV *Tiburon*. An application that we have not yet accomplished is to use repeat mapping to detect inflation/deflation of volcanic systems, but the 10 cm vertical and 1-m lateral resolution should support detection if surveys are repeated every few years. Such repeat surveys should also be capable of mapping any eruptions that occur after the initial survey.

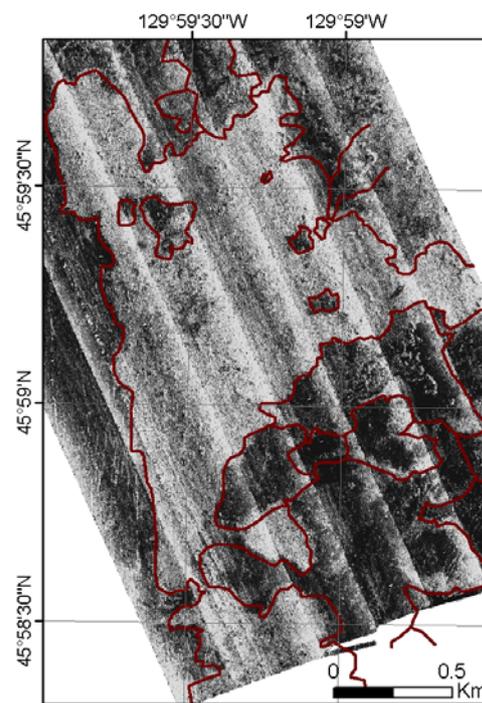


Fig. 9. Young lava flow (outlined in red) erupted onto volcanoclastic materials on NE flank of Axial Volcano, in backscatter data. Explorations by the ROV *Tiburon* confirmed our interpretations.

Hydrothermal vents were discovered while using the base map in Fig. 10 (found in the extreme lower right of Fig. 3) to navigate the ROV *ROPOS* in 2006 at Axial Volcano. Hydrothermal chimneys also stand tall in the AUV bathymetric data at the Endeavour Segment of the Juan de Fuca, north of Axial (Clague *et al.*, 2008). Over 900 edifices from 3 to 20 m tall were detected. Some are in known vent fields, but most are scattered throughout the axial valley and presumably inactive. Active venting was detected in the CTD data as temperature (Fig. 11) and salinity anomalies and generally aligns with known vent fields. However, several are not located at known vent sites and represent previously unknown active sites.

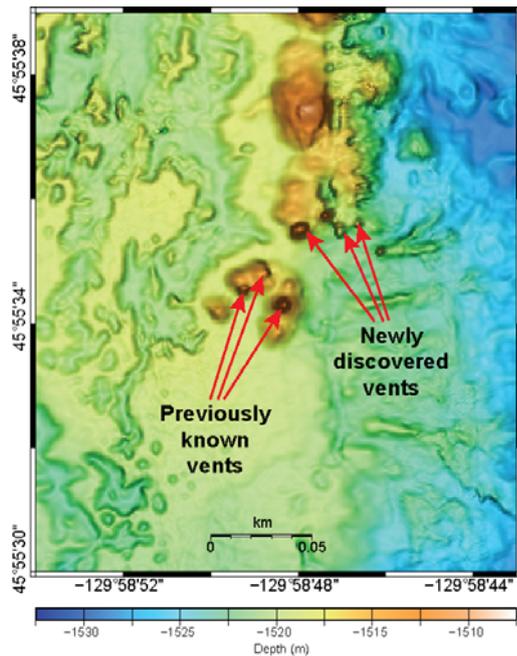


Fig. 10. Hydrothermal vents at Axial Volcano have been revisited and sampled over many years. Using this basemap made by the AUV 2 days earlier to navigate the ROV ROPOS, several new vents were discovered nearby.

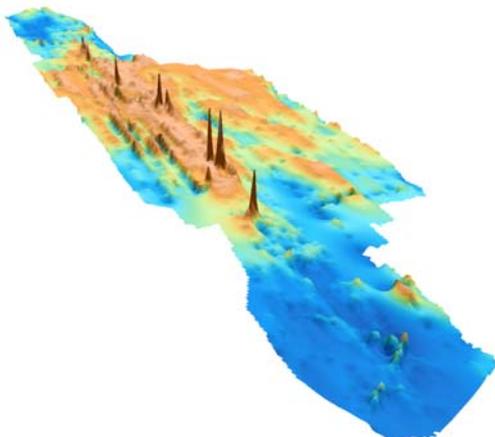


Fig. 11. Water temperature anomalies of up to 1 °C appear as spikes in the AUV's CTD data (view is from the northeast). The data are contoured along the navigation tracks of the AUV, which was flying at 50 m altitude, and interpolated between the lines, which were spaced 150 to 175 m apart.

Conclusions. The MBARI Mapping AUV has now been deployed in many different coastal and open ocean settings along the west coast of the United States and Canada. Bottom types mapped range from soft sediment to fresh lava flows. Entire lengths of several submarine canyons have been mapped, as well as volcanic seamounts and mid-ocean ridge segments with active hydrothermal systems. Slump deposits less than a meter thick have been resolved on flat, almost featureless terrain. The maps have guided the siting of undersea cable routes. Scientific and geohazard applications range from identifying benthic habitat, locating faults, hydrothermal vents, and methane seeps, mapping lava flow extent, morphology and stratigraphy, characterizing slumps and landslides, and repeat mapping for measuring volcanic deformation, fault movement, slumping, and sediment transport in submarine canyons.

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