APPLICATION OF A REMOTELY OPERATED VEHICLE IN GEOLOGIC MAPPING OF MONTEREY BAY, CALIFORNIA, USA

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Monterey Bay Aquarium Research Institute's Remotely Operated Vehicle (ROV) is being used to fill data gaps in the geologic maps of Monterey Bay. With the adaptation of classical field geology methods to ROV technology, preliminary detailed geologic mapping has been successfully undertaken in Monterey Canyon since 1991. The steep relief of this area has been nearly impossible to map using conventional techniques.

Our efforts have integrated biological and geological approaches to mapping geology. We delineate faults by the distribution of cold seep communities that are supported by venting sulfide-rich fluids. Conversely, we characterize biological assemblages associated with particular geomorphologies through structural and lithological mapping. Newly discovered rock types have been collected and rock cores have been obtained with the use of an ROV-mounted drill.

INTRODUCTION

Monterey Bay, a nearly crescentic embayment that indents the coastline of central California by nearly 25 km, is located approximately 115 km south of San Francisco (Fig. 1). Submarine topography of the bay is dominated by a large submarine canyon (Fig. 2). Monterey Canyon deeply incises the Cretaceous crystalline basement rocks and overlying Tertiary sedimentary sequences of the bay, exposing a geological chronology that to date has not been fully investigated. Using the Monterey Bay Aquarium Research Institute's (MBARI) remotely operated vehicle (ROV) *Ventana* (Fig. 3) has enabled us to directly examine canyon walls and sample the constituent rock types in order to determine the geologic and tectonic history of the region.

The geology and tectonic history of the Monterey Bay region is complex, owing to its position within the tectonic boundary marking the convergent (transformational) margin of the Pacific and North American plates. Here the San Andreas fault system is over 100 km wide, comprising several fault zones, located both onshore and offshore (Fig. 4). Two major fault zones, the Palo Colorado-San Gregorio and Monterey Bay fault zones, are part of the offshore fault system in Monterey Bay (Greene, 1990). Movement along these fault zones has dismembered and introduced exotic lithologies in the Monterey Bay region and has fractured and deformed Cretaceous and Tertiary rocks. Cretaceous granitic rocks that underlie the entire Monterey Bay are out of place, belonging to the allochthenous Salinian block that has been transported on the Pacific plate northward along the San Andreas fault proper (Page, 1970). Benthic communities are occasionally found along these faults where nutrient-rich fluids are discharged.

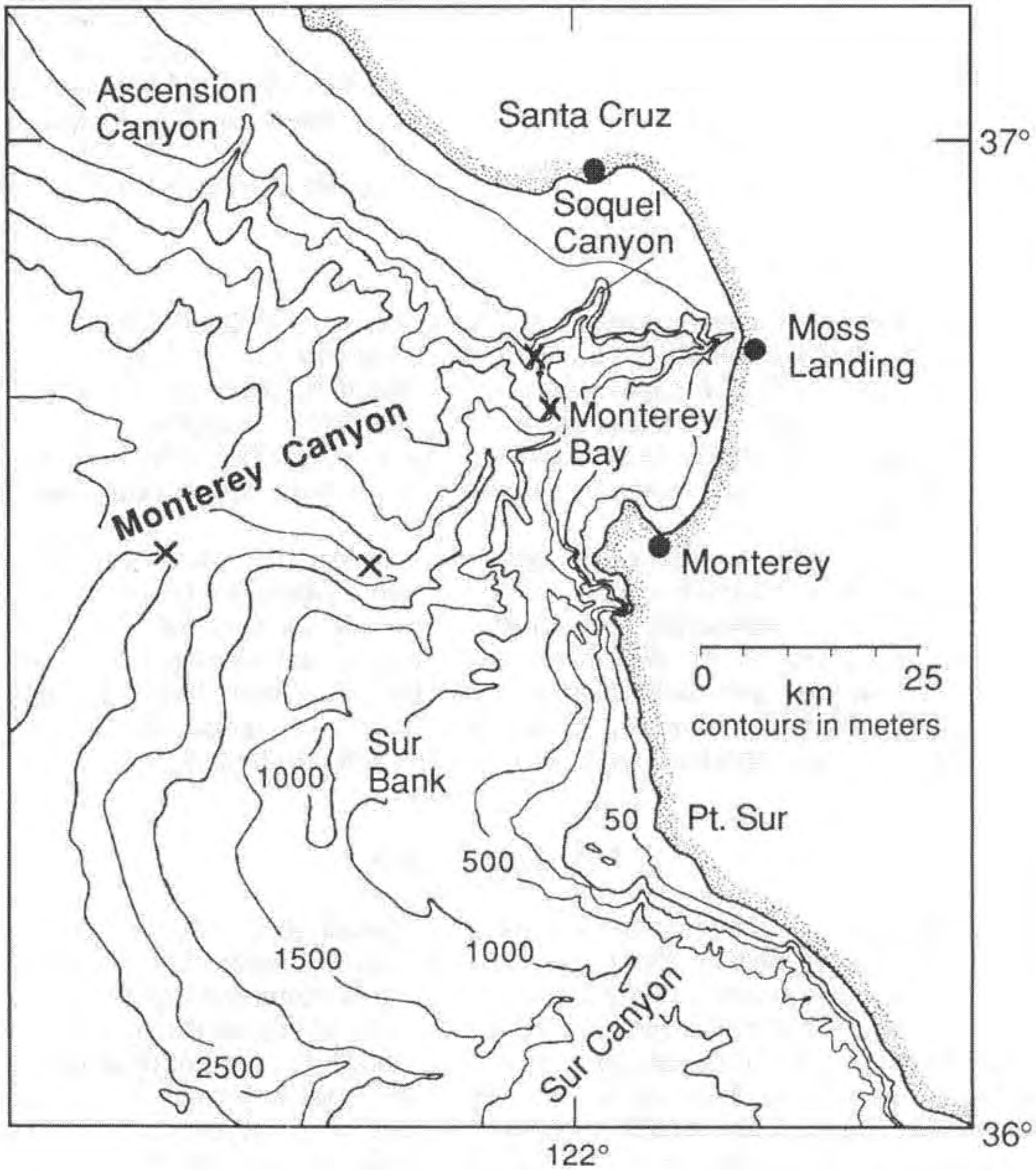

Figure 1. Location map showing general bathymetry and geographical points of references in the Monterey Bay region. Xs mark cold seep community sites.

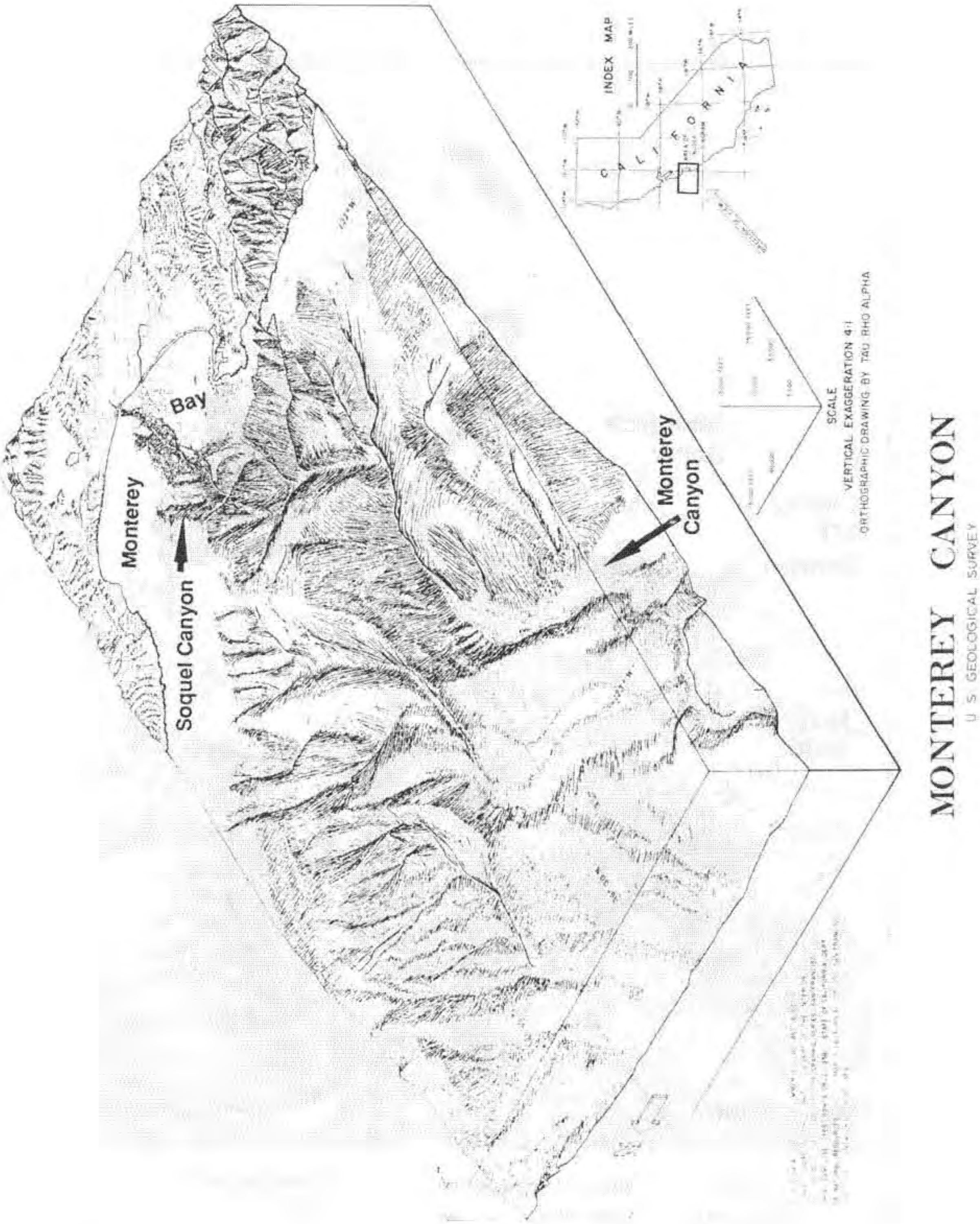

Figure 2. Physiographic drawing of Monterey Canyon.

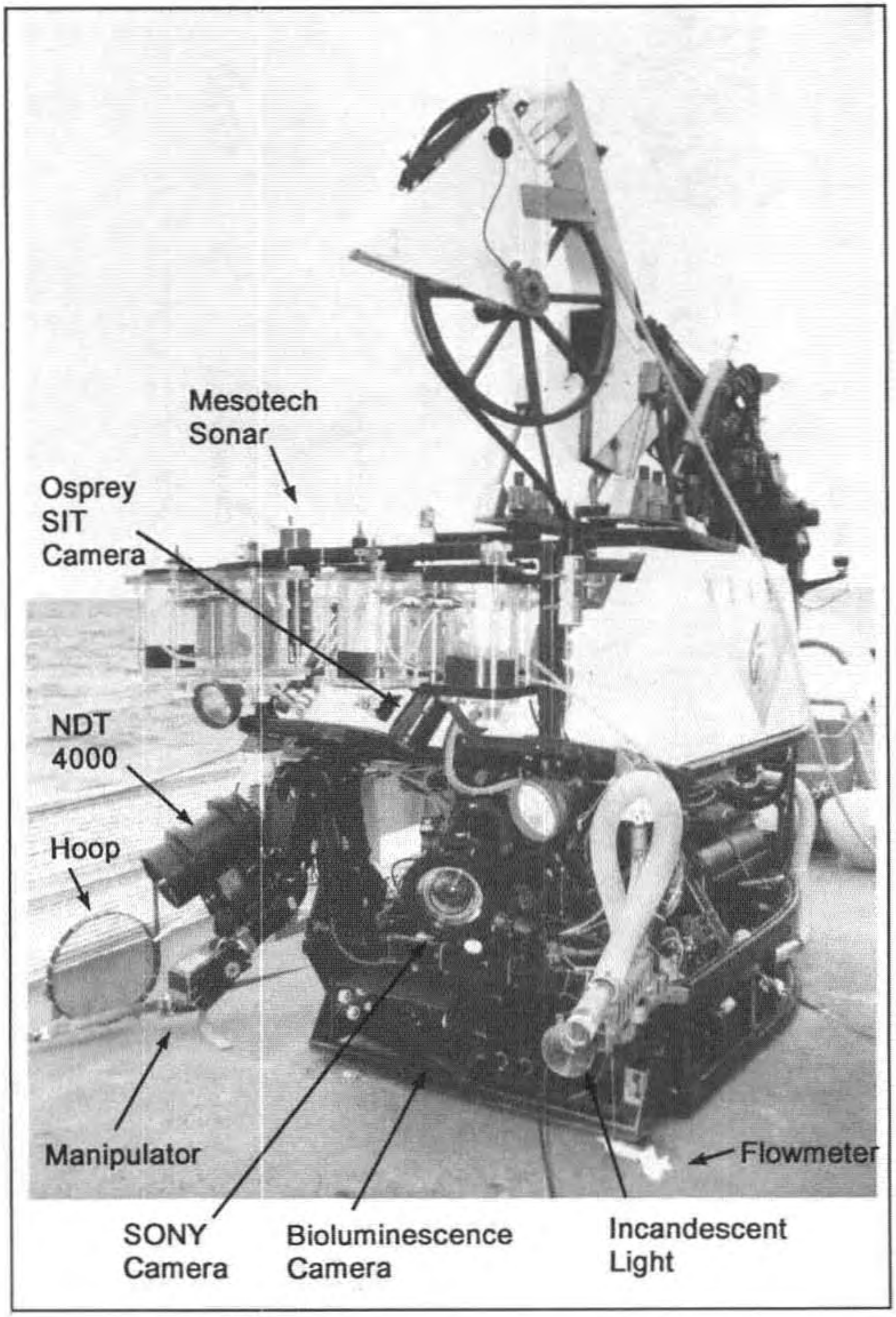

Figure 3. Photograph of MBARI's ROV *Ventana*.

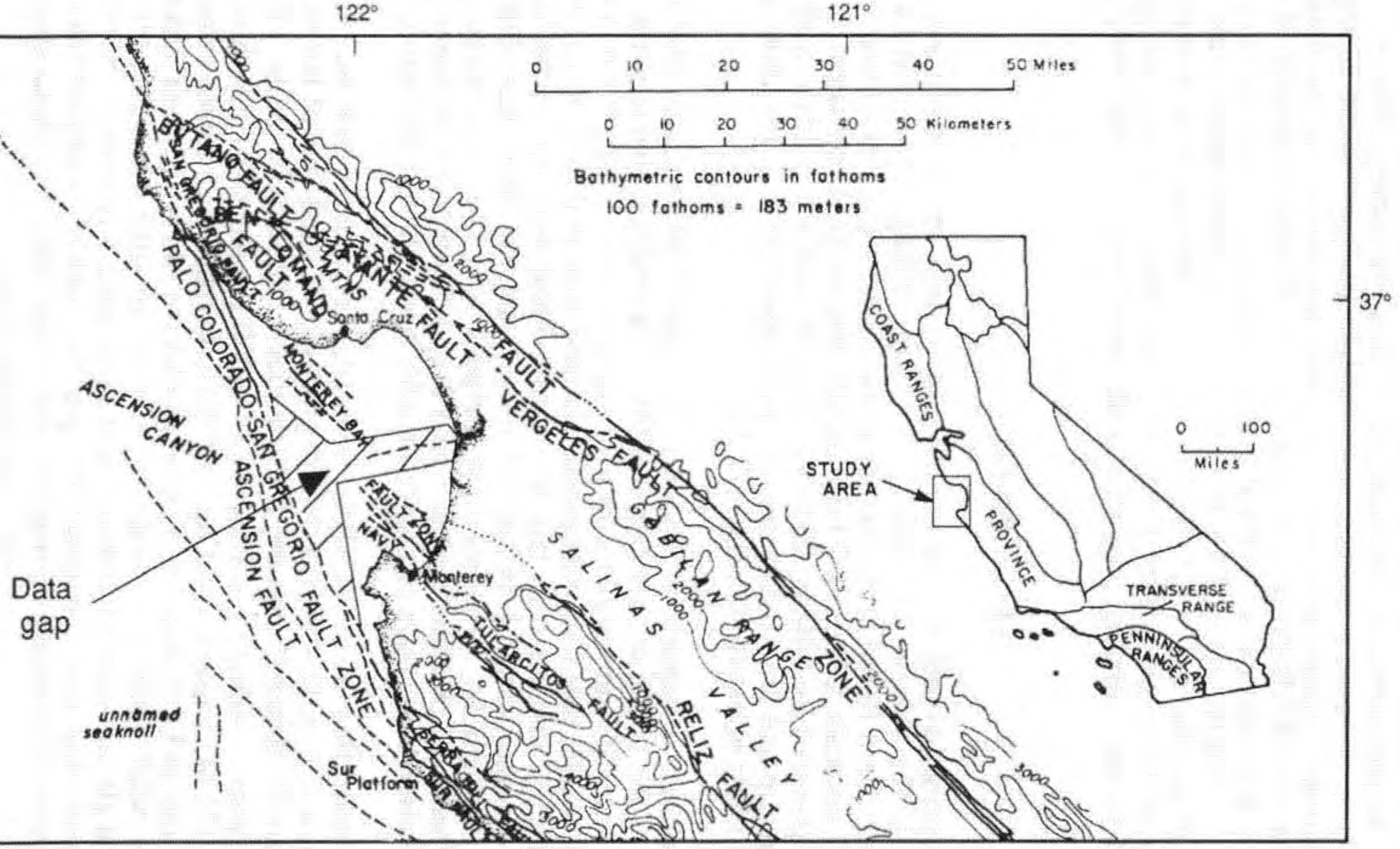

Figure 4. Fault map of the Monterey Bay region showing fault zones that compose the San Andreas fault system. Hachured area represents geologic data gaps in canyon area where present-day mapping is being done using the ROV *Ventana*.

The structural complexity of the bay and its relationship to the emplacement of exotic lithologies, to fluid flow through geologic conduits, to the support of biological communities, and to chemical flux are important to document if a comprehensive evaluation of the biogeochemical interactions within Monterey Bay is to be accomplished. We have initiated a unique multi-disciplinary (geological, biological, chemical, and hydrologic) systems approach to mapping the geology of the Monterey Bay region using the MBARI ROV as the principal tool. The physiography of steep terrain composed of near-vertical to vertical and overhanging relief that exists in Monterey Canyon is nearly impossible to image using conventional shipboard geophysical techniques. The use of ROV technology is necessary to complete a comprehensive map of the region. This paper describes briefly the technology and methodologies used in our mapping project and discusses some of our preliminary results.

TECHNOLOGY

Presently, the principal tool used in mapping the geology of Monterey Bay is the ROV *Ventana* (Fig. 3). This vehicle is of moderate size (2.51 m long, 1.42 m wide, 1.35 m high), has a syntactic foam flotation module attached to the top, is propelled with 6 hydraulic thrusters (2 verticals, 2 laterals, 2 fore and aft), and weighs approximately 4800 lb. The thrusters are powered by a 40 hp, 2300 VAC electric motor that drives a 25 gpm, 3000 psi hydraulic pump and the vehicle can travel at a speed of 1 to 1.5 knots across the ground and ~3/4 knots vertically (Robison, 1993).

Although *Ventana* is capable of diving to a depth of 1850 m, its operational depth limit, because of the length of its tether, is 1000 m. Generally a dive lasts for 5 to 6 hours, although the vehicle's submergence time is generally unlimited. The tether is a fiber-optic umbilical (cable) that transmits power via hard wire to the ROV and returns video signals, telemetry, and control data along individual fiber-optic conductors, providing real-time communication between the control room on the mother ship (R/V *Point Lobos*) and the vehicle. This umbilical includes five #12AWG wires, eight multimode optical fibers, and two single-mode optics encased with inner and outer layers of TPR with four intermediate layers of contrahelically wound Kevlar (Robison, 1993; Stakes et al., 1993).

Ventana is controlled by a GESPAC telemetry system aboard the vehicle communicating with a 486 surface unit; a 68000 processor is used aboard the vehicle. The primary information obtained with the ROV is video; the vehicle can be outfitted with several video cameras including a Sony[1] DXC-3000 broadcast-quality three-chip camera, an Osprey 1323 SIT camera, two Osprey 1359 low-light monochrome cameras, a Panasonic GP-CD1 and an EOS ultra low-light monochrome filterable zoom system. In addition, a Photosea NDT 4000 (macrovideo sighted stereo still) camera or Photosea 1000, 35mm (wide angle still camera with strobe) can be used. Lighting for both video and 35 mm still camera images are provided with up to four sodium-scandium lamps and four incandescent lights all powered through the connecting tether. *Ventana* also has a robotic manipulator arm and a compartmentalized sample drawer.

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[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U. S. Government.

The recently developed Holloway-Stakes-Tengdin-Rajcula (HSTR) drill system was deployed by the *Ventana* with great success and will be used as a principal hard rock collecting tool in the future. This system is composed of a small diameter (5 cm) double-barreled drill with a custom diamond bit. The drill is rotated by a hydraulic motor plumbed directly into the ROV's hydraulic network through a spare servo valve, which provides hydraulic flow up 10 gpm at 3000 psi (Stakes et al., 1993). Salt water circulates through the space between both barrels, forced down between them by a hydraulic rotary pump/saltwater pump that runs in series with the coring motor to flush chips and other debris past the bit and allow for smoother rotation of the drill (Stakes et al., 1993). Rates of drill rotation and water flow are variable; drill speeds are adjustable to greater than 1200 rpm. Cores recovered from this drill are 3.18 cm in diameter and can be as long as 35.56 cm.

A bank of video screens and computer keyboards located in the control room of the mother ship, the *Point Lobos*, is the working center for ROV operations. The *Point Lobos* is a 33.5 m long vessel used as a day boat out of Moss Landing. The control room seats an ROV pilot and co-pilot, a chief observer, and two assistant observers. The pilots control or "fly" *Ventana* by utilizing a joy-stick, a push-button instrument panel, and touch screen computer while the chief observer controls the primary video camera with a computer connected instrument box. Navigation for the *Ventana* is by differential GPS satellite navigation integrated to the *Point Lobus* with an ultra short base-line system used to position the ROV. Repositioning accuracy is variable (approximately 100 meters). A Mesotech 971 azimuthal and forward looking sonar with a 100 m range aboard the ROV are used to locate rock outcrops and steep slopes.

A microwave link between the *Point Lobos* and shoreside scientific facilities allows real-time audio-video-data communications between shipboard scientists and land-based scientists. This technology facilitates the participation of many more scientists than can be accommodated aboard ship and allows for real-time mapping outside of a cramped control room aboard ship, on a stable, large lay-out table.

METHODOLOGY

Seafloor mapping with an ROV differs from the classical forms of seafloor mapping, using marine geophysical (acoustical) and geological methodologies. These traditional methodologies produce a series of swath maps and cross sections that in turn are used to construct geologic maps. Rather, ROV mapping methodology is similar to that used on land and consists of in situ observations, measurements, and sample collection. Basically two types of mapping can be done with an ROV: (1) reconnaissance mapping and (2) detailed mapping. When mapping in a reconnaissance mode, selected seafloor sites, generally spaced far apart (1-10 km), are investigated in a relatively rapid fashion and sample collection, as well as lengthy examinations, is kept to a minimum. The detailed mode of mapping consists of careful sample collection, measurement of sections, and detailed examination of outcrops, structure, and seafloor morphology.

Like all geologic mapping methodologies, offshore mapping requires base maps. In the Monterey Bay region, NOAA full-resolution SeaBeam digital bathymetric data are currently being used to construct the base maps (Greene et al., 1989). Spatial scale is dependent upon the type of mapping to be undertaken (i.e., reconnaissance or detailed mapping). Sidescan songraphs are used in place of aerial photographs, which are commonly used onshore. Bathymetric maps are used to identify and locate areas of steep relief where rock exposures are most likely to occur and to identify linear features that likely are the expression of faults, fractures, and folds. Areas of varying reflectivity in sidescan sonographs are investigated to determine the types of substrata and structures that compose the seafloor. In addition to acoustical seafloor mapping tools used to construct the base maps, seismic reflection profiles are used to locate structures and seafloor exposures and to provide a third dimension (cross sections) to the mapping process.

Reconnaissance Mapping

For reconnaissance mapping, linear to zigzag transects across the seafloor are run, coupled with continuous updates of vehicle position via the ultra-short baseline/differential GPS integrated navigation system (Meridian Oceans Systems - MOS). Coordinates, in latitude and longitude, or UTM units, or both, are noted and recorded for sample stations, photo stations, and changes in course and are plotted aboard the ship at the end of the day's dive as way points. Continuous video is collected during the transect for future referencing and construction of photomosaics for specific sites of interest. A Mestotech azimuthal sonar is also used as a mapping tool, and sonar images are recorded on video tape for future referencing. For geologic transects, the vehicle heading, depth, altitude above bottom, pitch and roll of the vehicle, direction with pan and tilt of video camera, time (GMT), dive number, and current or vehicle speed are continuously recorded on the video tape. Real time observations and descriptions are recorded on the audio track of video tapes as well as in the observer's notebook. Particularly significant observations are signified on video tapes with a distinct sound spike intended to draw the attention of the curator of tapes and other researchers doing archiving or reviewing of tapes.

Presently, the attitudes of bedding planes, fault planes, and other structures, inclinations of slopes, scarps, and cliffs, and alignments of structural and morphological features are measured by aligning the ROV parallel or perpendicular to the feature of interest and estimating orientation. Dip and strike are measured by leveling the vehicle (pitch and roll = 0), leveling and aiming the master video camera straight ahead, and orienting the vehicle so that the camera is aimed along strike. A protractor placed against the video screen is used to estimate dip, and the heading of the ROV gives the strike. This arduous and primitive method of measuring attitude will soon change as an upgrade to a more sophisticated and accurate laser-based tool is in progress.

Detailed Mapping

The procedure for detailed geologic mapping with *Ventana* is very similar to reconnaissance mapping. A 100% video coverage of the transect is obtained with enhanced positioning and more fixes taken. Attitudes of structures are estimated in the same fashion, with care to obtain accurate navigational data. A principal difference between reconnaissance and detailed mapping is that more time is spent along the transect to note and record the details of the geology i.e., more stations are occupied. Stratigraphic sections are measured in detail either by using a laser rule (10 cm between laser points) or measured with the vehicle's depth meter. Detailed sampling is undertaken with the collection of rock samples at every distinct lithologic boundary or at regular spacing along an outcrop. In areas where structure is particularly complex, detailed examination is made with the ROV and the manipulator can be used to clean outcrops where close-up observations are needed.

Where it is not possible to collect rock samples with *Ventana*'s manipulator, such as on sheer steep cliffs of hard rock, the HSTR drill is used. Prior to the development of the drill, selected lithologies could not be routinely sampled as the manipulator is limited to just picking up fractured rock pieces. Areas for drilling are identified from previous reconnaissance dives and are relocated using the *Point Lobos*' positioning system. Once a drill site is located, the ROV transits to the location on the outcrop where coring is desired and using the thrusters,*Ventana* is pushed up to the outcrop with three-pointed docking bars snug against the rock. Drilling with forward thrusters used to maintain pressure on the outcrop requires skillful operation by the ROV pilots.

DISCUSSION

Preliminary detailed geologic mapping of Monterey Bay using MBARI's ROV *Ventana* was initiated in 1991 and continues today. The methodologies described above are currently being used in this investigation. New underwater mapping technologies and methodologies are continually being developed and applied to this mapping project, thus improving the techniques used with ROVs.

Our mapping activity is concentrated in the central part of Monterey Canyon, in the Monterey meander area near the intersection of Monterey and Soquel Canyons (Fig. 5). This is a region of steep relief and complex structure where faults of the Monterey Bay fault zone cut and deform Cretaceous basement and Tertiary sedimentary rocks (Fig. 6). Survey mapping indicates that many faults within the Monterey Bay fault zone vent cold fluids with sulfide concentrations (perhaps including methane) that support cold seep biological communities. Consequently, we use these communities to delineate faults and fractures within the bay. *Vesicomya* and *Calyptogena spp.* clams, some vestimentiferan tube worms, and various colored (orange, yellow, white, black, and gray) bacterial mats are concentrated along faults and fractures where fluids emanate. These communities appear to be restricted primarily within the fault zone, along the down canyon, western meander wall (Fig. 1 and 5), between 400 and 900 meters below sea level (mbsl).

The source of fluids is presently unknown. Since most of the cold seep communities are concentrated along faults and fractures within the Pliocene shallow-marine sandstone of the Purisima Formation, we suspect that fluids are aquifer driven along the Purisima Formation, with a recharge zone high up in the Santa Cruz Mountains. However, sulfide-rich fluids may also be derived from the Miocene Monterey Formation, an organic-rich shale and mudstone unit that is locally a source for petroleum; the Monterey Formation underlies the Purisima Formation and fluids may travel up along the faults. Future chemical sampling of the seeps should delineate the sources of fluids and promote our understanding of the hydrogeologic regime of the bay.

Faults mapped in detail are of two types, normal and thrust. Normal faults are vertical faults, many outlined with bacterial mats. Thrust faults are defined by areas of

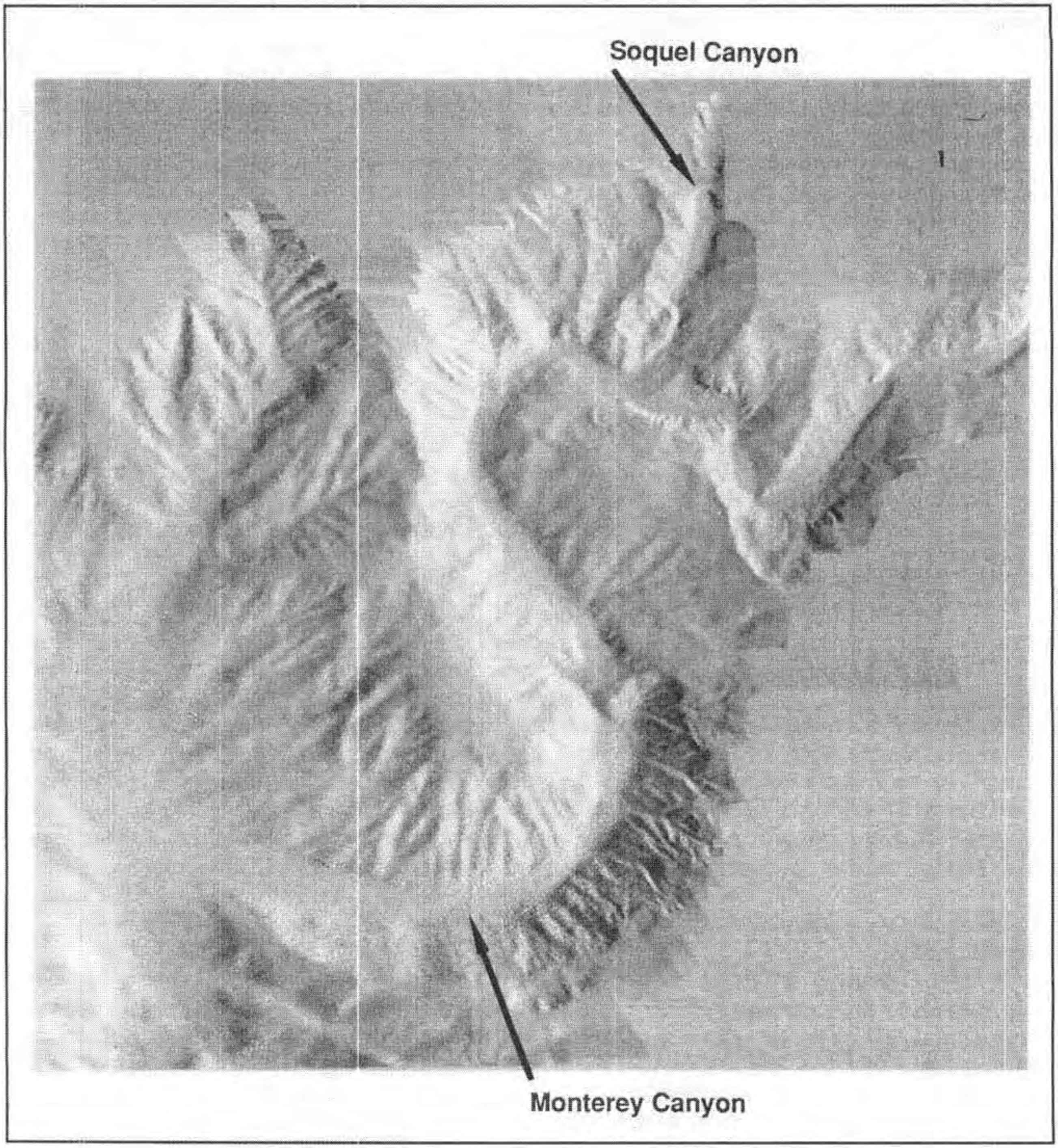

Figure 5. Computer generated physiography of Monterey Bay using NOAA full resolution digital SeaBeam data and showing Monterey meander and Soquel-Monterey Canyons intersection. Detailed mapping is presently being undertaken in the area of this image.

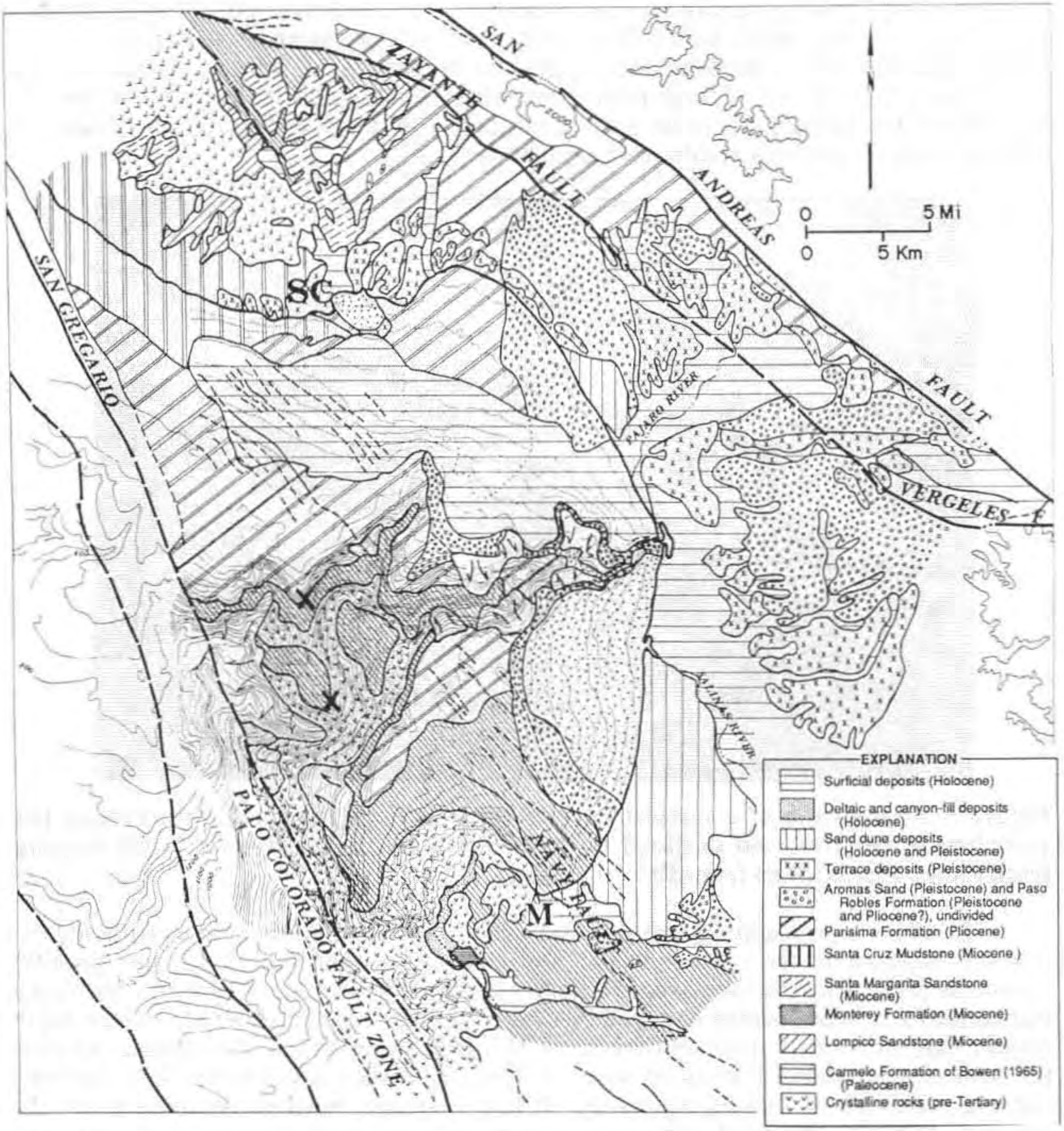

Figure 6. Geologic sketch map of seafloor in Monterey Bay region based on bottom samples (Martin and Emery, 1967; Greene, 1977) and from acoustical imaging (Greene, 1977) traditional mapping techniques. Rock contacts in canyon area are not well located due to difficulty in acoustical imaging in submarine canyons. This area is being re-mapped using the ROV *Ventana*. M = Monterey. SC = Santa Cruz. Landslides shown with curved arrows, faults by heavy and lightly dashed lines. Xs mark location of cold seep communities.

highly fractured rocks and steep eastward-dipping fractures. The majority of the faults are vertical and trend generally NW-SE. Many of these faults are outlined with bacterial mats (Fig. 7). In two places high (~400 mbsl) on the western meander wall, fractured and highly deformed Purisima sandstone appear to be broken by steep eastward-dipping thrust faults (Fig. 8). All of these faults occur along a section of the canyon that has not been mapped accurately due to its steep relief. Likewise, the occurrence of these faults is not detectable in the high-resolution SeaBeam data.

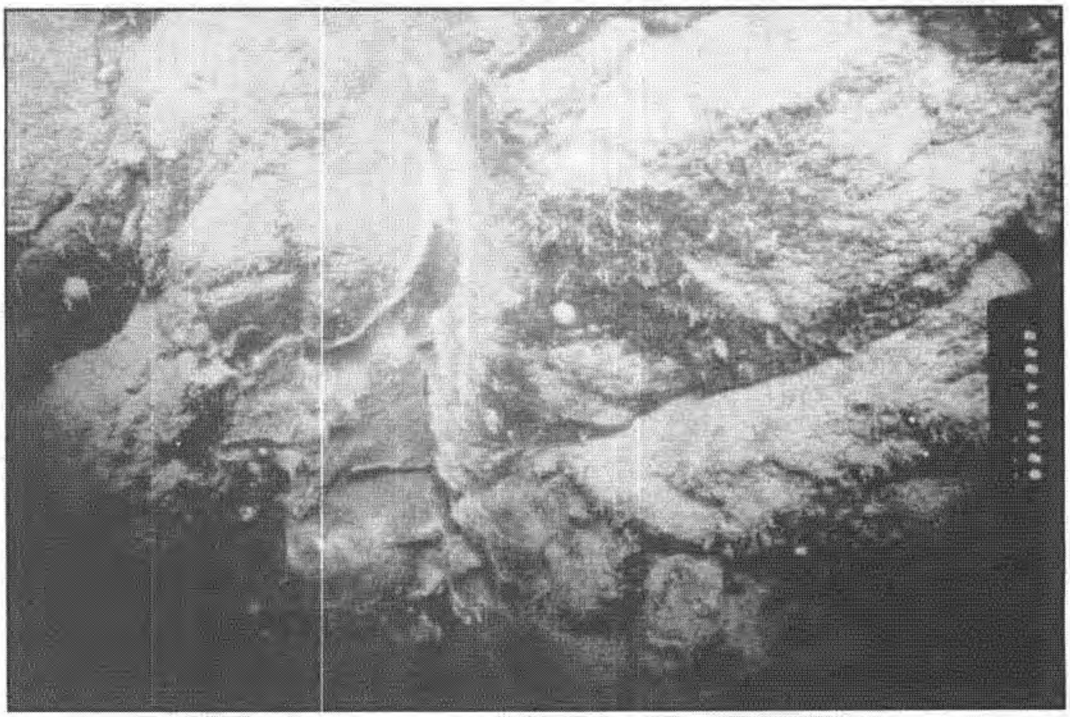

Figure 7. Photograph of a vertical fault in the Monterey Bay fault zone cutting the Purisima Formation and outlined by bacterial mats that thrive on fluids seeping from faults. Photo taken from ROV *Ventana*.

In addition to mapping structure, we have been mapping rock types (lithologies) that are exposed in the canyon walls. The contact between the Cretaceous granitic basement rocks and the overlying Tertiary sedimentary sequence (here the Monterey Formation) has been located and observed directly and is found to lie at a water depth greater than previously mapped (Greene, 1977; Fig. 6). However, the contact between the Miocene Monterey Formation and the Pliocene Purisima Formation has not been observed directly or located accurately. It has, however, been constrained to depths between 450 and 410 mbsl along the western meander wall, also much deeper than previously mapped. Evidently, the contact is buried everywhere beneath Quaternary erosional debris and pelagic muds. Recently, exotic greenstones and serpentinite rock types were collected in situ in Monterey meander with *Ventana* and indicate a more complex western boundary to the Salinian block than had previously been mapped. Video can usually be used to identify lithology, but not always, especially when rocks are deformed and altered in fault zones or are heavily encrusted with biota. In these areas, selective sampling is required.

Continued ROV mapping will lead to the construction of a comprehensive geologic map of Monterey Bay, especially in Monterey Canyon (Fig. 4). The ROV technologies and methodologies described above now enable mapping of complex physiographic areas, such as submarine canyons, in the detail commonly restricted to land mapping.

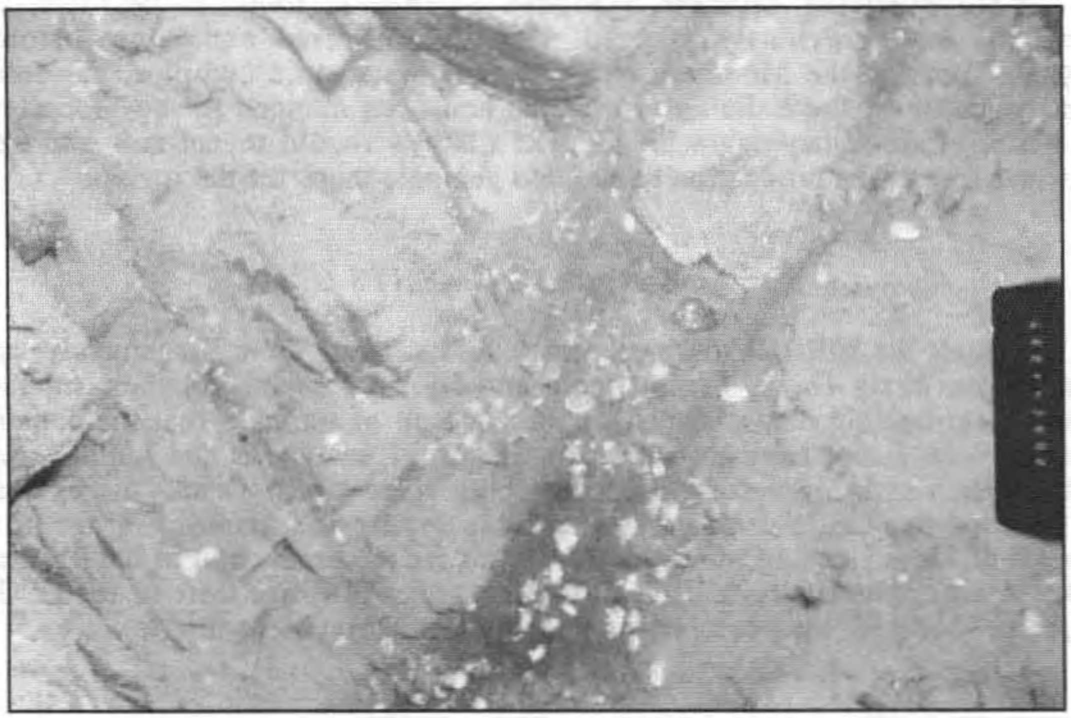

Figure 8. Photograph of crushed and fractured Purisima Formation sandstone that has been compressed from thrust faulting along faults in the Monterey Bay fault zone. Bacterial mats and clams, representing the cold seep communities, mark fractures where fluids are venting. Photo taken from ROV *Ventana*.

CONCLUSIONS

ROV technologies and mapping methodologies developed using MBARI's ROV *Ventana* have revolutionized the format of marine geologic mapping being carried out today. Mapping the great detail that is commonly accomplished on land is now possible. Moreover, to some extent, mapping offshore with ROVs can be considerably more effective and expedient than onshore mapping. The ability to collect 100% video coverage along tracklines, rock samples, still photos, and drill cores in hard, steep outcrops makes the *Ventana* an excellent and efficient tool for mapping geology.

Mapping with *Ventana* has filled data gaps in geologic maps of Monterey Bay. Areas in Monterey Canyon difficult or nearly impossible to image using conventional geophysical mapping techniques are now being mapped in detail using *Ventana*. We initially concentrated our mapping efforts in the Monterey meander of the canyon and are in the process of mapping the faults of the Monterey Bay fault zone exposed along the canyon wall. Here, two different types of faults exist, normal and thrusts. Sulfide-rich fluids vent from many of these faults and support cold seep communities of clams, tube worms, and bacterial mats. Often these biological communities are used to delineate faults, resulting in a biological-geological systems approach to mapping. The future chemical analysis of sulfide-rich fluids will assist us in determining the sources of fluids and increase our understanding of the hydrologic continuity of faults.

Ventana mapping has located the contact between Cretaceous granitic basement rocks and the overlying Miocene Monterey Formation, found to be lower on the canyon wall than previously mapped. Newly discovered exotic greenstone and serpentinite rocks in the Monterey meander indicate a more complex and deformed western boundary of the Salinian block than had been mapped in the Monterey Bay region before. Future mapping with MBARI's ROVs should reveal new and exciting geology and lead to the production of detailed geologic maps for the region.

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