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Bioerosion by chemosynthetic biological communities on Holocene submarine slide scars

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Abstract Geomorphic, stratigraphic, and faunal observations of submarine slide scars that occur along the flanks of Monterey Canyon in 2.0–2.5 km water depths were made to identify the processes that continue to alter the surface of a submarine landslide scar after the initial slope failure. Deep-sea chemosynthetic biological communities and small caves are common on the sediment-free surfaces of the slide scars, especially along the headwall. The chemosynthetic organisms observed on slide scars in Monterey Canyon undergo a faunal succession based in part on their ability to maintain their access to the redox boundaries in the sediment on which they depend on as an energy source. By burrowing into the seafloor, these organisms are able to follow the retreating redox boundaries as geochemical re-equilibration occurs on the sole of the slide. As these organisms dig into the seafloor on the footwall, they often generate small caves and weaken the remaining seafloor. While chemosynthetic biological communities are typically used as indicators of fluid flow, these communities may be supported by methane and hydrogen sulfide that are diffusing out of the fresh seafloor exposed at the sole of the slide by the slope failure event. If so, these chemosynthetic biological communities may simply mark sites of recent seafloor exhumation, and are not reliable fluid seepage indicators.

rapidly remove tens of meters of the loosely consolidated seafloor sediment cover, and expose firmer strata on the seafloor over large areas (e.g., Hampton et al. 1996). While the processes associated with slope failure have been the topic of numerous studies, the post-failure evolution of slide scars has received less attention (e.g., Mayer et al. 1988; Tappin et al. 2001; Hensen et al. 2003).

Multi-beam bathymetric data collected in Monterey Bay in 1998 (Greene et al. 2002) show that several large submarine slide scars mark the northern flanks of lower Monterey Canyon (Fig. 1). The largest is called Tubeworm Slump (Naehr et al. 2000). Two other fresh-appearing slide scars lie further to the east. Here, we report on observations of the post-failure history of Tubeworm Slump (Fig. 1).

Chemosynthetic biological communities (CBCs) were discovered on the seafloor within the scar of Tubeworm Slump on the initial exploration dive in 1998 (Naehr et al. 2000). CBCs composed of microbial and chemosynthetic benthic metazoans (i.e., animals that depend nutritionally on symbiotic chemoautotrophic bacteria) are known to exist wherever there is a supply of reduced chemical compounds (specifically, methane and hydrogen sulfide) on the seafloor. CBCs thrive on energy released by the microbial oxidation of these compounds.

Seafloor CBCs were first discovered at hydrothermal vents along the mid-ocean ridge crests (Corliss et al. 1979). Subsequently, similar communities were discovered along continental margins at sites where methane, hydrogen sulfide, or oil-bearing fluids occur in the immediate subsurface (e.g., Paull et al. 1984; Hovland and Judd 1988). CBCs found on continental margins are commonly called cold-seep communities, and their existence is commonly used as an indicator of fluid flow (e.g., Orange et al. 1999).

CBCs are known to occur at many sites along the canyon walls within Monterey Bay (Barry et al. 1996; Paull et al., unpublished data). The major faunal constituents of continental margin CBCs are identified easily during exploration with submersibles or ROVs (Sibuet

Introduction

Arcuate scars generated by gravity driven slope failures mark the continental margins of the world (e.g., Summerhayes et al. 1979). Large slope failures may

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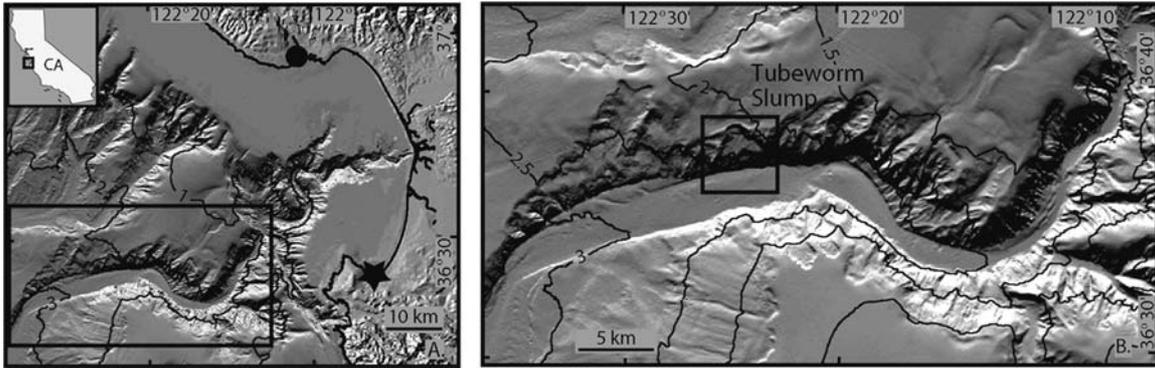


Fig. 1 Shaded-relief bathymetric map of Monterey Canyon showing the slide scars on the northern flanks of lower Monterey Canyon (after Greene et al. 2002). The area outlined with a box is expanded in Fig. 2. Locations of Santa Cruz (closed circle) and Monterey (closed star) are indicated

and Olu. 1998). In Monterey Bay, these include bacterial mats (i.e., *Thioploca* sp. and *Beggiatoa* sp.), several species of vesicomid clams that contain endosymbiotic chemolithoautotrophic bacteria (e.g., *Calyplogena* sp.), and tubeworms (Vestimentifera; Barry et al. 1996). The possibility that CBCs occur within Tubeworm Slump as a direct consequence of the disturbance associated with the slope failure is considered here.

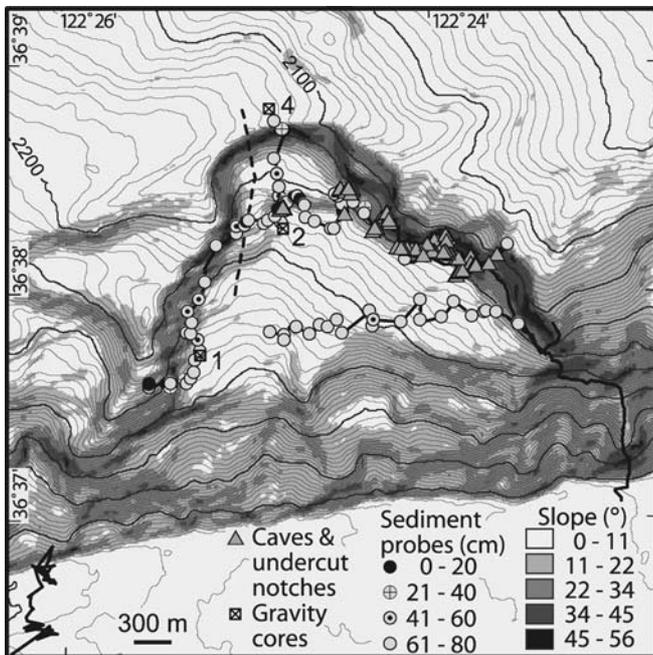


Fig. 2 Map showing the location of dive transects (solid lines for recent dives, and dashed line for dive T85 reported in Naehr et al. 2000), sediment probe measurements grouped by penetration depth, caves and other undercut notches, and gravity cores within Tubeworm Slump. The map is based on EM-300 multi-beam bathymetric data (Greene et al. 2002) contoured at a 10-m interval, with an underlay shading showing the slope angle as indicated in the key. Location is shown in Fig. 1

Materials and methods

In 2000, 2001, and 2002, seven dives of the ROV *Tiburion* (dives T160, T212, T217, T218, T230, T357, and T358) were conducted within the Tubeworm Slump slide scar, and within two unnamed slide scars on the northern wall of the lower canyon east of Tubeworm Slump (Fig. 2). The main objective was to observe and sample the headwalls, sidewalls and sole to determine the post-slide history of the disturbed seafloor. This area had been visited previously during *Tiburion* dive T85 (Naehr et al. 2000).

Video observations were recorded using cameras on the ROV. The mechanical arm and sample drawer on *Tiburion* allowed for collection of multiple sediment push-cores (up to 24 cm in length) and rock samples. Pore waters and gases were extracted from these cores, and analyzed using techniques described in Paull et al. (2002).

A ROV-mounted sediment probe was used to map the minimum thickness of the soft, post-failure sediment veneer. This probe consists of a 1-cm-diameter hydraulic ram mounted vertically on the base of the ROV, which can insert an 80-cm-long rod into the sediment below the ROV when the vehicle is sitting flat on the seafloor. When the soft sediment veneer was thicker than 80 cm, the rod penetrated fully into the sediment, but when the soft sediment veneer was thin, the ROV was pushed off the bottom when firmer sediments were encountered. By observing the rod during insertion with a remote video camera, it was determined quickly when (or whether) a firm, load-supporting surface was present within 80 cm of the seafloor. Eighty-five such measurements were made (Fig. 2).

Three gravity cores ranging from 55 to 97 cm in length were collected from the *Tiburion*'s support vessel (R/V *Western Flyer*) in 2001, two from within the slide scar and one from the headwall above the slide (Fig. 2). These cores were cut and described. To constrain sedimentation rates, two samples were taken for ^{14}C measurements from each of the cores (Table 1). These analyses were performed on the disseminated organic material within the bulk sediments at the Center for Accelerator Mass Spectrometry (CAMS) facility at Lawrence Livermore National Laboratories in Liver-

Table 1 ^{14}C age measurements on disseminated organic carbon from sediments collected during R/V *Western Flyer* cruise 09/01 from Tubeworm Slump

Sample	Interval (cm)	CAMS #	^{14}C age $\pm 1 \sigma$ error (radiocarbon years)
GC-1	10–11	81759	2,700 \pm 35
GC-1	90–91	81760	45,600 \pm 1,500
GC-2	10–11	81761	2,500 \pm 40
GC-2	50–51	81762	4,675 \pm 40
GC-4	14–15	81766	7985 \pm 45
GC-4	101–102	81767	21,270 \pm 210

more, California, using techniques outlined in Roberts et al. (1997).

To assess the rate at which seawater sulfate diffuses into sulfate-free sediment, as would be exposed on the seafloor by a submarine slide, a one-dimensional diffusion model was employed (Fig. 3). The model is based on Eq. (2.45) of Crank (1975) for a semi-infinite medium when the boundary is kept at constant concentration. In the model, the boundary condition at the sediment–water interface was maintained at 28 mM sulfate, no methane was present, and no sulfate was consumed within the sediment. These conditions provide a minimum estimate of the timescale for equilibration of sulfate-free sediment exhumed by a submarine slide with overlying seawater. The free-solution diffusion coefficient used for sulfate ion, $D_o = 5.8 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ at 5 °C (Li and Gregory 1974), is consistent with observed bottom water (1.8–3 °C) and estimated shallow sediment (up to 5 °C) temperatures at Tubeworm Slump. An effective sediment diffusion coefficient (D) was computed from $D = D_o \Phi^2$ (Lerman 1979), using a sediment porosity (Φ) of 50% that is characteristic of the exhumed sediment in the footwall of the submarine slide.

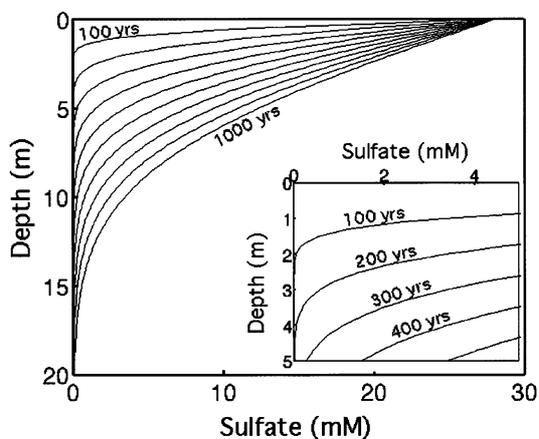


Fig. 3 Results of a one-dimensional diffusion model simulating the diffusion of seawater sulfate into sulfate-free sediment. Concentration profiles are in 100-year increments, starting at 100 years after exposure of sulfate-free sediment to seawater. The *inset* illustrates a more detailed portion of the main figure

Results

Geomorphology

Multi-beam bathymetry shows that the Tubeworm Slump slide scar is arcuate in shape, and about 3 km wide and 2 km long (Figs. 1 and 2). Its steep headwall is up to 100 m high, with average slopes of 20–40°. A secondary headwall scarp that is ~40 m tall exists 600 m downslope from the uppermost headwall scar. The average slope of the seafloor within the slide scar is less than 10°. Downslope, the slide scar intersects the substantially steeper slopes (>20°) found on the lower flanks of Monterey Canyon, and its toe cannot be resolved with existing bathymetric data.

Details of the slide scar’s shape suggest that multiple failure events formed this scar. The western side of this slide scar is smoother than its eastern side (Fig. 2). A distinctly deeper trough runs downslope on the western side of the scar, which may represent a discrete failure event. The headwall also shows a number of scalloped embayments, which also suggest that this scar may have formed during multiple slope failure events.

ROV video observations show that most of the seafloor within the slide scar, and even along its sidewall and headwall scars is covered with hemipelagic sediments. A few exposed boulders were seen on the seafloor along the western side of the slump. Some scattered local highs protrude from the sediment cover, which have shapes suggesting they are sediment-draped boulders. By contrast, bare-rock surfaces composed of massive beds of mudstone are observed along the headwall on the eastern side of the slide scar (Fig. 2).

Stratigraphy

Gravity cores collected along the western side of the Tubeworm Slump’s slide scar contained primarily uniform, un lithified, olive-green hemipelagic sediments, suggesting that the cored interval accumulated after the slide event. However, angular clasts of cohesive, firm, olive-green hemipelagic sediments and rubble occurred below 72-cm sub-bottom depth in one gravity core (WF 09/01 GC-1; Fig. 2), which may be materials associated with slope failure. The ^{14}C measurement on the matrix material between these clasts was ^{14}C -depleted (>45,000 years). Sedimentation rates estimated from the difference between the ^{14}C age measurements (Table 1) of samples from two depths in each of two additional cores were 6.5 and 12.5 cm per thousand years. These data suggest that between 6,000 and 11,000 years were required for the accumulation of 72 cm of post-slide sediment that drapes the seafloor in this area.

Of the 85 sediment probe measurements from the slide scar surface, 51 penetrated fully, showing that more than 80 cm of soft sediment covers most of the slide’s surface. The remaining penetration measurements

ranged from 2 to 75 cm. Sediment probe data confirm the video observations that the seafloor on the western flank and headwall of the slide is cloaked almost entirely with sediment. Conversely, sediment probe data and video observations (Fig. 2) indicate that the eastern section of the Tubeworm Slump slide scar has little sediment cover, and reveals fresh-appearing rock outcrops. The sediment probe was not used where visual observations showed rocks were exposed. Observational data show that the eastern flank of the slide scar has rock exposed on the headwall scars and in rubble fans at the base of the headwall. Sampling of the exposed rocks indicates that the cliffs are composed of thick to massively bedded, consolidated mudstone, considered equivalent to the Pliocene–Pleistocene formations existing in the adjacent land areas (Greene and Clark 1979).

Fauna

Numerous CBCs were observed near the base of the eastern headwall scar, and on the headwall scarp where the mudstones were exposed. Bacterial mats, vesicomyid

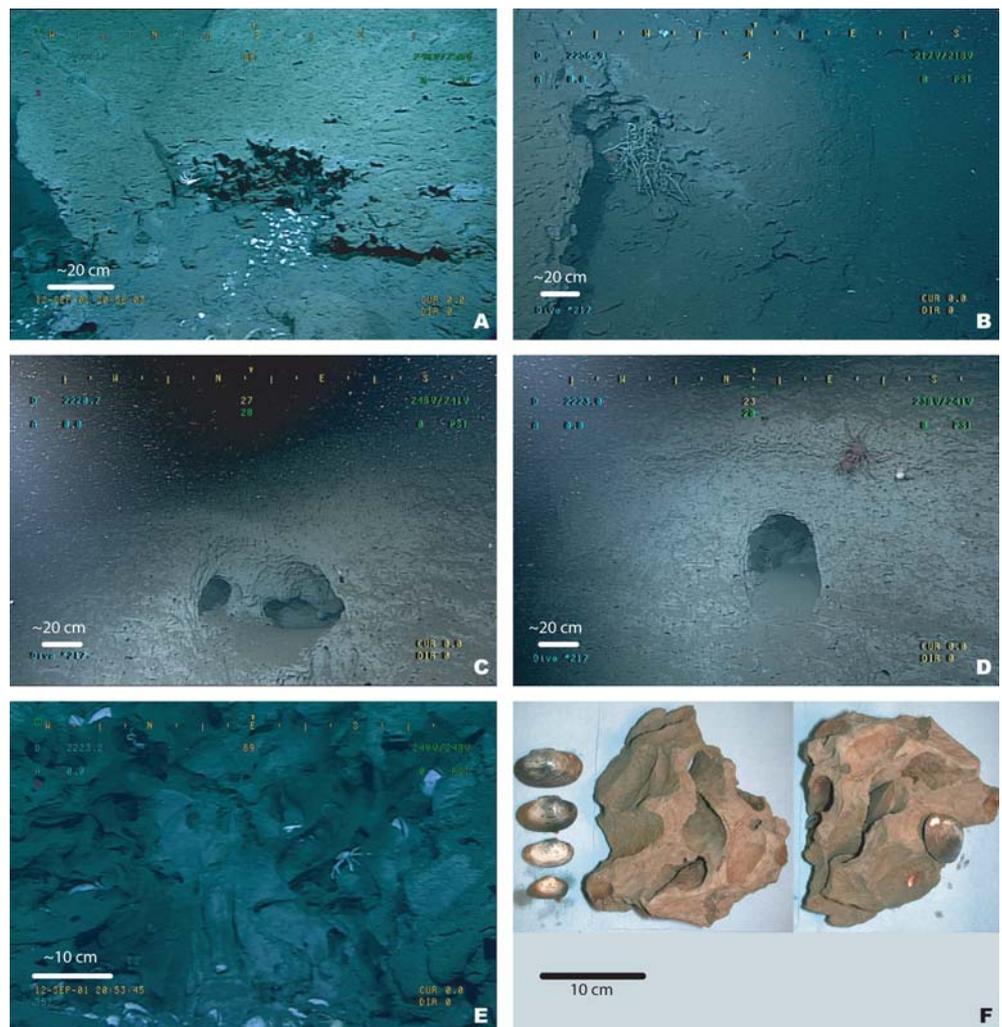
clams, and vestimentiferan worms are the dominant fauna observed in these communities. However, the faunal composition of individual CBCs varied among geomorphic settings.

Bacterial mats were observed primarily on the surfaces of exposed mudstones adjacent to vesicomyid clam patches. Vesicomyid clams were found typically in close association with hard mudstone substrates. The sediment over the rock surface was frequently so thin that only half their shell was covered by sediment. Many aggregations of vesicomyid clams occurred in undercut notches where the surface of the slide intersected a steep slope associated with the scar's headwall (Fig. 4).

Repeated attempts to sample the sediment under clam beds using ROV push-cores produced only short cores (< 10 cm), and indicated that a firm substrate was within ~10 cm of the seafloor under the clam beds. Thus, living vesicomyid clams commonly inhabit a thin sediment drape (e.g., 5–10 cm) overlying a firm substrate.

The occurrence of Vestimentifera varied from dense thickets containing numerous individuals to isolated individuals. The exposed portions of vestimentiferans

Fig. 4A–F Photographs showing the seafloor and samples collected from Tubeworm Slump with the ROV *Tiburon*. **A** Bed of living vesicomyid clams in a notch near the base of the slide scar. **B** Another notch with a cluster of tubeworms at its head. **C, D** Caves that extend into the mudstone wall too far to see the back. The cave shown in **C** widens inside, and bifurcates into two branches. Neither cave is developed along an obvious permeability horizon. **E** Burrows on the face of the notch shown in **A**, with some vesicomyid shells occupying these burrows. **F** Sample of burrowed mudstone and some living vesicomyid clams that were collected near each other. On the *right* in **F**, the clams have been placed into the sample, to illustrate that they fit into these burrows



that occur in thickets were characteristically near 1 m in length, while isolated individuals were typically longer (~2 m) and scraggly, suggesting that the isolated specimens were older. Virtually all tubeworms observed within the slide scar inhabited undercut notches or small caves on the scarp face. Dense thickets of tubeworms occurred in the smaller caves, and the number of tubeworms decreased as the size of the caves increased.

Post-slide re-equilibration

Organic-rich, fine-grained continental margin sediments undergo a series of biogeochemical reactions with increasing depth into the seafloor that involve the progressive reduction of oxygen, nitrate, iron, manganese, and sulfate in the pore waters, and the rapid accumulation of methane below the depth of sulfate depletion (Claypool and Kaplan 1974). One consequence of the sudden removal of the upper sediment veneer by a slope failure event is the exposure of methane-rich sediments on the newly formed seafloor (Fig. 5). Methane within these exposed sediments will be oxidized aerobically where it is in contact with oxygenated seawater, and anaerobically where it is exposed to oxygen-depleted, sulfate-bearing seawater (Reeburgh 1976). Anaerobic oxidation of methane (AOM) produces hydrogen sulfide (Orphan et al. 2001), a necessary chemical substrate for most chemosynthetic biological communities. Thus, the post-slide chemical evolution of sediments underneath surfaces exhumed by major deep-sea slope failure events should involve a progression of redox states that, in turn, affect faunal succession and consequently the geomorphic evolution of the seafloor. A one-dimensional model of sulfate diffusion into sediments that

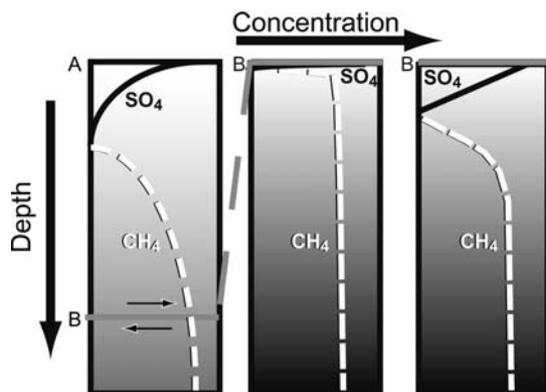


Fig. 5 Schematic representation of a slope failure event that removes part of the continental rise sediment prism, altering interstitial pore-water sulfate and methane gradients. *Left* Condition before a slump occurs, with a failure surface (*B*) that is below the depth of sulfate depletion. *Center* Conditions shortly after slope failure has removed the sulfate-bearing portion of the sediment column, exposing methane-bearing sediments at the seafloor. *Right* Conditions at a later stage, after the sulfate–methane interface has moved downward. Note that rapid erosion will have a similar effect on the position of the sulfate–methane boundary

underlie the slide scar indicates that the penetration of sulfate sufficient to fuel AOM will require at least a few centuries to penetrate to depths greater than 2 m (Fig. 3). Because the model only considered the diffusion of sulfate into the sediment, the presence of methane in the sediment pore water and its oxidation will lengthen the timescale for equilibration with overlying seawater.

Numerous (> 50) attempts to collect push-cores from the sole and adjacent slide scars and headwall of Tubeworm Slump were made with the intention of documenting pore-water gradients. However, the ROV was unable to insert the core tubes more than a few cm where there were living bacterial mats or vesicomid clam beds. This indicates that there consistently was only a thin veneer of sediment overlying the rock surface at these sites. Push-core samples of sediment beneath the clam beds and mats smelled of hydrogen sulfide. Single-point measurements of methane concentrations in the hydrogen sulfide-smelling cores varied from nominal amounts to 3 mM.

Cave observations

Over 75 distinct undercut notches and small caves were observed in ROV video obtained on the steep faces of the headwall at Tubeworm Slump. Most of these features were small, subsidiary scallops distributed along the entire eastern flank of the slide scar (Fig. 4). Caves observed at both the base of the headwall scarp and on its face were developed within massively bedded mudstone units devoid of obvious fractures. Such unfractured mudstones have very low permeabilities. No evidence was seen to suggest that the caves developed preferentially along fractures or permeable stratigraphic horizons.

A progression in size from what we refer to as notches (typically ~20 cm high and ~0.5 m deep) to the large features we call caves (typically 0.5–1.5 m high, and similar in width) was observed. All the caves are too small to enter with the ROV, and frequently the back wall could not be seen, which requires that some caves must be > 2 m deep.

The notches and caves occur within the face of lithologically uniform, cohesive and massively bedded Pliocene to Pleistocene mudstone. The surface of this mudstone is capable of supporting steep slopes, but soft enough to be scratched by the ROV's manipulator arm. Similar notches and caves occur where strata of the same mudstone facies are exposed elsewhere on the canyon's flanks.

Beds of vesicomid clams were often associated with notches and small caves. Living vesicomid clams typically were restricted to a small area on the floor and back wall of the overhanging notch (Fig. 4A). Numerous clam-sized borings and channels were observed on the sidewalls of the notches and caves, and some vesicomids were observed within the borings in the mudstones (Fig. 4E). Samples from these notches show that

clam-sized borings riddle the mudstone's surface (Fig. 4F).

Vestimentiferan worms were typically rooted in the back of caves. Many of the smaller caves or notches contained numerous (~10–40) vestimentiferans with short (< 1 m) tubes. The bigger caves often had one or two scraggly vestimentiferans with longer (> 2 m) tubes. The largest caves typically lacked vestimentiferans (Fig. 4C, D).

Mudstone on the exposed face of the tubeworm-bearing caves was too firm to penetrate using push-cores. Pore water from sediment push-cores obtained from the thin sediment veneer on the floor of the caves was only partially depleted in sulfate, and lacked substantial amounts of methane and hydrogen sulfide.

The surface texture of the cliff face within and between the caves varied. The smaller caves or notches containing living clams had sharper, fresher-appearing surfaces. Many of the notches and caves contained octopi and fish. Caves without living chemosynthetic organisms, and those containing octopi tended to have the smoothest walls, although the remains of old vesicomid clam borings were observed occasionally on their walls.

Discussion

Geomorphic environment

The combination of ^{14}C data, sediment thickness observations, and geomorphic appearance suggests that the western side of Tubeworm Slump has been inactive for most of the Holocene, and is older than its eastern side. Conversely, the most recent episodes of sediment failure have occurred on the eastern side of Tubeworm Slump, where the lack of sediment cover suggests that the scar surface has not been exposed long enough to accumulate a substantial sediment cover. Thus, fresh rock surfaces have been exposed on the eastern section of the Tubeworm Slump scar in recent times.

CBCs are common on the fresh surfaces of the Tubeworm Slump and adjacent slide scars. While such communities are often referred to as cold-seep communities and are presumed to be indicators of fluid flow, there is no evidence that these CBCs are located along particular horizons that may be permeable conduits. In this paper, we propose an alternative interpretation of these CBCs and their associated geomorphic environment.

Slide scar CBCs

Our observations indicate that CBCs exploit methane and hydrogen sulfide that are exposed on the seafloor by large submarine slides, and show patterns of faunal succession that are associated with, and likely driven by, the retreat of the redox boundary associated with the sulfate–methane interface into the subsurface (Fig. 5).

Immediately after a slope failure event, methane-bearing, sulfate-free sediment is exposed on the seafloor. Initially, methane exposed at the seafloor is oxidized aerobically, using the oxygen in seawater. As sulfate from the overlying seawater diffuses into the sediment, communities of methane-oxidizing archaea and bacteria flourish in the subsurface. Consortia of methane-oxidizing archaea and sulfate-reducing bacteria produce hydrogen sulfide by AOM (Orphan et al. 2001), some of which diffuses toward the seafloor. The availability of hydrogen sulfide in the sediment allows the successful colonization and survival of chemosynthetic organisms, including chemoautotrophic bacterial mats, vesicomid clams, and vestimentiferan worms.

As long as hydrogen sulfide is available within the near-seafloor sediments (upper ~2 m), CBCs may exist on the slide scar's surface. The position of the sulfate–methane interface, where hydrogen sulfide is produced, reflects a balance between the diffusive supply of methane from the underlying sediments and sulfate from seawater to this interface (Borowski et al. 1999), and local changes in the overlying sediments brought about by burrowing organisms and irrigation. The post-failure methane concentration profiles and their evolution beneath the slide scar are unknown, but the timespan over which sulfate diffuses into the seafloor after a slope failure can be estimated. Model results (Fig. 3) suggest that it would take on the order of a century or more for a significant amount of sulfate to reach 2 m below the seafloor by diffusion. Because these concentration–depth time curves neglect the anaerobic consumption of sulfate by AOM that will occur because methane would be present within the sediment prior to slumping, the rate of diffusive penetration of sulfate will be slower than indicated in Fig. 3. Thus, a diffusive supply of hydrogen sulfide to the surface sufficient to support CBCs within the upper ~2 m of the sediment column is predicted to persist on the order of at least a few hundred years after each major slide event. These results are essentially consistent with previous steady-state and transient models of sulfate gradients (e.g., Dickens 2001; Hensen et al. 2003).

Maintaining access to hydrogen sulfide and oxygen is essential for the survival of the dominant chemosynthetic organisms inhabiting CBCs in Monterey Bay. Various chemosynthetic taxa are capable of exploiting reduced chemical compounds at different depths below the seafloor. Bacterial mats occur where both oxygen and hydrogen sulfide are in close (~1 cm) proximity to the seafloor. Thiotropic bacteria (e.g., *Thioploca*) migrate by gliding from the seafloor to the shallow subsurface, to subtly adjust their position with respect to the available oxygen and hydrogen sulfide (McHatton et al. 1996). Vesicomid clams and vestimentiferan tubeworms straddle the redox boundary between oxygen and hydrogen sulfide morphologically. Some vesicomid clam species can span distances of 20 cm or more, by the distension of their muscular foot into sulfidic sediments, while maintaining contact with oxygenated seawater

through their ventilation siphons at their opposite end. Vesicomid clams may sustain short anaerobic periods during which mining of hydrogen sulfide in deeper sediment occurs. The occurrence of vesicomid clams indicates that the hydrogen sulfide-bearing sediments occur within ~20 cm of oxygenated seafloor (Sibuet and Olu 1998). Vestimentiferan tubeworms are known to have “roots” that grow as a posterior extension and may extend over 2 m into the seafloor to obtain hydrogen sulfide, whereas their anterior end is exposed to oxygenated seawater (Jullian et al. 1999; Freytag et al. 2001). Hydrogen sulfide is taken up deep within the sediment at the distal end of the tube, whereas oxygen exchange occurs in the obturaclular plume at the outer end of the worm’s body. Distention of the body within the tube or migration within the chitinous tube, or both, may allow the worm to exploit hydrogen sulfide deep within the subsurface. Thus, old, established vestimentiferans have the capacity to mine hydrogen sulfide dissolved in sediment pore waters at substantially greater depths below the seafloor than vesicomid clams or chemosynthetic bacterial mats.

The lifecycles of the dominant members of CBCs also vary considerably. Bacterial mats may form and die off on timescales of weeks. Vesicomid clams live for years to perhaps a century (Lutz et al. 1985; Barry and Kochevar 1998). Vestimentiferans may live over 250 years, and are known to survive on very low supplies of hydrogen sulfide (Fisher et al. 1997; Freytag et al. 2001). The diffusion of methane from the sole of the slide would stimulate production of hydrogen sulfide by AOM near the seafloor, and support these communities for time spans corresponding to the depth and succession of organisms that are observed. The actual community succession will depend on the rate at which sulfate diffuses into the sediment, and how quickly the zone of AOM retreats. The sulfate diffusion model (Fig. 3) shows that the time and space scales for post-failure sulfate diffusion into the exhumed seafloor is of the same order as those for CBCs observed on Tube-worm Slump.

Bioerosion and the origin of headwall caves

Many marine organisms bore into and erode sedimentary rocks (Neumann 1966). While the most obvious impacts of bioerosion are known from shallow-water habitats, bioerosion is also suspected to be a significant process in eroding firm substrates in the deep sea (Warme et al. 1978). Because considerable energy is expended when boring into firm substrates, there must be an adaptive advantage for this behavior to persist. Organisms typically are believed to benefit from the protected habitat they create. However, our observations suggest mining of sediments for an important energy source, such as hydrogen sulfide, may be another reason for boring into sediments, one with greater physiological benefit.

Cave development is hypothesized to be the geomorphologic result of the biogeochemical environment. The presence of the vesicomid communities would focus bioerosion on areas of greatest reduced chemical compound flux. Over time this would generate caves where there is a slow but persistent flux. However, we argue that fluid advection is not necessary, as diffusion alone could stimulate processes that would produce the observed caves in the mudstone, and explain the observed succession.

Burrowing activities of clams may be linked to hydrogen sulfide concentrations in the upper subsurface, or to other factors such as predator avoidance, competition for space, and perhaps reproduction or other unspecified behaviors. Clearly, if hydrogen sulfide availability is low, it will benefit the organism to increase burrowing activity to exploit deeper hydrogen sulfide pools. Regardless of their motivation for burrowing, these activities will ventilate the sediment and accelerate the retreat of the sulfate–methane interface, thereby accelerating the course of faunal succession. It remains unclear whether burrowing activities of chemosynthetic metazoans, or the solely diffusive retreat of the sulfate–methane interface dominates the re-equilibration of slides scars, and the rise and senescence of associated CBCs.

The rate at which reduced chemical compounds are provided by diffusion from the exposed slide scar would decrease, and the chemical gradients would relax with time. The fauna and biogeochemical zonation would change as the chemical gradients recede into the subsurface. As the hydrogen sulfide-bearing horizons retreat into the subsurface, the exposed bacterial mats would cease to be viable, and the vesicomids would be compelled to bore into the mudstone to follow receding hydrogen sulfide-bearing zones. Their excavation would produce notches at the base of local scarps. Clams and other bioeroding organisms preferentially focus on the back of the notch where the chemical gradients are sharpest (Fig. 6). The focusing of bioerosion generates notches in these friable rocks that progressively enlarge into the observed caves. The clams are more effective at digging laterally along the cliff than downward, because

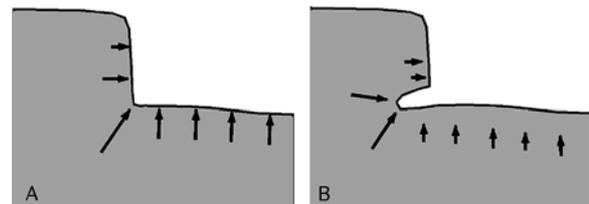


Fig. 6A, B Schematic representation of an idealized cross section of a submarine slope failure scarp. Arrows indicate relative diffusive flux of methane. **A** Topography shortly after the slide. The notch at the base of the scarp will have the greatest flux, and thus is a preferred microenvironment for chemosynthetic biological communities. **B** The same area at a later stage, with a cave generated by chemosynthetic bioeroding organisms

they have fewer problems with sediment removal and do not have to contend with excessive burial to remain in contact with seawater. Vestimentiferan roots can extend further into the notch than the foot of clams. Thus, of the faunal groups observed, vestimentiferans have the greatest potential for maintaining contact with the receding redox front associated with hydrogen sulfide produced by AOM. Once access to hydrogen sulfide is terminated, vesicomyid clams would die, shifting to a later successional phase dominated by vestimentiferan worms. Excavation by vesicomyid clams and other boring organisms is clearly forming undercut notches. The continued bioerosion observed in the notches ultimately results in the seafloor caves.

While this hypothesized sequence of bioerosion involves a succession of organisms that we observe in slide scar CBCs, other species may participate in the development of these features for similar reasons. For example, shells of dead solemyid clams are seen in this area. Solemyids are a family of burrowing clams that live entirely within sediment, and also contain endosymbiotic bacteria. Solemyids are rarely sampled alive (Sibuet and Olu 1998). The habitat of solemyids requires that they be considered as having bioeroding potential. Another indication of bioerosion comes from the small borings that are observed on the surface of the exposed mudstone. These borings indicate that unidentified small organisms are weakening these rocks. While we see bacterial mats on the surface of the rocks, the conditions to support chemosynthetic biological production may also exist in pore spaces of the strata within the subsurface. Thus, chemoautotrophic bacterial primary production along the receding chemical gradients within the mudstone may leave behind fresh organic residues, which could support an enhanced community of boring organisms living on the locally produced organic matter. Moreover, the presence of organisms that adopt these caves for refuge, like octopi, will continue to modify the surface of these caves and to keep them free of sediment. The weakness produced by bioerosion will enhance mechanical failures of the cliff face on all scales.

Conclusions

Examination of the surfaces of slide scars and headwalls on the flanks of Monterey Canyon indicates that multiple slope failure events expose surfaces of various ages that are in different stages of post-slope failure evolution. The occurrence of CBCs on fresher surfaces of Tubeworm Slump can be explained simply as a result of erosion. Fluid flow may support some of these communities—however, it is not required for these CBCs to exist. A faunal succession of CBCs appears to follow the retreating sulfate–methane interface into the subsurface as chemical equilibrium is reestablished after slope failure. Locally, organisms that are boring into the rocks to follow the retreating redox front cut notches and small caves. This faunal succession and geomorphic evolution

take place on a timescale that is short compared with the depositional processes that will ultimately blanket the seafloor. The frequent occurrence of notches and caves on recently exposed mudstone surfaces on the flanks of Monterey Canyon suggests that bioerosion caused by chemosynthetic organisms may be a substantial process in the continued evolution of continental margin slide scars.

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