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# A survey of seeps and vents in the Gulf of Mexico with manned submersibles
# *Esplorazione di flussi e centri di emissione nel Golfo del Messico, mediante batiscafo*

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ABSTRACT – Seeps and vents intimately associated with the tops and flanks of subbottom salt diapirs occurring along the passive continental margins of the northern Gulf of Mexico were surveyed with Johnson-Sea-Link and Alvin manned submersibles. These investigations have indicated that the impact of hydrocarbon seepage and venting on the seafloor is profound. Interaction between hydrocarbons, seawater-derived fluids and stacked microbial communites results in the formation of enduring point-source anoxic enclaves in an otherwise oxic ocean basin. Oxidation of hydrocarbons under anaerobic conditions results in excess of bicarbonate manifested in the deposition of $^{13}C$-depleted massive carbonates at the sediment-water interface. Advection of toxic chemical compounds (e.g., $HS_2$, $CH_4$, $NH_4$) are exploited by chemosynthetic communities of bacterial mats, tube worms, mussels and clams as energy sources for their metabolism. Venting of deep-seated barium-rich fluids is manifested in the deposition of barite deposits consisting of crusts draping mud volcanoes and vertical chimneys. The survey indicates that Gulf of Mexico slope and deep basin comprises a much wider variety of hydrocarbon emission features than other passive and active margin settings thus far described.

KEY WORDS: seeps, vents, hydrocarbons, Gulf of Mexico, chemosynthesis, submersibles.

RIASSUNTO – Efflussi e centri di emissione direttamente associati alla sommità e ai fianchi di diapiri salini subaffioranti, che si rinvengono lungo i margini continentali passivi della porzione settentrionale del golfo del Messico, sono stati iindagati mediante batiscafi Johonson Sea-Link e Alvin. Tali esplorazioni hanno messo in luce che l'impatto sul fondo marino dei flussi di idrocarburi e delle emissioni idrotermali è profondo. L'interazione tra i fluidi idrocarburici di origine marina e le comunità microbiche che vi si sviluppano risulta nella formazione di biocenosi anossiche localizzate all'interno di un bacino altrimenti ossigenato. L'ossidazione degli idrocarburi in condizioni anaerobiche produce un eccesso di bicarbonato che si manifesta nella deposizione di carbonati massivi impoveriti C all'interfaccia acquasedimento. La risalita di composti chimici tossici (es. $H_2S$, $CH_4$, $NH_4$) è sfruttata da comunità chemiosintetiche di batteri, policheti, molluschi e bivalvi come fonte per i processi metabolici. L'emissione di fluidi profondi ricchi in bario si manifesta con la deposizione di barite, consistenti in crostoni che ammantano vulcani di fango e camini verticali. L'esplorazione effettuata suggerisce che la scarpata ed il bacino profondo del Golfo del Messico comprendono uno spettro di caratteristiche da emissione di idrocarburi molto più ampio rispetto a quello di altri margini attivi o passivi riportati in letteratura.

PAROLA CHIAVE: efflussi, centri di emissione, idrocarburi, Golfo del Messico, chemiosintesi, batiscafi.

## 1. – INTRODUCTION

The so called "Information Explosion" which started in 1971 with the invention of the microprocessor has had a considerable impact on science in general, and on geology in particular. Presently, even remote areas of our planet can be accessed in the convenience of the homebase and displayed on computer screens at the stroke of a button. This situation prompted Datus C. Proper to lament that "*Discovery today is a caravel that never gets off the beach*" (The Last Old Place, SIMON & SCHUSTER NY 1992, p. 56). Considering the fact that humans have so far explored but an infinitely small fraction of the the ocean seafloor representing the greatest portion of the planet, it can be argued that Proper's lamentation is premature. The Portuguese caravels that spearheaded the "Geographic Revolution" in the 1400's are replaced in our time by the research submersibles.

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Over the last two decades, manned submersible forays to the ocean' seafloor resulted in the discovery of spectacular black (and white) hot smokers venting vigorously from the deep-sea spreading centers (CORLISS *et alii*, 1979; BALLARD, 1984). More recently, the same submersibles played a key role in the discovery of the more gentle but equally exceptional cold hydrocarbon seeps and vents occurring along convergent plate boundaries (KULM *et alii*, 1986; LALLEMAND *et alii*, 1992) and passive continental margins (PAULL *et alii*, 1984; HOVLAND, 1992; ROBERTS & AHARON, 1994). The seemingly inhospitable hydrothermal and cold hydrocarbon emission sites were found to be inhabited by a remarkably abundant benthic fauna of mussel and clam bivalves, gastropods, tube worms, and bacterial mats which have adopted chemosymbiosis (either sulfur and/or carbon based) as the principal mode of derivation of energy and nourishment (JANNASH & MOTTI, 1985; KENNICUT *et alii*, 1985; TUNNICLIFFE, 1992). Concerning the cold-vent domain, observations from submersibles also established that venting sites are associated with active deposition of carbonates, sulfides and sulfates displaying varied morphologies and complex mineralogies (COMMEAU *et alii*, 1987; KULM & SUESS, 1990; ROBERTS & AHARON, 1994; FU *et alii*, 1994). Equipped with the now axiomatic uniformitarian principle that "*the present is the key to the past*", and outfited with the carbon isotope tool that can unambiguosly identify hydrocarbon imprints, geologists have swiftly recognized the fossil analogs of modern seep and vent deposits in the Phanerozoic rock formations occurring at different locations around the world (CAMPBELL & BOTTJER, 1993; AHARON, 1994 a; AHARON & SEN GUPTA, 1994).

The northern Gulf of Mexico (Fig. 1) is arguably the most unusual and scientifically intriguing setting of extant hydrocarbon emissions on a passive margin. This is because: (i) hydrocarbon emissions are pervasive (ROBERTS & AHARON, 1994); (ii) fossil hydrocarbons reaching the seafloor occur in liquid (crude oil), gas, and solid (ice hydrate) forms, the latter two being derived from biogenic and/or thermogenic sources (ANDERSON *et alii*, 1983; ANDERSON *et alii*, 1992); (iii) seeps and vents host a highly diverse and abundant chemosynthetic biota (CARNEY, 1994; LARKIN *et alii*, 1994; AHARON, 1994 b) comprising all the known chemosymbiotic elements (i.e., mussels, clams, tube worms, bacterial mats), and (iv) bacterially-mediated processes of hydrocarbon oxidation and sulfate reduction lead to deposition of massive carbonate buildups (ROBERTS & AHARON 1994) and barite deposits (FU *et alii*, 1994). Equally important, the subsurface Jurassic-age salt diapirs have played a dominant role in the development of a network of growth faults that act as conduits for the transport of fluids and hydrocarbons to the sea floor (COOK & D'ONFRO, 1991; ROBERTS *et alii*, 1992) and have contributed to the geochemical diversity of the fluid emissions (AHARON *et alii*, 1992 a).

The objective of this study is to provide a concise overview of the last five years survey of hydrocarbon emissions in the northern Gulf of Mexico, documented from depths ranging from 120 m to 2200 m, and delineate the complex interactions between the abiotic and biotic processes occurring in association with the seeps and vents.

## 2. – MANIFESTATION OF HYDROCARBON EMISSIONS ON THE SEAFLOOR

Point-source anoxic enclaves attributed to hydrocarbon emissions are pervasive within the terrigenous sediments blanketing the outer continental shelf, slope, and deep basin of the northern Gulf of Mexico (Fig. 1). Two classes of manned submersibles were used for the purpose of observation and sampling of these hydrocarbon seepage sites. The Johnson-Sea-Link submersible (Fig. 2 A), whose maximum diving range is 1000 m, was deployed at sites located on the outer neritic and upper to middle bathyal depths. For deeper sites at the slope break and in the deep basin the submersible was DSV Alvin (Fig. 2 B) whose diving range is 4000 m. Both submersibles are equipped with mounted video and still cameras for continuous documentation of seafloor features, ports for visual observations, as well as with sampling and storage equipment allowing recovery of box and push cores, grab and suction samples and lithified rocks. Accurate deployment of the manned submersibles to the point-source seep and vent sites was facilitated by the acoustic tracking system mounted on the surface ship and exploiting the satellite navigation capability afforded by the GPS (Global Positioning System). The diving activities were preceded by careful documentation of the sites using high resolution acoustic data and subbottom profiler records (ROBERTS *et alii*, 1992; ROBERTS & AHARON, 1994). The use of manned submersibles for seafloor sampling represents a significant refinement over the conventional dredging and coring techniques performed from surface ships as it affords sampling with a pre-

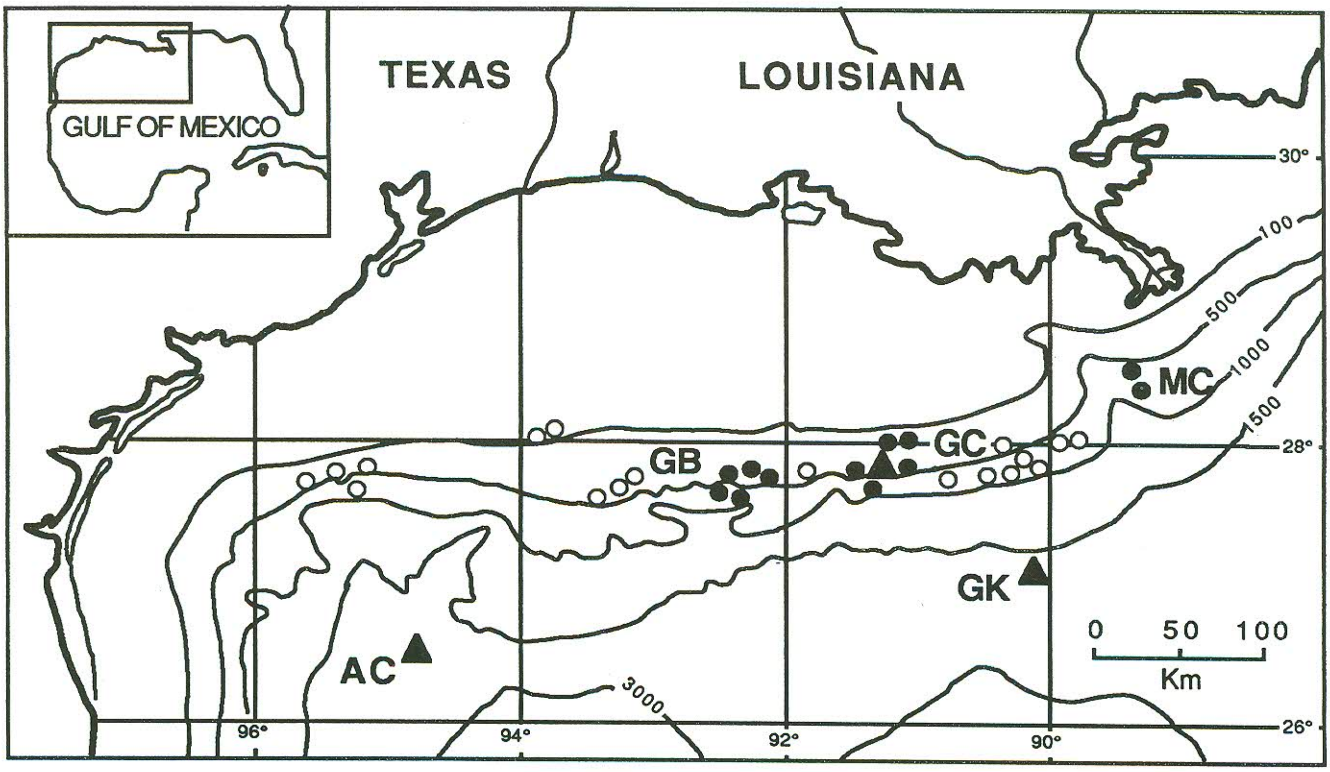


Fig. 1 – Bathymetric map of the northern Gulf of Mexico showing location of sites where hydrocarbon seeps and vents have been documented (MC=Mississippi Canyon; GC=Green Canyon; GK=Gren Knoll; GB=Garden Bank; AC=Alaminos Canyon). Filled dots and triangles indicate sites surveyed with the Johnson-Sea-Link and Alvin submersibles, respectively, over the period 1989-1993. Empty dots show known seeps and vents not yet surveyed by submersibles.

*Carta batimetrica della parte Nord del Golfo del Messico che mostra i siti dove sono stati documentati efflussi di idrocarburi (MC=Mississippi Canyon; GC=Green Canyon; GK=Gren Knoll; GB=Garden Bank; AC=Alaminos Canyon). I pallini e i triangoli indicano i luighi investigati rispettivamente con i batiscafi Johnson-Sea-Link e Alvin nel periodo 1989-1993. I cerchietti vuoti mostrano i centri di emissione e gli efflussi non ancora investigati da batiscafo.*

cision comparable to the one achieved by geologists on land outcrops.

Detailed observations from submersible dives indicate that the continental slope of the northern Gulf of Mexico comprises a wide variety of geologic features that are intimately associated with the hydrocarbon emission sites. These features include: (i) authigenic carbonates displaying morphologies of mounds, pavements and pinnacles (Fig. 3 A) that occasionally attain a relief of up to 20 m above the seafloor; (ii) hydrate mounds containing solid ice-like clathrates at water depths >400 m (Fig. 3 B); (iii) active mud volcanoes discharging gas-rich fluids and fine sediment plumes (Fig. 3 C); (iv) barite deposits comprised of crusts draping the flanks of mud volcanoes (Fig. 3 D) and vertical barite chimneys (Fu *et alii*, 1994), and (v) braided streams of brine floored by unindurated iron oxide deposits and flowing downslope (Aharon *et alii*, 1992 a). These products of seepage and venting are accompanied by a host of low diversity, high density chemosynthetic communities comprised of bacterial mats (principally Beggiatoa sp., Fig. 4 A), methanotrophic mussels (principally Bathymodiolus sp., Fig. 4 B), tube worms (Lamellibrachia sp. and Escarpia sp., Figs. 4 C & D) and clams (vesicomyids and lucinids).

The complex manifestation of the hydrocarbon emissions on the Gulf of Mexico seafloor can be attributed to the following factors:

(1) Advection of hydrocarbon-rich fluids from conduits intersecting the seafloor is pervasive from the shelf to the abyssal plain (Roberts & Aharon, 1994).

(2) The nature of the hydrocarbons is diverse, including deep-seated crude oil and thermogenic methane (Anderson *et alii*, 1983) as well as shallow-seated biogenic methane (Sassen *et alii*, 1993).

(3) The thermal stability of the venting hydrocarbons varies from fluid-gas phases to hydrate solid-ice phases in accord with the changing hydrostatic pressure/temperature profiles along the slope (Anderson *et alii*, 1992). The ambient temperature varies from about 15 °C at 250 m depth to 4 °C at the deepest sampling point at 2200 m (Fig. 1).

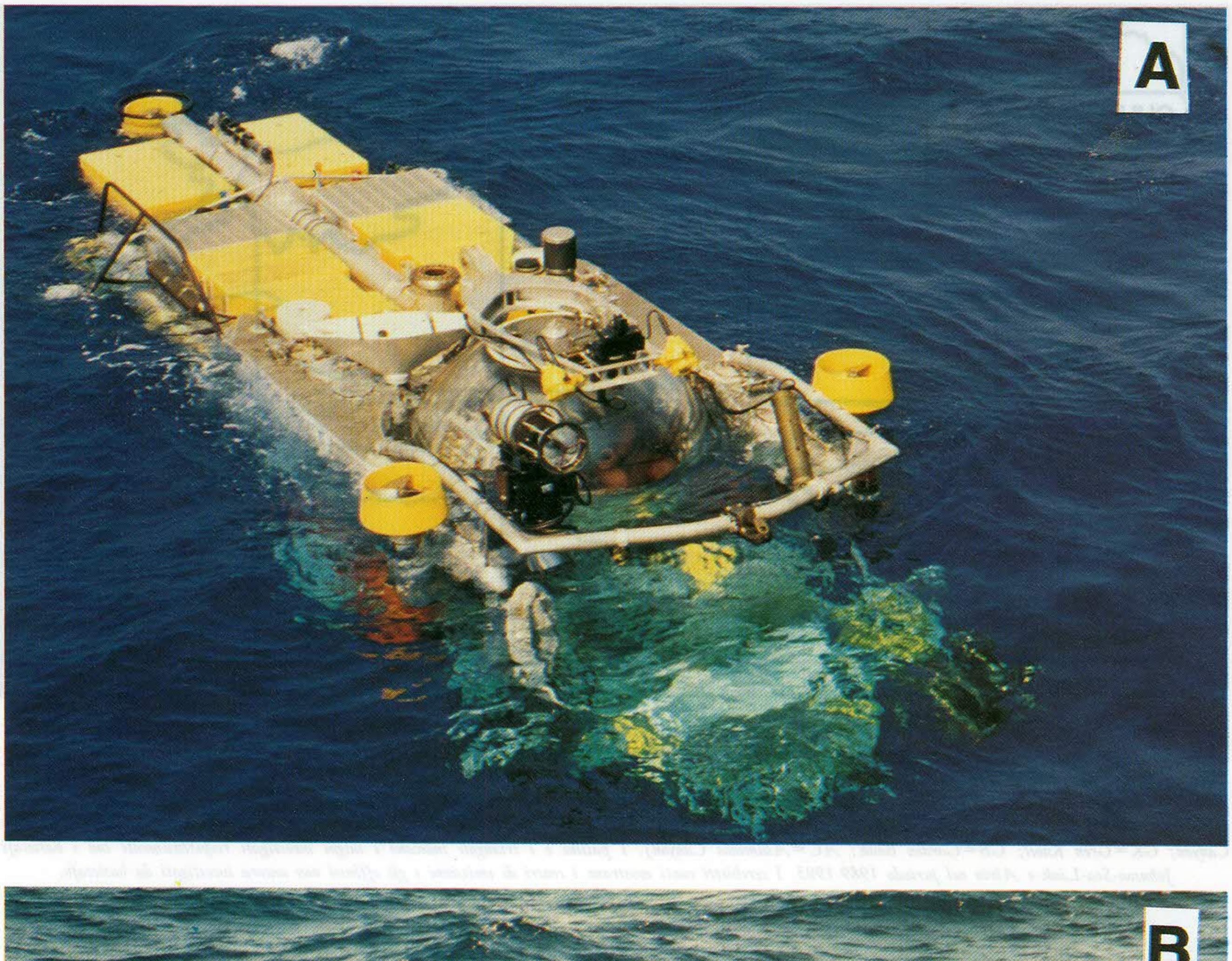


Fig. 2 - Manned submersibles deployed in the Gulf of Mexico for the study of seeps and vents. A: Johnson-Sea-Link; B: DSV Alvin.
*I batiscafi impiegati nel Golfo del Messico per lo studio dei centri di emissione di idrocarburi. A: Johnson-Sea-Link; B: DSV Alvin.*

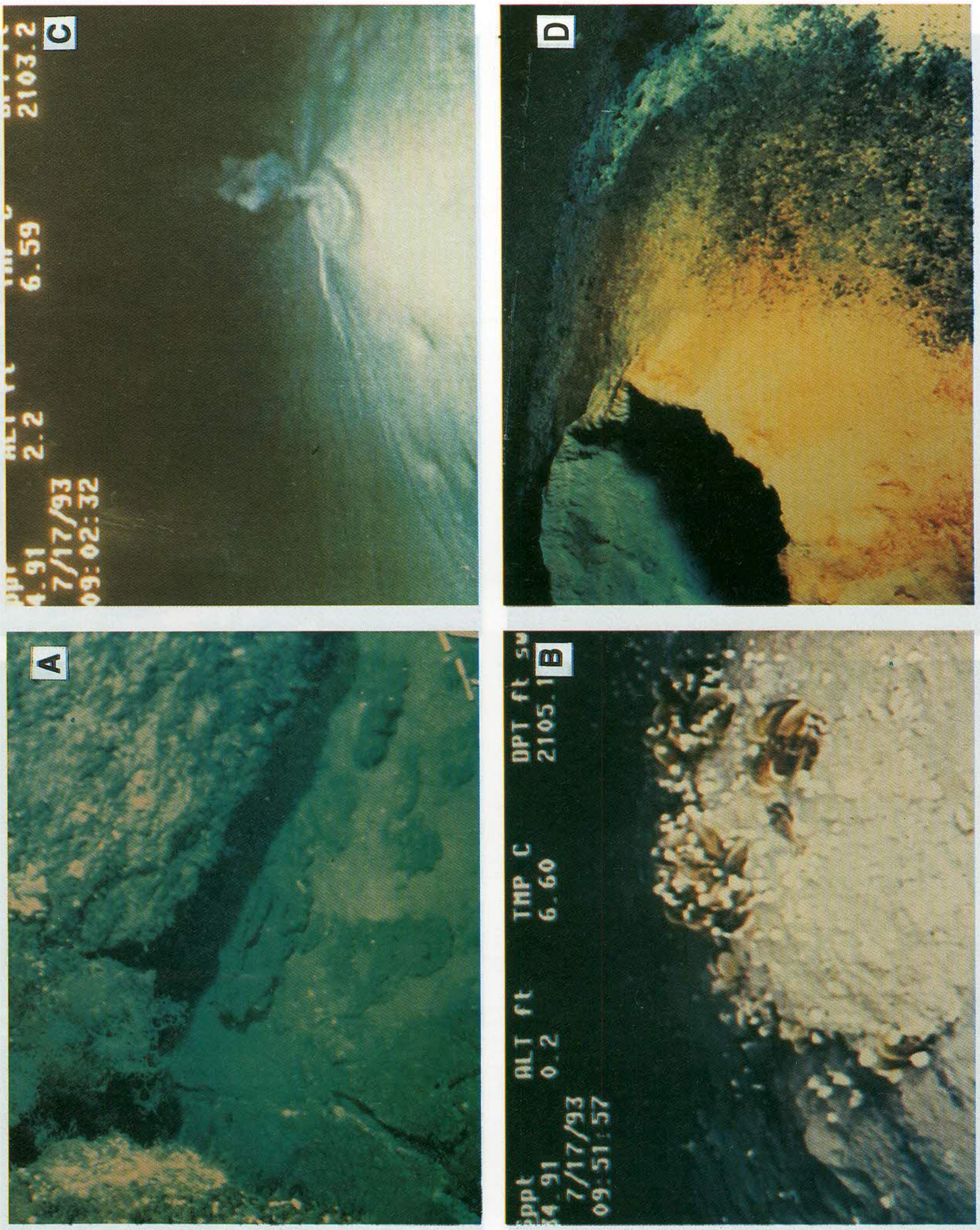


Fig. 3 - Manifestations of hydrocarbon emissions on the seafloor. Field of view is about 2 m. A: Carbonate buildups (*chemoherms*-AHARON 1994 a) occurring around a senescent seep at 333 m depth in GC area; gas seepage occurs from the linear fracture intersecting the seafloor. B: Hydrate mound at 642 m in the MC area; note the methanotrophic mussels clustering around conduits where methane is released by slow sublimation of the clathrates. C: Cone-shaped mud volcano at 641 m water depth in the MC area; the visible plume rising from the cone into the water column consists of methane and fine sediment particles. D: "Dormant" mud volcano at 641 m depth in the MC area; note the yellow-redish barite crusts precipitated from Ba-rich fluids and draping the flanks of the volcano.

*Manifestazioni di efflussi di idrocarburi sul fondo del mare. Il campo visivo è di circa 2 m. A: costruzioni carbonatiche (*chemioherme AHARON *1994 a) che si trovano intorno a un centro di emissione senescente a -333 mnell'area GC; fuoriuscite di gas si manifestano da una frattura lineare intersecante il fondo marino. B: piccolo crostone a –642 m nell'area MC; si notino i molluschi metanotrofi che bordano tutt'intorno il condotto dove il metano è rilasciato dalla lenta sublimazione dei clatrati. C: vulcano di fango a forma di cono a -641m nell'area MC; il pennacchio visibile che sale dal cono è formato da metano e particelle di sedimenti fini. D: vulcano di fango "dormiente" a -641 m nell'area MC; notare la crosta di barite giallo-rossastra precipitata da fluidi ricchi in bario che drappeggiano i fianchi del vulcano.*

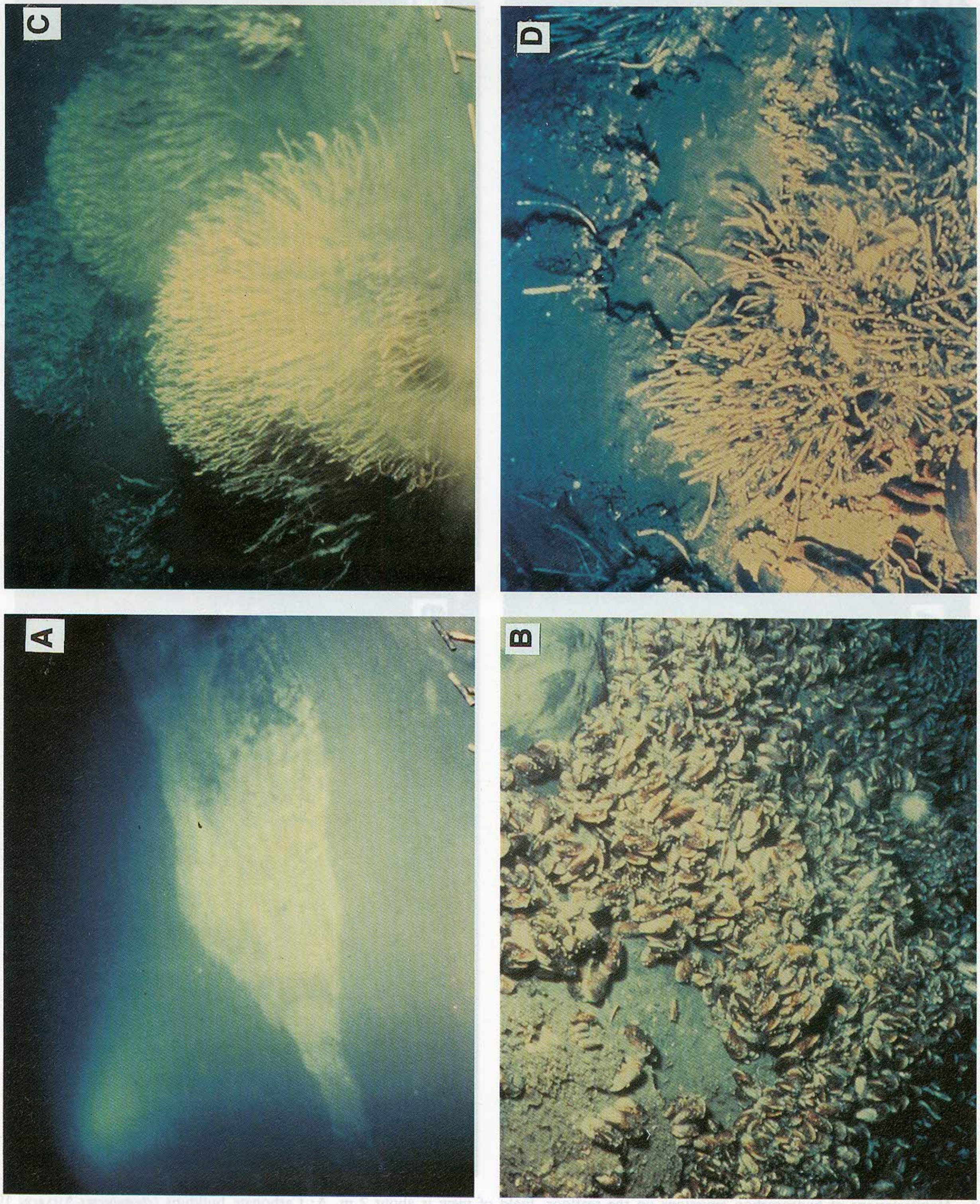


Fig. 4 - Chemosynthetic biota inhabiting seep and vent sites. Field of view is about 3 m wide. A: White-grey bacterial mat of *Beggiatoa* sp. blanketing a hydrocarbon seep at 217 m depth in the GC area; these bacteria exploit the hydrogen sulfide released from biodegradation of oil pools in the underlying sediment. B: "Reef" of methanotrophic mussels (*Bathymodiolus* sp.) at 677 m depth in the GC area "feeding" on methane escaping through fractured carbonate slabs. C & D: Bush-like aggregates of tube worms (*Lamellibranchia* sp.) at 577 m and 677 m depths in the GC area, respectively, that use hydrogen sulfide as energy source for their metabolism.

*Biota chemiosintetico che abita i centri di emissione di idrocarburi. Il campo visivo è ampio circa 3 m. A: feltro bianco-grigiastro di batteri* Beggiatoa *sp. ricoprente un efflusso di idrocarburi a -217 m nell'area GC; questi batteri sfruttano l'idrogeno solforato rilasciato dalla biodegradazione delle pozze di olio nei sottostanti sedimenti. B: "reef" di molluschi metanotrofi (*Bathymodiolus *sp.) a −677 m nell'area GC mentre si alimentano del metano che fuoriesce dalle placche carbonatiche fratturate. C e D: aggregati di vermi tubiformi (*Lamellibranchia *sp.) a −577 m e −677 m nell'area GC, che usano l'idrogeno solforato come fonte di energia per il loro metabolismo.*

(4) The high degree of diversity of the hydrocarbon venting products appears to be largely controlled by the rate of venting ranging from slow seepage, manifested by accretion of carbonate buildups at all depths, to fast venting manifested by mud volcanoes and barite deposits (ROBERTS & AHARON, 1994; AHARON 1994 a; FU *et alii*, 1994).

## 3. – INTERACTIVE PROCESSES IN SEEPS AND VENTS FUELED BY HYDROCARBONS

The exclusive association of hydrocarbon emissions and their geological and biological products with tops and flanks of subbottom salt diapirs, documented by high resolution acoustic and seismic data (COOK & D'ONFRO, 1991; ROBERTS et al. 1992; ROBERTS & AHARON, 1994), suggests that a cause and effect relationship exists between the seeps and vents and the underlying salt diapirs (Fig. 5). Observations from the submersibles indicate that seeps and vents occur in diverse stages of activity, from a juvenile "nascent" stage of fast venting represented by the active mud volcanoes and barite deposits (Fig. 5 A), to a mature "senescent" stage of slow and diffuse seepage represented by widespread carbonate buildups and chemosynthetic "reefs" (Fig. 5 B).

The survival of the chemosynthetic communities of cold seeps and the duration of carbonate and barite deposition depends on the supply of reduced sulfur and carbon forms, and barium-rich fluids, respectively, which in turn are controlled by the efficiency of the "plumbing" system. However, the seepage of hydrocarbon-rich fluids is likely to have a geologically short life span of unknown duration because of one or more of the following factors: (i) exhaustion of the hydrocarbon sources; (ii) shifts in the direction of compression and/or thrusting of the subbottom salt diapirs causing the closure of old conduits and the opening of new ones, and (iii) clogging of the plumbing system due to extensive carbonate deposition and cementation. Once the seepage is extinguished, the benthic fauna which it supports vanish as well and the only vestige of the seepage remains in the long-lasting geological products consisting of the carbonate and barite deposits and the calcareous shells of the chemosynthetic bivalves.

Advection of hydrocarbons to the seafloor through conduits opened by salt diapirism (Fig. 5) triggers a number of interactive geochemical and microbiological processes that leave unambiguous marks on the stable isotope compositions of the products. In the absence of dissolved oxygen, stacked microbial communities below the sediment-water interface use $SO_4$ (and probably $NO_3$) as electron acceptors for oxidizing reduced carbon, hydrocarbons and sulfur compounds for their metabolism (EHRLICH, 1990). The waste products of these microbiological reactions (e.g., $H_2S$, $HCO_3$ and $CO_2$) are preferentially acquiring the light stable isotopes and therefore their migration and partition can be traced with relative ease using the isotope tracer techniques (AHARON, 1994 b).

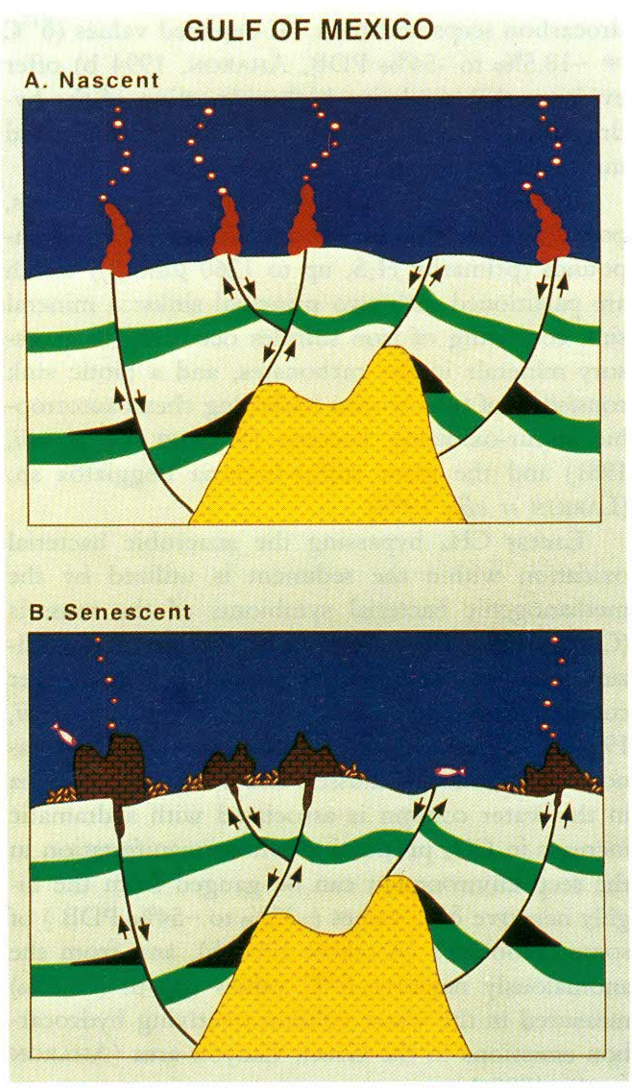


Fig. 5 - Simplified model of nascent (A) to senescent (B) evolution of hydrocarbon emissions in the northern Gulf of Mexico. Salt diapirism opens growth faults in the overlying sediments that act as conduits for hydrocarbon advection to the seafloor from the breached reservoirs.
*Modello semplificato della evoluzione di un centro di emissione di idrocarburi da nascente (A) a senescente (B) nella parte Nord del Golfo del Messico. Il diapirismo salino apre faglie di accrescimento nei sedimenti soprastanti che funzionano come condotti per la risalita degli idrocarburi sul fondo del mare dai serbatoi.*

Pore fluids from sediments affected by hydrocarbon emissions in the northern Gulf of Mexico display unusually high dissolved inorganic carbon (DIC) and alkalinity levels (up to a factor of 7 higher than "normal" seawater) and a range of negative $\delta^{13}C$ values (-13‰ to -37‰) reflecting the ongoing microbial oxidation of the hydrocarbon substrates and reduction of $SO_4$ to $H_2S$ via sulfate reduction (GRABER *et alii*, 1990). Under these circumstances, carbonate supersaturation of the pore fluids is achieved below the sediment-water interface and precipitation of either aragonite, calcite, or dolomite ensues (FERRELL & AHARON, 1994). The ubiquitous carbonate deposits occurring around hydrocarbon seeps and their $^{13}C$-depleted values ($\delta^{13}C$ = −18.5‰ to -54‰ PDB, AHARON, 1994 b) offer evidence that a relative high proportion of the hydrocarbon-derived carbon is chemically converted into solid carbonates.

In addition to high DIC and alkalinity levels, pore fluids are also enriched in reduced sulfur compounds (primarily $H_2S$, up to 1260 μmol/l)) which are partitioned into two principal sinks: a mineral sink consisting of iron sulfides occurring as accessory minerals in the carbonates, and a biotic sink consisting of tube worms harboring chemoautotrophic sulfur-oxidizing bacteria (SOUTHWARD *et alii*, 1981) and the giant sulfur-bacteria Beggiatoa sp. (LARKIN *et alii*, 1994).

Excess $CH_4$ bypassing the anaerobic bacterial oxidation within the sediment is utilized by the methanogenic bacterial symbionts of the mussels (CHILDRESS *et alii*, 1986) and by the methane-oxidizing microbial communities thriving in the seawater column above the emission points (LAROCK *et alii*, 1994). The consumption of methane by the methanotrophs within the mussels and by the free bacteria in the water column is associated with a dramatic increase in $CO_2$ production whose manifestation in the seep environment can be gauged from the highly negative $\delta^{13}C$ values (−35‰ to −54‰ PDB ) of some carbonates (AHARON 1994 b), and from the anomalously negative $\delta^{13}C$ values (up to (−4.5‰) measured in the water column overlying hydrocarbon emissions in the Green Canyon area (AHARON *et alii*, 1992 b).

The contrast in tissue $\delta^{13}C$ compositions between mussels (-43.2.1‰, n+18) and tube worms (−29.3±2.9‰, n=7) is likely to be a manifestation of different habitats, habits, and sources of carbon used in the metabolic functions. Concerning the mussels, the low $\delta^{13}C$ compositions of the tissues and the external periostracum offer direct evidence of methane consumption by the methanotrophic symbionts (CHILDRESS *et alii*, 1986).

The sulfur-based chemosymbiotic tube worms (SOUTHWARD *et alii*, 1981) seem to consistently yield more positive $\delta^{13}C$ values relative to mussels (AHARON, 1994 b). Whether or not the observed isotope contrast is caused by distinct chemosymbiotic pathways or by utilization of different carbon sources is unclear. The difference between the $\delta^{13}C$ of the organic compounds in the mussels and the tube worms may stem from the fact that the former are filter feeders of free-living methanotrophs while the latter are utilizing carbon derived from their chemosynthetic symbionts that have a more restricted carbon source. In this context, the vestimentiferan tube-worms habit of posterior insertion into the sediment tapping the flux of sulfide (Figs. 4 C & D) also affords access to the pore water carbon. The agreement observed between the $\delta^{13}C$ values measured by GRABER *et alii*, (1990) in the pore waters of vent sediments (i.e., -13‰ to −37‰), and the $\delta^{13}C$ values yielded by the tube worms (i.e., −25.6‰ to −34.9‰ for n=7) tend to support the contention that the vestimentiferan symbionts are likely to metabolize carbon from the pore waters.

## 4. – CONCLUDING REMARKS

Investigations of the topographically rugged northern Gulf of Mexico seafloor with manned submersibles has allowed documentation of remarkably diverse occurrences of seeps and vents and their geological and biological products located above subbottom salt diapirs. Complex interactions between advecting hydrocarbon-rich fluids and microbial communities within the terrigenous sediments are responsible for the formation of point-source anoxic enclaves in an otherwise oxic ocean basin. Reduced sulfur and carbon compounds serve to sustain a highly unusual epifaunal biota that adopted chemosynthesis as the principal metabolic pathway. Conversion of oxidized carbon compounds into massive carbonates results in long lasting geologic products of seepage and venting which could serve as recorders of submarine hydrocarbon emission history and of ambient changes in the bathyal and abyssal environments. Additionally, the ubiquitous extant seeps and vents of the Gulf of Mexico could serve as excellent modern analogues of fossil seep occurrences recently discovered in the Phanerozoic rock record.

Seeps and vents research is presently emerging from the survey stage to a more demanding mode requiring the tracing and quantitative analysis of the interactive geochemical and biochemical processes. The prospect of using the seeps as useful models for conversion of toxic wastes (e.g., $H_2S$; $CH_4$; Ba) into innocuous geologic products (e.g., carbonates; sulfides/sulfates) is promising once the chemical pathways are firmly established.

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