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Paul Aharon

Geology and biology of modern and ancient submarine hydrocarbon seeps and vents: An introduction

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Almost two decades ago, manned submersible forays to the ocean floor resulted in the discovery of spectacular hot smokers venting vigorously from deep-sea spreading centers (Corliss et al. 1979; Ballard 1984). More recently, similar missions have played a key role in the discovery of the more gentle but equally exceptional cold hydrocarbon seeps and vents (Fig. 1) along convergent plate boundaries (Kulm et al. 1986; Lallemand et al. 1992) and passive continental margins (Paull et al. 1984; Hovland 1992). The seemingly inhospitable hydrothermal and hydrocarbon venting sites have been found to be inhabited by a remarkably abundant benthic fauna of mussel and clam bivalves, gastropods, and tube worms, which have adopted chemosymbiosis (either sulfur and/or carbon based) as the principal mode of derivation of energy and nourishment (Jannash and Mottl 1985; Kennicutt et al. 1985; Tunnicliffe 1992). Concerning the cold-vent domain, observations from submersibles have also established that venting sites are associated with active deposition of carbonates, sulfides, and sulfates of varied morphologies and complex mineralogies (Commeau et al. 1987; Kulm and Suess 1990; Roberts et al. 1992a; Fu et al. 1994). Furthermore, equipped with the uniformitarian axiom and outfitted with the carbon isotope tool to identify hydrocarbon imprints long after hydrocarbon emissions ceased, geologists (e.g., Beauchamp et al. 1989; Campbell and Bottjer 1993) have swiftly recognized the fossil analogs of modern seep and vent deposits in the Phanerozoic rock formations at different locations around the world (Fig. 1).

A large body of scientific literature has resulted from the investigations of the deep-sea hydrothermal vents. In contrast, the domain of cold vents has received considerably less attention even though: (1) the interaction between the geological and biological systems is more complex at low than at high temperatures; (2) the diversity of cold vents is far greater, and (3) the identifiable fossil cold-vent occurrences in the geologic record are rapidly increasing in number (Fig. 1). The principal objective of this special *Geo-Marine Letters* issue is to focus attention on cold-vent research by placing under one roof the results of the past five years of investigations by several research teams from the United States, Italy, and Israel. Rather than being geographically broad and topically narrow, the contributions to the volume are topically comprehensive but geographically limited to three cold-vent locations in the modern northern Gulf of Mexico and previously little known fossilized vent deposits in the northern Italian Apennines and the coastal plain of Israel (Fig. 1).

The northern Gulf of Mexico is arguably the most unusual and scientifically intriguing setting for extant cold vents on a passive margin. This is because: (1) hydrocarbon emissions are pervasive within the terrigenous sediments blanketing the outer continental shelf, slope, and deep basin (Roberts and Aharon 1994); (2) hydrocarbons reaching the sea floor occur in liquid (crude oil), gas, and solid (hydrate) forms (R. K. Anderson et al. 1983; A. L. Anderson et al. 1992), the latter two being derived from biogenic and/or thermogenic sources; (3) cold vents host a highly diverse and abundant chemosymbiotic biota (Carney 1994) consisting of all the major elements (i.e., mussels, clams, tube worms) plus the sulfur oxidizing bacteria *Beggiatoa* sp. aggregating in mats (Larkin et al. 1994); and (4) bacterially mediated processes of hydrocarbon oxidation and sulfate reduction lead to the deposition of massive carbonate buildups that are bathymetrically segregated (Roberts and Aharon 1994). Equally important, the subsurface Jurassic-age salt diapirs of the northern Gulf of Mexico play a dominant role in the development of a growth-fault network that provides conduits for the transport of fluids and hydrocarbons to the sea floor (Roberts et al. 1992b) and contribute to the geochemical diversity of the fluid emissions (Aharon et al. 1992; Fu et al. 1994). Recent cold-vent studies in the northern Gulf of Mexico have directly contributed to the recognition of ancient hydrocarbon emissions that left imprints in the Miocene-age rocks of Italy (e.g., Terzi et al. 1994; Taviani 1994; Aharon and Sen Gupta 1994) and the Quaternary-age rocks of Israel (Druckman et al. 1994).

Paul Aharon
Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana 70803, USA

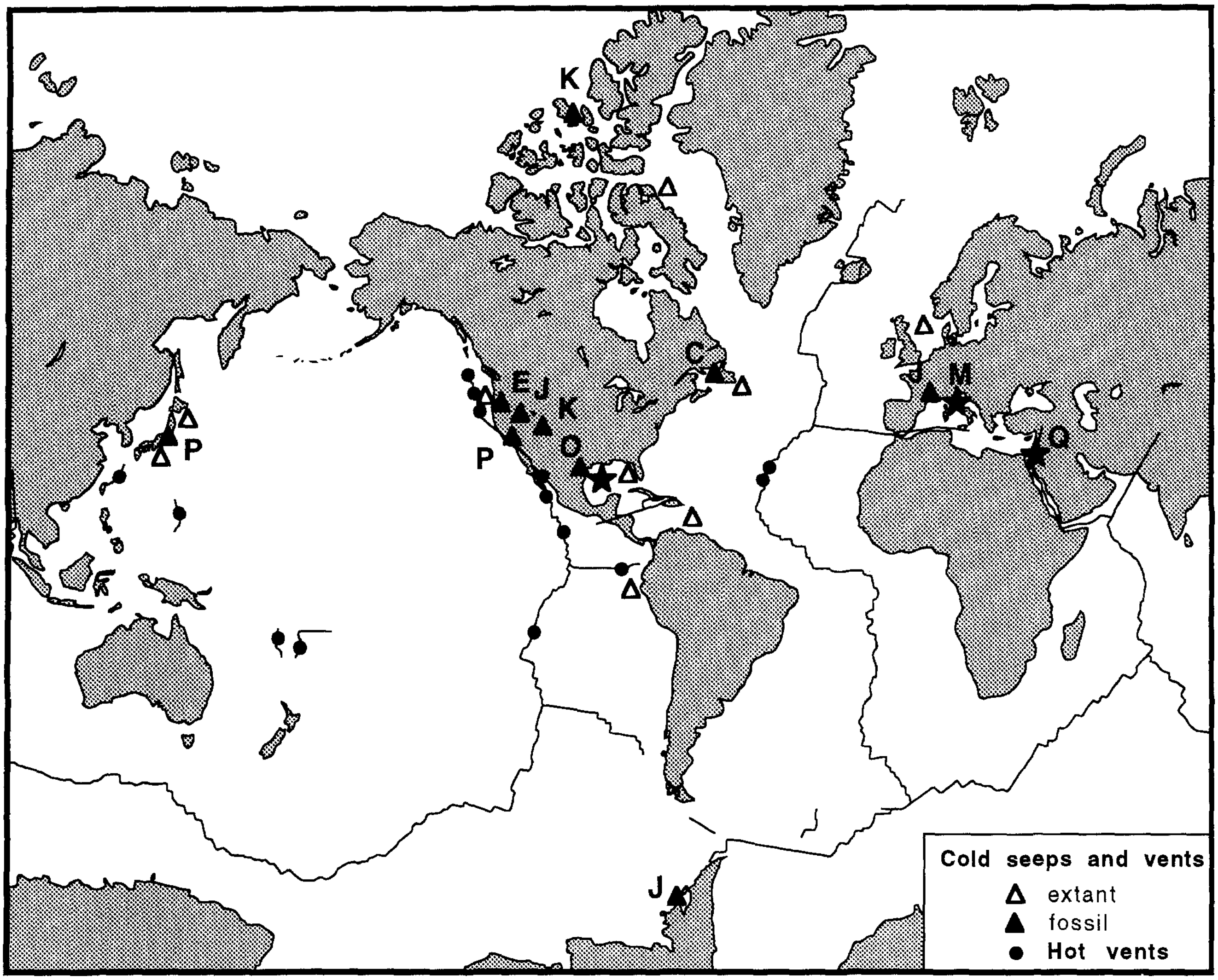
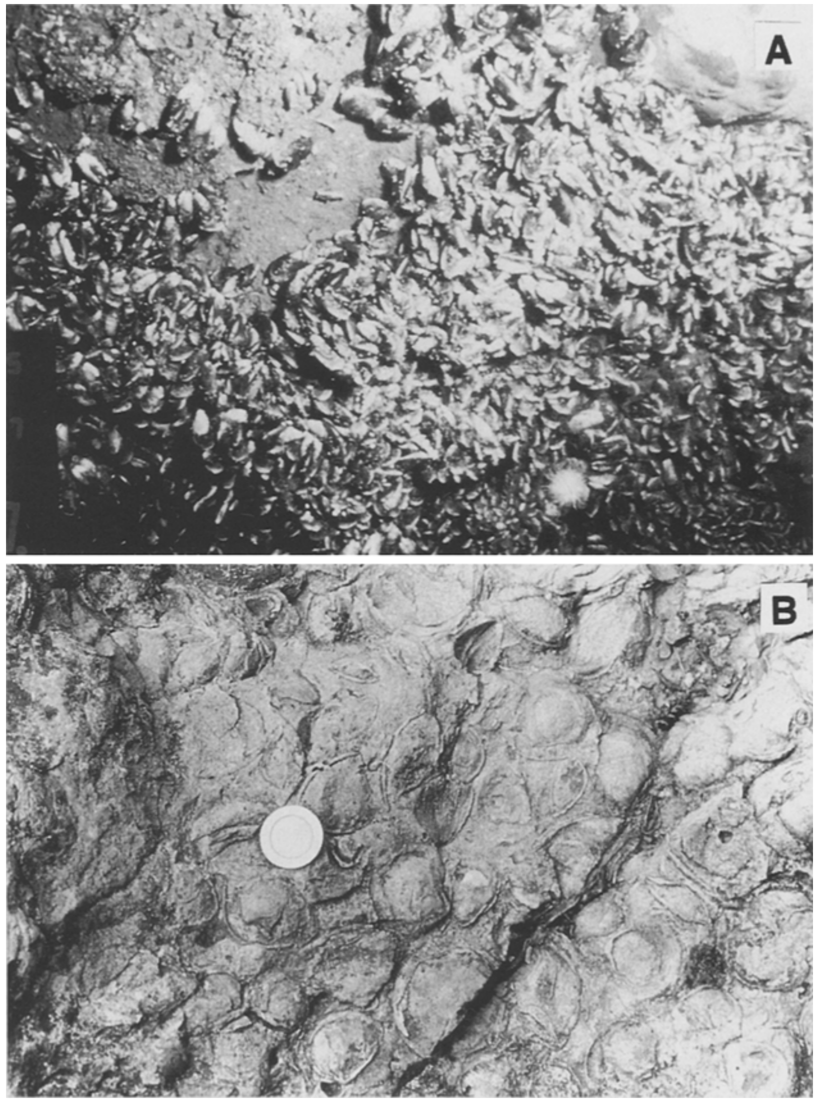


Fig. 1 World distribution of extant hot vents and known modern and fossil occurrences of cold hydrocarbon seeps and vents on the seabed. Sites discussed in this special *Geo-Marine Letters* issue (northern Gulf of Mexico; northern Italian Apennines, and Coastal Plain of Israel) are marked by stars. Letters next to the fossil sites indicate the stratigraphic age of the deposits (C = Carboniferous; J = Jurassic; K = Cretaceous; E = Eocene; O = Oligocene; M = Miocene; P = Pliocene; Q = Quaternary). Sources are: 1. North America: Sassen (1980); Arthur et al. (1982); Goedert and Squires (1990); von Bitter et al. (1992); Campbell and Bottjer (1993); 2. Canadian Arctic: Beauchamp et al. (1989); 3. Japan: Niitsuma et al. (1989); 4. Europe: Gaillard et al. (1992); Ricci Lucchi and Vai (1994); 5. Middle East: Druckman et al. (1994); 6. Antarctica: Kelly et al. (1994)

Some of the terminology commonly used by scholars of submarine emissions seems to be incompatible with the observations made by several workers, including this author, during submersible dives in the Gulf of Mexico, and during field investigations of the fossil deposits in Italy and Israel. As a matter of convenience rather than reason, extant hydrothermal and hydrocarbon emissions have traditionally been distinguished by the terms "hot vents" and "cold seeps" on the basis of assumed rather than determined temperatures and rates of emissions. These terms were subsequently rolled over to the fossil occurrences (e.g., Campbell and Bottjer 1993) in spite of the fact that "venting" (fast) and "seepage" (slow) imply knowledge of the emission rates that were unavailable. Detailed observations, however, indicate that rates of present day hydrocarbon emissions range over a wide spectrum, from imperceptibly slow and diffuse (Fig. 2A) to fast and vigorous (Fig. 3A). The emission rates can not only be discerned on the basis of direct observations, but can also be distinguished on the basis of their geological and biological products. For example, sites delineated by hydrocarbon seepage of oil and gas are normally associated with massive carbonate deposition and with remarkable abundance of diverse chemosymbiotic faunal elements (most particularly tube worms, mussel and clam bivalves) and *Beggiatoa* mats. In contrast, sites of hydrocarbon venting from cone-shaped mud volcanoes (primarily methane-rich fluids loaded with fine sediment particles, Fig. 3A) are typically carbonate-poor (carbonates being locally replaced by barite deposits) and are associated with drastically impoverished chemosymbiotic fauna, generally restricted to methanotrophic mussels. Geological and biological products associated with distinct hydrocarbon emission rates can also be recognized in the fossil Miocene record of the northern Italian



MODERN

ANCIENT

Fig. 2 Manifestations of slow hydrocarbon emission rates. Extant and fossil chemosymbiotic bivalve-rich carbonates derived from seepage of microbial hydrocarbon-oxidation products showing remarkable similarities in their morphology. **A** Northern Gulf of Mexico (modern), with abundant methanotrophic mussels *Bathymodiolus* sp. accompanying the fractured carbonate slabs (view area is about 2 m wide). **B** northern Apennines, Italy (late Miocene-age), with abundant lucinids in the indurated limestone and cement-filled fractures

Apennines (Figs. 2B and 3B). Under these circumstances, two considerations are relevant: (1) to label sea-floor emissions (i.e., hydrothermal and hydrocarbon) as “vents” when the rates of emission are unknown, or (2) to distinguish emissions on the basis of known rates (i.e., hydrocarbon seeps and/or vents). When the temperatures of fluid emissions are known, the thermal attribute may also be added as a prefix, for example “hot vents” and “cold seeps and/or vents.” In this special issue, the contributors have used these optional terms at their own discretion.

The second problem arising from an assessment of definitions concerns the terms used for geological products of seepage and venting, specifically the carbonate buildups. They have been variously described as bioherms, lithoherms, pseudobioherms, biostromes, etc. using terms borrowed from the literature of carbonate petrology (see review of terms by Roberts and Aharon 1994). Such traditional carbonate terminology seems adequate to describe shallow- to deep-water carbonate buildups whose carbon is derived primarily from seawater, and their carbon isotope compositions reflect this derivation. These terms, however, are inadequate for the portrayal of the carbonates associated with hydrocarbon emissions. In this issue, I and several other contributors have used the term “chemoherm” to designate buildups of chemical carbonates and calcareous skeletal debris of chemosymbiotic fauna whose carbon is primarily derived from microbial processes in domains of cold hydrocarbon venting and which possess anomalously negative carbon isotope compositions relative to the seawater carbon pool.

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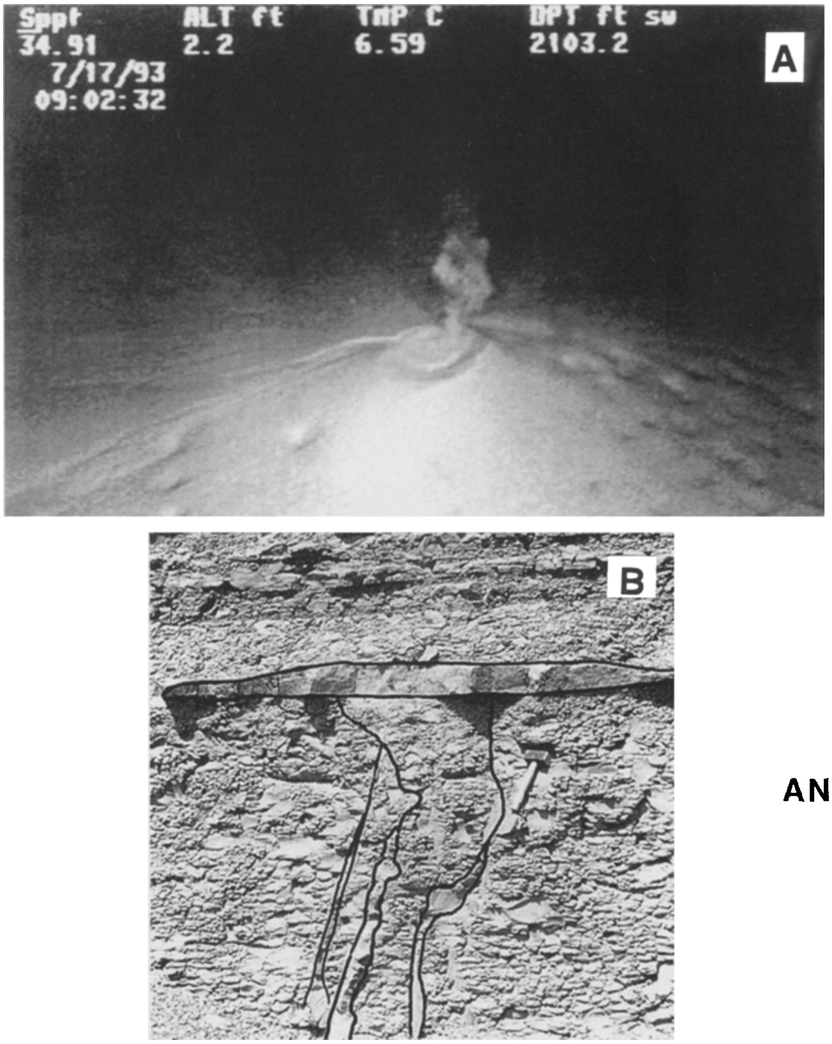

Fig. 3 Manifestations of fast hydrocarbon emission rates. Extant and fossil cone-shaped mud volcanoes derived from submarine venting of fluid-rich methane and sediment. **A** northern Gulf of Mexico at 641 m water depth. The visible plume rising from the cone top into the water column consists of methane and fine sediment particles. Field of view is about 2 m wide. **B** northern Apennines, Italy (middle Miocene-age). Road section through a sequence of deep-sea turbidites in the Marnoso-arenacea Formation reveals a mud volcano within hemipelagic units exhibiting "a" to "e" Bouma sequences (A. Landuzzi personal communication). The circumstantial evidence for methane venting is based on the remarkable similarities between *the modern and ancient forms* in **A** and **B**. Geochemical work in progress would confirm or refute this inference. For the purpose of clarity, the conduits and the section through the cone have been outlined. Note hammer for scale

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