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Miocene cold seep faunas and carbonates from Barbados

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Introduction

On active plate margins, compressive tectonics dewater the offscraped accretionary prism sediments expelling chemically reduced fluids ('cold seeps') through faults, fissures, and such structures as mud volcanoes. Henry et al. (1996) indicate that fluid flow, in Barbadian mud volcanoes, enriched in CH_4-rich fluids in the zones of sulphide-reduction and methanogenesis within the bottom sediment, gives rise to characteristic authigenic carbonates ('chemoherms'). These carbonate masses can be recognized in the fossil record from their extremely complex, cyclical precipitation/dissolution fabrics, pronouncedly negative $\delta^{13}C$ signatures and content of an often abundant but low diversity molluscan and tube-worm fauna of known chemosynthetic affinity (Campbell & Bottjer, 1993).

Barbadian geology and sample localities

Barbados represents a subaerial exposure of the crestal zone of the Barbados accretionary prism, on the eastern margin of the Caribbean tectonic plate (Olu, et al., 1997: Fig. 1). Erosion of the Pleistocene reef cap in NE Barbados exposes two Eocene-Miocene aged structural units: the accretionary Basal Complex, and the overlying pelagic Oceanic Series oozes. These units are everywhere in fault contact and overlap in depositional ages. Westward (arcward) migration of the western margin of the accretionary prism caused contraction and uplift of the outer Grenada Forearc Basin strata, emplacing the Oceanics as allochthonous backthrust nappes overriding the crest of the accretionary complex (Torrini, et al., 1985; Speed, 1990: Fig. 1C). These two units are separated by a major tectonic unit, the sub-Oceanic fault zone (SOFZ of Torrini, et al., 1985: Figs. 2 and 4), a detachment surface along which fluid migration from dewatering of the accretionary prism appears to have been concentrated (Torrini, et al., 1990). The SOFZ is a laterally continuous zone 3-20 m thick, the central zone of which was apparently the 'surface' of greatest displacement. Fluid migration and authigenic, methane-derived carbonate precipitation within the SOFZ were apparently genetically related to the emplacement of the Oceanic nappes and the late intraprism contraction. Fluid migration was syn- to early post-faulting (early Miocene), with authigenic carbonates locally cross-cutting and replacing foliated fault zone rocks (Torrini, et al., 1990). The authigenic carbonates have yielded fossil cold seep faunas and carbonate chimneys.

The material examined from Bath Cliffs, consists of both in situ specimens and eroded beach cobbles, whereas at Windy Hill, Belleplaine and Morgan Lewis the carbonates occur as ex situ clitter, either as 'remainé' horizons from long-eroded fault zones previously existing at higher structural levels, or eroded from buried fault zones. Specimens have also been collected at Coconut Grove, from the Joe's River mélange, a sandy, organic-rich mudstone containing large angular exotic blocks. This extensive mélange is believed to be a massive diapiric structure, intruded into surrounding strata post-nappe emplacement (Speed, 1990).

Results

I. Authigenic carbonates

Two different types of authigenic carbonates have been found at most localities, which differ in the nature of their fabrics. At Bath, Belleplaine and Windy Hill carbonates are found as a calcitized radiolarian ooze protolith with an unusual, early-formed fabric of coarse-grained calcite 'spherules' ≤1.5 mm diameter. At Bath, this fabric is also seen in several well preserved carbonate chimneys ('conduits' - Harding & Aharon, in prep.). This spherulitic fabric is indicative of bacterially-mediated precipitation, resembling laboratory-produced concentrically 'zoned' intergrowths of aragonite and calcite, and fabrics described from the Italian Miocene 'calcari a Lucina'. The calcitization of the radiolarian protolith indicate that the chimneys grew within the seafloor sediments rather than protruding from the seafloor.

The remaining authigenic carbonates are volumetrically most important and consist of polymict matrix-supported calcirudites. Clast composition is varied, the most common type again being a calcitized radiolarian ooze with partially pyritised radiolarian 'ghosts' filled with coarsely crystalline calcite. An extremely complex sedimentary history must be invoked to explain the varied clast composition. The matrix and cement phases exhibited by this lithology are likewise of an extremely complex nature (see below).

In the Joe's River mélange, some of the exotic grey-brown silty sandstone blocks within the mélange are cemented by authigenic carbonates and have carbonate veins up to 8 cm wide containing gastropod fossils. All carbonates are often heavily impregnated with hydrocarbons, and at Joe's River are streaked with jarosite.

II. Fossil faunas

An abundant but relatively low diversity fauna has been identified in these deposits (a detailed discussion of which will appear elsewhere). In the authigenic carbonates of the SOFZ taxonomic discrimination is limited due to post-depositional dissolution of the aragonitic/calcitic shells and partial replacement by chert (beekite). The specimens are thus preserved as internal and external moulds and internal casts. Sinuous cylindrical casts of an average diameter of 0.5 cm and length ≤ 15 cm are here interpreted as pogonophoran worm tubes. Although they lack diagnostic features for generic/specific determination, their mode of occurrence in intertwined 'stands' of tube-casts of similar diameters clearly confirms their biological identification. The molluscan faunas have similarities with fossil material described by van Winkle (1919) from Trinidad, and many of the forms described by Kugler et al. (1984) from the Joe's River mélange are also found: the bivalves include the vesicomyid *Pleurophopsis* (≤ 15 cm long), *Nuculana senni* Jung, 1984, lucinids, thyasirids and rare solemyids, along with the gastropods *Solariella, "Diastoma" sensu* Kugler et al. (1984), and ?fissurellid gastropods. Both encrusting and possibly erect serpulids also occur.

The molluscan faunas of the Joe's River mélange retain shell material and include *Pleurophopsis* (≤ 18 cm long), large lucinids (≤ 10 cm) and *"Diastoma"*, and are largely found in the mélange matrix. Although the bivalves in the mélange are almost invariably perfectly articulated they are pervasively shattered (complicating collection) and overgrown with oxide films.

III. Research on living cold seep faunas from the Barbados accretionary prism

There has been extensive study of the seismic structure and fluid flow of the Barbados accretionary prism, but relatively little research has been directed towards the cold seep faunas supported by fluid emissions until the last few years. Five cruises have reported living chemosynthetic faunas on the Barbados accretionary prism (see references in Henry et al. 1996; Lance et al. 1998; Olu et al. 1996, 1997), although only two recovered biological specimens. The majority of information on faunas, species densities, spatial distribution and community structure comes from videotape shot during submersible dives.

The living communities on the southern part of the prism are dominated by two bivalve species (yet to be described), smaller numbers of vesicomyid clams, rare solemyids and thyasirids. The gastropods are represented by several species. The worm fauna consists of pogonophorans and polychaete serpulids; cladorhizid sponges are also found. The mud volcano faunas from seaward of the deformation front are less diverse, with lower abundance, being dominated by vesicomyids, and solemyids (*Acharax*); *Phymorrhynchus* sp. is the sole gastropod, and one pogonophoran occurs along with stands of tubiculous polychaetes.

IV. Comparison of fossil Barbadian fauna with living Barbadian and other modern and fossil faunas

Regrettably the degree of comparison between the living and fossil Barbadian cold seep faunas is low, due to the low level of taxonomic determination presently possible on both faunas. As regards the fossil fauna, identification to species level is limited by the mode of preservation and the paucity of descriptions of fossil cold seep faunas of this geological age. Taxonomic definition of the living fauna is still rudimentary with several species of the molluscan megafauna still awaiting description.

The fossil *Pleurophopsis* sp. recovered from Belleplaine, Windy Hill and Joe's River may be conspecific with the taxon described by Olu et al. (1996), as *Bathymodiolus* sp. A. These Barbadian fossils, being of Miocene age, may thus provide the first direct evidence for temporal longevity of species living on a single accretionary prism over extended time periods. This is an extremely important finding in the light of evidence which indicates that some hydrothermal vent molluscs are descended from cold seep forms, an hypothesis that fits well with the idea that cold seep sites may act as refugia during mass extinction events, and thus source areas for subsequent evolutionary radiations.

Although species level comparisons of other faunal elements are not yet possible, solemyid, thyasirid, vesicomyid bivalves and several turrid gastropod taxa are present in both modern (Barbados, Cascadia, Nankai, Peru, Costa Rica prisms) and fossil assemblages (e.g. Campbell & Bottjer 1993). Serpulid taxa are relatively common in ancient cold seep faunas, although, bar extreme abundance on the modern Peruvian margin, generally less common in modern cold seep faunas.

However, not all elements of the modern and ancient Barbadian faunas show the same evolutionary stasis since the Miocene: the most commonly recovered fossil bivalve, the nuculanid, is thus far unreported from the living assemblages, whereas by contrast several of the modern gastropod taxa are unrepresented in the fossil assemblages. This may partially be explained by the fact that thus far the most detailed studies of living Barbadian prism faunas come from mud volcano locations: faunas which may presently exist in areas of indurated (carbonate-cemented) bottom sediments may have a different taxonomic composition.

V. Spatial distribution of faunal elements: a comparison of living and fossil assemblages.

The locus of fluid emissions at cold seep sites is variable and of great importance in determining faunal distribution. On a regional scale many seepages are focused along tectonic features such as faults and associated scarp faces, submarine slides or mud volcanoes, and give rise to patchy, localized, high biomass faunas. Other emissions may be more diffuse, where fluid flow is dispersed over a greater area of sedimentary cover, supporting a lower biomass of even more sporadic occurrence (e.g. Olu, et al., 1996, 1997).

1. Sub-Oceanic Fault Zone (SOFZ)

Evidence from Bath cliffs indicates that fossilized tube-worm clusters only occur along the edges of carbonate slabs and blocks showing the distinctive early-formed spherulitic calcite fabric: the worms apparently grew within fissures/microfaults which must have focused fluid flow. Analogous occurrences of living tube-worm clusters growing in fissures and attached to the underside of authigenic carbonate blocks have been reported from the Cascadia and Nankai prisms. The fossil tube-worms are likely to have been chemoautotrophic, given their association with fissures which focused the flow of CH_4- and H_2S-rich fluids.

Molluscs and tube-worm remains co-occur extremely rarely in the fossil carbonate blocks. This apparent degree of spatial separation of the fossil organisms in life, is not a situation seen in living Barbadian seep communities (e.g. Olu, et al., 1996), or those from other locations. Similarly, in the fossil record, co-occurrences of molluscs and 'pogonophoran' tubes have been reported from the USA and Italy, as have the serpulid/molluscan associations (USA, Canada). The spatial distribution of the molluscan fauna in the SOFZ is difficult to assess due to the lithological context in which it is found.

2. Joe's River mélange

Tube-worms are very rare and only found associated with authigenic carbonate blocks which are interpreted in the same manner as those at Bath Cliffs. Gastropods are also associated with these carbonates, and were thus also living in areas of focused fluid flow. By contrast, most of the bivalve fossils are found in the mélange matrix as biocoenoses of loosely aggregated 'nests' of perfectly articulated vesicomyids (*Pleurophopsis*) and lucinids, covering several square metres in area. Given their taxonomic affinities, the bivalves are therefore likely to have been chemoautotrophic and probably lived in areas of diffuse fluid seepage.

Conclusions: interpretation of the fossil-yielding lithofacies

1. Sub-Oceanic Fault Zone (SOFZ)

A geological interpretation of the spherulitic carbonates and their associated tube-worm fauna has already been provided. The mollusc-bearing calcirudites were initiated with the calcitization of a radiolarian ooze protolith, probably by precipitation of a pyrite-rich methane-derived subsurface carbonate crust in the sulphate-reduction zone, a scenario similar to those postulated for modern and ancient cold seep carbonates. The uncemented surface sediments supported a relatively diverse cold seep assemblage including chemoautotrophic molluscs. The community was established for some time, comprising individuals at different growth stages and also dead shells representing fauna already dead from senescence. Irregular fluid flow rates resulted in autobrecciation of the indurated layer by explosive release of ponded gas from below the crust. The cold seep fauna would have been killed suddenly and incorporated into the breccia, apparently with little disarticulation, along with some disarticulated, partly corroded dead shells.

Enhanced fluid flow following brecciation allowed re-establishment of the fauna and infilling of the interstices of the breccia with peloids and ?methane-derived micrite. Cementation of some remaining voids resulted from bacterial oxidation of methane at shallow burial depths in the aerobic zone. Dissolution events are indicated not only by corrosion and rounding of brecciated clasts, but also by truncations of earlier cement fabrics. Carbonate fabrics indicate cyclical brecciation, dissolution, cementation and sediment infilling of dissolution vugs, related to fluid flow fluctuations. Molluscan shells were largely dissolved and partially replaced by late-stage precipitation of beekite in the mouldic porosity.

Given the presence of benthic fauna and the fabric of the authigenic carbonates, the SOFZ clearly had an expression on the Miocene seafloor. It would appear that the cold seep 'oases' which became established along the sediment-water interface expression of the SOFZ owe their preservation to the eastwards propagation of the SOFZ which overran them. As the Oceanic nappes were backthrust onto the prism, the carbonate blocks and fauna were thus preserved within the central zone of this tectonic horizon (Speed, 1990; Torrini, et al., 1990).

2. Joe's River Mélange

Some previous references to the megafauna of the Joe's River mélange have viewed the molluscs as allochthonous, being incorporated into the mud matrix from older sediments during mélange intrusion. However, preservation of the articulated bivalve assemblages in life position clearly points to the occurrence of an autochthonous molluscan fauna, supporting the ideas of Kugler et al. (1984). Furthermore, given that the taxonomic affinities of the bivalves lie with known chemosynthetic forms, an association with a cold seep habitat is indicated. Thus, the mélange must logically be interpreted as having been erupted as an emergent seafloor feature, probably a mud volcano (diatreme) subject to sustained fluid expulsion. The reduced fluids supported chemosynthetic faunas including vesicomyids and lucinids, prior to the mélange being overrun by the Oceanic nappes (Speed, 1990). Later mobilization of the mélange material resulted in intrusion into the Oceanics.

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