ORIGINS, COMPOSITION, AGE AND STRUCTURAL DIVERSIFICATION OF VIOSCA KNOLL *LOPHELIA* CORAL REEFS AND SUBSTRATE – A SYNOPSIS OF PRELIMINARY RESULTS

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ABSTRACT

Incidental collections of live *Lophelia pertusa* fronds, coral rubble, rocks and reef sands during 2004-2005 submersible investigations of *Lophelia* reefs on Viosca Knoll, northern Gulf of Mexico, enabled an opportunistic group of primarily geological analyses to proceed. Radiometric ages of living coral and dead subfossil coral were obtained. One substrate rock was analyzed for mineralogy via x-ray diffraction and for stable ^{13}C and ^{18}O isotopic signatures. Gravimetric analyses of specific gravity were undertaken for fresh coral, coral rubble, and rocks. Reef sand collected was analyzed to identify major biotic contributors. Results suggest an age of <400 yrs for contemporary Viosca Knoll *Lophelia* reefs, and of 25.0-26.0 ky for the overall *Lophelia* ecosystem in the northern Gulf of Mexico. This indicates that reefs flourished during the low sea-level stand of the Pleistocene Wisconsonian Glaciation. From the young age of contemporary reefs, relative to the much greater age of subfossil *Lophelia*, it may be hypothesized that reef-building has occurred episodically over geological time, a concept raised by Paull et al. (2000), but not further elaborated. Results of analysis of one black substrate rock revealed unexpected goethite mineralogy, whereas methanogenic carbonates had been anticipated in the area of methane seeps. The atypical rock substrate mineralogy, and the exclusive occurrence of well-developed *Lophelia* reefs on Viosca Knoll suggest a uniquely favorable environmental context for reef development on this feature, relative to other similar slope-depth features further to the west. The absence of coral mounds and of extensive rubble fields indicates a distinct difference in the development of *Lophelia* reefs and associated biotopes in the northern Gulf of Mexico, relative to reefs off the southeastern U.S. East Coast, and in the northeastern Atlantic. Soft substrates found on Viosca Knoll may be characterized as biogenic reef sands, comprised predominantly of eroded calcium carbonate shells, spines, and skeletons. Thus, *Lophelia* reefs do create a unique sedimentary regime very different from that of the surrounding abiogenic fine sediment of the open slope.

INTRODUCTION

Very little is known about the origins, age, or development of slope-depth *Lophelia pertusa* (herein generally referred to as *Lophelia*) coral biotopes in the northern Gulf of Mexico, or the development and diversification of *Lophelia* reef and reef-associated communities. Similarly, very little is known regarding the interrelationship between geology and biology in the formation of *Lophelia* reefs anywhere. Aside from the primary objectives of U.S. Geological Survey (USGS) Viosca Knoll megafaunal community structure investigations (Randall et al. Chapter 1; Sulak et al., Chapters 2 and 3), additional peripheral objectives were added based on opportunities provided by samples obtained incidentally or opportunistically during the investigation, or originally obtained for other purposes. Such samples include living *Lophelia* fronds representing two divergent growth forms, dead *Lophelia* rubble, black substrate rock, gray basal reef rock, and 'reef sand' sediment. Several external collaborators contributed their expertise and laboratory capabilities to address these peripheral objectives (framed as empirical questions) regarding the Viosca Knoll biotopes available to megafaunal invertebrates and demersal fishes. Some of the questions addressed were:

1. What is the age of contemporary, well-developed Viosca Knoll *Lophelia* reefs, and of individual coral colonies?
2. What is the origin and age of the gray basal reef rock containing subfossil *L. pertusa* and bivalve inclusions?
3. What is the fundamental mineral composition of the nearly ubiquitous black Viosca Knoll substrate rock (plates, slabs, boulders)?
4. What stable carbon isotope signatures characterize the inorganic carbonate found in both black substrate rock and gray-white carbonate rock?
5. What is the specific gravity of both types of rock, and of *L. pertusa* fronds and rubble?
6. What differences in calyx density and mass characterize and differentiate the two *Lophelia* growth forms found on northern Gulf of Mexico *Lophelia* reefs?
7. What is the fundamental source of the sparse reef sands found within Viosca Knoll hard-bottom and *Lophelia* reef biotopes? What are the predominant biotic and abiotic sources contributing to these sands?

METHODS

Submersible missions were undertaken by the USGS on Viosca Knoll study sites in 2004 and 2005 (Randall et al., Chapter 1), with primarily objectives focused on fish community structure and characterization of dominant biotopes (Sulak et al., Chapters 2 and 3). During multiple-purpose submersible dives, samples of the deep-water scleractinian coral *L. pertusa*, antipatharians (black corals), rocks, and sediment were obtained opportunistically for investigations of age of coral and substrate, composition of substrate rock, and composition of reef sand substrate covering basal rocks in some areas. Specimens were returned to the laboratory for eclectic analyses, detailed below by numbered topic, as follows:

1. Radiometric carbon dating (age determination via ^{14}C methodology, accomplished at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, California) of two samples of the same living *L. pertusa* coral (specimen G147), and one sample of dead coral (specimen G249) from the interior base of a large coral thicket. The determined ages were expressed in radiocarbon years using the Libby half-life of 5,568 years, following the conventions of Stuiver and Polach (1977). Correction for the modern fraction of ^{13}C was made as per Stuiver and Polach. The living coral was a single linear coral frond, 38 cm total length, with only a few minor side branches (Fig. 8.1). This specimen was obtained from 'Big Blue Reef' (unofficial USGS research team name designated for this well-developed reef) on Viosca Knoll 826 (VK-826), Cruise 2004-03, Dive Station 4751 at 459 m depth[1]. Ages were obtained for samples taken 1.0 cm inward from the proximal (near basal) end (sample G147D), and 1.0 cm in from the distal (growing tip) (sample G147A) of the coral frond. Radiometric aging was accomplished at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, California. Dead coral specimen G249 came from Cruise 2004-03, Dive 4752, 470 m depth. Additional ages were obtained for two specimens of antipatharians. One specimen (orange-red living tissue) tentatively identified as *Leiopathes* sp. (cf. *glabberima*) (specimen AG002, base diameter ca 1.12 cm; Fig. 8.2) was collected from Viosca Knoll 906/862 (VK-906/862) during Dive 4744 at 307 m depth. This specimen was dated via extrapolated radial growth rate, based on radiometric ages and comparative radial growth rates for

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[1] Refer to Randall et al., Chapter 1, Table 1.2, for complete station data for all samples referenced in this chapter.

specimens of the same black coral species dated using ^{210}Pb dating through daughter ^{210}Po measurements, following Druffel et al. (1990) (Williams et al., Chapter 7). A specimen of a second antipatharian species, *Leiopathes* sp. (white living tissue, >2.0 m tall, basal holdfast diameter ca 15 cm; stem diameter above holdfast 3-4 cm) (Fig. 8.3), was obtained from black substrate rock (Fig. 8.4), VK-906/862, 2005-04-4876, 312 m depth. This specimen is pending dating by ^{14}C radiocarbon methodology at the Radioisotope Geochemistry Laboratory, Centre-GEOTOP-UQAM-McGill (RCL-GEOTOP).

2. Radiometric dating of subfossil *L. pertusa* and a vesicomyid? clam embedded in gray carbonate basal reef rock (Figs. 8.5A, C, D). The rock was collected during Cruise 2004-03, Dive 4752, VK-826, Big Blue Reef, 469 m depth. Collection of this aggregate rock is shown in a video clip embedded in the interactive dive track for Dive 4752 (Master Appendix A). Embedded specimens were mechanically chipped out and dated by Uranium/Thorium methodology at the RCL-GEOTOP.
3. X-ray powder diffraction analysis (Cu Kα radiation) of the mineralogy of the ubiquitous black plate-like rock covering much of the Viosca Knoll study sites. One sample taken from a plate of goethite (Figs. 8.4, 8.6) was analyzed at the USGS Florida Integrated Science Center (FISC)-St. Petersburg, Florida.
4. Stable isotope (^{13}C) determinations for inorganic carbonate in both gray reef rock and black substrate rock. Analyses were accomplished at the University of Alabama at Tuscaloosa. Stable oxygen (^{18}O) isotopic analysis was also conducted simultaneously. Reference standard used was Pee Dee Belemnite (VPDB).
5. A - Gravimetric determination of the specific gravity of rock samples including: the gray carbonate aggregate rock from topic 2 above (Fig. 8.5A), another gray-white carbonate aggregate rock from Cruise 2005-04, Dive 4879, VK-826 that was partially buried in soft substrate when collected (Fig. 8.7A), and three examples of the black substrate rock (Figs. 8.4, 8.8, 8.9). B - Gravimetric determination of specific gravity of three samples of two distinct *L. pertusa* growth forms: an open growth form (Fig. 8.10A) frond with limited branching and anastomosing (Fig. 8.11A); versus a compact growth form (Fig. 8.10B), extensively branched and anastomosed frond (Fig. 8.11B), and two composite samples of dead *Lophelia* rubble. Since the compact growth form

of *Lophelia* is relatively rare on Viosca Knoll reefs, coral specimens that had earlier been collected from *Lophelia* reefs off North Carolina were used to facilitate this comparative analysis. These samples were obtained during NOAA Ocean Exploration program cruises in 2001 and 2003. Rubble samples consisted of a composite mix of gray eroded coral pieces obtained opportunistically from the forward collecting basket of the submersible following two dives, and comprised of mixed branches and fragments that had fallen outside numbered collection baskets during sampling for other purposes. All rock, coral and rubble samples were dried for 24 hrs at 60ºC prior to dry mass determinations on a laboratory balance to 1.0 g. Displacement volume was determined to the nearest 1.0 ml in water. Coral samples and porous rock samples were immersed in water for several hours prior to definitive determination of displacement volume, allowing trapped gas bubbles to escape.

6. Comparative coral calyx density counts (calices per unit area) for the open versus compact growth forms of *L. pertusa* were accomplished at USGS FISC Gainesville, Florida. The three specimens chosen for calyx count determinations were fan-like in morphology, facilitating estimation of lateral surface area presented perpendicularly to the prevailing current in life. Counts were performed manually, marking each calyx as it was enumerated to prevent duplicate counts, thus insuring count accuracy. Area was determined to the nearest 1.0 cm^2 via digital image analysis.
7. Preliminary photographic image analysis of Viosca Knoll 'reef sand' substrate was accomplished in the laboratory at USGS-FISC-Gainesville to determine biotic source origins (major contributing taxa) of the soft substrate veneer sporadically present on the study sites.

The objective of all of the above eclectic analyses was to gain preliminary insights into the origins, composition, age, and diversification of northern Gulf of Mexico *Lophelia* reefs and associated hard and soft substrate biotopes, to provide a better understanding of the environmental context in which these contemporary reefs arose, and of the contemporary habitat context populated by *Lophelia* and *Lophelia* reef-associated invertebrates and fishes.

RESULTS

Results are presented below in the same numbered sequence of topics as presented in Methods (above):

1. Carbon-14 dating of specimen G147A, the distal growing tip of a single elongate stem of *L. pertusa* yielded an uncorrected age of 480±35 years (Table 8.1). Since the actual age of the growing tip when collected was zero, the methodological correction was established as -480 years. Thus, for the proximal basal sample from this frond (G174D), the uncorrected age of 540±35 years yielded a corrected actual age of 60±35 years (Table 8.1). Since the sampled length of main stem of this coral frond is 36 cm, the mean annual incremental skeletal growth (linear extension) is 0.60 (range 0.38-1.44) cm yr^{-1}. Conversely, the mean time interval to achieve a skeletal increment of one centimeter is 1.67 (range 1.05-4.00) yr cm^{-1}. Furthermore, since there were 22 coral calices along the entire length of this main stem, on average a new calyx was added (a new polyp budded off asexually from the margin of the preceding polyp) once per 2.7 yr. Carbon-14 dating of specimen G249, the dead coral sample from the inner basal portion of the reef thicket, yielded a corrected radiocarbon age of 305±35 years (Table 8.1). This provides a first-order estimate of the age of a large well-developed *Lophelia* reef thicket, from Big Blue Reef on VK-826. Aging via extrapolated radial growth rate (based on comparative dual-age determined specimens) yielded an estimated age of 390 yrs for *L.* cf. *glabberima* antipatharian specimen AG002 (basal diameter 1.12 cm) from VK-906/862 (Williams et al., Chapter 7). Radiometric ^{14}C dating of the much larger *Leiopathes* sp., (stem diameter above holdfast 3-4 cm diameter) also from VK-906/862 is pending (as of 15 April 2008). The specimen is currently in the queue at RCL-GEOTOP; the radiometric age determined will be reported in a later scientific publication.
2. Uranium/Thorium dating of three subfossil coral and bivalve inclusions in the gray aggregate basal reef rock from Big Blue Reef yielded *L. pertusa* ages of 24,993 and 24,633 yrs (+477, -474 yrs), and a bivalve age of 22,460 yrs (+439, -437 yrs).
3. X-ray powder diffraction of a sample (Dive 4876, rock sample 2) of the typical black (exterior color) plate-like rock (Fig. 8.4) comprising the fundamental hard substrate on Viosca Knoll revealed a mineralogy comprised of goethite (an ironstone), hydrated

ferric oxide/hydroxide, $Fe^{3+}O(OH)$, with low Mg calcite and forms of quartz (analysis courtesy of L. Robbins, USGS-FISC, St. Petersburg, Florida). Both this specimen, and another specimen of goethite collected, are dense and microscopically grained, porous and highly pitted on some surfaces (Figures 8.6A, 8.8A,B), nearly solid on others (Figs. 8.6C, 8.8A). Pores and pits appear to be biogenic due to surficial colonization and deeper boring. Internally, the mineral color is tan to yellow-tan.

4. Stable carbon isotope analysis of both black goethite rock and gray-white reef rock revealed very similar $\delta^{13}C$ values (Table 8.3). Stable carbon signatures for all four samples are more consistent with carbon derived from a water column plankton or particulate source, rather than from a methanogenic source.
5. Specific gravity of rock samples obtained for isotopic and mineralogic analyses are presented in Table 8.3. Gray-white carbonate rocks (both authigenic and aggregate) were less dense (specific gravity 2.12-2.18) than black goethite rocks (specific gravity 2.51-2.63). Specific gravities of living *L. pertusa* fronds are presented in Table 8.4. With the few samples opportunistically obtained for analysis, statistical comparisons are precluded. However, preliminary data from three samples suggest relatively slight difference in comparative skeletal specific gravity of the compact growth form of *L. pertusa* (2.43) compared to the open growth form (2.17-2.20). Eroded *L. pertusa* rubble yielded similar specific gravity data (2.29-2.35).
6. Comparative coral calyx counts and related data for three well-developed coral fronds are presented in Table 8.5. Per unit area (calices per 100 cm^2), the dense growth form sample presented 2.8-3.7 times as many coral polyps to the current in life as the open growth form. However, individual open growth form polyps were probably substantially larger in life than individual compact growth form polyps. Mean skeletal mass per calyx (the cup housing an individual coral polyp) was 3.37-3.46 g per calyx in the open growth form samples, versus 2.86 g per calyx in the compact growth form sample (Table 8.5).
7. Qualitative laboratory imaging of surface sand samples from Viosca Knoll revealed a soft substrate comprised predominantly of eroded calcium carbonate fragments originating from *L. pertusa* and other reef-associated biotic sources. Pelagic sources, pteropod and heteropod tests, were minor contributors. The list of preliminarily

identified major taxa contributing to Viosca Knoll 'coral sands' from submersible-obtained samples is presented in Table 8.6 and illustrated in Figs. 8.12, 8.13.

DISCUSSION

Only a small number of rock, coral and sediment samples were obtained opportunistically during the overall USGS submersible *Lophelia* investigation. Thus, samples obtained for all analyses undertaken herein were insufficient for statistical comparisons. Moreover, geological analyses were not in the original investigation plan. Finally, most laboratory analyses depended upon the contributed expertise and laboratory facilities of interested colleagues, most of whom did not participate in the field missions, and have been only secondarily involved in interpretation of results. Therefore, the empirical results discussed below should be considered very preliminary, statistically untested, and serving primarily to stimulate further inquiry of a more intensive and quantitative nature.

AGE OF CONTEMPORARY VIOSCA KNOLL *LOPHELIA* COLONIES AND REEFS – The radiometric age of 60±35 yrs determined for a 36 cm segment of a single 38 cm branch of open growth form *L. pertusa* provides a scaling reference value of 1.67 yr cm^{-1} for estimating the age of individual large coral colonies of known height on Viosca Knoll. During submersible dives, coral bushes as tall as 2.0 m were observed at Big Blue Reef on VK-826. Using the reference value, a 2.0 m tall bush would be 334 yrs old. This compares with a similar radiometric age of 305±35 yrs determined for dead coral samples from the interior base of a reef thicket on Big Blue Reef. Thus, contemporary *L. pertusa* thickets at ca 450 m depth on VK-826 appear to be no older than 350 yrs. This may be an underestimate of reef age since it was difficult with the submersible mechanical arm to get very far into the interior of the base of the reef thicket. Moreover, linear extension may proceed more slowly for the compact growth form, in which much of colony growth goes into the proliferation of lateral branches, and in which individual calices are smaller. Furthermore, there is stable isotope evidence that the outer portion of a gorgonian colony may grow more slowly (Heikoop et al., 1998), as also indicated by Mortensen (2001) based on the growth of live *Lophelia* maintained in aquaria. Allometric growth with age (i.e., linear extension rate slowing with age) is a situation that might reasonably be hypothesized as well for mature colonies of *Lophelia*. Thus, the present age extrapolation for a mature 2.0 m tall *Lophelia* bush may be an underestimate. Nonetheless, an age of 334 yrs compares closely with an estimated age of 366 yrs for a 1.5 m tall *Lophelia* colony (Breeze et al., 1997 – cited in Risk et al., 2002). Wilson previously offered a similar maximum age in his estimated range of 200-366 yrs for a hypothetical 1.5 m tall colony. The radial-growth estimated age of one specimen (AG002) of the orange-red black coral, *Leiopathes* sp. (cf. *glabberima*) from VK-906/862, with a basal stem diameter of 1.12 cm, is similar at 390 yrs (Williams et al., Chapter 7). Thus, the contemporary sessile megafaunal invertebrate community across both Viosca Knoll study sites appears to be less than 400 yrs old. However, this may be an underestimate pending more robust sampling. Moreover, the age of the overall megafaunal community may substantially exceed this estimate. Radiometric age determination for a very large specimen of the white black coral, *Leiopathes* sp. from VK-906/862, Dive 4876 (Fig. 8.3), currently awaits radiometric aging. However, since the stem diameter above the basal holdfast of this specimen is 3.0-4.0 cm, an age of >1,000 yrs might reasonably be hypothesized. Previously published comparative ages available for the deep-water gorgonian *Primnoa* are 100+ yrs (Andrews et al., 2002) and 300+ yrs (Risk et al., 2002). Andrews et al. (2002) estimated ages of ca 200 yrs for specimens of bamboo coral (*Keratoisis* sp.) and precious coral (*Corallium* sp.) from the Davidson Seamount off California. Druffel et al. (1995) determined an age of 1,800±300 yrs for a large specimen of the gorgonian *Gerardia*, the oldest marine organism yet aged.

Paull et al. (2000) reported rather older comparative ^{14}C radiometric ages for *Lophelia* coral and sediments sampled from mounds on the Florida-Hatteras Slope. Live coral age was estimated as 700±80 yrs, dead coral as 960±80 yrs. Sediment trapped within coral interstices was older, with an estimated age of 13,320±140 yrs. The logical interpretation from Paull et al.'s age data would be that trapped sediment represented remobilized reef sediment from an older reef, trapped in the younger reef matrix. Freiwald et al. (1997) reported an estimated age of 526-2,500 yrs for a contemporary 10-m thick Norwegian *Lophelia* reef mound.

Present results suggest an age of <400 yrs for contemporary Viosca Knoll *Lophelia* reefs, and of 25.0-26.0 ky for the overall *Lophelia* ecosystem in the northern Gulf of Mexico. This indicates that reefs flourished during the low sea-level stand of the Pleistocene Wisconsonian Glaciation. From the young age of contemporary reefs, relative to the much greater age of subfossil *Lophelia*, it may be hypothesized that reef-building has occurred episodically over geological time, a concept raised by Paull et al. (2000), but not further elaborated. Episodes when *Lophelia* flourishes would be punctuated by periods of regional extinction. Mikkelsen et al.

(1982) have presented evidence of such regional extinction of *Lophelia* along the coast of Norway, where radiometrically-aged fossil coral dates from 7.8-8.7 ky before present (BP).

The present estimate of *L. pertusa* skeletal growth (linear extension) of 0.58 cm yr^{-1} is similar to that reported by Wilson (1979) for colonies growing on submarine cables (0.41-0.75 cm yr^{-1}), and in the middle of the range of all available estimates summarized in Mortensen (2001) (0.02-2.25 cm yr^{-1}) and in Roberts (2002) and Hall-Spencer et al. (2002) (0.02-1-2.5 cm yr^{-1}). The present estimated growth rate is 38% lower than Mortensen's (2001) linear extension rate of 0.94 cm yr^{-1} for *L. pertusa* maintained in aquaria, and less than 25% of the growth rate estimated by Mikkelsen et al. (1982) based on oxygen isotope determinations. In general, *L. pertusa* appears to be a relatively fast growing deep-water coral. The species colonizes upcurrent ridge slopes (Messing et al., 1990), gaining a spatial advantage over competing particulate feeders in the interception of current-borne food. *Lophelia* can also capture live zooplankton up to 2 cm in length (Mortensen, 2001), promoting rapid growth. Indeed, the fate of *Lophelia* may be closely linked with accelerated delivery rate of zooplankton in areas of abrupt topography, in the same way that planktivorous fishes are so linked (Genin, 2004). Linear extension rate, growth form, and density per unit area of coral thickets may all depend directly upon the supply of zooplankton in relation to topographic current forcing. In contrast to the rapid growth documented for *Lophelia*, the annual linear extension rate is an order of magnitude lower ($0.05\text{-}0.1 \times 10^{-1}$ cm yr^{-1}) in another deep-living ahermatypic scleractinian, *Desmophyllum cristagalli* Milne-Edwards and Haime, 1848 (Risk et al., 2002). This is a species that attains an age of at least 200 yrs, a lifespan comparable to that of *L. pertusa*. Adkins et al. (2004) also determined a similarly low radiometric growth rate for *D. cristagalli* ($0.05\text{-}0.2 \times 10^{-1}$ cm yr^{-1}), but a higher vertical extension rate (0.5×10^{-1} cm yr^{-1}) for another deep-water scleractinian, *Enallopsammia rostrata*, reported by these same authors to live to an age over 100.

While antipatharians deposit skeletal material in concentric rings (Williams et. al., Chapter 7) that potentially may correspond to annual rings, *L. pertusa* grows by alternate lateral budding, linear elongation, and lateral branching, in a calyx-to-calyx fashion that is not amenable to successive annual ring counts. An individual *L. pertusa* calyx from present samples does appear to show 1-2 high optical density marginal growth rings (Fig. 8.14), as similarly reported earlier (Mortensen and Rapp, 1998) for northeastern Atlantic specimens. However, if such rings are annual, these relate only to the age of the one polyp under observation among thousands comprising a single arborescent *Lophelia* colony. With a growth pattern of sequential alternate marginal budding, with frequent lateral branching, it is impossible to age *Lophelia* via ring counts.

GEOLOGICAL AGE OF THE VIOSCA KNOLL *LOPHELIA* REEF ECOSYSTEM - Radiometric ages determined for subfossil *L. pertusa* branches and a bivalve embedded within the basal carbonate aggregate reef rock from Big Blue Reef ranged between 22.5-25.0±0.5 ky (BP). This provides evidence that *Lophelia* reefs and methane vent communities have been established on Viosca Knoll since at least the late Pleistocene, during the peak of the Wisconsin Glaciation sea-level low stand (Aharon, 1983; Hallam, 1992) (Fig. 8.15). Furthermore, age results may suggest that *Lophelia* reefs existed in the northern Gulf of Mexico when sea level was as much as 125 m lower than at present (Fairbanks, 1989), when oceanographic conditions may have been very different than today. The present northern Gulf of Mexico *Lophelia* reef maximum reef age estimate is closely similar to the age of >26.0 ky BP determined for lithified carbonate crusts capping lithoherm mounds on the Florida-Hatteras Slope (Neumann et al., 1977), and within the range of ^{14}C radiometric ages of 17.8-33.4 ky BP (i.e., origins also in the Pleistocene) determined by Paull et al. (2000) for lithoherms on the Florida-Hatteras Slope. These mounds are inhabited by contemporary ahermatypic reefs comprised of *L. pertusa* and *Enallopsammia profunda* (= *Dendrophyllia profunda*). No contemporary *Lophelia* reefs or live coral have yet been found on the West Florida Slope. However, Newton et al. (1987) have reported ^{14}C radiometric ages for fossil *Lophelia* material from that region, determining ages of 27.7->40.0 ky BP. The latter age is a minimum estimate of earliest geological age for *Lophelia* in the region since 40.0 ky is the limit of age resolution via the ^{14}C method.

When not incorporated into resilient rock, dead *Lophelia* branches on Viosca Knoll appear to degrade and erode rapidly (e.g., the highly eroded reef rock in Figs. 8.7A-C). Since *L. pertusa* rubble is conspicuously rare on Viosca Knoll (Sulak et al., Chapters 2 and 3; Sulak et al. 2007), it may be hypothesized that either a reducing benthic boundary layer environment or bioerosion is responsible. If a reducing environment is the agent responsible for dissolution of calcium carbonate, such an environment may wax and wane episodically in relation to the magnitude of hydrocarbon venting. The goethite encapsuled carbonate-core rock sample from Viosca Knoll (Fig. 8.9) also suggests at least one switchover event between alternate benthic boundary layer conditions.

HARD SUBSTRATE ROCK TYPES ON VIOSCA KNOLL - The limited sampling undertaken in the present study revealed three rock types on Viosca Knoll. The most common type is the black (externally) goethite rock (Figs. 8.4, 8.8) that typically occurs in plates, slabs and boulders. A previous report has described the hard substrate on Viosca Knoll and other northern Gulf of Mexico slope hard-grounds as comprising plates, slabs, blocks, boulders, rubble, and outcrops (Schroeder, 2002), and several reports indicate that such rock consists of authigenic carbonate, formed biogeochemically (MacDonald, 1992; Roberts and Aharon, 1994; Schroeder, 2002; Schroeder et al., 2005), via methanogenic bacteria in areas of hydrocarbon seepage. However, analysis via x-ray powder diffraction (conventional Cu K_{α} methodology) of a sample from one large slab (Fig. 8.4) of the typical dense, black-surface, tan-interior rock (Fig. 8.6B) abundant on Viosca Knoll revealed a fundamental composition not of one of the dominant authigenic carbonates, i.e., magnesium calcite, aragonite, and dolomite found in areas of slope seeps from Mississippi Canyon westward (Ferrell and Aharon, 1994; Roberts and Aharon, 1994), but of the mineral goethite (hydrated ferric hydroxide). Goethite can also be formed by anaerobic bacterial oxidation of methane (L. Robbins, USGS, pers. comm.; Ocean Drilling Program, 2002), but has not been reported among authigenic minerals associated with seeps and vents in the northern Gulf of Mexico by Roberts and Aharon (1994). Nor has goethite been reported from Florida-Hatteras Slope lithoherm crusts composed of aragonite, high Mg calcite, and low Mg calcite (Paull et al., 2000). However, Pequegnat et al. (1972) have reported ironstone deposits at 1,746-3,348 m depth in the Mississippi Fan region of the eastern Gulf of Mexico. The thin section of one sample of ironstone illustrated by Pequegnat et al. (1972; Fig. 8.5) appears strikingly similar in color, texture, and biogenic borings to the freshly exposed interior of the goethite sample from Dive 4876, VK-906/862 (Fig. 8.6B). Relative to bottom waters at the apex of the Mississippi Fan (in close proximity to Viosca Knoll) Pequenat et al. (1972) suggest that there is “sufficient iron available here in the interstitial waters to precipitate iron if sufficient oxygen is available.” They presented data showing high oxygen concentrations (5.00-5.39 ml/L) in bottom waters at all stations where ironstone was sampled. Based on x-ray diffraction analyses, iron is absent from authigenic carbonates typifying hard grounds on the continental slope in the western Gulf of Mexico, Green Canyon to Alaminos Canyon (Ferrell and Aharon, 1994). This corresponds with Betzer and Pilson’s (1971) finding that suspended particulate iron values in the nepheloid layer were much higher in the eastern than the western Gulf of Mexico. Pequenat et al. (1972) suggest ironstone precipation may be favored in the eastern Gulf by loop current generation of favorable bottom currents. They state that "…ironstone is probably formed when ferric iron is hydrolyzed and precipitated in contact with oxygen-rich bottom waters of the deep Gulf." Aharon et al. (1992) have also reported ferric hydroxide precipitation on the Sigsbee Escarpment at 1,920 m depth in the central Gulf of Mexico, but by a different process associated with salt brines.

The specific gravity range of 2.51-2.63 determined for three samples of the common Viosca Knoll black rock type (Table 8.3), identified as goethite based on x-ray diffraction results of one sample, is below the published standard ranges for goethite range (3.3-4.3), as well as for three forms of carbonate: aragonite (2.85-2.94), calcite (2.71), dolomite (2.80-2.99). Both Viosca Knoll rock types are typically highly porous, so specific gravity contrasts remain equivocal. Nonetheless, the black goethite rock samples are substantially denser than the gray-white aggregate reef rock type (2.12-1.18). The unanticipated oxidized iron mineralogy of the predominant Viosca Knoll substrate rock may explain the resilience of this rock in the hypothesized context of a reducing benthic boundary layer environment during periods of active hydrocarbon seepage.

The $\delta^{18}O$ (3.76 to 6.53‰) to $\delta^{13}C$ (-26.88 to -14.62‰) stable isotope values determined for four Viosca Knoll rock samples (analysis courtesy of P. Aharon, University of Alabama at Tuscaloosa; results interpreted by M. Taviani, ISMAR, Bologna, Italy) (Table 8.3), including two subfossil pieces of *Lophelia* (removed from authigenic gray carbonate rock matrix; Fig. 8.5C), lie far outside the respective values ($\delta^{18}O$: -3 to +3‰; $\delta^{13}C$: -10 to +2‰) and the well-defined linear relationship between $\delta^{18}O$ and $\delta^{13}C$ graphically displayed for *Lophelia* samples from the northeastern Atlantic (Blamart et al., 2005). But, Viosca Knoll $\delta^{18}O$ values do correspond with the upper end of the range of +1.5 to +5.5‰ reported by Mikklesen et al. (1982), suggesting ambient paleo-water temperatures somewhat different (i.e., colder) than contemporary water temperatures at the depth of living *Lophelia* in the Gulf of Mexico. Much less enriched $\delta^{13}C$ values (e.g., -40‰ to -55‰) would have been expected (Roberts and Aharon, 1994) for methanogenic carbonates formed via anaerobic bacterial oxidation of methane (GEOMAR, 1999), although the presently obtained $\delta^{13}C$ signatures fell within the range of values reported for authigenic carbonates from the northern Gulf of Mexico (-18.5‰ to -54‰) (Aharon and Roberts, 1990; Roberts and Aharon, 1994). The comparatively enriched $\delta^{13}C$ signatures for carbon in the analyzed subfossil *Lophelia* pieces seem more consistent with a water column carbon source (i.e., signatures are within the range of those typical of particulate organic matter and phytoplankton) than a methanogenic source. This indication is consistent with the findings of Griffin and Druffel (1989), which establish that *Lophelia* obtains the carbon in its calcareous skeleton "solely from dissolved inorganic carbon (DIC) in sea water from the depth at which the corals grew". The significance of stable isotope results remains to be evaluated in future based on more systematic and intensive sampling of all three rock types found in the present study.

The second rock type collected is a gray-white calcium carbonate aggregate (Figs. 8.5A, 8.7A). The fundamental framework for this type of rock is dead *L. pertusa* coral clumps, branches and fragments. That framework becomes in-filled with calcium carbonate shell, spine, and skeleton fragments from diverse reef invertebrates, coarse highly-degraded (bioerosion, and/or mechanical erosion) reef-derived sediment, and finer sediments probably of benthic and pelagic origins (Mullins et al., 1981). Some larger settled pelagic particles, including pteropod and heteropod tests, are also incorporated. The carbonate aggregate rock sample collected from Dive 4879 on VK-826 showed evidence of extensive erosion (appearance consistent with chemical erosion), both in exposed and buried portions of the rock (Fig. 8.7A). The aggregate rock from Dive 4752 on VK-826 (containing the dated coral and bivalve inclusions) was also highly porous (Fig. 8.5A). For several days after its collection at sea, the rock smelled strongly of hydrogen sulfide, apparently from outgassing at 1.0 atmosphere pressure, following retrieval from depth (ca 45 atmospheres pressure). This aggregate rock had a specific gravity of 2.18, more consistent with a composition of calcium carbonate, rather than the denser goethite. Allowing for inclusion of low-density organic matter, and for high porosity due to biotic boring and weathering, the specific gravities of all field samples of live and dead coral skeletal material were also reasonably close to the known specific gravity of pure aragonite (2.85-2.94).

The third Viosca Knoll rock type collected (Fig. 8.9) appears to be a combination of the first two types. A freshly-exposed section (Fig. 8.9B) reveals a gray-white grainy core consistent in appearance with calcium carbonate. However, the external rock surface is black, and the inner core is coated with irregularly layered brown goethite (Fig. 8.9C). The sample figured suggests a temporal alternation of carbonate deposition and goethite precipitation.

SOFT SUBSTRATE ON VIOSCA KNOLL - Schroeder (2002) characterized VK-826 sediments as consisting of unconsolidated clay, silty clay, disarticulated shells, and shell hash. In the present study, very localized fields of eroded disarticulated vesicomyid shells were observed (Sulak et al., Chapter 3; Master Appendix D, Plate 28A). But, more typically, the soft substrate found in samples obtained via the submersible suction sampler can be characterized as coarse reef sand, containing abundant large fragments of *Lophelia* branches, segments of black and bamboo coral branches, urchin spines, broken mollusk shells, polychaete tubes, and sponge crusts (Table 8.6; Figs. 8.12, 8.13). On Faroe shelf *Lophelia* reefs, Jensen and Frederiksen (1992) listed invertebrate sources of calcium carbonate deposition as including *Lophelia*, bryozoans, mollusks, and sedentary polychaetes. While these larger particles are consistent with Schroeder's (2002) shell hash description, and with Teichert's (1958) list of taxa contributing to calcareous fragments to coral bank substrates, the coarse sand fraction predominates (but see final sentence, this paragraph). Particle size distribution or the mineralogy of substrate particles was not quantitatively analyzed in the present investigation. However, under a binocular microscope, even the small highly degraded particles appeared to consist almost entirely of gray-white calcium carbonate pieces derived from the coral branches, shells, spines, and skeletons of reef-dwelling invertebrates, a composition very similar to that reported by Paull et al. (2000) for *Lophelia* reef soft substrate on the Florida-Hatteras Slope. Eroded black particles of goethite (Fig. 8.12), and the tests of pelagic pteropods and heteropods (neither abundant in the samples) (Figs. 8.12, 8.13) also contribute to the coarse reef sands/reef hash mix. It should be noted that samples obtained with the submersible suction device and associated sieve top collection buckets are biased against smaller sediment particles, which tend to be washed out of any sample obtained.

Mullins et al. (1981) speculated that sediments associated with deep-water mounds (formed over time as a framework of *Lophelia* coral debris traps sediment particles) would be dominated by planktonic material of pelagic origin. This may prove true for mounds on the Florida-Hatteras Slope and Blake Plateau, based on qualitative observations of submersible sediment samples (K.J.S., personal microscopic observations of samples obtained during 2001-2004 NOAA Ocean Exploration cruises), in which pteropods and heteropods are very abundant. However, pteropods, heteropods, and other pelagic components appear to be minor components of Viosca Knoll reef sands, where carbonate fragments derived from *Lophelia* coral and a wide variety of benthic shelled animals predominate (Figs. 8.12 and 8.13)

LOPHELIA GROWTH FORMS – Observations during submersible dives indicate that *L. pertusa* exhibits two rather distinct growth forms in the Gulf of Mexico. The open growth form appeared much more prevalent on Viosca Knoll during USGS 2004-2005 submersible dives. The open growth form, consisting of elongate, minimally-branched, minimally-anastomosing fronds, displays fundamentally different calyx counts and mean mass per calyx (Table 8.5). The compact growth form appears more prevalent for *Lophelia* reefs off the U.S. East Coast (K.J.S., unpublished observations, NOAA Ocean Exploration Missions, 2001-2004), and seems typical as well of *Lophelia* in the northeastern Atlantic (e.g., Wilson, 1979, Fig. 2 and Plate 2; Jensen and Frederiksen, 1992, Figs. 1-2; and Rogers, 1999, Fig. 12). With reference to Late Pleistocene fossil *Lophelia* specimens, Taviani et al. (2005) have termed the thick-stemmed compact growth form the 'glacial morphotype'. In the northeastern Atlantic, Wilson (1979) noted the presence of both compact and extended growth forms within the same *Lophelia* colony. He explained this as indicating different rates of budding in relation to maximizing exploitation of available food. However, Wilson observed that the extended (open) growth form was typical of the lower and inward facing branches of a colony. This observation is opposite of colonies observed and imaged during the present study in the northern Gulf of Mexico, where extended linear branches are most characteristic of the outermost and uppermost coral fronds. It is hypothesized here that on Viosca Knoll, the compact growth form develops either: 1) as a function of colony age, as new polyps bud off laterally from open growth form linear branches, gradually filling in the open spaces and becoming compact; 2) as a function of the local environment in which a colony develops over the course of its life. The difference in calyx count between the two growth forms (Table 8.5) tends to support alternative 1. The present observation that most Viosca Knoll *Lophelia* colonies, in which the open growth form predominates, consist almost entirely of live white coral, also supports the hypothesis that an open growth from characterizes young, rapidly-growing colonies. In young colonies, extending vertically as rapidly as possible (i.e., by limiting lateral branching and proliferating larger calices) may provide a competitive advantage relative to other sessile planktivores. Alternatively, the difference in comparative calyx mass (Table 8.5) seems to support a fundamental morphological dichotomy that persists throughout the lives of comparative *Lophelia* colonies. Observations of linear growth extension in aquarium maintained *Lophelia* (Mortensen, 2001) also tend to support hypothesis 2. Mortensen reported that starved corals had a low linear extension rate. Thus, the shorter, less massive calices of the compact growth form may indicate slow growth in a less favorable feeding regime. In a local environment where current velocity is relatively low (i.e., low rate of delivery of planktonic prey), or where plankton density is reduced, the compact growth form may confer a competitive advantage by maximizing the total surface area of feeding polyps (i.e., via extensive arborescent branching, and the proliferation of smaller, but more numerous calices).

SYNOPSIS

The limited number of rock sampled from the two Viosca Knoll study sites yielded three distinct rock types. In addition to the ubiquitous dense black goethite, authigenic carbonate is present, along with biogenic calcium carbonate aggregate reef rock. A combination goethite coated carbonate-core rock also occurs. While calcium carbonate reef rock has apparently formed both by authigenic processes and aggregation/cementation within reef matrix, the extensively degraded samples (e.g., Figs. 8.7A-C) suggest that carbonate reef rock is eroding rapidly, perhaps during episodes of more active hydrocarbon seeping, when pore water hydrogen sulfide may promote acidic dissolution. The predominant blackish goethite substrate rock departs in fundamental mineralogy from the better-studied methanogenic iron-poor carbonate substrates found at seep sites from Mississippi Canyon westward to Alaminos Canyon (Ferrell and Aharon, 1994; Roberts and Aharon, 1994). Stable carbon isotope signatures of Viosca Knoll carbonate basal reef rock also differ from expectations from the literature.

Viosca Knoll *Lophelia* reefs, apparently the only well-developed *Lophelia* reefs known in the Gulf of Mexico (but see Reed et al., 2006 regarding the recent discovery of live *Lophelia* on the West Florida slope), also depart from expectations compared to reefs along the U.S. East Coast and in the northeastern Atlantic. Based on radiometric ages from very limited sampling, contemporary Viosca Knoll reefs may be younger than 400 yrs (or, if somewhat older, still young relative to former Viosca Knoll *Lophelia* reef stands dating to at least 24+ ky BP). Relative to the radiometric age determined for two subfossil *Lophelia* inclusions within basal reef rock, it may be hypothesized that the living reef represents the most recent round of *Lophelia* reef-building in the northern Gulf of Mexico. Living reefs along the U.S. East Coast, North Carolina to Florida, and in the northeastern Atlantic, are typically larger, better-developed, geographically more extensive and continuous, and probably older (Paull et al., 2000). They consist largely of dead or senescent brown-gray *Lophelia*, capped by white living coral (Reed, 2002; Costello et al., 2005) – predominantly of the compact growth form (K.J.S., unpubl. 2001-2004 submersible observations, NOAA Ocean Exploration missions).

Reef-building appears to have been a more continuous process along this coast than in the northern Gulf of Mexico. East Coast reef mounds, also referred to as bioherms or lithoherms, range up to tens or hundreds of meters high, and over a kilometer in linear dimension (Teichert, 1958; Stetson et al., 1962; Reed, 2002). These East Coast *Lophelia* mounds consist entirely of biogenic reef debris and trapped sediment that has accumulated over time (Teichert, 1958). Low-frequency echo-sounding surveys demonstrate that the mounds rest unconformably upon the gently-sloping continental slope (Fig. 8.16), creating their own biogenic topography. Moreover, East Coast reefs, and similarly reefs in the northeastern Atlantic, shed extensive fields of reef rubble (Messing et al., 1990) that may extend up to several hundred meters away from the reef proper, coating the surrounding soft substrate with a persistent layer of rubble up to a meter thick (K.J.S., unpubl. 2001-2004 submersible observations, NOAA Ocean Exploration missions). Such rubble fields constitute a distinct and important biotope for an associated fauna of fishes and invertebrates (Teicher, 1958; Wilson, 1979; Jensen and Frederiksen, 1992; Mortensen et al., 1995).

In marked contrast, *Lophelia* reefs in the northern Gulf of Mexico are apparently well-developed only on Viosca Knoll (but see Reed et al., 2006), despite the scattered geographic occurrence of sparsely-developed *Lophelia* outposts farther west (e.g, Bush Hill, Green Canyon; W. Schroeder, Dauphin Island Marine Laboratory, pers. comm.). Also, in striking contrast, the Viosca Knoll reefs do not consist of biogenic mounds, but of a thin veneer of contemporary, largely white living *Lophelia*, predominantly of the open growth form, perched atop elevated geological features (diapirs and ridges) (Figs. 8.17A, B). Finally, these reefs have not developed notable rubble fields around them. Indeed, reef rubble is curiously scarce (Sulak et al., Chapters 2 and 3), and essentially unavailable as a distinct megafaunal and macrofaunal biotope.

The absence of large biogenic *Lophelia* mounds, and of extensive rubble fields over a span of at least 24+ ky is surprising, suggesting that the interaction of biological and geological processes on Viosca Knoll *Lophelia* reefs is fundamentally different than on East Coast *Lophelia* reefs. Furthermore, in the northern Gulf of Mexico, the unique occurrence of well-developed *Lophelia* reefs only on the Viosca Knoll diapir again suggests a fundamentally different context for reef development here than off the U.S. East Coast where a large series of reefs populates the slope from North Carolina to Key West (Reed et al., 2004, Reed et al., 2006).

RECOMMENDATIONS

With respect to the seven questions posed at the outset of this preliminary analysis of Viosca Knoll *Lophelia* reef and substrate, these recommendations can be advanced for continuing research into the geology of Viosca Knoll and the origins and age of its reef ecosystem:

1. What is the age of contemporary, well-developed Viosca Knoll *Lophelia* reefs, and of individual coral colonies? Additional radiometric aging of *Lophelia* should be undertaken of both living *Lophelia* (particularly long branches with the growing tip intact), of both types of carbonate rock (with particular focus on aging subfossil *Lophelia* coral inclusions), of goethite substrate rock, and of antipatharians and gorgonians.
2. What is the origin and age of the gray basal reef rock containing subfossil *L. pertusa* and bivalve inclusions? Additional sampling of basal reef rock should be undertaken to more robustly define the fundamental geological age of the Viosca Knoll *Lophelia* ecosystem. It is important to determine if the presently-determined age of 24+ ky BP truly represents the approximate origin of *Lophelia* in the northern Gulf of Mexico, or if this coral has been present over a much longer span of geological time.
3. What is the fundamental mineral composition of the nearly ubiquitous black Viosca Knoll substrate rock (plates, slabs, boulders)? More samples should be obtained of the blackish basal substrate rock to enable a more robust x-ray diffraction determination of mineralogy and the relative importance of goethite on Viosca Knoll. X-ray diffraction analyses of the two carbonate rock types would also be valuable in a comparative context. Based on literature from the western Gulf, a fundamental question will be whether Viosca Knoll carbonates are also relatively iron-free, suggesting an alternation of water chemistry during periods of carbonate (vs goethite) deposition.
4. What stable carbon isotope signatures characterize the inorganic carbonate found in both black substrate rock and gray-white carbonate rock? Preliminary indications from a few samples of carbonate rock cannot readily be interpreted within the context of known carbon and oxygen stable isotope values from comparative Atlantic *Lophelia* sites. More comprehensive rock sampling and isotopic analysis is recommended.
5. What is the specific gravity of both types of rock, and of *L. pertusa* fronds and rubble? Preliminary findings of a specific gravity difference between the open versus compact

growth forms of *Lophelia* suggest alternative hypotheses of either a genetic or an ecophenotypic difference between these two forms. These alternative hypotheses are worthy of further investigation. Rocks and rubble proved to be so highly bioeroded and porous that specific gravity results here are not very informative.

6. What differences in calyx density and mass characterize and differentiate the two *Lophelia* growth forms found on northern Gulf of Mexico *Lophelia* reefs? Both calyx density per unit area and mass per calyx appear to differ dramatically between the two growth forms. More sampling and analysis should be undertaken to determine if preliminary findings will be statistically verifiable. Calyx density per unit area, in particular, may prove very important ecologically, perhaps reflecting long-term mean differences in bottom water current velocity and/or local food supply.
7. What is the fundamental source of the sparse reef sands found within Viosca Knoll hard-bottom and *Lophelia* reef biotopes? What are the predominant biotic and abiotic sources contributing to these sands? All samples taken both on and off reef in the present study were dominated by coarse carbonate sands composed of broken and eroded fragments of animals with calcareous sketetons or tests. However, sampling was limited and biased toward areas with *Lophelia*. Additional and more evenly and widely distributed sediment sampling is recommended to assess the importance of reef-derived carbonate debris in forming unique areas of reef-derived substrate on the slope of the northern Gulf of Mexico. The peculiar and striking general absence of coral rubble in the form of large branches and fragments also deserves further investigation. The apparent rapid erosion of coral branches suggests a peculiar benthic boundary layer chemical environment. Study of bottom water and sediment pore water chemistry may prove instructive in this regard.

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DISCLAIMER

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Table 8.1. Data for contemporary *L. pertusa* specimens from Big Blue Reef, VK-826 (Dive 4751), aged via ^{14}C methodology.

Sample Name	**Dive # Depth (m)**	**δ^{13}C ‰**	**δ^{13}C Fraction Modern**	**± CI**	**D^{14}C**	**±**	**Uncorrected ^{14}C age yrs**	**± CI yrs**	**Corrected ^{14}C age yrs**
G249	4752 470 m	-2	0.9067	0.0034	-93.3	3.4	785	35	305
G147A	4751 459 m	-2	0.9417	0.0038	-58.3	3.8	480	35	0
G147D	4751 459 m	-2	0.9349	0.0036	-65.1	3.6	540	35	60

Table 8.2. Data for subfossil *L. pertusa* and a vescicomydid? bivalve embedded within aggregate carbonate reef rock from Big Blue Reef, VK-826 (Dive 4752), aged via ^{14}C methodology.

Datum: Sample	**^{230}Th/^{234}U**	**± ^{230}Th/^{234}U**	**^{234}U/^{238}U**	**± ^{234}U/^{238}U**	**Age (ky)**	**+ CI**	**- CI**
L. pertusa #1	0.206303	0.003445	1.1604	0.0119	24.993	0.477	0.474
L. pertusa #2	0.203701	0.002709	1.1711	0.0114	24.633	0.374	0.373
Bivalve #1	0.187398	0.003257	1.1603	0.0114	22.460	0.439	0.437
Const. ^{230}Th	0.009195						
Const. ^{234}U	0.002835						

Table 8.3. Stable isotope and specific gravity determinations for samples of black goethite substrate rock, and gray-white carbonate aggregate reef rock from Viosca Knoll sites.

Rock Type	**Sample Site (JSL Dive) & Depth (m)**	**Rock Sample #**	**$\delta^{13}C$ (‰ VPDB)**	**$\delta^{18}O$ (‰ VPDB)**	**Specific Gravity**	**Figure**
Black Goethite Plate	JSL 4876 312 m	2	-23.08	3.76	2.63	8.4
Carbonate Reef Aggregate Rock	JSL 4879 454 m	1	-26.88	4.37	2.12	8.7
Black Goethite Block	JSL 4875	1	-21.95	5.69	2.51	8.8
Goethite Coated Carbonate Rock	JSL	1	-14.62	6.53	2.55	8.9
Authigenic Carbonate/Shell Aggregate Rock	JSL 4752 469 m	1	NA	NA	2.18	8.5
Aragonite Standard	CRC Handbook Datum	NA	NA	NA	2.85-2.94	NA
Calcite Standard	CRC Handbook Datum	NA	NA	NA	2.71	NA
Dolomite Standard	CRC Handbook Datum	NA	NA	NA	2.80-2.99	NA
Goethite Standard	Website Sources*#	NA	NA	NA	4.27-4.29[*] (3.3-4.3)[#]	NA

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[*] http://www.mindat.org/min-1719.html.

[#] http://www.galaries.com/minerals/oxides/goethite/goethite.htm and http://webmineral.com/dta/Goethite.shtml.

Table 8.4. Specific gravity data for live collected *L. pertusa* fronds, compact and open growth forms, and dead *Lophelia* rubble. The *L. pertusa* fronds are the same as used for comparative calyx density per unit area determinations (Table 8.5).

Sample or Standard	**Specimen Number**	**Cruise & Station**	**Growth Form**	**Specific Gravity**	**Figure**
Lophelia 1	NA	NOAA-OE-2001-4366	Compact	2.43	8.11A
Lophelia 2	NA	NOAA-OE-2003-4703	Open	2.20	8.11B
Lophelia 3	G147	USGS-GM-2004-03-4751	Open	2.17	
Rubble 1	NA	NA		2.35	
Rubble 1	NA	NA		2.29	
Pure Aragonite	NA	CRC Handbook Datum		2.65	
Lophelia		Faroe Shelf*	not given	Mean = 2.07	

* comparative data reported by Jensen and Frederiksen (1992): mean density (g cm^{-3}) based on mass and displacement volume reported for 11 samples of *Lophelia* (live when collected).

Table 8.5. Comparative calyx density data for three specimens of *L. pertusa*, representing both the compact and open growth forms (same specimens as in Table 8.4).

Sample or Standard	**Specimen Number**	**Growth Form**	**Calyx Count**	**Calices per Unit Area (100 cm^2)**	**Mean Mass per Calyx (g)**
Lophelia 1	NA	Compact	593	126	2.86
Lophelia 2	NA	Open	254	34	3.46
Lophelia 3	G147	Open	29	45	3.37

Table 8.6. Recognizable taxa contributing to *Lophelia* reef 'coral sand' soft substrate on Viosca Knoll study sites (taxa identified from all submersible-collected soft substrate samples).

Major Taxon	**Description**	**Figures**
Cnidaria		
Lophelia pertusa	Broken, eroded and degraded branches, rubble, fragments	8.12, 8.13A
Keratoisis flexibilis (bamboo coral)	Stolon and branch segments	8.13C
Leiopathes spp. (black coral)	Broken stem segments	8.13D
Bryozoans	Broken pieces of honeycomb lattices and candelabra-like branching forms	NA
Mollusca		
Bivalves (several taxa)	Whole and broken shells, fragments	8.12
Pteropoda	Chevron and horseshoe shaped tests	8.12, 8.13D
Heteropoda?	Tubular tests	8.13B
Gastropoda (several taxa)	Whole and broken shells, fragments (top shells, turret shells, keyhole limpet shells)	8.12, 8.13A
Echinodermata (regular urchins)	*Cidaris rugosa* spines: *Diadema*? spines	8.12, 8.13B
Polychaeta	Serpulid worm tubes	8.12, 8.13C
Spongia	Crusts on *Lophelia* debris	8.12

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surface (with eroded serpulid tube); C - Freshly exposed section where sample was taken.

Figure 8.9. Goethite coated carbonate-interior rock from Viosca Knoll collected by JSL (image DSCN 5349): A - Whole specimen as collected; B – Freshly exposed section where sample was taken; C - Enlargement to illustrate distinct separation between carbonate core and irregularly-layered goethite crust (arrow).

Figure 8.10A. Open growth form of *L. pertusa*, characterized by elongate branches with limited lateral branching and inter-branch anastomosing, a by loose, open matrix.

Figure 8.10B. Compact growth form of *L. pertusa*, characterized by extensive lateral branching and inter-branch anastomosing, and by dense matrix.

Figure 8.11A. A frond of the open, loosely branching growth form of *L. pertusa* used for gravimetric and coral calyx per unit area determinations.

Figure 8.11B. A frond of the compact, densely branches growth form of *L. pertusa* used for gravimetric and coral calyx per unit area determinations.

Figure 8.12. Viosca Knoll sand sample from Dive 2004-4747 (image DSCN 5212). Identifiable reef-derived biotic components: A – *L. pertusa* coral, B – *Cidaris rugosa* pencil urchin spines, C – encrusting sponge, D- eroded bivalve fragment, E – broken gastropod shells, F- serpulid worm. Water-column derived biotic component: G – pteropod test. Abiotic component: H – fragment of black goethite rock.

Figure 8.13. Biotic components of Viosca Knoll sand sample from Dive 2004-4747 (images B1-10, 8, 5, 11): A -Keyhole limpet; B -Heteropod test; C -Serpulid annelid worm tube; D —*eratoisis flexibilis* bamboo coral, pteropod test.

Figure 8.14. Micrograph of a thin section through an individual *L. pertusa* calyx, appearing to show 1-2 marginal growth rings.

Figure 8.15. Sea level (m) stands versus geological time (kyr before present) to provide a temporal frame of reference for the potential age of Gulf of Mexico *Lophelia* reefs (adapted and modified from Aharon, 1983).

Figure 8.16. Subbottom (1.2-4.8 kc) echo-sounder profile of Blake Plateau *Lophelia* biogenic reef mounds (> 40 m thick) lying unconformably on the essentially horizontal

sedimentary plane of the plateau – the strong linear acoustic reflector (adapted after Stetson et al. 1962).

Figure 8.17A. Single-beam echo-sounder profile through a portion of Big Blue Reef on Viosca Knoll-826, displaying the underlying geology of ridges and valleys, and a well-developed *Lophelia* reef, appearing as a thin veneer, returning a weak acoustic signal from an echo-sounder tuned to subbottom profiling.

Figure 8.17B. Single-beam false-color acoustic profile of Big Blue Reef, a well-developed, high-profile living *Lophelia* reef sitting unconformably atop a geological ridge on a portion of the VK-826 study site, 450 m, from an echo-sounder tuned as a fish-finder.

Figure 8.18. Two small, mound-like features in the northeastern Gulf of Mexico, off Florida and lying east of Viosca Knoll, unexplored potential *Lophelia* reef sites, identified from a NOAA composite bathymetric map provided by the Naval Research Laboratory, modified by USGS (courtesy of Bill Teague).

Figure 8.1. A single, largely-unbranched, 38 mm-long frond of the open growth form of *Lophelia pertusa*, sampled from Viosca Knoll, USGS-2004-05, Dive 4751. Subsamples were taken 1.0 cm in from either end for ^{14}C radiometric age determination.

Figure 8.2. *Leiopathes glabberima*? (orange-red living tissue) black coral from Cruise 2005-04, Dive 4876 (image JSL1_4876_066). A similar specimen collected during Cruise 2004-03, Dive 4744, VK-906/862, 307 m, was utilized for radial growth aging.

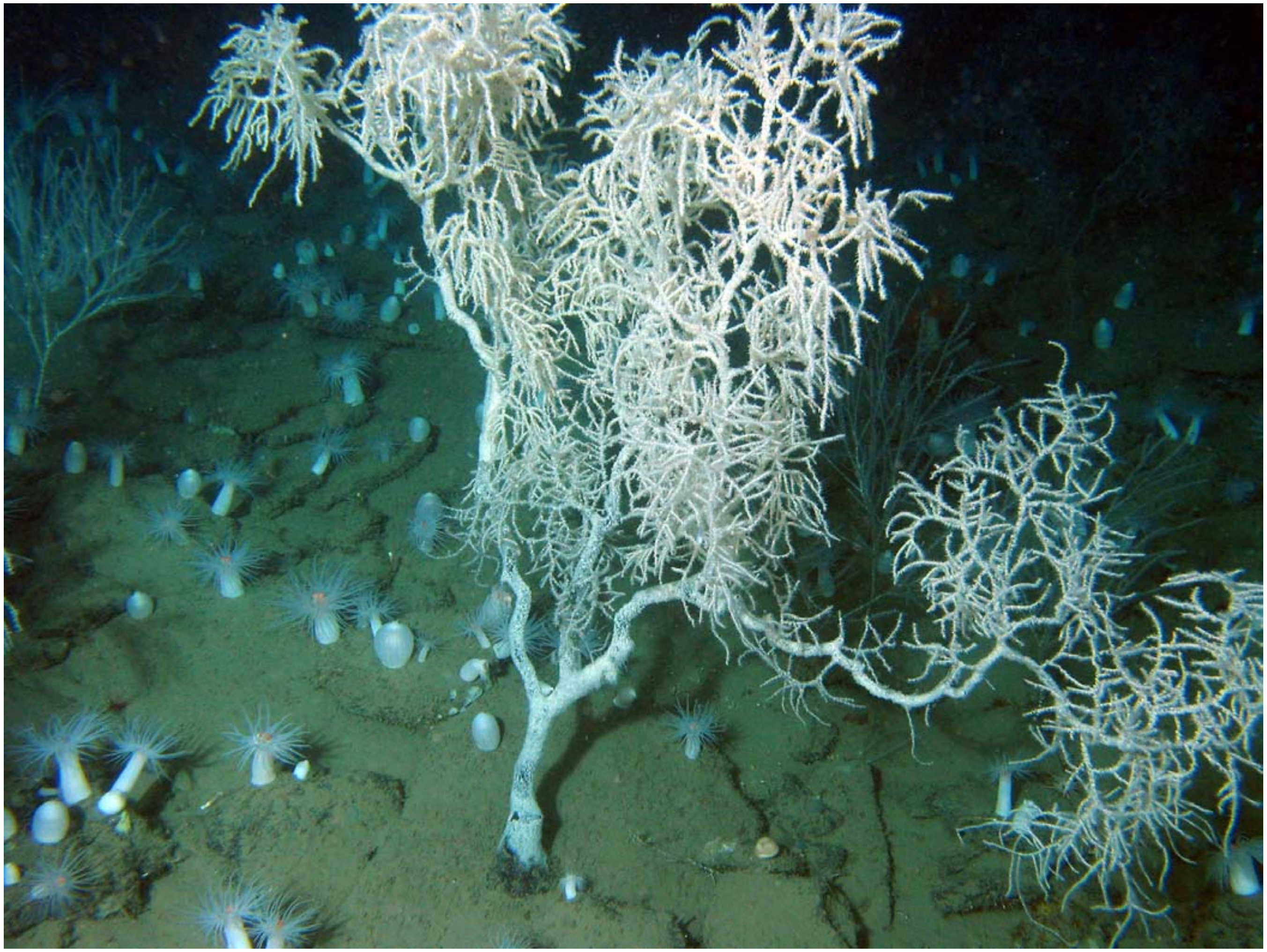


Figure 8.3. *Leiopathes* sp. (white living tissue) black coral attached to a plate of black goethite substrate rock, collected together during Cruise 2005-04, Dive 4876, VK-906/862 (image JSL1_4876_079). Both were utilized for radiometric aging.

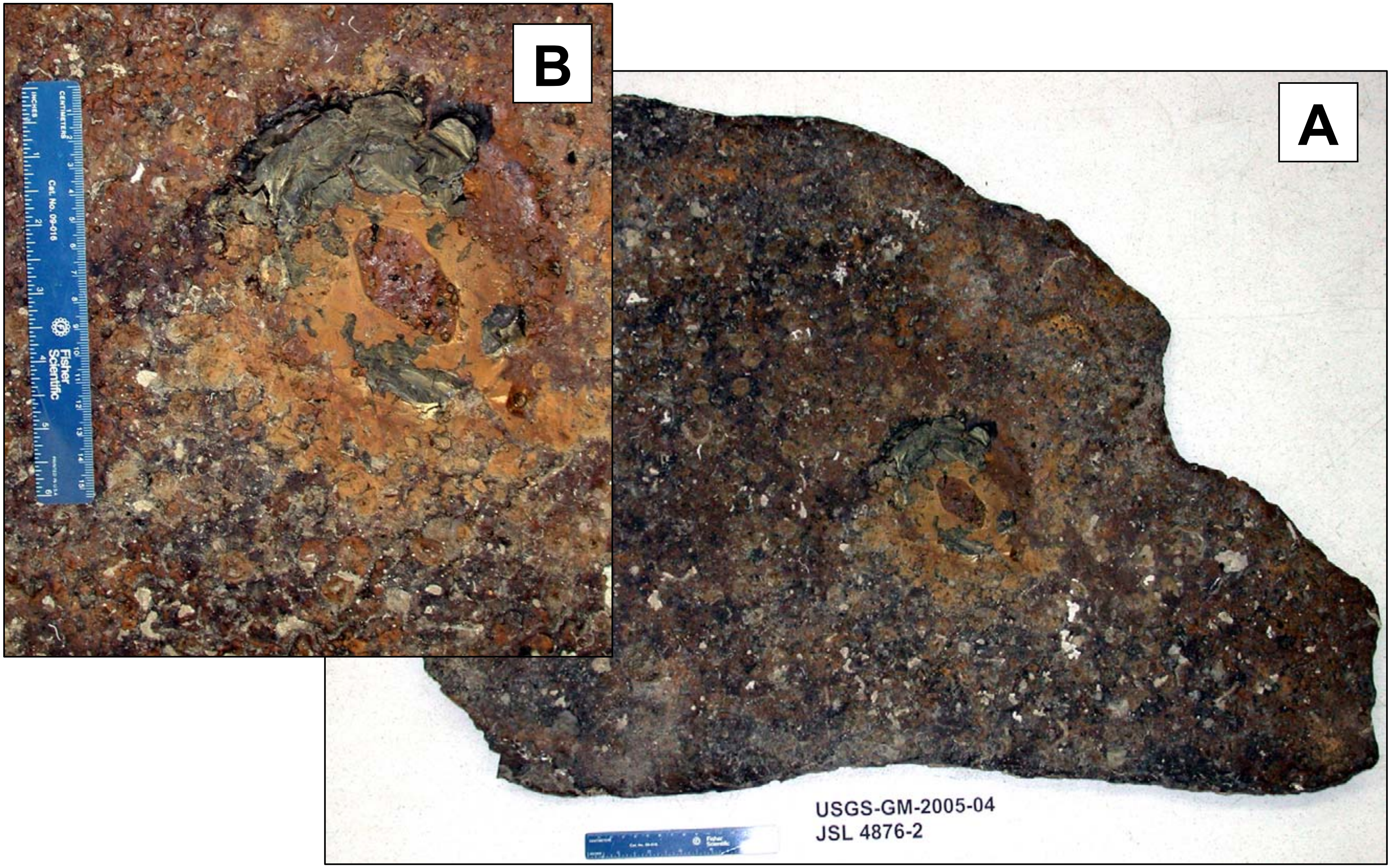


Figure 8.4. A - Specimen of plate-like black goethite substrate rock upon which a 2-m tall *Leiopathes* sp. black coral was attached; B - Close-up of attachment scar (ca 15 cm diameter) left when the black coral was removed with a saw. A sample of the rock was used for gravimetric and ^{13}C stable isotope determinations. Specimen was obtained during Cruise 2005-04, Dive 4876, VK-906/862.

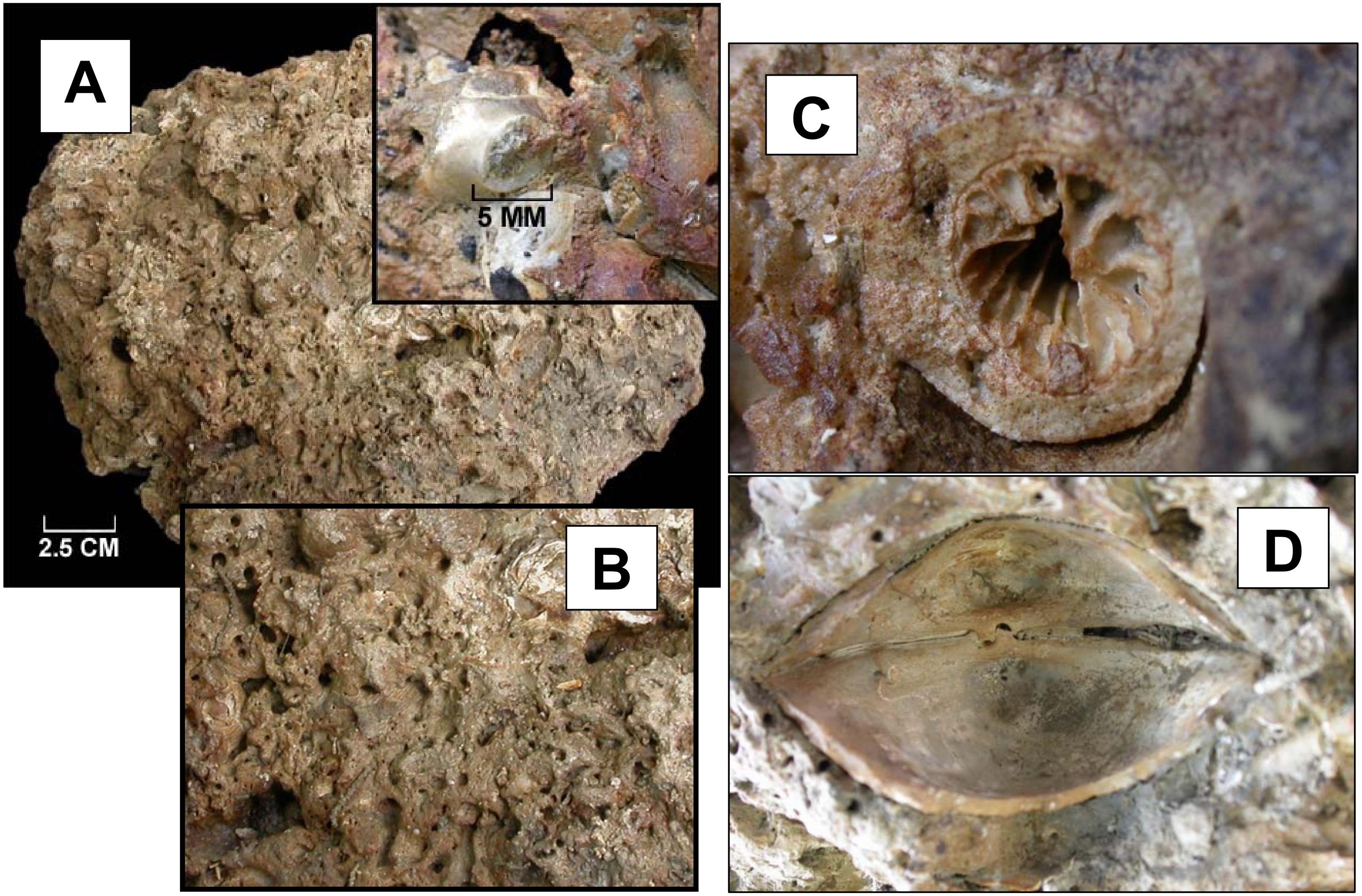


Figure 8.5. Authigenic carbonate/biogenic aggregate basal reef rock, Cruise 2004-03, Dive 4752, VK-826, with subfossil biotic inclusions: A – Whole rock, inset illustrating broken bases of living *L. pertusa* coral using rock as substrate; B – Close-up to show methanogenic pores; C - subfossil *L. pertusa* embedded in rock matrix; D – subfossil bivalve (vent clam?) embedded in rock matrix. Inclusions C and D were mechanically removed and ^{14}C dated.

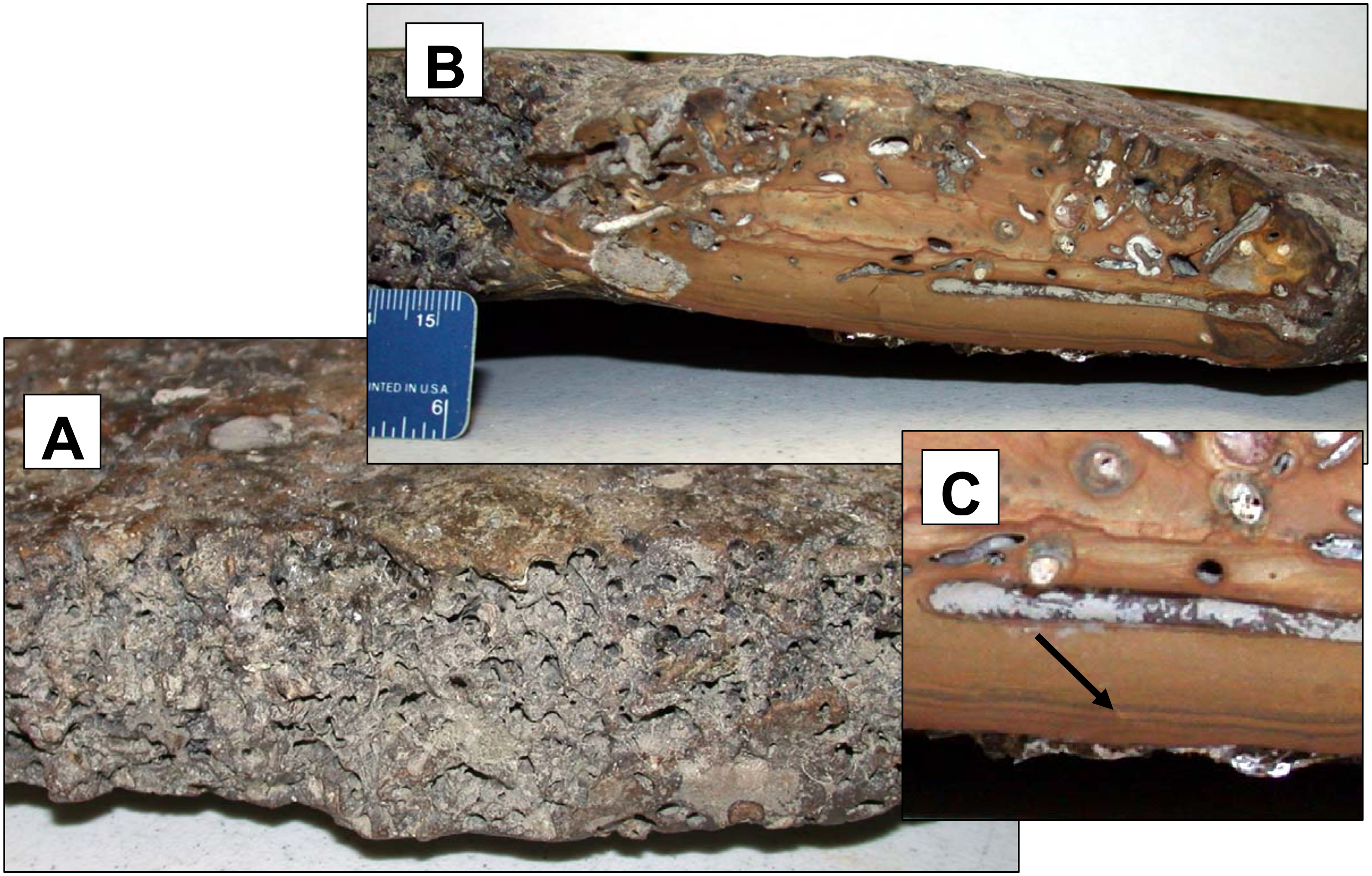
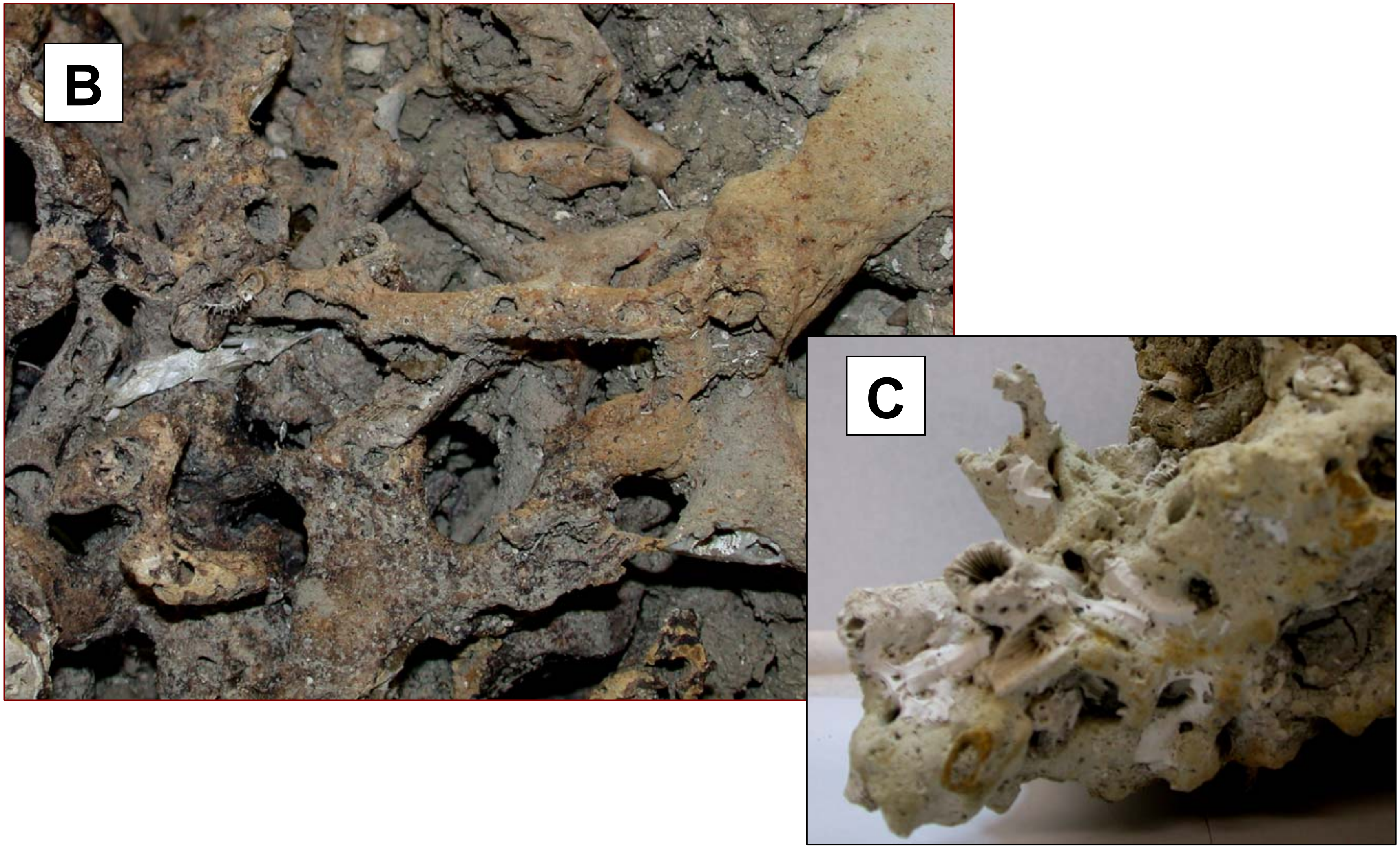


Figure 8.6. Specimen of plate-like black goethite substrate rock from Cruise 2005-04, Dive 4876, VK-906/862 (same as in Figure 8.3): A – Pitted and eroded edge of plate; B – Freshly exposed section through plate where sample was taken for gravimetric and x-ray diffraction analyses; C – Enlargement to denote sub-mm laminated/layered pattern of mineral deposition (arrow).

Figure 8.7A. Calcium carbonate aggregate reef rock from Cruise 2005-04, Dive 4879, comprised predominantly of highly eroded *L. pertusa* coral, with carbonate from other biotic sources included, and semiconsolidated sediment trapped within interstices. Specimen was used for gravimetric and ^{13}C stable isotope determinations. Dark portion was exposed above substrate, light portion buried.



Figures 8.7B & C. Close-ups of calcium carbonate aggregate reef rock from Cruise 2005-04, Dive 4879: B – Heavily eroded and cemented *L. pertusa* reef matrix (branches and calices) in the above-substrate portion of the rock; C – Eroded coral calices at the distal below-substrate end of the rock.

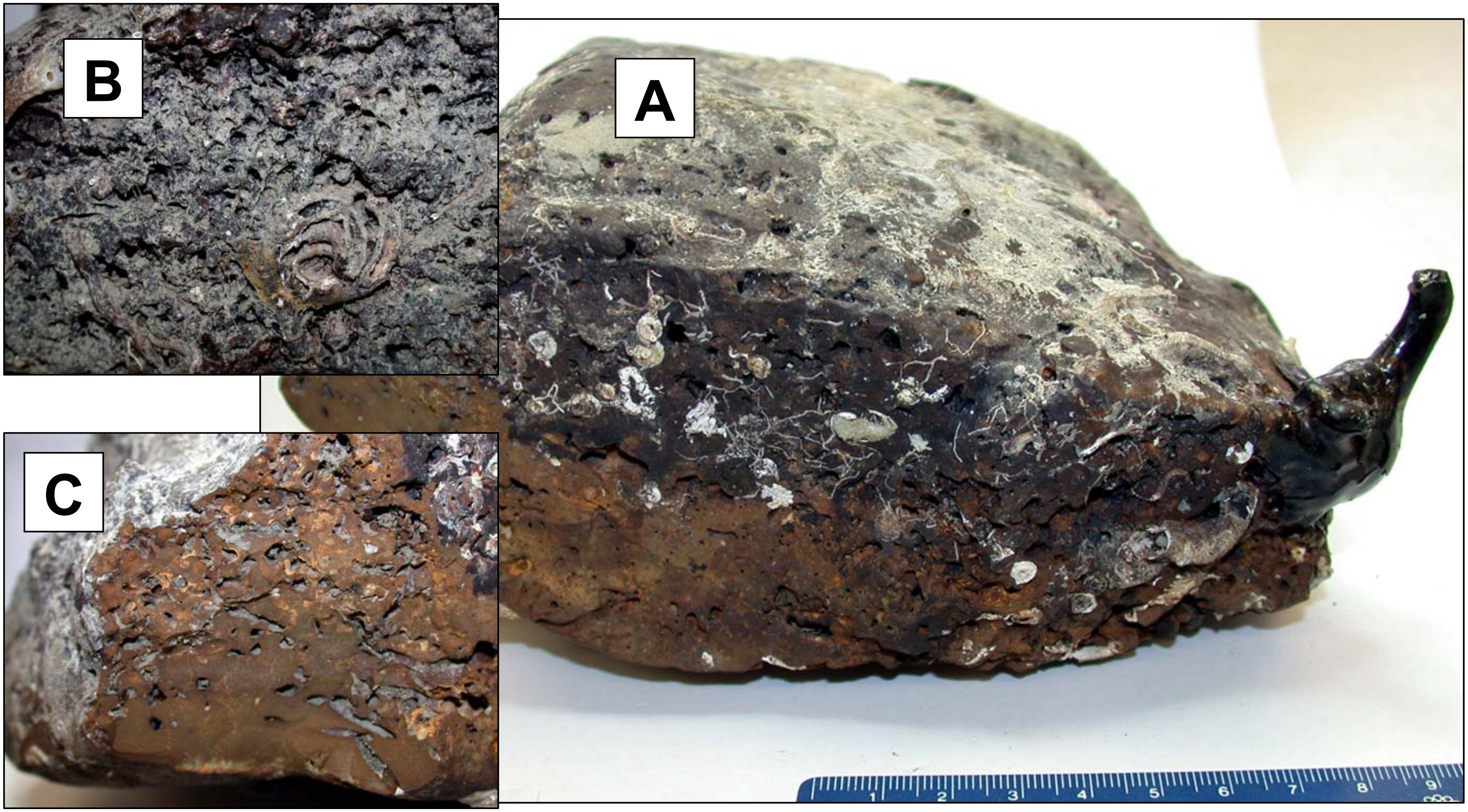


Figure 8.8. Layout image of black goethite substrate rock from Cruise 2005-04, Dive 4875, VK-826: A - Whole specimen as collected; B - Highly eroded and pitted reverse surface (with eroded serpulid tube); C - Freshly exposed section where sample was taken. Sample was used for gravimetric and ^{13}C stable isotope determinations. Shiny black projection is the holdfast and broken basal stalk of *Leiopathes* sp.

Figure 8.9. Goethite coated carbonate-interior rock collected on Viosca Knoll by JSL (image DSCN 5349): A – Whole specimen as collected; B – Freshly exposed section where sample was taken; C – Enlargement to illustrate distinct separation between carbonate core and irregularly-layered goethite crust (arrow). Sample was used for gravimetric and ^{13}C stable isotope determinations.

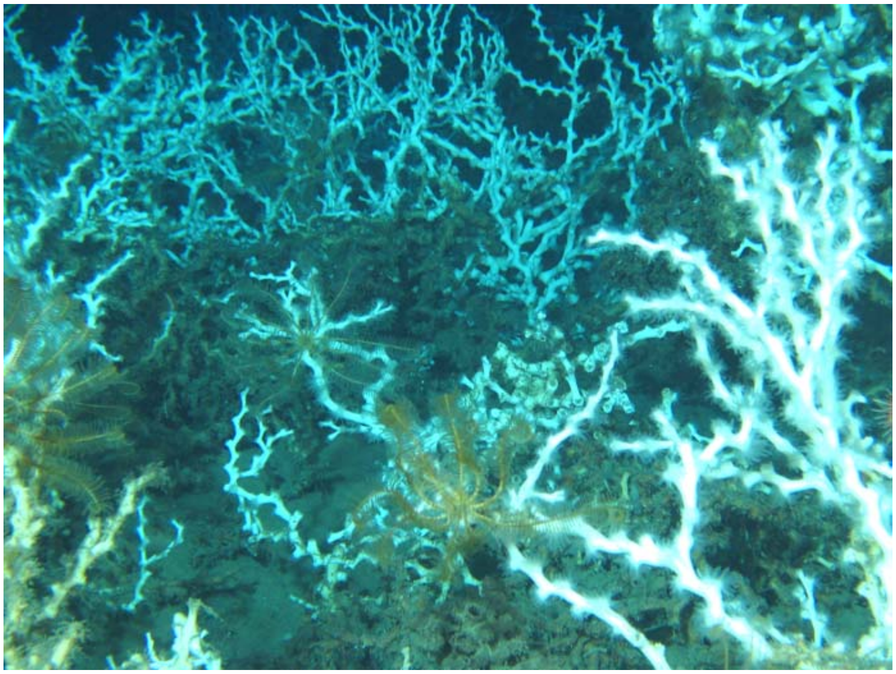


Figure 8.10A. Open growth form of *L. pertusa*, characterized by elongate branches with limited lateral branching and inter-branch anastomosing, an by loose, open matrix. External digital image from Cruise 2005-04, Dive 4880 (image JSL1_4880_082).

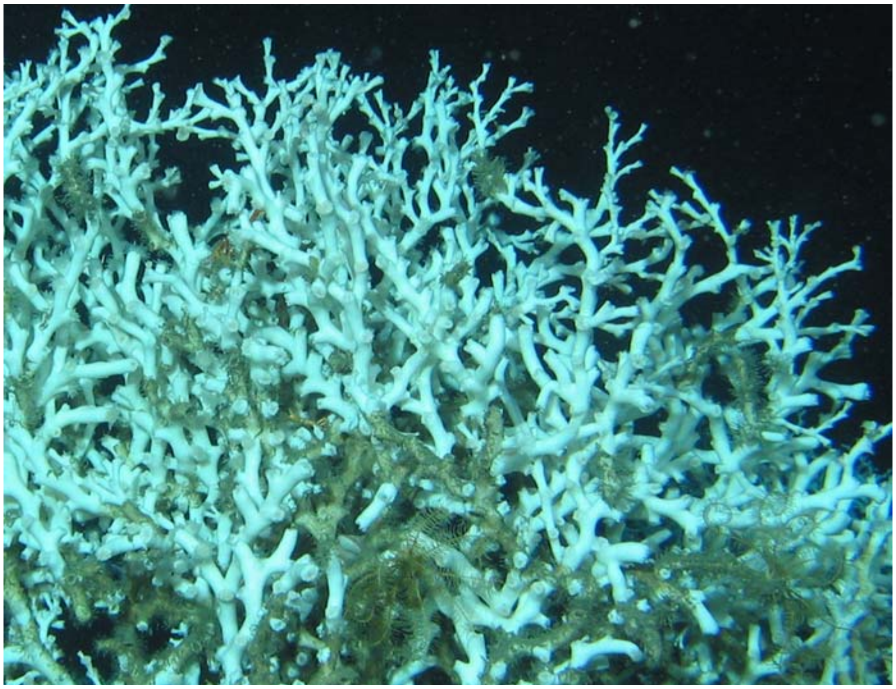


Figure 8.10B. Compact growth form of *L. pertusa*, characterized by extensive lateral branching and inter-branch anastomosing, and by dense matrix. Cropped external digital image from Cruise 2005-04, Dive 4879 (image JSL1_4879_020).

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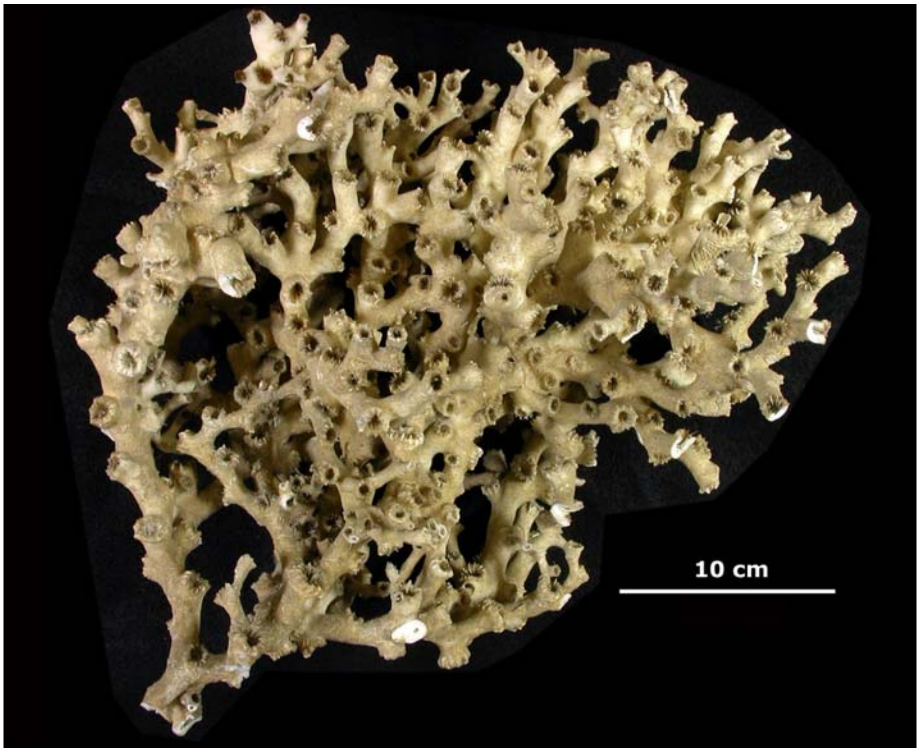

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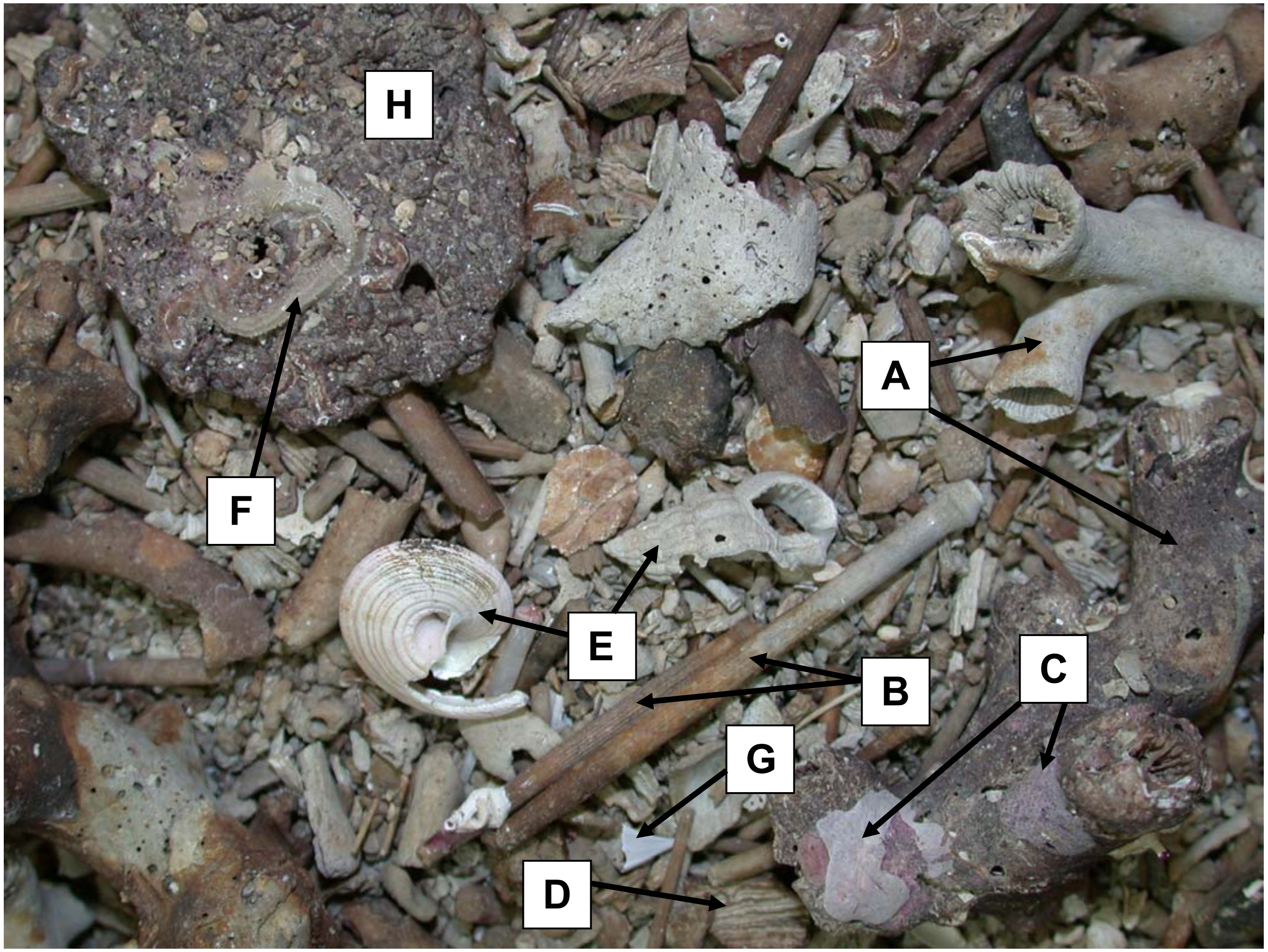

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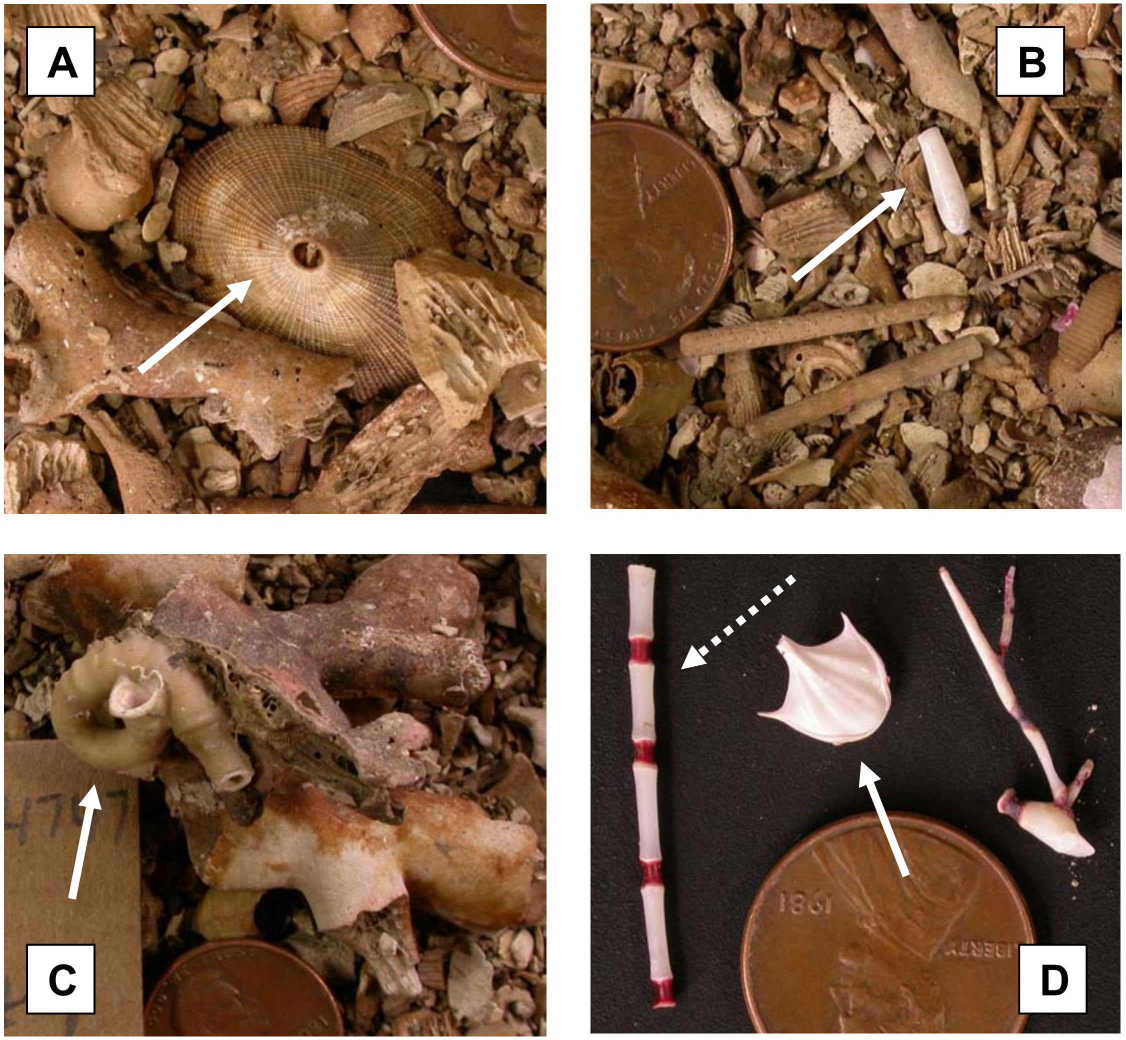

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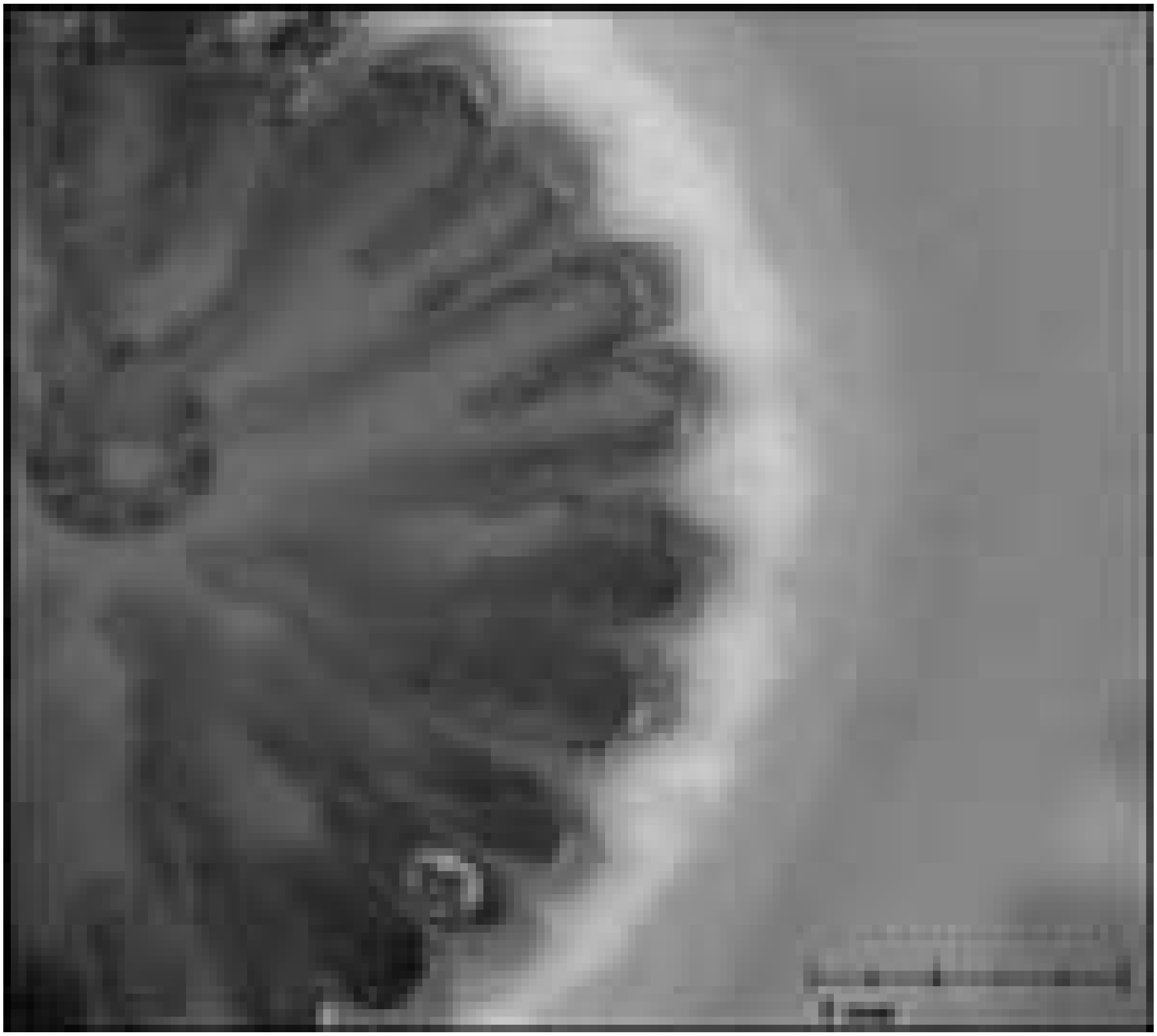

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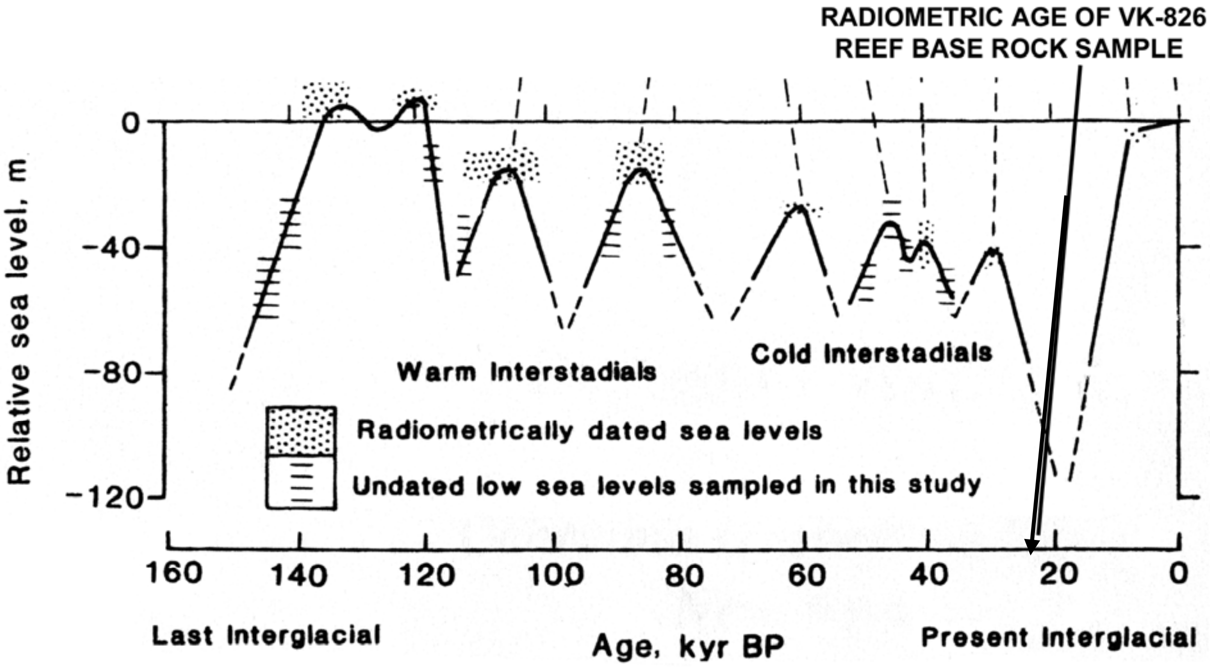

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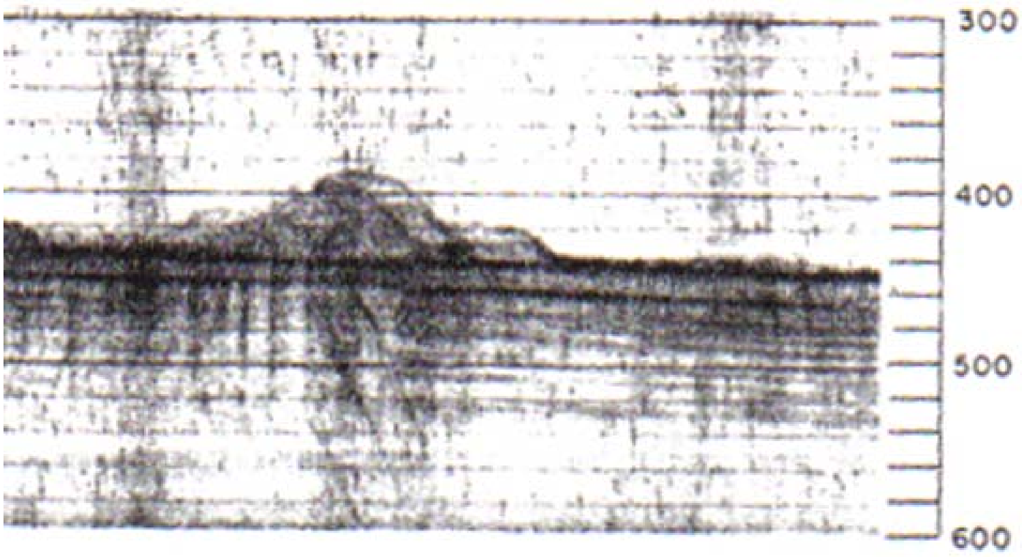

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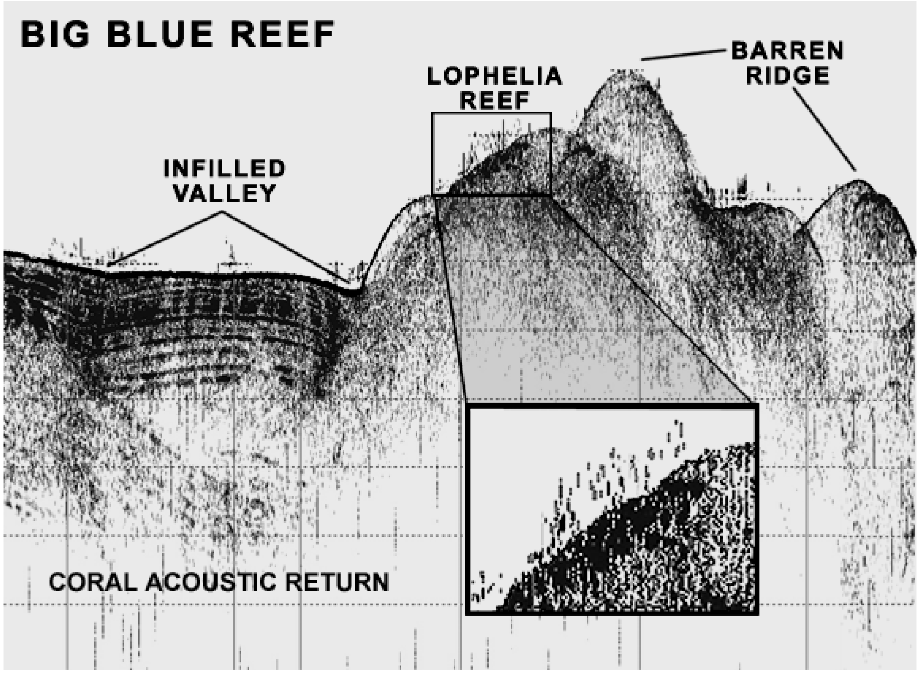

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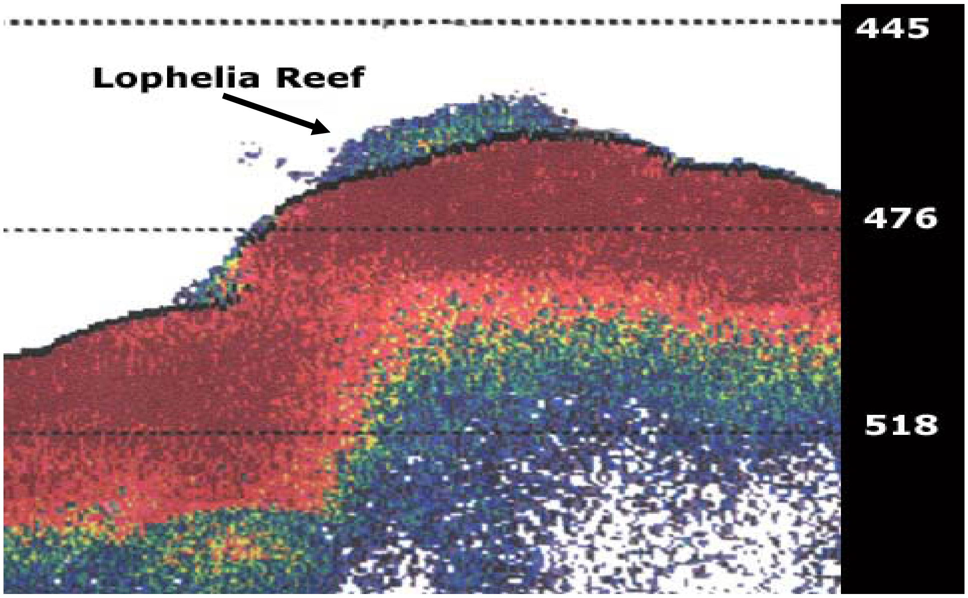

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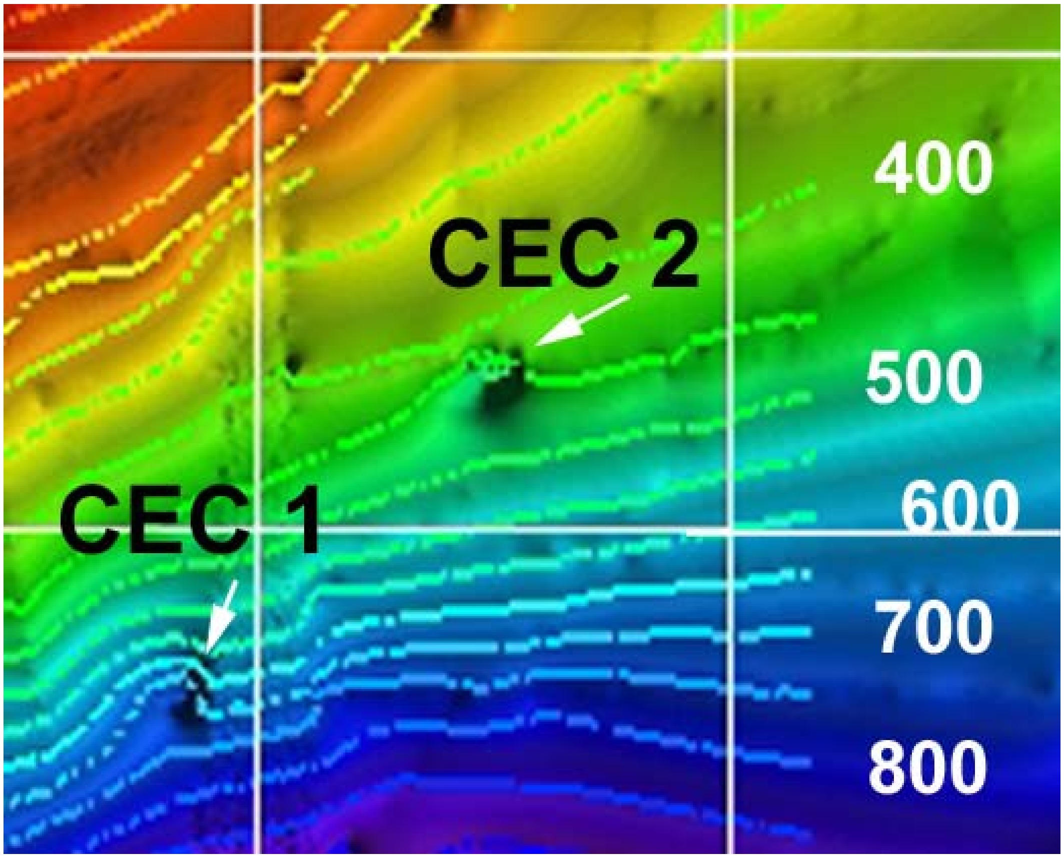

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