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Relationship Between Carbonate Deposits and Fluid Venting: Oregon Accretionary Prism

LAVERNE D. KULM AND ERWIN SUESS[1]

College of Oceanography, Oregon State University, Corvallis

Active fluid venting and its surface manifestations (unique animals and carbonates) occur over the accretionary prism in the Cascadia subduction zone located off central Oregon. A large variety of authigenic carbonate deposits and unique carbonate structures have been observed from submersibles and remotely operated vehicles and recovered with aid of submersibles and bottom trawls from the outermost continental shelf and lower continental slope. The carbonate deposits range from relatively thin crusts and slabs to irregular edifices and well-formed circular chimneys that rise from 1 to 2 m above the seafloor. Mineralogically, the carbonate cement consists of aragonite, calcite, Mg-calcite, or dolomite with varying amounts of detrital constituents. Stable carbon and oxygen isotope data identify four distinct subgroups of methane-derived carbonates from several different vent sites and different fluid source zones. Subgroup I represents one vent site on the lower slope and is characterized by oxygen isotope values ranging from +6.8‰ to +4.7‰ PDB. Subgroup II represents another vent site about 1 km away and exhibits oxygen values of +3.4‰ to +4.9‰ PDB. Carbon isotopic values range from -40.96 to -30.23‰ versus -44.26 to -53.44‰ PDB, respectively, for the two vents. An irregular edifice from the outer shelf has the same isotopic composition as subgroup II. A companion study shows that the expelled fluids contain largely biogenic methane and methane-derived dissolved carbonate; a shallow fluid source zone (<1 km) is indicated. The isotopic carbon values of the subgroup I and II carbonates are consistent with the carbon composition of the expelled fluids and apparently represent a historical record of the composition of these fluids. In subgroup III, strong ^{18}O enrichment and heavier carbon values characterize the dolomitic chimneys from the outer continental shelf. Cemented sandstones from a "window" in the accretionary complex of the lower slope (subgroup IV) are characterized by extreme $\delta^{18}O$ (-5.9 to -5.98 ‰) and moderate $\delta^{13}C$ (-18.7 to -12.67‰) -depleted carbonates. This "light" oxygen isotope composition most likely originated from the upward migration of warm hydrothermal fluids along the main décollement, which tapped the warm subducting basaltic slab, during the early stages of formation of the accreted complex. Well-defined plumbing tubes within some carbonate chimneys on the shelf infer a single well-defined subsurface conduit with a fairly energetic fluid flow. The majority of the chimneys probably formed above the seafloor as long as the rate of carbonate precipitation exceeded the rate of detrital input during their formation. We calculate a minimum of one conduit for each 35 m^2 at one vent site on the shelf. A less energetic flow is suggested by the chaotic plumbing network of an irregular edifice and by the widespread occurrence of the carbonate slabs and crusts at numerous vent sites.

INTRODUCTION

The convergence of the Juan de Fuca plate with the North American plate produces several manifestations on the seafloor that indicate expulsion of fluids from accreted sediments of the Oregon continental margin (Figure 1). Among these manifestations are authigenic carbonate deposits that have been observed and sampled using submersibles, remotely operated vehicles (ROV) and trawls of commercial fishing vessels. The significance of these deposits was not recognized until active fluid venting of pore waters was first documented from the accretionary complex of the Oregon subduction zone [*Kulm et al.*, 1986]. Carbonate slabs, crusts, and chimneys occur within several of the active vent sites on the lower continental slope (*Ritger et al.* [1987] and this study). Benthic animal communities, consisting of living giant white clams (*Calyptogena* sp.), the sewage clam (*Solemya* sp.) and tube worms (*Lamellibrachia barhami*), commonly characterize these sites [*Suess et al.*, 1985].

Three large chimney-like structures were recovered from the outer edge of the Oregon continental shelf by the fishing vessel *Kodiak* in 1985 [*Schroeder et al.*, 1987]. Interestingly, some of these chimneys are similar in morphology, mineralogy, and stable isotopic composition to the carbonate chimney structures observed on the lower continental slope. The recovery of shelf chimneys was the first suggestion of possible fluid venting structures in the shallow waters of the continental shelf off Oregon. Subsequent inquiries by the senior author among commercial fishermen document dozens of chimney recoveries on the Oregon shelf and uppermost slope during the past 20 years. Additional submersible and ROV surveys during 1987 and 1988 have shown the widespread occurrences of carbonate structures on both the continental shelf and slope. These carbonate structures are among a growing number of features associated with fluid venting sites reported from both shallow and deep-water areas of the active and passive continental margins of the United States [*Paull et al.*, 1984; *Kulm et al.*, 1986; *Childress et al.*, 1986; *Brooks et al.*, 1987), North Sea [*Hovland et al.*, 1987], Japan [*Boulègue et al.*, 1987; *Le Pichon et al.*, 1987], and Marianas [*Haggerty*, 1987]. Venting sites off Oregon, Japan, and the Marianas are all associated with modern subduction zones.

The objectives of this study are (1) to document and summarize the occurrences of carbonate chimneys and slabs on the continental shelf and slope in relation to the geologic structure and stratigraphy of the surrounding seafloor, (2) to determine the morphology, chemical, mineralogical, and isotopic characteristics of the carbonate chimneys, and (3) to describe the plumbing network of the carbonate structures and their relationship to

[1]Now at GEOMAR, Forschungszentrum für marine Geowissenschaften, Kiel, Federal Republic of Germany.

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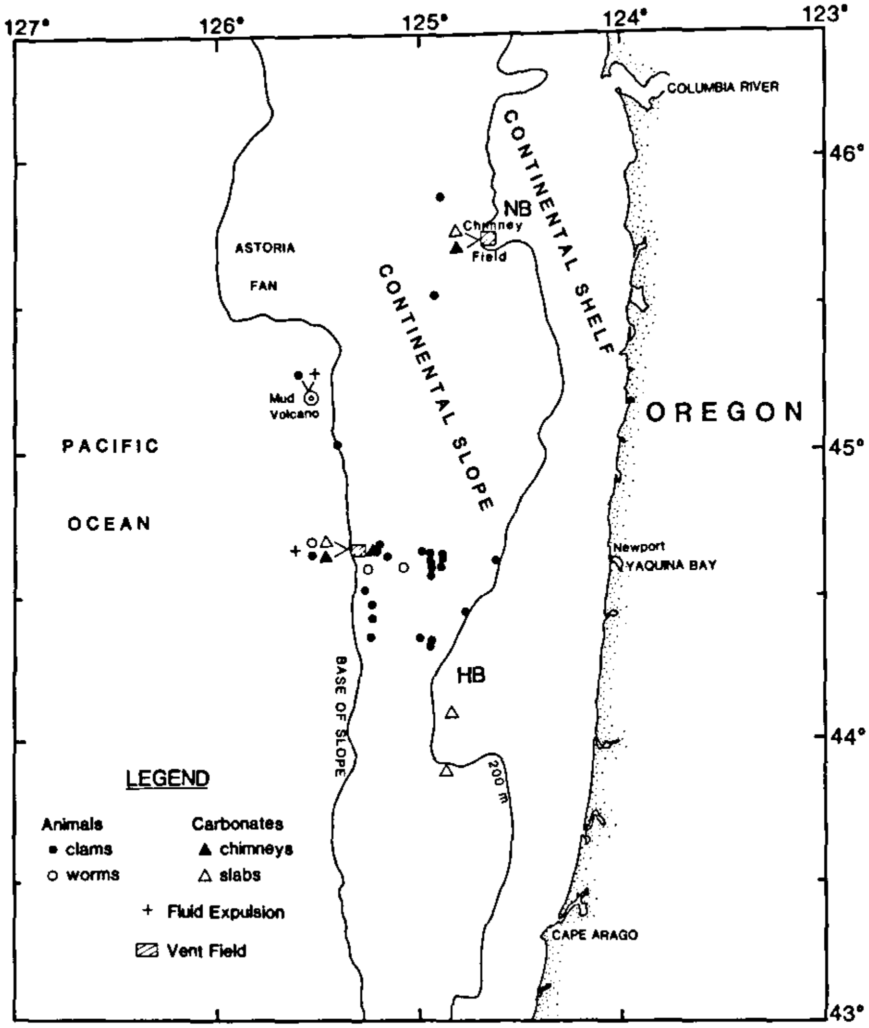

Fig. 1. Fluid venting sites on the Oregon outer continental shelf, continental slope, and mud volcano on abyssal plain. Thin lined boxes indicate several venting sites studied within the area. Symbols adjacent to box designate type of venting evidence (animals, carbonates, fluid expulsion). Submarine banks on outer continental shelf are designated HB, Heceta Bank, and NB, Nehalem Bank. Edge of shelf denoted by 200-m contour. Base of slope labeled (water depth ranges from 2250 m in the north to 3000 m in the south).

probable fluid conduits, and (4) to infer the nature and source of fluids whose expulsion at the seafloor builds up these carbonate structures.

GEOLOGIC SETTING

The subduction of the Juan de Fuca plate beneath the North American plate during the past 60 m.y. has developed a structurally and stratigraphically complex continental margin [*Kulm and Fowler*, 1974; *Snavely et al.*, 1980]. Clastic sediments are scraped off the subducting oceanic plate forming an accretionary prism which is composed of a series of fold and thrust ridges, with intervening basins, striking subparallel or parallel to the Oregon-Washington margin (Figure 2) [*Silver*, 1972; *Carson et al.*, 1974; *Kulm and Fowler*, 1974; *Barnard*, 1978]. The most recently uplifted and deformed ridges (<2 Ma) lie farthest seaward at the toe of the continental slope, and the basins generally contain less than 200 m of late Pleistocene hemipelagic sediment [*Kulm et al.*, 1973; *Kulm and Fowler*, 1974]. These ridges become successively older and more complexly deformed and faulted on the middle and upper continental slope where they are covered by Pliocene-Pleistocene clastic sediments in the overlying sedimentary basins.

Uplifted submarine banks occur along the outer edge of the continental shelf [*Kulm and Fowler*, 1974] and form some of the most strikingly folded and faulted areas of the continental margin. The chimneys described here are located in the vicinity of Nehalem and Heceta banks on the outermost edge of the shelf (Figure 1). The Oligocene to Miocene portion of the accretionary prism underlies these banks and underthrusts the Eocene volcanics to the east [*Snavely et al.*, 1980]. Several hundred meters of Miocene to Pleistocene sedimentary deposits overlie the prism here and contain unconformities that are late Miocene to late Pliocene in age [*Kulm and Fowler*, 1974].

NATURE AND DISTRIBUTION OF CARBONATE DEPOSITS

Several recent studies have discovered a great variety of authigenic carbonate deposits and unique carbonate structures on the outer continental shelf-upper slope (*Schroeder et al.* [1987] and this study) and the lower continental slope (*Kulm et al.*

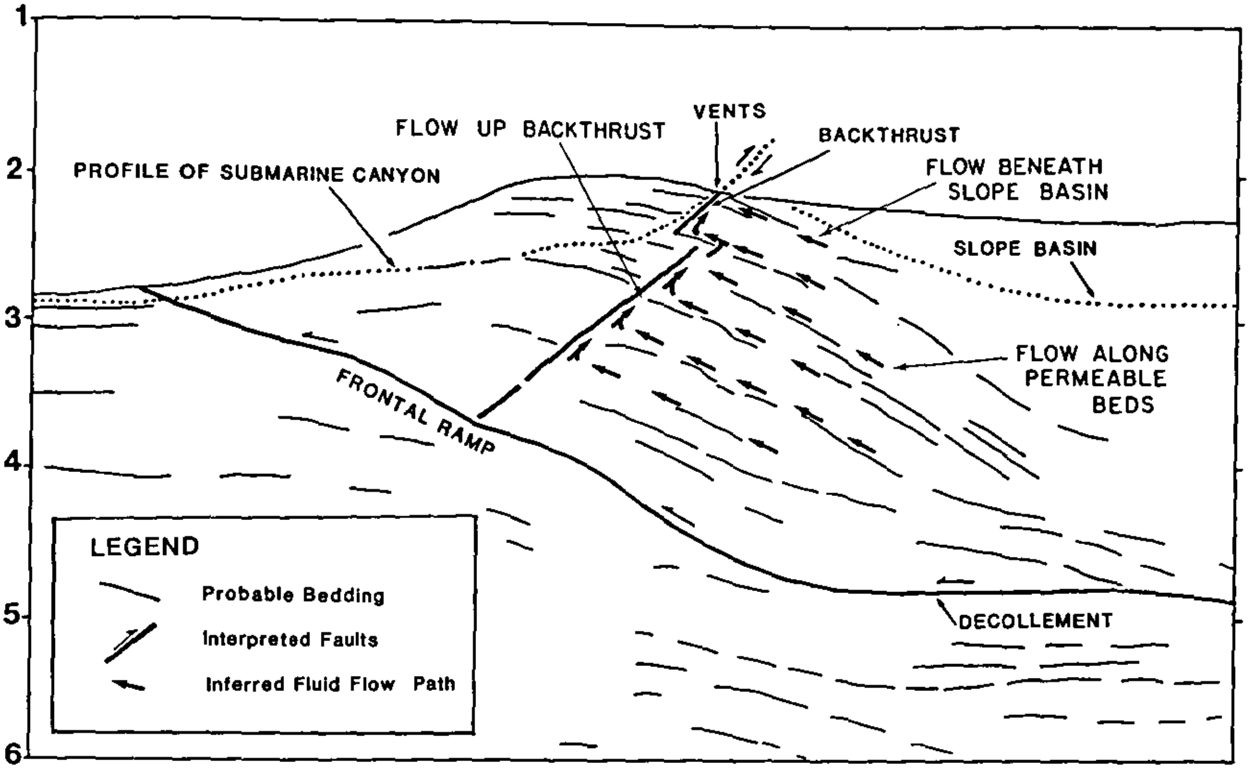

Fig. 2. Depth section of multichannel seismic line WO76-4 across the abyssal plain and marginal thrust ridge (*Moore et al.*, [this issue]; original data from *Snavely et al.*, [1986]). Note position of major venting areas atop backthrust on crest of ridge. See Figure 9 for location (MCS WO76-4).

[1986], *Ritger et al.* [1987], and this study) off Oregon (Figure 1). Six different morphological types of carbonates have been documented to date by direct observations on the seafloor and in collections by commercial fishermen and samples stored at Oregon State University (Table 1).

Chimneys and Slabs on the Shelf and Upper Slope

Submersible observations (*Alvin*, *Mermaid*, and *Delta*), ROV surveys, and samples of rock collections yield an amazing variety of carbonate chimneys and slabs from the continental shelf and

TABLE 1. Classification of Authigenic Carbonate Structures on the Oregon Continental Margin

Type	Description
1	Slabs (5-15 cm thick) with single or multiple open holes and thin crusts (<1 cm); shapes may be rectangular, somewhat oval or irregular.
2	Irregular edifices up to 1 m in height and any shape; some cemented with shell hash (broken and whole clam shells; fine-grained carbonate material, and coarse glauconite; shapes may be elongate or nearly equal-dimensional; random interconnection plumbing network of small openings; conduit walls with variable thickness of white sparry cement.
3	Single and stacked doughnuts (10-25 cm thick and 30-90 cm in diameter) with circular openings ranging from 1 to 40 cm in diameter; they may be stacked in groups of 2-5 with each doughnut cemented to the adjacent one and a constriction between the two; entire stack may range from 45 to 75 cm in height and the central hole extends through the stack forming a large open conduit.
4	Cylindrical chimneys (30-170 cm high and 30-45 cm in diameter); with circular openings (15-20 cm in diameter); walls are relatively thin (3-15 cm), and the central opening much larger; central conduit may be open or partly obstructed by smaller diameter open conduit (2 cm in diameter) which runs the length of the partly filled central conduit; some chimneys visibly slanted (about 5°-15°) or twisted like a hemp rope during growth.
5	Elongate mound-like chimney with a hole in the top (5 cm in daimeter) which bifurcates (Y-shaped) into two large tubes (6-10 cm) that slant to either side within the mound.
6	Conical chimneys (90-120 cm high) with wall thickness 10-30 cm; top diameter (30-50 cm) and base diameter (40-75 cm) variable; vertical vent hole in top (10 cm) and bottom (18-30 cm) multiple openings in the top and sides; weight 1000-2000 kg.

uppermost slope in water depths between 100 and 700 m (e.g., Figure 3). Slabs and crusts are generally several centimeters to tens of centimeters thick, have an irregular shape and are about 1 m across at the widest dimension (type 1, Table 1). The slabs clearly rise above the surrounding sediment for several tens of centimeters. They are whitish in color along their edges which helps identify them as carbonate deposits during submersible and ROV surveys. Several of these structures have holes on their surfaces and are free of sediment while others appear to have a thin veneer of sediment. Crinoids are attached to most slabs and crusts in great numbers. One of these slabs was recovered with the submersible.

Many irregular carbonate edifices were encountered in the surveys (type 2, Table 1). These features are generally covered with abundant benthic organisms, especially crinoids. They rise <1 m above the seafloor, and many have a constricted stem just above the sediment-water interface and a bulbous thicker structure above it with numerous intertwined tube sections which appear to be remains of the internal plumbing network. The surfaces of these edifices are covered with numerous holes, borings, and sharp protrusions which harbor benthic organisms, such as chitons, worms, and solitary and encrusting corals. One of these edifices was recovered intact from the outer shelf in an otter trawl from the vessel *Aloha* (Figures 3 and 4). This structure (weighing 90 kg) consisted of carbonate-cemented glauconitic sand and showed a clear demarcation line separating a chalky, whitish upper section covered with knobs and irregular protrusions to a sulfide-stained black lower section having essentially the same surface features. Iron oxide stains near the boundary indicate that it marks the oxidation-reduction boundary which, in the area of investigation, roughly coincides with the sediment-water interface. This indicates that the lower portion of the structure was buried in the sediment. Several white clam shells are cemented in the sand matrix of the lower portion which is typical of shell hash deposits on the shelf (Figure 5*a*). We suspect that these are chemosynthetically supported bivalves, but recrystallization (?) and intimately cemented matrix preclude a positive identification based on stable isotope characteristics (discussed later). It is noteworthy that live clams are presently not found in the immediate area. They are also absent from the upper portion of the edifice, perhaps indicating that active venting has ceased. In the upper portion of the edifice there is a profusion of cemented tubes which are exceedingly complex in shape, but they clearly indicate a plugged (cemented) plumbing network. Several generations of interior and exterior cement can be recognized, notably a white fibrous carbonate cement which fills the last remaining voids within the tubes (Figures 4 and 5*a*). Another generation of cement is a 5-mm-thick botryoidal cement with amber-colored laminae which covers the exterior of the tubes and the interstices between adjoining tube segments.

Six submersible dives with *Delta* on the outer shelf off northern Oregon in 1988 discovered dozens of chimneys consisting almost exclusively of doughnut-shaped carbonates (type 3, Table 1) at three separate vent sites (about 400-600 m²) within the vent field off Cape Falcon (Figure 3). Carbonate slabs also occur at some of these sites, but they are more prevalent in other areas where few chimneys are present. The carbonate doughnuts on the shelf commonly occur as single features, either lying on the sediment surface or buried 5-15 cm within the unconsolidated sediment, or as stacks. They are rounded at the top and either rounded or flat on the bottom. Doughnuts recovered from the central and southern Oregon shelf-upper slope provide a view of both the top and bottom morphology (Figure 6*a*). Several two-, three- or four-doughnut stacks were cemented into one unit with a hole extending through the entire stack and were observed at all sites off Cape Falcon (Figure 6*b*). The upper one or two doughnuts from a single stack may be shifted off center (i.e., positioned to one side). In one case, a pointed carbonate plug protrudes from what appears to be the base of the stack. All doughnuts are cemented together along their horizontal surfaces and, due to their rounded edges, form constrictions between them. In other cases, one or two doughnuts were cemented to a carbonate slab

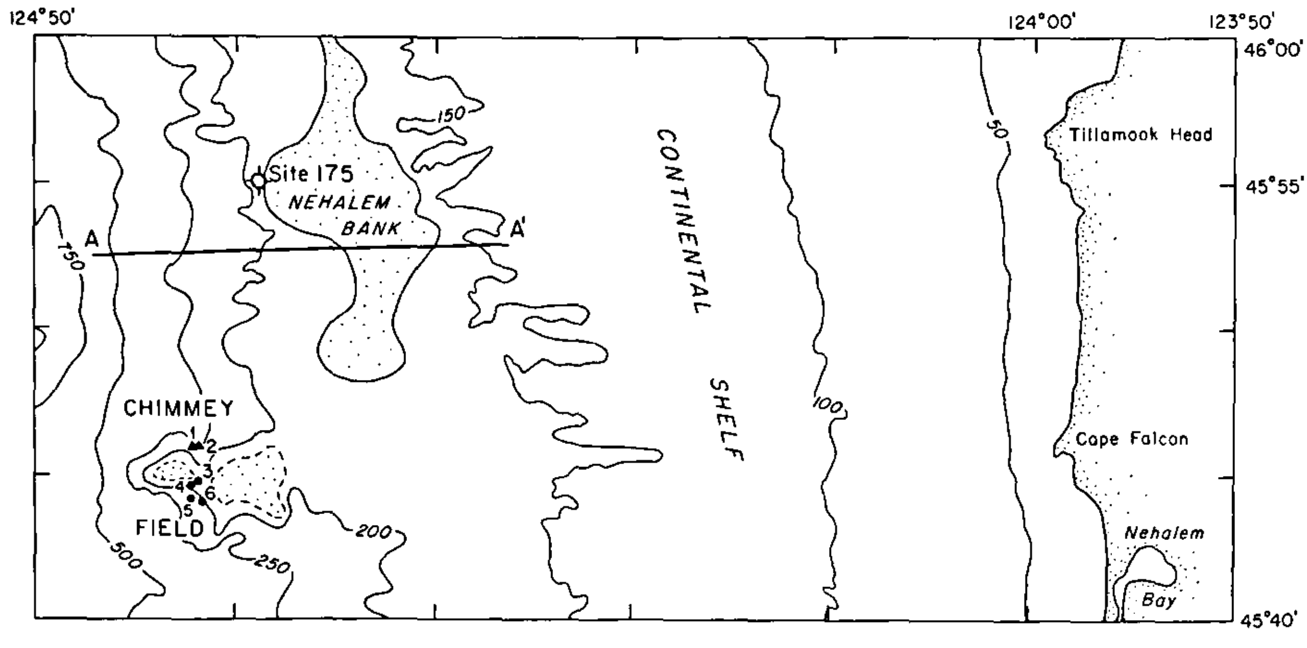

Fig. 3. Location of chimney field and uplifted Miocene to Pliocene sediments on submarine banks (dotted pattern) on outer continental shelf off northern Oregon. Note location of DSDP drill hole 176 and multichannel seismic section A-A' on Nehalem Bank. 1, *Kodiak* trawl; 2, *Aloha* trawl; 3, ROV observation; 4, *Delta* dive 1252; 5, *Delta* dive 1254; and 6, *Delta* dive 1257. Contours in meters.

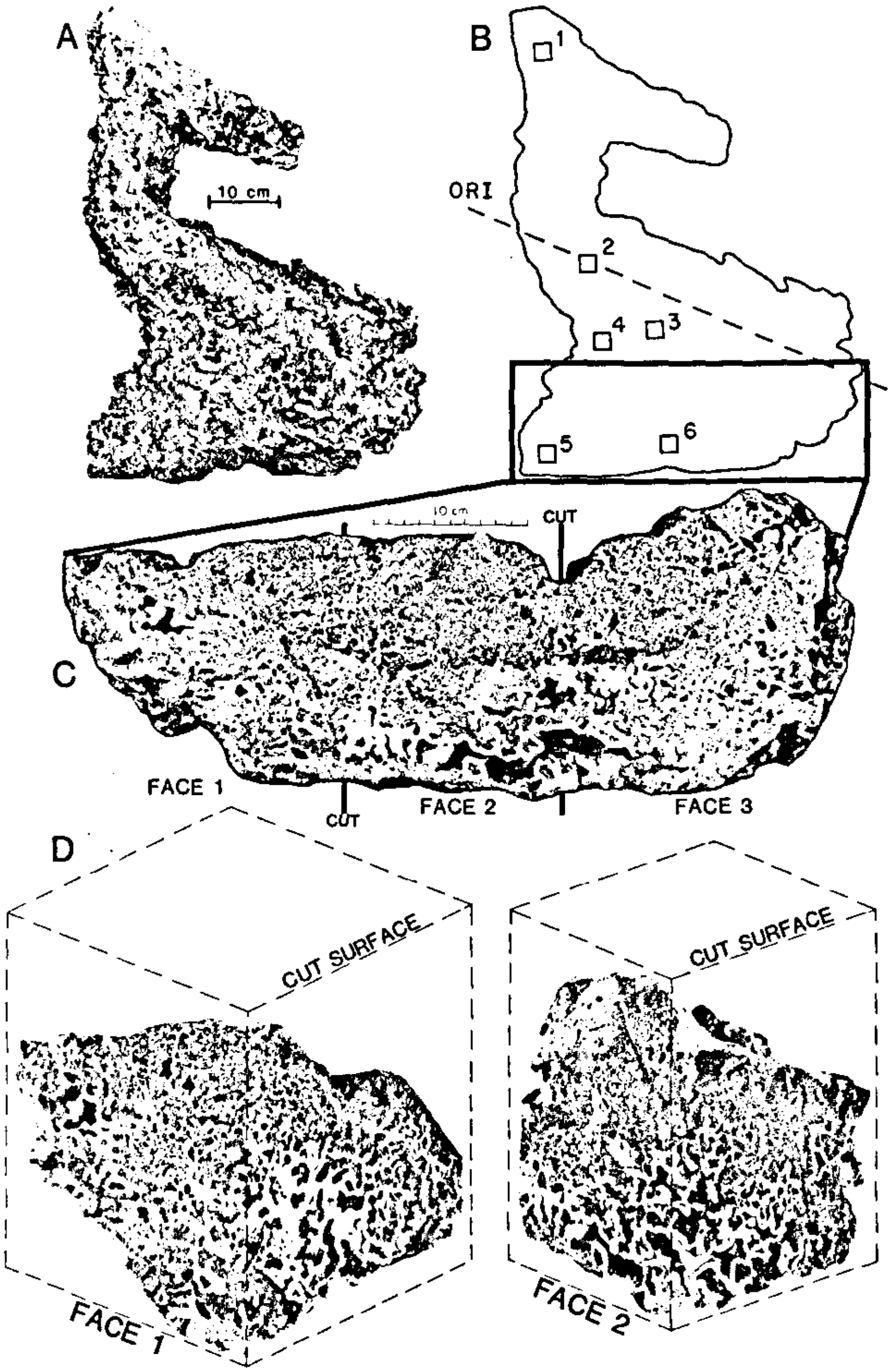

Fig. 4. (*a*) Irregular carbonate edifice recovered from outer continental shelf off northern Oregon in *Aloha* trawl (site 2 in chimney field, Figure 3). (*b*) Sketch of edifice showing samples locations (1-6) taken for geochemical analyses; analyses are given in Tables 2 and 3. ORI is the oxidation-reduction interface. (*c*) Vertical section through basal portion of edifice showing random plumbing network with white carbonate cement lining the walls of the tubes. (*d*) Edge view of cuts made normal to vertical section (Figure 4*c*). Note plumbing network consists of numerous short and discontinuous tubes or openings partly to completely filled with carbonate cement.

with a hole penetrating the stack. Several doughnuts were easily pushed by the submersible over the sediment surface; there does not appear to be a solid connection to a fluid conduit. In the area of the *Delta* dives, tracks from the doors of bottom trawls in the sediment indicate that the area has been fished, and the trawls undoubtedly moved the carbonate chimneys about the seafloor, tilting several of them at an angle to the seafloor.

Additional doughnut-like stacks have been recovered by fishermen off central and southern Oregon (Heceta Bank and south on the shelf) between 100 and 700 m water depth. They

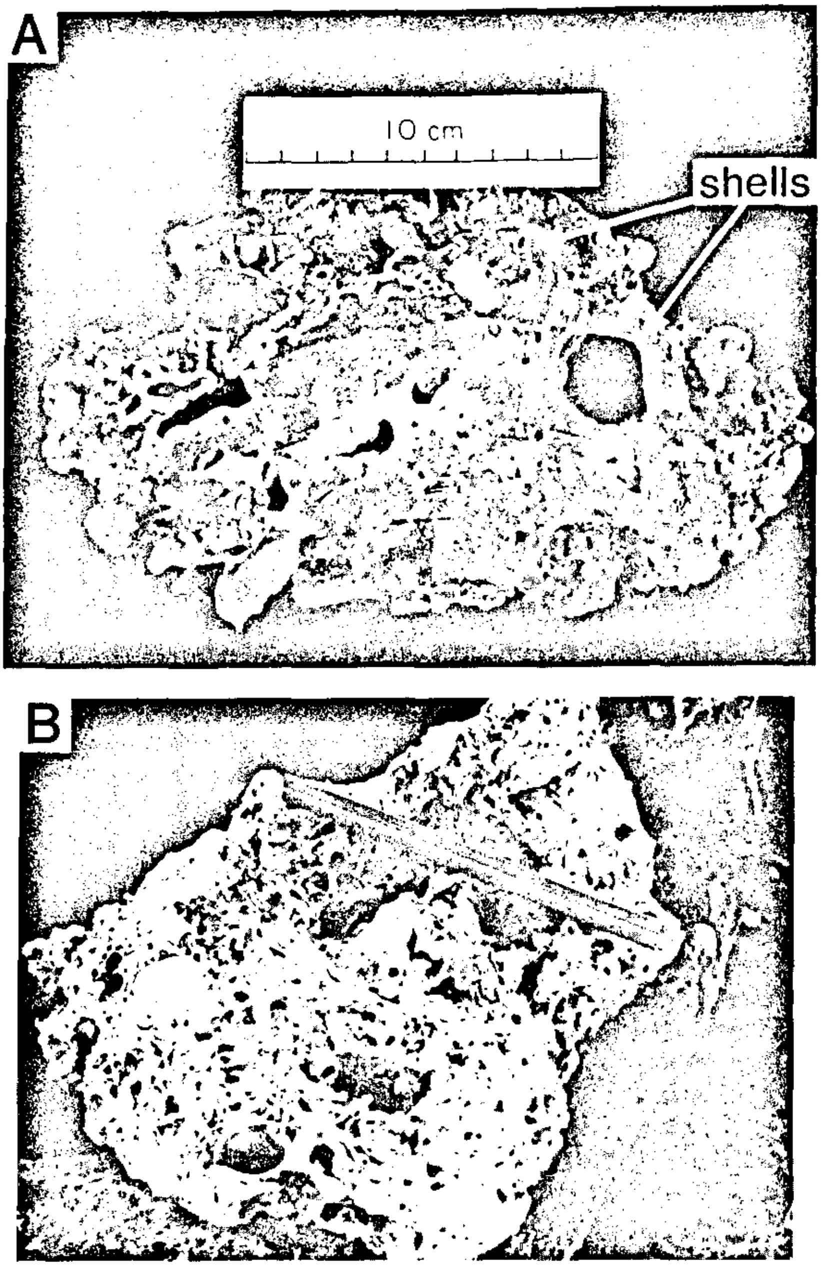

Fig. 5. (*a*) White clam shells contained in carbonate cemented glauconitic sand of uppermost part of irregular edifice on shelf (see Figure 4*a*). (*b*) White clam shells contained in shell hash with carbonate cemented matrix from continental shelf off central Oregon, scale 12-inch (30-cm) ruler.

have smaller central openings (2-3 cm), are smaller in diameter (20-30 cm), and are somewhat differently shaped individual doughnuts than the stacks observed to the north (Figures 7*a* and 7*b*). In one case, two doughnuts are stacked upon a short pedestal.

Three large chimneys and two smaller chimneys were recovered in one bottom trawl by the vessel *Kodiak* on the outer continental shelf in the vicinity of Nehalem Bank off northern Oregon (Figure 3). The large chimneys are quite dense with very little detrital material and range in height from 1 to 2 m (Figure 8) [*Schroeder et al.*, 1987]. One of the recovered chimneys is cylindrical in shape (type 4, Table 1); it contains small tubes and cavities (Figures 8*a*-8*c*). A secondary tube that runs parallel to the main cavity extends the length of the chimney. Skeletons of encrusting corals and sponges were attached to the chimney. Several other chimneys from central and southern Oregon show a variety of cylindrical shapes (some with superb radial symmetry) and open central chambers of various sizes (Figure 7*c*). In one case, the wall appears to be twisted like a hemp rope (Figure 7*d*).

The conical shelf chimneys (type 6, Table 1) are similar in shape and size to those found on the lower slope (compare Figure 8*d* with Figure 6*c*). Each chimney has an open vertical cavity with at least one large cavity in the side wall; numerous smaller secondary conduits penetrate the walls. The walls are frequently cracked or broken and vary greatly in thickness from 3 to 30 cm. External surfaces are pitted and grooved, either from dissolution by seawater or by the burrowing and secretion activities of benthic animals.

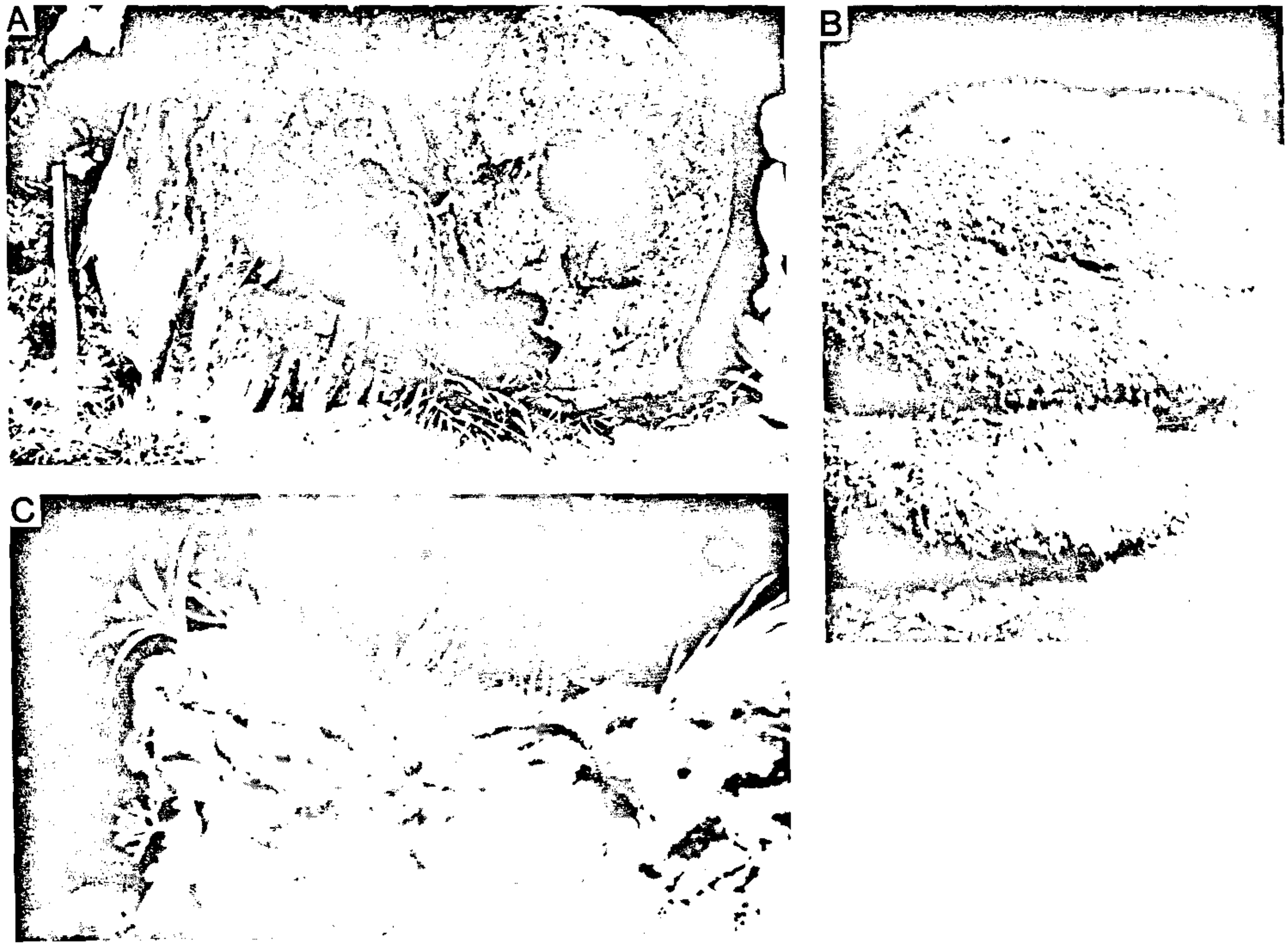

Fig. 6. (*a*) Single doughnuts recovered from outer shelf off central and southern Oregon in bottom trawls by commercial fishermen; left structure is slablike with irregular central opening and right structure is rounded with circular opening; scale 12-inch ruler (30 cm). (*b*) Stack of three cemented carbonate doughnuts observed in chimney field (Figure 3) from submersible *Delta* on outer shelf off northern Oregon. (*c*) Carbonate chimney observed from *Alvin* on the lower continental slope off central Oregon (see lined box, Figure 1).

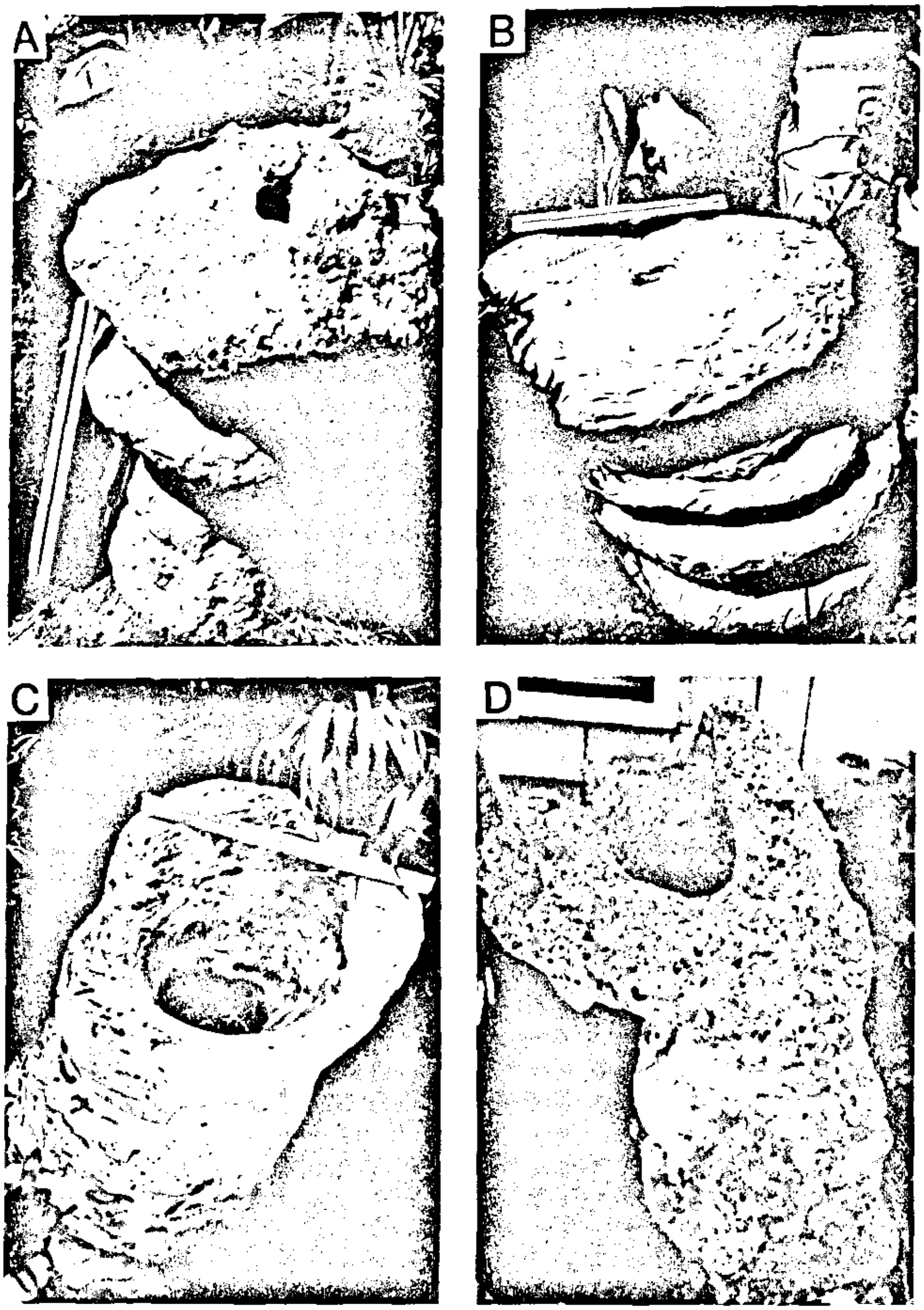

Fig. 7. Variety of carbonate chimneys recovered from the outer continental shelf off central and southern Oregon in bottom trawls of commercial fishermen. (*a*) Doughnut-shaped chimney mounted on pedestallike foundation with small central opening; scale 12-inch (30-cm) ruler. (*b*) Stack of thin, cemented doughnuts or platterlike features with small central opening; scale 12-inch (30-cm) ruler. (*c*) Cylindrical-shaped chimney with large central opening and thin walls; chimney attained a 5°-15° slant during growth, scale 12-inch (30-cm) ruler. (*d*) Cylindrical-shaped chimney with central opening and thick walls; chimney twisted or rotated clockwise progressively as it grew upward; central opening is 18 cm in diameter for scale.

Chimneys and Slabs on the Continental Slope

Alvin submersible dives revealed that carbonate deposits also occur at vent sites on the lower slope (Figures 9 and 10*a*). However, irregularly-shaped structures are more common here than chimneys on the shelf. The morphologies of carbonate structures on the lower slope can be divided into four basic types: (1) cemented layers, crusts, or pavements on rock outcrops devoid of sediment cover; (2) partial slab exposure with a thin hemipelagic cover; (3) slabs located beneath a 2-10 cm sediment cover (detected with a probe) and generally underlying clusters of living clams; it is unclear how extensive these subsurface pavements are or if the slabs are interconnected or single pieces; and (4) conical chimneys. Live tube worms are frequently rooted in the cracks between carbonate layers and are tangled around open holes that punctuate many of the slabs and crusts (Figure 10*b*). The few carbonate chimneys, one each at three different vent sites that have been observed on the lower slope occur as solitary structures conical in shape with numerous openings (Figure 6*c*). They rise about 1 m above the seafloor and are

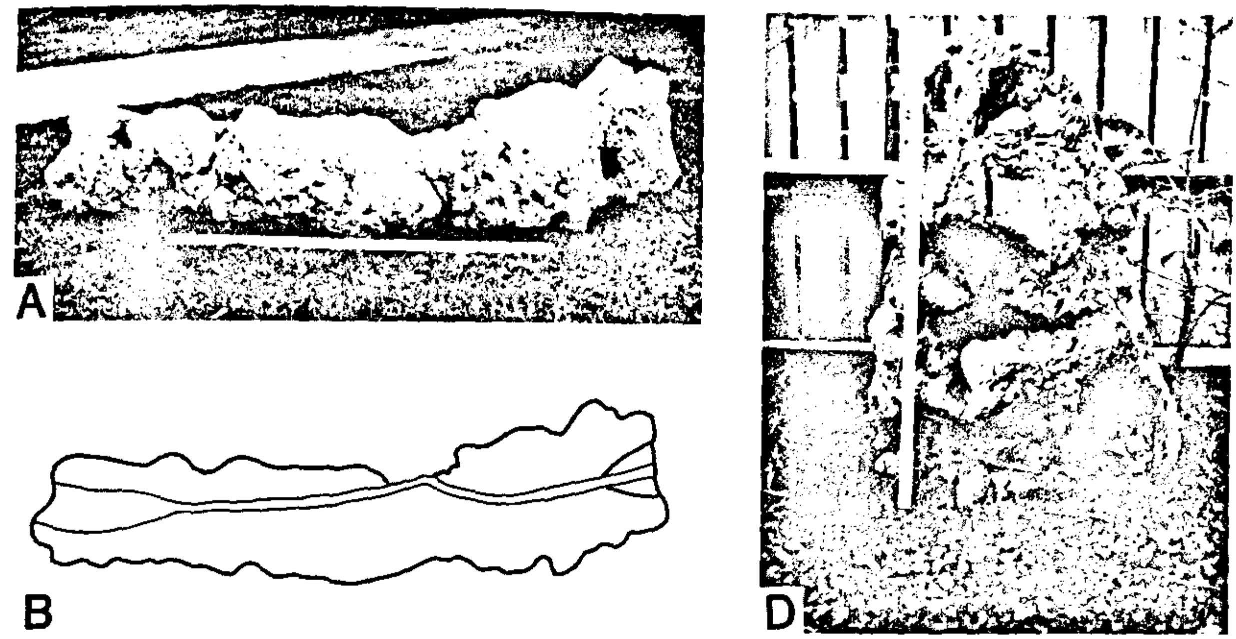

Fig. 8. (*a*) Long cylindrical chimney, scale is 1-m ruler; (*b*) Sketch showing well-developed, small internal plumbing tube extending 150 cm along length of chimney; and (*c*) end view of internal tube, opening is 2 cm in diameter. (*d*) Conical chimney with large internal cavities viewed through openings in the side walls, scale is 1-m ruler. All chimneys collected by commercial fishermen aboard the vessel *Kodiak* off northern Oregon (symbol 1, Figure 3).

about 1 m in diameter at the base. They exhibit numerous cavities, grooves, and flutes, which have smoothly rounded edges producing a sculptured appearance [*Ritger et al.*, 1987]. Each chimney is covered by corals and sponges. The chimneys are commonly associated with carbonate slabs and crusts at each vent site.

Composition of Carbonates

Mineralogy

The chimneys and slabs on the lower continental slope consist of aragonite, calcite, magnesian calcite, and dolomite and minor amounts of detrital clays, silt, and sand (*Ritger et al.* [1987] and this study). Small patches of pure aragonite occur throughout the matrix of one chimney. Individual grains rarely exceed 10 μm and are frequently <2 μm (*Ritger et al.* [1987] and this study). Another chimney contains abundant rounded, cemented mudstone pebbles or clasts. Microprobe analyses of thin sections of the carbonate slabs at two lower slope vents (sites 1428 and 1900, Figure 9) show they consist largely of a fine-grained micritic matrix (clay and fine silt) with no apparent detrital carbonate particles. Carbonate cement is pervasive throughout the matrix material. Pyrite is found in most thin sections.

We studied the major element chemistry in conjunction with X ray diffraction data of the two conical and one cylindrical shelf chimneys recovered off northern Oregon to determine if they are

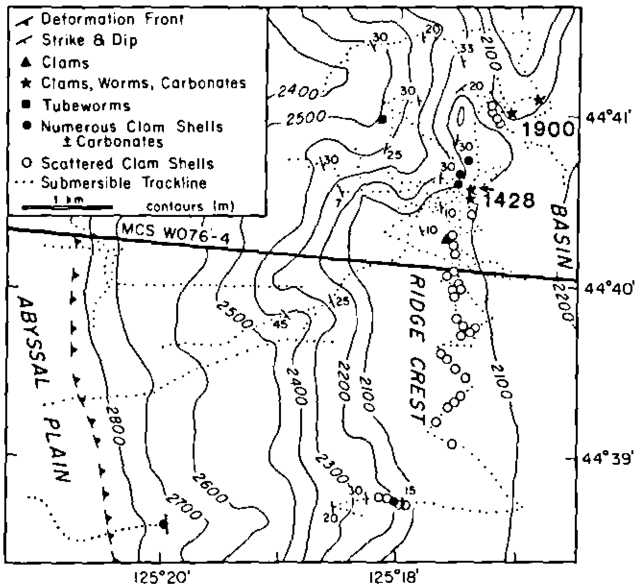

Fig. 9. Location map of major fluid vent sites (solid star) and other isolated vents/seeps (triangle, square, and circles) on the lower continental slope mapped with the *Alvin*. Note location of vent sites 1428 and 1900 on ridge crest. Structure of the seaward verging thrust sequences on marginal ridge shown by dip and strike symbols (simplified from *Moore et al.* [this issue]). Sea Beam bathymetry data collected during *Atlantis* II survey in 1987; contours in meters.

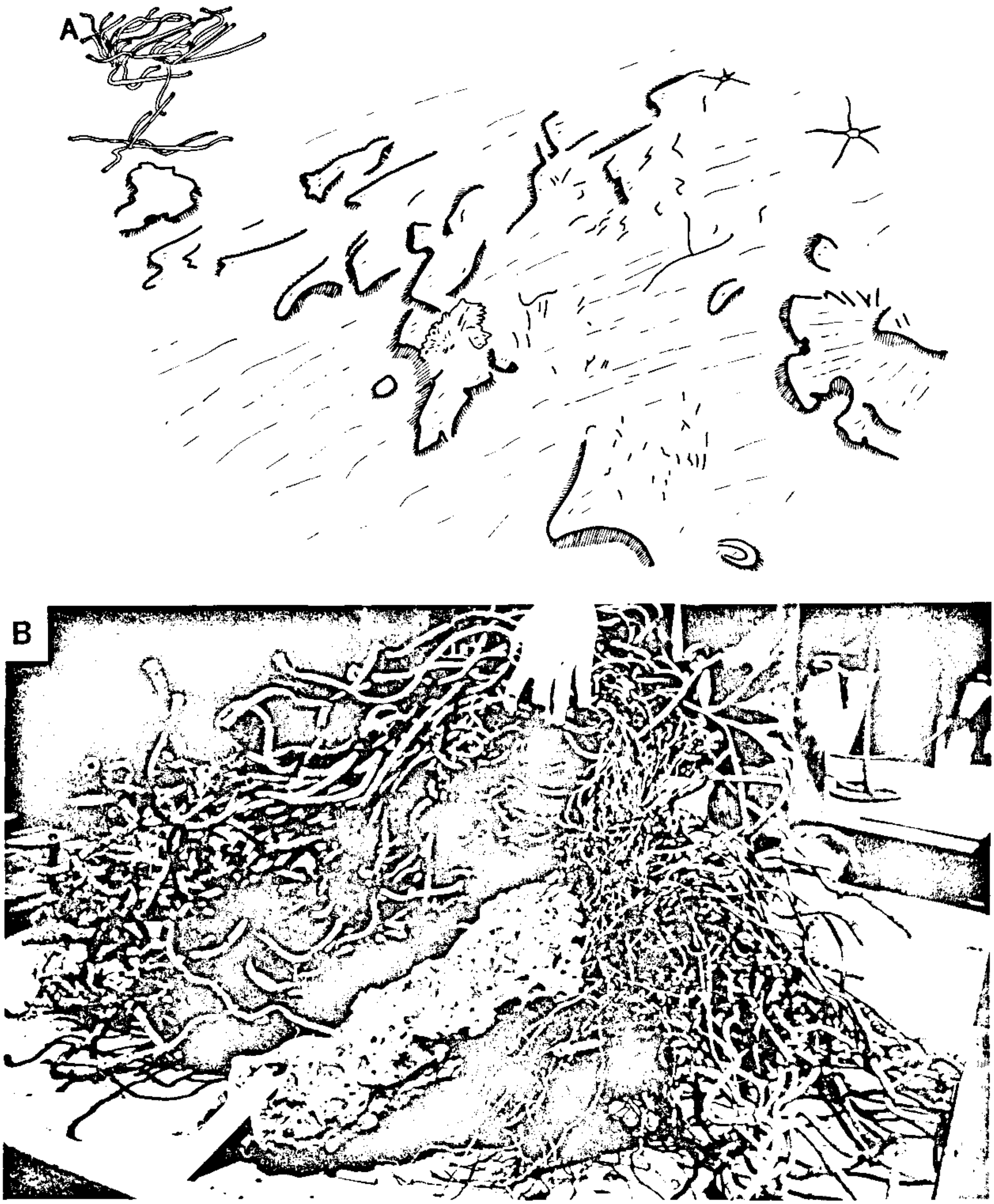

Fig. 10. (*a*) Sketch of vent site 1428 on lower slope (see Figure 9) showing distribution of carbonate slab and crust exposures interspersed with sediment cover of hemipelagic sediment (thin long lines). Slabs may be covered by <10 cm of sediment over large areas of the vent field. The scale of the carbonate exposures is approximately 3 by 4 m. (*b*) Carbonate slab with cluster of tangled live tube worms obtained with submersible *Alvin* at vent site 1900 on lower slope (Figure 9); roots of tube worms coiled around a hole in the slab. Slab was buried a few centimeters below the sediment-water interface.

of similar origin. These analyses indicate they are quite similar in composition and consist chiefly of dolomite (69-89% carbonate) SiO_2 (14-22%), and Al_2O_3 (4-6%). Detrital quartz, feldspar, and authigenic pyrite grains are scattered throughout the carbonate matrix. Late Miocene to Pliocene benthic and planktonic foraminifera also occur within the matrix and resemble microfossil assemblages of the Quinault Formation which overlies the Hoh Formation beneath the Washington shelf (P. Snavely, Jr., personal communication, 1987). The latter strata is an accretionary complex consisting of Oligocene melange and broken formation.

The bulk of the cemented glauconitic sand of the irregular edifice as well as the walls of its open plumbing network consist of aragonite and/or Mg-calcite (Table 2). Insoluble fractions of

TABLE 2. Mineralogy and Stable Isotopes of Irregular Carbonate Edifice Obtained From *Aloha* Trawl

Sample Description	Principal Mineralogy	$\delta^{18}O$, ‰PDB†	$\delta^{13}C$, ‰PDB†
1, Weathered surface, chalky cemented glauconite sand			
a, Groundmass dominating	aragonite	+4.20	-49.91
b, Cement dominating	aragonite	+4.37	-50.63
2, Weathered surface, gray oxic-reducing boundary			
a, Groundmass, soft, whitish	aragonite, Mg-calcite	+4.42	-51.59
b, Groundmass, fresh interior, hard, black	aragonite, Mg-calcite	+4.49	-51.24
c, Gravelly groundmass with white cement	aragonite	+4.32	-48.27
3, Cemented tube segment			
a, Fresh tube wall, black cemented sandy groundmass	aragonite, Mg-calcite	+4.56	-51.54
b, Interior cement, gray	Mg-calcite	+4.84	-52.23
c, Interior cement, white	aragonite	+4.30	-51.75
4, Groundmass, black with "laminated" exterior cement			
a, Fresh interior groundmass, black	aragonite, Mg-calcite	--	--
b, Exterior cement, white	aragonite	+4.19	-51.96
5, Fresh groundmass, black with yellowish fibrous cement			
a, Fresh groundmass, black	aragonite, Mg-calcite	+4.42	-51.80
b, Exterior cement	aragonite	+3.95	-53.31

Refer to Figure 4 for sample locations (1-5). †Carbonate standard derived from the rostra of *Belemnitella americana* from the Pee Dee Formation of South Carolina.

two representative samples range from 29 to 68 wt % and consist of well-sorted glauconitic grains (0.063-0.25 mm in diameter) and some small fraction of clays (Table 3). The dark glauconitic groundmass generally consists of aragonite and Mg-calcite or just aragonite. Gray colored cement is usually Mg-calcite, while the white cement is aragonite. Microprobe analyses of thin sections show that the authigenic cement invades the pore spaces between the glauconitic grains and the grains themselves. No individual detrital carbonate particles were recognized within the matrix material or the cement.

Stable Isotopes

Carbonates on the Oregon-Washington margin have a distinct bimodal distribution in grain size and isotopic composition [*Ritger et al.*, 1987]. One group consists of soft, low carbonate (generally <10% $CaCO_3$) terrigenous material with detrial carbonate grains. They are characterized by low negative $\delta^{18}O$ values (-1.6‰ to -13‰ PDB) and $\delta^{13}C$ values of about +1‰ to +6‰ PDB. The other group consists of high carbonate (25-90% $CaCO_3$), highly indurated material authigenic carbonate which binds variable amounts of clastic clay and silt particles. They are strongly depleted in carbon-13 ($\delta^{13}C$ -66.7‰ to -34.9‰ PDB) and have positive $\delta^{18}O$ values (+2.78‰ to +8.27‰ PDB). At each vent site the authigenic high carbonates of chimneys, concretions, and slabs are inferred to have formed from pore fluids enriched in dissolved methane and carbonate. The fluids are being expelled from the underlying sedimentary sequences [*Kulm et al.*, 1986; *Ritger et al.*, 1987]. The dissolved carbonate, for the most part, is generated by the bacterial oxidation of methane. Based on $\delta^{13}C$ values of dissolved gases, *Suess and Whiticar* [1989] estimate that one-third to one-half of the dissolved carbonate ions in pore fluids at vent sites off Oregon are derived from biogenic methane. The authigenic carbonates reflect this source as was previously suggested for these and other samples found at active and passive margins [*Ritger et al.*, 1987; *Friedman*, 1988; *Thornburg and Suess*, 1989]. We present new stable isotope data from a suite of 51 samples from several different vent localities on the Oregon margin (Table 4). These high carbonate samples contain at least 25 wt % calcium carbonate. The carbonate samples were cut into sections and examined, and the most carbonate pure portions were then cut from each deposit with an ultrathin band saw blade. The samples were analyzed at the stable isotope laboratory in the College of Oceanography with a Finnigan/MAT

TABLE 3. Insoluble Residues of Cemented Groundmass of Carbonate Structure From *Aloha* Trawl

Grain Size, μm	Sample 2 E Chalky White Groundmass, wt %	Sample 4 D H-2S Stained Groundmass, wt %	Dominant Mineralogy
>250	7.8	12.6	glauconite
150-250	13.4	20.7	glauconite
150-63	5.4	7.8	glauconite
<63	2.2	27.4	clay
Total glauconite	26.6	41.1	
Total clay	2.2	27.4	
Total carbonate	71.2	31.5	Mg-calcite aragonite

TABLE 4. Stable Carbon and Oxygen Isotopic Values and Mineralogy for Carbonate Deposits Obtained From Numerous Vent Sites on the Oregon Continental Slope and Shelf

Sample	Type Feature	$\delta^{18}O$,‰ PDB†	$\delta^{13}C$, ‰ PDB†	Mineralogy
Alvin				
1426-02	slope chimney	5.4	-32.6	aragonite, Mg-calcite
1428-01	slope concretion	-5.9	-18.7	calcite
1428-02-1	slope concretion	6.39	-39.1	Mg-calcite
1428-02-2	slope concretion	6.1	-38.3	Mg-calcite
1428-02-3	slope concretion	6.3	-37.1	Mg-calcite
1428-02-4	slope concretion	5.9	-35.6	Mg-calcite
1428-02-5	slope concretion	6.04	-34.9	Mg-calcite
1428-02-6	slope concretion	6.5	-35.9	Mg-calcite
1428-02-7	slope concretion	5.4	-36.1	Mg-calcite
1428-02-8	slope concretion	6.79	-38.6	Mg-calcite
1428-02-9	slope concretion	6.8	-38.6	Mg-calcite
1428-02-10	slope concretion	6.4	-37	Mg-calcite
1428-02-11	slope concretion	6.3	-35.5	Mg-calcite
1428-02-12	slope concretion	5.9	-36.5	Mg-calcite
1428-02-13	slope concretion	6	-35.8	Mg-calcite
1428-03	slope chimney	6.2	-32.5	Mg-calcite
87 1898-2	slab, inner black	5.09	-33.93	calcite
87 1898-3	slab, inner black	5.82	-30.23	calcite
87 1898-5S	slab, shell	4.72	-22.92	aragonite, calcite
87 1898-5M	slab, coarse matrix	4.75	-33.72	calcite
87 1898-5FG	slab, dk. fine grained	5.14	-35.49	calcite
1898-CY Blk	Alv 1428 crust			aragonite
1898-CY Blk RP	Alv 1428 crust			calcite
1907-BX blk	Alv 1428			aragonite
87 1900 BS A	slab, crust/slab	3.83	-50.7	Mg-calcite
87 1900-2	slab, dark matrix	3.52	-51.29	calcite
87 1904-1	slab, dark matrix	5.7	-40.74	calcite
87 1904-2	slab, dark matrix	5.38	-40.96	calcite
87 1904-3	slab, dark matrix	5.62	-34.39	calcite
87 1904-4 C2	slope slab	4.72	-40.61	Mg-calcite
87 1904-4 C1	slope slab	4.82	-40.41	Mg-calcite
87 1904-4 A1	slope slab	5.03	-36.52	Mg-calcite
87 1904-5	slab, dark matrix	5.73	-30.27	calcite
88 2046-1	slab, dark matrix	3.66	-52.07	calcite
88 2046-3	slab, dark matrix	3.86	-44.26	calcite
88 2049-1a	dark sandstone	3.47	-51.19	calcite
88 2049-1b	dark sandstone	3.44	-47.60	calcite
88 2052-1a	slab, dark matrix	4.39	-53.44	calcite
88 2053	slab, dark matrix	4.07	-46.92	calcite
88 2053/w tube	slab, dark matrix	4.25	-48.15	calcite
88 2053-3	block, dark matrix	4.05	-52.17	calcite
Aloha				
1A	shelf edifice	4.2	-49.91	aragonite
1B	shelf edifice	4.37	-50.63	aragonite, Mg-calcite
2A	shelf edifice	4.42	-51.59	aragonite, Mg-calcite
2B	shelf edifice	4.49	-51.24	aragonite, Mg-calcite
2C	shelf edifice	4.32	-48.27	aragonite, Mg-calcite
3A	shelf edifice	4.56	-51.54	aragonite, Mg-calcite
3B	shelf edifice	4.84	-52.23	aragonite, Mg-calcite
3C	shelf edifice	4.3	-51.75	aragonite, Mg-calcite
4A	shelf edifice			aragonite, Mg-calcite
4B	shelf edifice	4.19	-51.96	aragonite
5A	shelf edifice	4.42	-51.8	aragonite, Mg-calcite
5B	shelf edifice	3.95	-53.31	aragonite
Kodiak				
Chimney 1	shelf chimney	7.87	-21.85	dolomite
Chimney 2	shelf chimney	7.28	-16.9	dolomite
DE1A		7.34	-16.03	dolomite
DE3A		7.44	-14.62	dolomite
DE5A		7.79	-19.15	dolomite
Chimney 3	shelf chimney	7.26	-20.48	dolomite

A number of values (samples 1426, 1428) from the slope were obtained from Ritger et al. (1987) whereas the remainder are from this study.

† Carbonate standard derived from the rostra of *Belemnitella americana* from the Pee Dee Formation of South Carolina.

251 mass spectometer, a microinlet system, and automated small-sample carbonate extraction facilities.

Several subgroups of methane-derived carbonates were defined for specific vent sites from which different fluid sources may be inferred (see *Suess and Whiticar* [1989] for a discussion of the methane-derived CO_2 in expelled pore fluids) . The majority of samples (48) belong to two subgroups (I and II) with $\delta^{13}C$ values centered broadly around -35‰ and -53‰ PDB, respectively (Figure 11). The first subgroup (I) comprises samples from two chimneys (*Alvin* 1426-02, 1428-03), several slabs (*Alvin* 1904 and 1898), and one concretion (*Alvin* 1428-02), all of which were collected from the active vent area, *Alvin* 1428, first discovered in 1984 [*Kulm et al.*, 1986]. One sample, *Alvin* 1898-5S, is not considered in this context because it contains significant cemented shell debris which raises the carbon isotope composition well above that of other methane-derived carbonates. Carbon isotopic values for subgroup I range from -40.96 to -30.23‰ PDB. The oxygen isotope values of this subgroup span a large range from +6.8‰ to +4.7‰ PDB. This is much larger than can reasonably be expected from the minute temperature anomaly at vent site *Alvin* 1428. These fluids appear to be "cold"; their measured temperature is only slightly elevated (0.3°C), if at all different from that of the ambient bottom water of about 1.8°C [*Kulm et al.*, 1986].

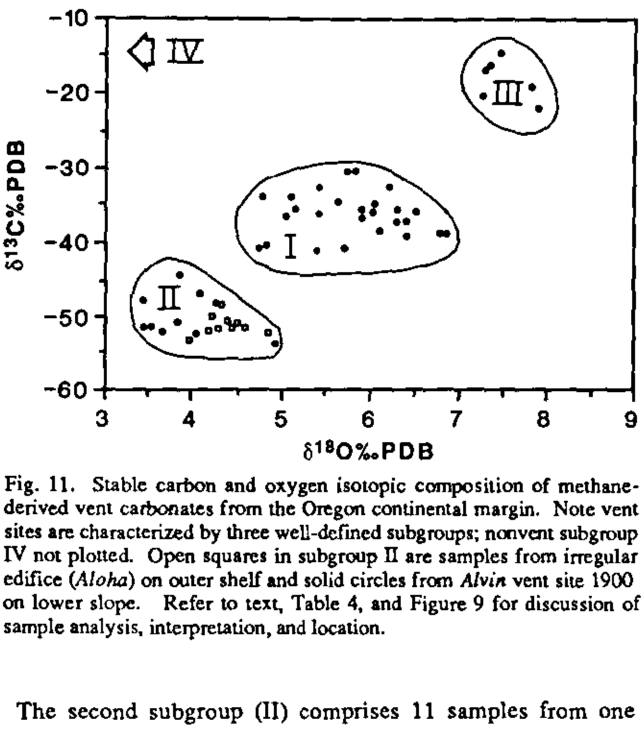

Fig. 11. Stable carbon and oxygen isotopic composition of methane-derived vent carbonates from the Oregon continental margin. Note vent sites are characterized by three well-defined subgroups; nonvent subgroup IV not plotted. Open squares in subgroup II are samples from irregular edifice (*Aloha*) on outer shelf and solid circles from *Alvin* vent site 1900 on lower slope. Refer to text, Table 4, and Figure 9 for discussion of sample analysis, interpretation, and location.

The second subgroup (II) comprises 11 samples from one irregular carbonate edifice (*Aloha*) which was dredged on the northern Oregon shelf, and 10 samples from six slabs (*Alvin* 1900 and 2046) from the second vent site, *Alvin* 1900, discovered on the lower slope off Oregon in 1987 (Figure 11). The samples of the irregular edifice (open squares) were taken from various parts of the chimney structure (see Figure 4*b* for location). In addition, two white clam shells, cemented in the matrix of the edifice (Figure 5*a*), yielded the following stable isotope data: $\delta^{13}C$ = -19.0‰ and -6.8‰ PDB; $\delta^{18}O$ = +4.52‰ and +4.18‰ PDB, respectively. This range of carbon isotopes suggests progressive contamination of the shell carbonate with methane-derived cement matrix. In this situation the chemosynthetic signature preserved in other vent clams (J. Boulègue et al., manuscript in preparation, 1990) cannot be verified. The carbon isotope values for subgroup II are much lighter (-44.26 to -53.44 ‰ PDB) than for subgroup I. The oxygen isotope values of the second subgroup (II) are also much lighter than those of the first (+3.4‰ to +4.9‰ PDB), but they also appear inconsistent with equilibrium formation at ambient temperatures. This is immediately obvious if one considers that the two vent sites, *Alvin* 1428 and 1900, are both at water depths of around 2050 m where the ambient temperature should be the same but the oxygen isotope signature of the carbonates differs by almost 2‰. Furthermore, the carbonate edifice (*Aloha*), which was dredged from outer shelf depths of around 250 m where the temperature is about 7°C, shows an oxygen isotope composition close to that of the samples from the deep vent site *Alvin* 1900.

The other subgroups (III and IV) are also differentiated on the basis of extreme oxygen and less so on carbon isotopic signatures (Figure 11). In subgroup III, strong ^{18}O enrichment characterizes the dolomitic samples from each of three large conical and cylindrical chimneys recovered by the vessel *Kodiak*. Subsamples of the inner, middle, and outer portion of the wall of the cylindrical chimney showed no significant changes in either the carbon or oxygen isotopes (*Kodiak* DE-1A-5A, Table 4). These ^{13}C-depleted carbonates indicate an organic source such as methane or other organic matter, whereas the oxygen isotopes appear to be inconsistent with the inferred temperature of formation, even when taking into account the effect of the dolomite mineralogy.

The two samples (Alvin 1428-01 and 1899-5) in subgroup IV are characterized by extreme $\delta^{18}O$ (-5.9 to -5.98‰) and moderate $\delta^{13}C$ (-18.7 to -12.67‰) -depleted carbonates, respectively (Table 4). They were collected from cemented sandstone outcrops exposed near the rim of the submarine canyon cutting the accretionary complex (Figure 9). This is presently an inactive venting setting because the backthrust is diverting the fluid flow to the crest of the ridge [*Moore et al.*, this issue]. This "light" oxygen isotope composition of -6‰ PDB is characteristic of formation either from hydrothermal fluids or meteoric groundwaters [*Thornburg and Suess*, 1989]. However, the light carbon isotopic values of the cements preclude a meteoric orgin for the fluids. The reason for the extreme ^{18}O-depletion of the carbonates within this tectonic setting still remains an enigma (see section on source and migration of fluids).

DISCUSSION

Internal Plumbing Network of Chimneys

Chimneys recovered from the continental shelf exhibit a variety of open internal plumbing networks consisting of cavities of various sizes, small circular tubes with thick walls, or an intertwined network of irregular tubes and openings that are conduits for venting fluids (Table 1). Using all of these observations, we will speculate about the growth stages of these various chimney structures.

A fairly energetic fluid flow with a single conduit is inferred from the cylindrical chimneys that form at the sediment-water interface. The conduit opening is believed to be the same size as the diameter of the central tubes (up to 30 cm) in the observed and recovered chimneys. Considerable volumes of methane and CO_2-charged fluids probably emanate from a fault or permeable zone in the underlying strata and generate a roughly circular flow-path within the porous unconsolidated sedimentary cover. In this scenario, carbonate precipitation commences at the point of exit by either pressure release or when the Ca-depleted pore fluids mix with Ca-rich bottom waters. Precipitation proceeds along the edges of the conduit and begins to construct the wall of a roughly circular chimney. As the fluid flow continues, precipitation thickens the conduit wall from the inside thereby decreasing the diameter of the initial opening. This would increase the flow rate and hence the chimney grows upward above the sediment-water interface as high as 170 cm. As precipitation occurs uniformly over the entire structure, the same external diameter and shape, in the case of the cylindrical chimneys, would be maintained. The best developed plumbing tubes apparently form during the later stages of chimney formation when its diameter decreases through carbonate precipitation and, perhaps, as the flow rate increases correspondingly. The overall development of an individual chimney can terminate at any stage depending upon the fluid pore pressure and longevity of the fluid source or after complete cementation of the plumbing network.

A less energetic flow is suggested by the chaotic plumbing network observed in the carbonate edifices and shell hash (Figures 4 and 5*b*) and by the widespread occurrence of carbonate slabs and crusts at many vent sites (Figure 10). These structures suggest slow but continuous seepage of fluid from cracks or fractures in the underlying strata. The circuitous movement of the fluids apparently originates in the unconsolidated detrital sands, where present on the seafloor, and in the process cements the sands. The plumbing network appears to be completely random because cementation of a given portion of the plumbing network diverts the flow to other parts of the structure, creating rather massive carbonate edifices or crusts of different size and shape not unlike travertine deposits on land. In contrast, thin (<10 cm) slabs lying on the sediment surface or encountered in the subsurface show no plumbing network, except that the numerous holes completely penetrating the slab might be orifices through which fluids escape.

Distribution of Fluid Conduits

Direct observations of the vent sites from submersibles, a remotely operated vehicle and thousands of bottom photographs taken from these devices show evidence for fluid venting at the seafloor. Active fluid escape is best identified by clusters of live clams and colonies of live tube worms. The clams invariably reside in sand-sized sediments where life-sustaining fluids escape. It appears that the hemipelagic sediments have been winnowed by the action of the expelled fluids and transported elsewhere by bottom currents. Past zones of fluid escape are recognized by dead clams (disarticulated shells with no soft parts), carbonate slabs, irregular edifices, and chimneys.

While we have not yet determined the nature of the subsurface conduits that provide the fluids, we can make inferences about their size and configuration from the surface and near-surface manifestations originating at fluid expulsion sites. On the lower continental slope, the vent sites range from a few square meters to about 400 m^2. They frequently contain several clusters of densely packed individual live clams (dominantly *Calyptogena* sp. with lesser numbers of *Solemya* sp. [*Suess et al.*, 1985]) ranging from tens to several hundreds per square meter. The clams may also form a ring-shaped feature, which is devoid of organisms in the center, several tens of centimeters in diameter. We think these configurations indicate a circular well-defined subsurface conduit directly beneath the vent. The highest fluid flow appears to emanate from the densest clam clusters [*Carson et al*, this issue]. Linear belts of live clams occur in other areas of the vent site, suggesting flow from a porous stratigraphic horizon (sand turbidites) or a fault that breaches the seafloor. These belts generally range from one to several meters in length and 10-30 cm in width. Large areas of the vent site are characterized by random distributions of live and dead clams, suggesting a less organized system of conduits or just numerous small areas of fluid escape. Few of the same species of live clams and tube worms seen on the lower slope have been obtained in bottom trawls from the outermost continental shelf and upper continental slope (Figure 1) [*Carey et al.*, 1988]. Submersible and ROV surveys of these areas in 1987 and 1988 failed to find a single live animal.

Many of the carbonate deposits are devoid of hemipelagic sediment raining down at the vent site, which suggests a fairly high rate of fluid expulsion and resulting carbonate precipitation. Carbonate slabs commonly occur beneath a thin sediment cover (detected by probing from the submersible) from within the vent site and could represent either present or past fluid venting. Live tube worms are commonly rooted in the cracks between carbonate layers or are tangled around the holes that characterized many of the slabs, suggesting that the cracks and strata beneath the slabs are pathways of fluid escape. The few carbonate chimneys (one each at three different vent sites) that have been observed on the lower slope are solitary features which have a conical shape with numerous small openings in the structures. This configuration infers the fluid flow emanates from a circular conduit. The rather ubiquitous carbonate slabs and cemented rock surfaces demonstrate a continuing fluid flow from an as yet undefined system of conduits or fractures in the underlying strata. We estimate that the surface and subsurface carbonates cover from 10% to 40% of the area at vent sites *Alvin* 1428 and 1900 on the lower slope (Figure 9).

The numerous conical, cylindrical, and doughnut-shaped carbonate chimneys observed and recovered on the outer continental shelf vent field strongly indicate a well-developed subsurface conduit and the carbonate slabs a more diffuse flow through fractures or permeable sands within the underlying strata. Considering the inside diameter of the chimneys, the conduit could be from 1 to 40 cm in diameter, assuming that the flow is concentrated at the center of the opening. Submersible observations document from one to two dozen doughnuts, many with 2-4 in a stack, in each of two different vent sites, measuring about 400 m^2. Assuming that each doughnut represents a separate fluid conduit, we calculate a minimum of one conduit for each 35 m^2 in these vent sites. The nets of bottom trawlers have disturbed the chimneys so their actual distribution in a given area cannot be confirmed.

Source, Composition, and Migration of Fluids

Methane- and CO_2-charged fluids are presently being expelled at the seafloor at several major vent sites on the lower slope off central Oregon. They were sampled in a benthic chamber deployed at site *Alvin* 1428 in 1987 and at site *Alvin* 1900 in 1988 [*Carson et al.*, this issue] (Figure 9). The methane is depleted in ^{13}C (i.e., $\delta^{13}C$ = -67 and -76.4‰ PDB, respectively) as well as the dissolved CO_2 resulting from oxidation of this methane [*Suess and Whiticar*, 1989]. These isotopic characteristics of the dissolved gases indicate that the fluids originate in the shallower portions (<1.0 km) of the underlying accretionary complex. While the two vent sites on the lower slope are about 1 km apart (Figure 9), they probably represent fluid flow from two different sources. A deep-towed seismic reflection record made over site *Alvin* 1900 shows a highly disturbed zone which is interpreted as large diapiric structures with onlapping basin deposits, whereas the seismic record over site *Alvin* 1428 displays essentially a seaward verging structure with onlapping basin deposits with only a probable small diapir at depth [*Lewis and Cochrane*, this issue]. Fluids may be migrating upward through the diapirs as well as through the permeable sand turbidites of the accreted material at site 1900. At site 1428, fluids may be migrating upward through the backthrust from intersecting permeable strata [*Moore et al.*, this issue] or along the interface between the seaward verging accreted sediments and the onlapping slope basin deposits (i.e., dotted line of slope basin, Figure 2) [*Lewis and Cochrane*, this issue].

A total water flow of 188 liters m^{-2} d^{-1} was measured at site *Alvin* 1428 over a circular cluster of approximately 100 living clams [*Carson et al.*, this issue]. The ultimate source of the biogenic methane is the buried pore waters of the Pleistocene sand turbidites of the Astoria Fan ($\delta^{13}C$ ranges from -80‰ PDB at 30 m below the seafloor to -66‰ PDB at about 340 m in a deep-sea drill hole [*Claypool and Kaplan*, 1974]) which have been accreted to the lower continental slope during the past 300,000 years (Figure 1) [*Kulm and Fowler*, 1974]. These fluids have migrated upward along permeable sand zones and/or faults to several vent sites mapped along the crest of the marginal ridge (Figure 2) [*Moore et al.*, this issue]. A diffusion-advection model predicts mean upward flow of fluids at a rate of 6-28 cm/yr regionally over the accreted complex comprising the marginal ridge, whereas much higher rates can be expected if the flow is confined to small-diameter conduits [*Han and Suess*, 1989].

The highly depleted $\delta^{13}C$ values of the irregular carbonate edifice from the outer shelf off northern Oregon also suggest a biogenic methane source for the expelled fluids. This source most likely lies within the upper one kilometer of the clastic Cenozoic deposits which apparently overlie subducted sediments from an early Cenozoic period of subduction (Figure 12) [*Snavely and McClellan*, 1987]. Although the seismic section is located north of the vent field, the numerous faults in this section could be the migration pathways for these fluids in the vent field observed from the submersible *Delta* in 1988. We have not found any active vents on the continental shelf although live chemosynthetic-type clams have been recovered in bottom trawls from this part of the margin [*Carey et al.*, 1988] and commercial fishermen report probable gas expulsion zones observed with high- frequency fish scanners (i.e., gas bubbles produce acoustic wipe-out zones).

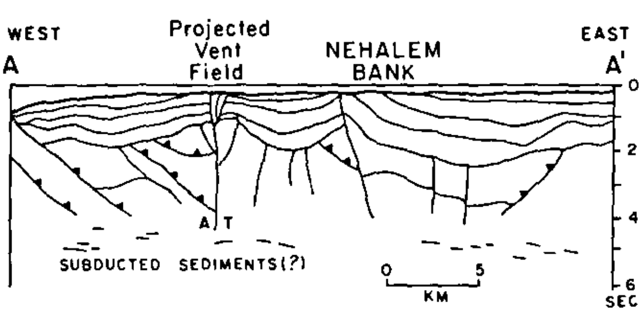

Fig. 12. Depth section of multichannel seismic line across outer continental shelf and upper slope (simplified from *Snavely and McClellan* [1987]). See Figure 3 (A-A') for location. Truncated folds and numerous faults in the Cenozoic sedimentary strata crop out on seafloor providing fluid migration pathways to the vents. The vent field is located 8 km to the south in the vicinity of a bank; it is projected onto the fault in a similar structural position.

The extremely ^{18}O-depleted cements (-6‰ PDB) of a few sandstones that are not associated with presently active vents suggest that during the past fluid sources, other than buried pore water of the Astoria Fan deposits, were active. While the circulation of groundwater of meteoric origin through these strata could produce these oxygen isotopic values, the light carbon isotopic values preclude such an origin, and the benthic foraminifera in these 0.3-m.y.-old accreted deposits of the lower continental slope indicate paleodepths of >3000 m for the original depositional environment of these source deposits and typical deep water conditions. Furthermore, there is no obvious structural or stratigraphic connection above the master décollement to meteoric waters on the continent or the continental margin during lowered sea levels. If meteoric waters were the source fluids, they would have to percolate downward into the continental crust, near the edge of the continent or the continental margin during lowered sea level (Figure 2). They would then have to migrate seaward along the permeable sand horizons in the turbidites to eventually be tapped by the master décollement with subsequent migration upward through the seaward verging thrust sequences comprising the marginal ridge where the carbonate cementation takes place. Seaward migration of fluids in the subducting sediments is postulated along a 30-km-long zone beneath the Barbados accretionary complex from the occurrence of thermogenic methane and low chloride content of pore fluids [*Moore et al.*, 1988]. However, the Oregon flow pathways are considerably more complex than documented for Barbados.

The most likely source of fluids with this ^{18}O-depleted value is the enclosed hydrothermal fluids presumably contained within the young, warm subducting basaltic slab of the Juan de Fuca plate. Hydrothermal circulation on the spreading Juan de Fuca Ridge is sealed off by the thick turbidite sediments that onlap the ridge shortly after the formation of the basaltic crust. This crust reaches temperatures of 180°C beneath the toe of the accretionary wedge [*McClain*, 1981]. It may contain enough of these hydrothermal fluids to provide a source of fluid in the accreted strata. Using the measured ^{18}O value (-6‰ PDB) of the cements in the sandstones, and assuming $\delta^{18}OH_2O$=0.00‰ SMOW, the calculated temperature of the recrystallized calcite is 45 ± 5°C. These warm fluids could migrate upward along the master décollement (Figure 2) as the fault-bend anticline began to evolve along the initial deformation front about 0.3 Ma ago [*Kulm et al.*, 1986; *Kulm and Fowler*, 1974]. Carbonate cementation of the sands would have occurred at an early stage (approximately 0.3-0.2 Ma) since the sands within the canyon are no longer venting pore fluids [*Moore et al.*, this issue]. In this area, sediments in an accretionary basin, situated between the marginal and second thrust ridges, have a high heat flow which is attributed to the advection of warm pore fluids from the accretionary complex below [*Langseth and Hobart*, 1984]. Further work is needed on the composition of the cements before more definitive conclusions can be drawn about a hydrothermal influence on these cements.

In each geologic setting with active venting the methane apparently migrates upward to the surface through permeable sand horizons or fault zones [*Moore et al.*, this issue] where it is oxidized by oxygen or sulfate-consuming microbes in order to precipitate carbonate at each vent site. An over pressured sedimentary section, like that commonly associated with an accretionary prism, would facilitate the upward movement of fluid and gas through one or more conduits.

Age of Carbonate Structures

Radiocarbon ages of carbonate samples from the continental slope vent sites show that the carbon in the cement is derived from an old carbon source. The carbonate carbon (authigenic carbonate cement) invariably gives an age >40,000 years on the Oregon margin [*Ritger et al.*, 1987]. The maximum estimated depositional age, based upon the rate of clastic sedimentation on top of the carbonate slabs, ranges from zero to about 5000 years. Sediment-free carbonate slabs and cements on rock outcrops are clearly forming today on the continental slope, but the older chimney structures on the shelf may range from a few thousand to several hundred thousand years in age.

Growth of Chimneys

We envision three probable scenarios for the origin of the carbonate chimneys: (1) upward growth above the seafloor; (2) upward growth at the sediment-water interface, which keeps pace with the surrounding clastic deposition and continued burial of the older portions of the chimney; and (3) formation below the seafloor, buried within the sediment column with later exhumation by uplift and erosion. The sediment-free, open plumbing network of all chimneys observed and recovered on the shelf and the scarcity of incorporated detrital material suggest there is a nearly continuous and unrestricted fluid flow through the chimney and growth above the seafloor. Despite the fact that the hemipelagic sedimentation rate is 2-6 cm/1000 years on the shelf and slope, respectively [*Kulm et al.*, 1975; *Kulm and Scheidegger*, 1979], most chimneys have only minor amounts of sand and silt-sized quartz and feldspar in the authigenic carbonate matrix.

Other chimneys may grow upward at approximately the same rate as the clastic sediments are deposited on the surrounding seafloor. For example, the bottom portion of the complex intertwined plumbing network noted in the irregular carbonate edifice formed within the glauconitic sand. These structures may form completely within the sandy deposits since it is difficult to imagine how the seeping fluids could elevate the sands above the seafloor. They are later exhumed by mechanical erosion of the surrounding unconsolidated deposits and are preserved because of their cemented structure. However, we have not yet observed a chimney with a well-developed plumbing network that was deeply buried in the clastic sediment or recovered a chimney that was broken off at its subsurface base. If the rate of clastic sedimentation is high or the fluid flow slows or terminates, the upward growth of the chimney through carbonate precipitation will not keep pace and the structure will be buried. Interestingly, we have not yet observed a single chimney, with the exception of the irregular carbonate edifice, where the internal plumbing network is completely plugged by clastic or carbonate material.

The formation of chimneys completely within the sedimentary strata by diagenetic replacement processes would help explain the inclusion of detrital material and late Cenozoic benthic and planktonic foraminifera in the carbonate matrix (P. Snavely, Jr., personal communication, 1987) of three of the shelf chimneys recovered off northern Oregon. Alternatively, the relatively strong bottom currents on the outer shelf [*Kulm et al.*, 1975] could erode the uplifted and exposed older strata and plaster these residual components onto the precipitating chimney. It is also difficult to envision how the internal plumbing network and, in some cases, the exterior holes in the chimney walls remain open as observed in all structures.

Several chimneys on the continental shelf were located at water depths between 150 and 250 m which is below the lowest position of sea level (about 130 m) attained during the Pleistocene glacial periods. In addition, the shelf is being uplifted at an average rate of 100-200 m/m.y. [*Kulm and Fowler*, 1974] which places the initial site of formation at somewhat deeper water depths during these earlier glacial periods. Subaerial erosion and truncation, similar to that seen over the uplifted Nehalem Bank could have exhumed the chimneys; this would require the subsidence of the vent field to the present water depth of 250 m after the chimneys were exhumed. However, all doughnut stacks observed here have large openings through the center of the stack which is difficult to produce if the chimneys once were encapsulated within the strata.

Therefore we believe that the majority of the chimney structures formed above the seafloor and that the rate of carbonate precipitation from subsurface fluid flow through a conduit exceeded the rate of detrital input during the formation of the chimney.

CONCLUSIONS

A great variety of carbonate structures, crusts, slabs, irregular edifices, concretions, and highly developed chimneys characterize the fluid venting sites of the accretionary complex and overlying basins of the Oregon continental margin. They occur near the crest of structural features, such as the sedimentary thrust ridges along the initial deformation front of the lower slope and the older thrust sequences of the middle slope, and in the vicinity of uplifted sedimentary strata of submarine banks along the outer continental shelf.

Carbonate deposition produces various shapes and sizes of structures whose plumbing networks appear to be related to the configuration of the fluid migration pathways. Circular chimneys are particularly common on the outer shelf suggesting a single well-defined subsurface conduit with a continuous, concentrated, and moderately high flow through the main body of the chimney or through tubes cemented within the main cavity of the chimney. This contrasts with widespread occurrence of carbonate slabs and crusts on the seafloor of the lower slope which imply more diffuse, widespread, and possibly slower flow from fractured/faulted strata or broad permeable zone within the underlying sedimentary strata.

The mineralogy of the carbonate cement in these structures consists of either aragonite, calcite, Mg-calcite or dolomite or combinations of these minerals; Mg-calcite (6-23 mol %), calcite and aragonite are the most common phases. Detrital components within the carbonate matrix may include quartz, feldspar, and authigenic pyrite and glauconite grains.

Stable carbon and oxygen isotope data identify four distinct subgroups of methane-derived carbonates from several different vent sites and different fluid source zones. Most carbonates are highly depleted in carbon 13 (i.e., much less than -35‰ PDB), implying that methane is the ultimate carbon source. The expelled fluids contain largely biogenic methane and methane-derived dissolved carbonate. Such a source is located at shallow subsurface depths of <1 km. The isotopic carbon values of the carbonates from vents on the lower continental slope are consistent with the carbon composition of the expelled fluids and apparently represent a historical record of the composition of these fluids. Carbonate cemented sandstones, obtained from a canyon cut into the accretionary complex along the lower slope, most likely originated from the upward migration of warm hydrothermal fluids along the main décollement which tapped the warm subducting basaltic slab early in the history of the formation of the accreted deposits.

The open plumbing network, the dominant carbonate content, and our direct observation of these authigenic structures on the seafloor suggest that they form close to the sediment-water interface. We envision that most chimneys grow upward above the seafloor through carbonate precipitation at a rate that exceeds the rate of clastic deposition at the vent site. The chimney may rise to a substantial height (1-1.5 m) above the floor. If the sedimentation rate is high or the fluid flow is slow or ceases, the chimney eventually will be buried.

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L.D. Kulm, College of Oceanography, Oregon State University, Oceanography Admin. Bldg. 104, Corvallis, OR 97331-5503.

E. Suess, GEOMAR, Forschungszentrum für marine Geowissenschaften, Wischhofstrasse 1-3, D-2300 Kiel 14, Federal Republic of Germany.

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